SMiRT 24
15th Interantional Seminar on FIRE SAFETY IN NUCLEAR POWER PLANTS AND INSTALLATIONS
- Proceedings -

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SMiRT 24 15th International Seminar on FIRE SAFETY IN NUCLEAR POWER PLANTS AND INSTALLATIONS - Proceedings -

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Deskriptoren

Nuclear fire safety, experimental research, Fire PSA, fire simulations, future designs, human factor, operating experience, regulations, safety assessment, standards

Kurzfassung

Im Rahmen des vom Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB) beauftragten Vorhabens 3617R01550 fand im Oktober 2017 das mittlerweile fünfzehnte internationale Seminar "Fire Safety in Nuclear Power Plants and Installations" als Post-Conference Seminar der 24th International Conference on Structural Mechanics In Reactor Technology (SMiRT 24) in Brügge, Belgien statt.

Die vorliegenden Proceedings des Seminars enthalten alle einundzwanzig Fachbeiträge des zweitägigen Seminars mit insgesamt sechzig Teilnehmern aus zehn Ländern aus Europa, Asien und Nordamerika.

Abstract

In the frame of the project 3617R01550 funded by the German Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit, BMUB) the meanwhile fifteenth international seminar on “Fire Safety in Nuclear Power Plants and Installations“ has been conducted as Post-Conference Seminar of the 24th International Conference on Structural Mechanics In Reactor Technology (SMiRT 24) in Bruges, Belgium in October 2017.

The following seminar proceedings contain the entire thirty technical contributions to the two days seminar with in total sixty participants from ten countries in Europe, Asia and Northern America.

Contents

1 Foreword and Introduction

The meanwhile 15th International Seminar on 'Fire Safety in Nuclear Power Plants and Installations' was held as Post-conference Seminar of the 24th International Conference on Structural Mechanics In Reactor Technology (SMiRT 24) in Bruges, Belgium in October 2017. In total sixty participants from Belgium, Finland, France, Germany, Hungary, Japan, Korea, The Netherlands, United Kingdom and the United States of America followed the thirty presentations in the different scientific sessions and participated actively in a final short expert panel discussion on future challenges with regard to fire safety of existing as well as new built nuclear facilities at the end of the seminar.

The two-day expert seminar started with a session on general issues in fire protection of nuclear facilities including recent developments in regulation and standards. Presentations were given on the role of quality assurance with regard to fire protection in the United States, on the significance of the human factor from a viewpoint of past large fire events in nuclear power plants (NPP) worldwide followed by two presentations on a very recent French standard for the safety demonstration of NPP fire barriers and on the expectations of ONR as regulatory body in the so-called Generic Design Assessment (GDA) process for new reactors to be designed and built in the United Kingdom.

The session was continued with presentations on a more recent approach applied to NPP in Belgium in the FHA (*f*ire *h*azard *a*nalysis) for containing fires in fire compartments, on the treatment of event combinations in fire safety assessment, a new French standard for NPP fire protection and an overview on implementation of recently improved fire protection features in the frame of the restart of NPP in Japan after the Fukushima accidents.

The second expert session was focused on the issue of high energy arc faults (HEAF) having the potential to inadmissibly impair the fire safety of a nuclear installation and to induce ensuing fires. In total four presentations highlighted the most recent insights from the operating experience from national as well as international experimental research, which will result in regulatory actions in different countries.

In total three expert sessions addressed the most recent issues in experimental fire research, modelling and fire safety analysis. During the two years period between the last SMiRT post-conference fire seminar and the actual one, various of experimental as well as analytical research actvities have been carried out and resulted in remarkable progress and lots of valuable insights. As an example, current transformer fires have been observed in the near past in nuclear facilities and recognized to represent fires which may cause some damage. Experimental investigations have been therefore carried out in the USA and the results of experimental study were presented. Other experimental activities presented at the seminar were forklift and glove box fires. Another issue which still needs further analysis (e. g. failure mode and effect analysis, FMEA) is the impact of heat and smoke gas products on electrical equipment.

Cable fires still represent a not yet completely resolved issue. This is the reason that the most recent international experimental fire project by OECD Nuclear Energy Agency (NEA) PRISME 3 partly focuses again on cable fires. Experimental and analytical results on the effect of cable arrangements on trays on mass loss rate (MLR) and fire propagation as well as the influence of fire retardant cable coatings on the cable fire behaviour were presented and lively discussed between the participants.

The presentations on analytical fire research highlighted insights on the combustion phenomena in a small-scale mechanically ventilated fire compartment, on the consideration of water based fire extinguishing systems in the modelling of compartment fires with different types of fire simulation codes and the most recent developments of analytical tools and expert systems based on fire simulations in France and Belgium for different purposes, e. g. the fire hazard analysis (FHA).

Last but not least, one paper was devoted to the development of a PSA for plant internal fires in the frame of the GDA for nuclear power plants to be newly designed in the United Kingdom.

The last session representing another major topic of the seminar was devoted to the operating experience with fires in nuclear installations and lesons learned. The in total four presentations covered a variety of aspects important for fire safety and the whole life cycle of a nuclear station. One important insight from the more recent operating experience with fire events in nuclear power plants is the non-negligible amount of event combinations with fires. Such combinations observed do not only cover causally related (so-called consequential or subsequent) events but also two or more events correlated by a common cause (which might also be an external hazard) and events occurring independently but simultaneously. It was clearly recognized that further in-depth analyses are needed on this issue and that these combinations have to be addressed in the regulations as well as in safety asssessment. Other lessons learned addressed in the session were the applicability of modern low pressure water mist extinguishing systems for electrical, in particular cable fires, and insights from a vulnerability study on the effects of smoke on diesel generators. One presentation particularly focused on fire safety issues in the last decommissioning phase of the nuclear life cycle including the handling of radioactive waste.

It has to be clearly pointed out that from the first seminars of this series starting in 1987 when the safety significance of fires in nuclear reactors had just been recognized up to today fire safety in nuclear power plants and other nuclear facilities has significantly increased. This does in general concern the plants' design and, in particular, of structures, systems and components (SSCs) important to safety as well as the operation of such installations, but also all areas of assessment, inspection and maintenance. Over more than thirty years, methodological approaches for assessing the fire risk and the respective analytical tools have been and are still being continuously improved and extended.

Further and to some extent new challenges do arise, affecting the analyses of fire hazards and their consequences in nuclear installations. Nuclear fire risk assessment also requires to continue research and development activities on a theoretical as well as an experimental basis. The new as well as updated and enhanced methodologies and analytical approaches need verification in general and explicit validation for their areas of application. It has also to be mentioned that the existing data have also to be continuously updated and adapted to the state-of-the art.

The seminar topics highlighted the quite broad scope of the issues related to fire safety in nuclear installations. The presentations and discussions again indicated that fires not only in existing nuclear facilities designed according to former standards but also in modern ones are still a "hot" topic and need to be addressed not only as single events, but also in the context of event combinations with other internal and external hazards.

One main goal of this fifteenth seminar on 'Fire Safety in Nuclear Power Plants and Installations' was to reflect the actual challenges and to provide insights in how to resolve fire safety issues identified, for existing nuclear installations as well as for reactor facilities to be built and safely operated in the future.

The seminar was hosted with great hospitality by Charles Fourneau and Pieter De Gelder from the Belgian Technical Safety Organisation (TSO) Bel V in Bruges, Belgium. The organizers are indebted to the invitation and support by the hosts during the two days seminar.

Moreover, the organizers want to thank the speakers, authors and chairpersons as well as the entire participants for their highly active and fruitful participation and valuable, high level contributions during this 15th International Seminar on ‘Fire Safety in Nuclear Power Plants and Installations’ which made this venue again a very successful one.

The next, 16th seminar of this series is intended to be held as SMiRT 25 Post-conference Seminar in late summer 2019.

Dr. Marina Röwekamp
- Scientific Chairperson and Permanent Organizer -

2 Seminar Agenda

Tuesday, October 3, 2017

19:00 h ***Welcome Reception in the conference hotel***

Wednesday, October 4, 2017

09:15 h	***Introduction by Hosts***	P. De Gelder, C. Fourneau	Bel V, Belgium
	Welcome by the Organizers	M. Röwekamp	GRS, Germany
09:25 h	**General / Regulation, Standards and Guidelines**	***Chairpersons:*** ***A. Alexiou, M. Lehto***	
	Quality Assurance and Its Role in Fire Protection: The U.S. Perspective	R. Sims	JENSEN HUGHES, USA
	“Once upon a time …" - Historic Large-Scale Fire Events in Nuclear Power Plants and the Limits of Transferability of Human Behaviour	D. Baumann, L. Gaukel	TÜV SÜD Energietechnik, Germany
	UK Regulatory Expectations in the Assessment of Internal Fire and Explosion Hazards through the Generic Design Assessment Process	D. F. Lisbona, et al.	ONR, United Kingdom
	ISO/DIS 18195: A New Standard for Justification of Nuclear Power Plants Fire Barriers	B. Gautier, D. Joyeux	EdF, France EFECTIS, France
11:05 h	***Coffee Break***		
11:25 h	**General / Regulation, Standards and Guidelines (contd.)**	***Chairpersons:*** ***M. Lehto, A. Alexiou***	
	Fire Protection Implementation and the Restart of Nuclear Power in Japan	P. Boulden Jr, B. Collyer	Appedix R Solutions, USA
	Development of a Fire Containment Approach of the Fire Hazard Analysis for the Belgian Nuclear Power Plants	X. Leblanc, et al.	Tractebel ENGIE, Belgium
	Assessment of Hazard Combinations Including Internal Fire	L. Nyogeri, et al.	ONR, United Kingdom
	AFCEN RCC-F: A New Standard for Fire Protection of Water Cooled Nuclear Power Plants	B. Gautier	EdF, France
13:05 h	***Lunch Break***		

14:15 h	**Special Issue: HEAF**	***Chairpersons:*** ***H.-P. Berg, G. Taylor***	
	U.S. NRC Actions and Path Forward as a Result of HEAF Phase 1 Testing Results	N. Melly, G. Taylor, et al.	NRC, USA
	Experimental Study on High Energy Arcing Faults (HEAF) to Assist Fire Safety Regulation	H. Kabashima, et al.	NRA, Japan
	Proposal for Evaluation Methodology on Total Arc Discharge Energy During HEAF (High Energy Arcing Fault) Events for High and Low Voltage Switchgears	K. Shirai, et al.	CRIEPI, Japan
15:30 h	***Coffee Break***		
16:00 h	**Experimental Fire Research**	***Chairpersons:*** ***G. Taylor, C. Fourneau***	
	Glove Box Fire Behaviour in Free Atmosphere	M. Coutin, L. Audouin	IRSN, France
	Insights from Recent Fire Testing - Current Transformers and Instrument Circuit Response to Fire	G. Taylor, A. Muña, C. LaFleur	NRC, USA; SNL, USA
	Experimental Characterization of a Forklift Fire	L. Audouin M. Coutin	IRSN, France
	Effects of Smoke and Thermal Stress on Electrical Equipment Failures	M. Piller, M. Coutin	IRSN, France
18:00 h	***Adjourn of the first day***		
19:00 h	***Hosted Dinner Event***	All participants enscribed and spouses	

Thursday, October 5, 2017

09:15 h	**Experimental Fire Research and Modelling**	***Chairpersons:*** ***W. Pluemecocq, M. Röwekamp***	
	Fire-Retardant Cable Coatings - A Fresh Look into Their Role in Risk-Informed Performance-Based Applications	F. Gonzales, G. Taylor, K. McGrattan, et al.	NRC, USA NIST, USA
	Experimental and Numerical Investigations of the Influence of Cable Arrangements on Cable Trays Concerning Mass Loss Rate and Fire Propagation	J. Spille, et al.	iBMB, Germany

	Experimental and Numerical Study of the Oscillatory Combustion Phenomenon in a Small-Scale and Mechanically Ventilated Compartment Fire	J. F. Pérez Segovia, et al.	Ghent University, Belgium
10:30 h	***Coffee Break***		
11:00 h	**Fire Safety Analysis and Modelling**	***Chairpersons:*** ***M. Röwekamp, H.-P. Berg***	
	Numerical Method for Determining the Droplet Size Distributions of Spray Nozzles Using a Two-Zone Model	W. Plumecocq, et al.	IRSN, France
	Blind and Open COCOSYS Calculations of the PRISME 2 Fire Extinguishing Systems (FES) 1 Experiment	D. Krönung, W. Klein-Heßling	GRS, Germany
	Numerical Simulations of Mechanically Ventilated Multi-Compartment Fires	J. Stewart, A. Kelsey	HSE, United Kingdom
	An Expert System Approach Based on a SYLVIA Data Base	E. Chojnacki, W. Plumecocq	IRSN, France
12:45 h	***Lunch Break***		
13:45 h	**Fire Safety Analysis and Modelling (contd.)**	***Chairpersons:*** ***M. Lehto, H.-P. Berg***	
	OPEPPI: Tool for Assessment of Passive Fire Protection	Y. Elmalki, et al.	Nuvia, France
	Focus on the Studies in Support of Fire Safety Analysis: IRSN Fire Modelling Approach for Nuclear Power Plants	R. Meyrand, J. Espargillière	IRSN, France
	Development of an Integrated Tool (FOCUS) for Fire Influence Approach Analysis in the Framework of the Fire Hazard Analysis for the Belgian Nuclear Power Plants	L. P. Kwahou Kezembo	Tractebel ENGIE, Belgium
	Development of Internal Fire PSA for New Build UK Generic Design Assessment	G. Georgiev, et al.	Jacobsen Analytics; United Kingdom
15:25 h	***Coffee Break***		
15:55 h	**Operating Experience and Lessons Learned**	***Chairpersons:*** ***C. Fourneau, M. Röwekamp***	
	Fire Protection for Nuclear Power Plants During Dismantling and for Sites Where Radioactive Materials Are Handled (Out of Application Area of Atomic Energy Act)	M. Schwenker, et al.	TÜV SÜD Industrie Service, Germany

	Development of a Low Pressure Water Mist System to Ensure Functionality of Low Voltage Cables	F. Bonte, F. Xu, E. Maillet	Flex-A bvba, Belgium, Tractebel ENGIE, Belgium
	Event Combinations with Fires – Update from the OECD FIRE Database	A. Iancu; H.-P. Berg, N. Fritze	BfE, Germany
	Vulnerability Assessment of Diesel Generators against Fire/Explosion Fumes	B. Forell, J. Park	GRS, Germany
17:45 h	**Panel Discussion**	***Chairperson: L. Kuriene (Netherlands)***	
	Panel participants:	H.-P. Berg C. Fourneau M. Lehto W. Pluemecocq M. Röwekamp G. Taylor	
18:15 h	***Seminar Adjourn***		

3 Seminar Contributions

In the following, the seminar contributions prepared for the 15th International Seminar on 'Fire Safety in Nuclear Power Plants and Installations' held as Post-conference Seminar of the 24th International Conference on Structural Mechanics In Reactor Technology (SMiRT 24) are provided in the order of their presentation in the seminar.

4 Seminar Conclusions and Outlook

The 15th International Seminar on 'Fire Safety in Nuclear Power Plants and Installations' clearly demonstrated ongoing progress in nuclear fire safety with respect to experiments and assessment performed in the recent past. However, there are still challenges since the knowledge on some fire related phenomena is still not yet mature and the analytical tools applied need further enhancement.

The presentations at this seminar provided an added value to the state-of-the-art in nuclear fire safety highlighting recent developments, but also describing in an open manner still unsolved issues in this area.

The following conclusions have been drawn from the seminar sessions and the final panel discussion:

Remarkable progress has been achieved with respect to fire safety in nuclear installations and its assessment. This is also reflected in the recent nuclear regulations, standards and guidance documents, internationally as well as in different countries worldwide. One aspect in this context is an adequate quality management system based on generic high-level criteria to address the necessary elements to ensure that the fire protection programs are implemented correctly and to verify the efficiency of a fire barrier with regard to the potential fire hazard conditions in a given location of the installation.

The seminar has indicated that in some countries the focus of fire safety for nuclear reactor facilities is currently more or less on the planning, construction and operational phase. In other countries with existing nuclear power plants close to the end of their operational lifetime several activities are ongoing on fire safety during the post-commercial safe shutdown and the decommissioning phases.

It has to be underlined that fire safety is still an important issue, which has to be addressed at all types of nuclear facilities from their construction throughout their operational and post-operational lifetime until decommissioning has been finally completed. The provisions for a nuclear power plant in the decommissioning process have to include a procedure that allows appropriate and reliable measures for fire prevention and protection and should also cover fire protection means needed in those facilities where radioactive material is handled, treated and/or stored.

In some countries, new fire protection regulations and standards are being issued for deterministic as well as probabilistic safety assessments of operating nuclear power plants in order to identify significant improvements, e. g., for demonstrating that the capabilities required to safely shut down the reactor, to remove the residual heat and to contain the radioactive material are maintained in case of any single internal fire or to refine post-fire safe shutdown procedures to ensure an adequate fire response.

In case of new nuclear power plants expectations are that the optimization of the plant layout in order to reduce adverse effects from internal hazards will take place at the early stages of design. This involves the avoidance of large combustible inventories as well as a minimisation of the number of fire barrier penetrations, including doors, ventilation ducts, cabling and pipework in plant areas important to safety.

International operating experience from nuclear power plants has underpinned that electrical distribution equipment (e. g., switchgears, bus ducts, etc.) can be subject to a failure mode that causes extensive damage known as HEAF. Recent investigations of event data from the international fire events database OECD FIRE have indicated that the vast majority of event combinations of fires and other anticipated events are fires as consequential events resulting from HEAF. Equipment failures that result in HEAF cause a rapid release of extremely high electrical energy in the form of heat, vaporized metals such as copper and aluminium, a plasma build-up, and explosive mechanical forces.

An international test program launched by the OECD NEA and conducted by the United States Nuclear Regulatory Commission (NRC) Office of Research as Operating Agent focused on investigations of high energy electrical breakers and bus ducts covering components of various manufacturers and dates of production, with different configurations and materials used for the components and operated on different medium and high voltage levels. Although the tested components provided significant insights into the performance of equipment installed in nuclear facilities, too many uncontrolled variables exist in order to fully understand their effect on the severity of a HEAF and the potential for an ensuing fire. However, the results of the first phase of the test program indicated the importance of the interaction with aluminium materials to be a potential exacerbating contributor to the extent of damage, commonly referred to as zone of influence.

Therefore, a further set of full-scale experiments to further explore the damage conditions created by HEAF events is intended to be started in 2018. The results from this experimental series called HEAF, Phase 2 experiments are expected to provide more insights on the thermal and mechanical damage caused by HEAF fire events to different types of targets, such as cables and electrical cabinets.

HEAF fire tests were also conducted in Japan in order to obtain technical knowledge about the arc energy level at which an ensuring fire occurs, and the impact of arc discharge. In the new Japanese HEAF regulatory requirements, prevention of ensuing fires and mitigation of explosions are required. One of the possible counter measures is a replacement of analogue type over-current relays to digital type ones. The response of the digital type over-current relays is much faster than that of old analogue type ones. Moreover, concerning the degree of the HEAF impact and other factors, safety research and investigations are foreseen to be continued.

Further experimental research efforts have taken place in order to understand the different failure modes of current transformers and instrumentation cables from thermally damaging conditions. In case of current transformers, the research demonstrated the difficulty in developing conditions that support ignition of materials and components in a secondary location from the induced open circuit fault. This evidence provides a strong technical basis to support updates of current guidance.

Further experiments in France address the heat and combustion product transfers from a fire compartment to adjacent rooms. The results highlight that smoke combined with thermal effects behaves like aggravating agents which favour the malfunction occurrence of electronic relays.

The routing of cables on cable trays has a strong influence on fire propagation within various industrial buildings and power plants. Cables themselves represent a major fire source within these buildings, with non-negligible fire load but also acting as ignition source due to technical malfunction. Experimental results show a large impact of the cable arrangement on fire development and propagation. A tight cable arrangement leads to different flow properties associated with a different burning behaviour as well as a decrease in the maximum mass loss rate, if neighbouring cables protect parts of the cable sheath surface.

Computational Fluid Dynamics (CFD) is increasingly being used in nuclear industry for fire consequences modelling. The ability of models to adequately capture the fire behaviour in confined, mechanically ventilated environments is of key importance. The publicly available Fire Dynamics Simulator (FDS) code is often used for modelling scenarios relevant for nuclear industry. FDS simulation results have been compared to experimental data obtained from the international OECD PRISME INTEGRAL test series conducted by the French Institut de Radioprotection et de Sûreté Nucléaire (IRSN). In this specific case, a well-sealed mechanically ventilated multi-compartment configuration has been simulated. A comparison of analytical and experimental results has demonstrated that reasonable predictions of fire consequences are possible for well-defined fire sources. Additional analytical work is required in order to develop combustion modelling approaches which can adequately capture the influence of under-ventilated conditions on the fire behaviour.

In order to comply with the nuclear safety goals, safety functions of items important to safety, which need to be maintained, have to be identified for performing an adequate fire safety analysis. For that purpose, the safety goals have to be associated with key parameters and performance criteria. One of the key issues of such a fire safety analysis is the assessment of all relevant fire scenarios in the respective plant.

Another aspect recognized by the seminar participants is the role of passive fire protection means (e. g., fire barriers and their elements) and their significance during all phases of the entire life cycle of a nuclear power plant. In this context, the main difficulty results from deviations between the original design and the real situation in the facility due to modifications of the environment during construction, addition of new equipment and materials in the room, fire protection improvements, etc. However, for the purpose of an as far as realistic assessment, an appropriate and not too complex tool would be helpful.

Operating experience from different types of industrial installations has shown that combinations of different types of hazards do occur during the entire lifetime of these installations. Typically, site specifically occurring hazards cause or induce other hazardous events (so-called cascading effects) to occur. In particular, natural hazards rarely happen alone. Thus, it is very important to note that almost any event combination of hazards with plant internal fires is possible and that it is necessary to identify such potential interactions specifically for each type of industrial facility and to determine ways to mitigate as far as possible the effects of hazard combinations. This was one reason for analysing in more detail the different types of event combinations of fires and other events based on the most recent version of the OECD FIRE Database with more than 10 % of the events representing such event combinations. The investigations have demonstrated the need for identification of hazard combinations in an as far as possible systematic and comprehensive manner. In this context, key principles for identification, analysis and mitigation of hazard combination sequences have to be provided and to be addressed in the regulatory framework in future.

The participants from Asia, Northern America and Europe, representing the different parties involved in nuclear fire safety, nuclear industry as well as regulatory bodies, research institutions and technical expert and support organizations (TSO), emphasized the added value of and benefits from the information provided in this experts' seminar to be shared inside the nuclear fire community. They strongly expressed their wish of continuing this series of fire safety seminars on a regular basis in time intervals of approximately two years. The next, 16th seminar of this series is therefore planned to be conducted in late summer 2019 in conjunction with the 25th 'International Conference on Structural Mechanics In Reactor Technology' (SMiRT 25), which will take place in Charlotte, NC, United States of America in August 2019 (cf. http://www.smirt25.org/).

QUALITY ASSURANCE AND ITS ROLE IN FIRE PROTECTION THE U.S. PERSPECTIVE

Roger Sims

JENSEN HUGHES, Inc., United States of America

ABSTRACT

In the review of the Browns Ferry fire event, the U.S. Nuclear Regulatory Commission (NRC) drew the conclusion that many of the aspects leading up to the event represented lapses in quality assurance. As a result, the NRC mandated the use of an “augmented” quality assurance program, imposing select criteria from 10 CFR 50, Appendix B [1] for non-safety related features of the fire protection program. This represented the first application of a graded approach to quality assurance in the nuclear power industry. This paper will review the quality assurance criteria that have been applied to fire protection systems, structures and components in U.S. nuclear plants. These criteria will then be compared to the requirements contained in such documents as ISO 9001, Quality Management Systems – Requirements [2], IAEA Safety Guide GS-G-3.1, Application of the Management System for Facilities and Activities [3], and IAEA Safety Guide NS-G-2.1, Fire Safety in the Operation of Nuclear Power Plants [4]. The comparison will demonstrate any significant differences between these standards and the practices in US nuclear facilities.

BACKGROUND

On March 22, 1975, a fire occurred in the of the Unit 1/Unit 2 Cable Spreading Room of the Browns Ferry Nuclear Plant in Athens, Alabama, USA. The fire occurred during modification activities for Unit 3. The fire event lasted for over seven hours, with the loss of the safety systems for Unit 1 outlined in the following Table 1.

Table 1 Consequences of Cable Damage Attributable to Fire at Browns Ferry Unit 1*

Consequence of Fire Damage	Attributed Cause
Loss of power supplied from 480 V shutdown boards 1A and 1B	Fire-induced hot-short in circuit breaker trip indicator light caused voltage to be backfed to the breaker trip coil, thereby keeping it energized Power cables faults
Spurious closure and inability to reopen MSIVs	Fire damage to MSIV control circuits
Spurious trip of the train A reactor feedwater pump	False high reactor water level signal to feedwater pump controller. Note: Remaining Train B and C pumps were manually tripped at the time of the scram.
Inoperability of the steam operated HPCI	Fire-induced faults to cables associated with 250 V DC Motor Operated Valve (MOV) board 1A, which powers HPCI valve controls. In addition, cables associated with 480 V MOV board 1A which powers the steam isolation valve.

Consequence of Fire Damage	Attributed Cause
Inoperability of redundant RHR systems	Fire-induced failure of 480 V MOV boards 1A and 1B caused loss of power to these valves. Also, fire-induced loss of power supplied from 4 kV shutdown board C caused a loss of RHR pump 1B
Inoperability of redundant CS systems 1A, 1B, 1C, and 1D	Fire-induced failure of 480 V MOV board 1A and 1B caused loss of power to valves. Also fire-induced loss of power supplied from 4 kV shutdown board C caused loss of CS pump 1B
Inoperability of redundant trains of Standby Liquid Control Systems (SLCSs) 1A, 1B	Fire-induced loss of power from redundant 480 V shutdown boards 1A and 1B to pump motors and valves
Inoperability of steam driven RCIC	Inability to electrically operate steam isolation valve as a result of a cable fault and loss of power of 480 volt MOV board 1B
Loss of ability to operate all relief valves	Spurious closure and inoperability of 7 of 11 relief valves attributed to loss of power supplied from redundant 250 V DC boards 1A and 1B. Subsequent spurious closure of drywell air compressor flow control valve cut off air supply to remaining 4 relief valves, thereby rendering them inoperable for 4 h
Abnormal behaviour of instrumentation: Observed ECCS alarms were contrary to system status Random lights on ECCS panel began glowing alternately bright and damage	Fire damage to ECCS instrumentation circuits
Loss of operability of Emergency Diesel Generator (EDG)C and Loss of remote control capability of EDG B and EDG D	Fire damage to EDG control and instrumentation circuits.

* Hearings Before the Joint Committee on Atomic Energy, Congress of the U.S., First Session," September 16, 1975 [5].

Although not as severe, the fire also impacted Unit 2 operations for approximately 6 hours following initiation of the fire. Examples of abnormalities noted by Unit 2 operators include the loss of electrical power supplied from various 4160 V and 480 V shutdown boards, closure of the Main Steam Isolation Valves (MSIVs), loss of the manual actuation capability of all Safety Relief Valves (SRVs), and loss of High Pressure Coolant Injection (HPCI), because of spurious closure of torus suction valves [5].

The U.S. NRC formed a Special Review Group (SRG) whose report was issued in NUREG 0050 [6]. One of the findings of the SRG related to Quality Assurance was reported as follows:

"*1.6.4 Quality Assurance*

Quality assurance (QA) programs are intended to catch errors in design, construction, and operation, and to rectify such errors; QA is an essential component of defense-in-depth. Many aspects of the Browns Ferry fire can be considered as lapses in QA. Examples are unfinished fire stops, inadequate separation of cables containing indicator lamp circuits, testing *operations with a candle, use of highly flammable material to plug leaks in fire stops, and failure to pay attention to earlier small candle-induced fires.*

The Review Group believes that the causes, course, and consequences of the Browns Ferry fire are evidence of substantial inadequacies in the Browns Ferry QA program …

The extensive QA requirements of the NRC are applied to systems and components designated as important to reactor and public safety. Before the Browns Ferry fire, this did not include such items as fire protection systems or sealing of penetrations in walls, floors, and other barriers aside from radioactivity containment structures."

The NRC first issued QA requirements for fire protection programs in Branch Technical Position (BTP) APCSB 9.5-1, Appendix A [7]. These requirements applied to plants which were docketed prior to July 1, 1976. Subsequent guidance was issued to expand the plants they applied to in Generic Letter (GL) 77-02 [8], NUREG 0800, Section 9.5-1 [9], and Regulatory Guide (RG) 1.189 [10]. With some minor wording differences, these documents all provided the same basic guidance. Therefore, the guidance used in RG 1.189 will be used for the purposes of this paper.

FIRE PROTECTION QUALITY ASSURANCE REQUIREMENTS

The criteria from 10 CFR 50, Appendix B [1] are shown in Table 2 below. Items shown in Bold are included in the program required by the NRC. While not specifically called out, Organization, QA Program and Document Control are implied to be required by RG 1.189 [10]. RG 1.189 stated that the QA program would be administered by the QA organization. The first criteria provided for FP programs is Design and Procurement Document control, which involves the Document Control criteria.

Table 2 10 CFR 50 Appendix B Criteria

Organization	**Inspection**
QA Program	**Test Control**
Design Control	Control of Measuring and Test Equipment
Procurement Document Control	Handling, Storage and Shipping
Instructions, Procedures and Drawings	**Inspection, Test and Operating Status**
Document Control	**Control of Nonconforming Items**
Control of Purchased Items and Services	**Corrective Action**
Identification and Control of Items	**QA Records**
Control of Special Processes	**Audits**

The QA requirements disseminated by the NRC were the following:

Design and Procurement Document Control

Establish measures to include the guidance presented in this regulatory guide in its design and procurement documents. Deviations from this guidance should be controlled to ensure that the following occurs:

a. Design and procurement document changes, including field changes and design deviations, are subject to the same level of controls, reviews, and approvals that were applicable to the original document.

b. The design documents, such as appropriate fire protection codes and standards, specify quality standards, and deviations and changes from these quality standards are controlled.
c. Qualified personnel review new designs and plant modifications, including fire protection systems, to ensure inclusion of appropriate fire protection requirements. These reviews should include items such as the following:
    i. design reviews to verify the adequacy of wiring isolation and cable separation criteria, and
    ii. design reviews to verify appropriate requirements for room isolation (sealing penetrations, floors, and other fire barriers).
d. Qualified personnel perform and document the review and approval of the adequacy of fire protection requirements and quality requirements stated in procurement documents. This review should determine that fire protection requirements and quality requirements are correctly stated, able to be inspected, and controllable; there are adequate acceptance and rejection criteria; and the procurement document has been prepared, reviewed, and approved in accordance with applicable QA program requirements.

Instructions, Procedures, and Drawings

Documented instructions, procedures, or drawings should prescribe inspections, tests, administrative controls, fire drills, and training that govern the FPP, and the program should ensure that the following occurs:

a. Indoctrination and training programs for fire prevention and firefighting are implemented in accordance with documented procedures.
b. Activities such as design, installation, inspection, test, maintenance, and modification of fire protection systems are prescribed and accomplished in accordance with documented instructions, procedures, and drawings.
c. Instructions and procedures for design, installation, inspection, test, maintenance, modification, and administrative controls are reviewed to ensure that the proper fire protection requirements are addressed, such as control of ignition sources and combustibles, provisions for backup fire protection capability, disablement of a fire protection system, and restrictions on material substitutions unless specifically evaluated.
d. The installation or application of penetration seals, fire barrier systems, and fire-retardant coatings is performed by trained personnel using approved procedures.

Control of Purchased Material, Equipment, and Services

Establish the following measures to ensure that purchased material, equipment, and services conform to the procurement documents:

a. provisions, as appropriate, for source evaluation and selection, objective evidence of quality furnished by the contractor, inspections at suppliers, or receipt inspections, and
b. source or receipt inspection, at a minimum, for those items that, once installed, cannot have their quality verified.

Inspection

Establish and execute a program for independent inspection of activities affecting fire protection that allows the organization performing the activity to verify conformance to documented installation drawings and test procedures. This program should include the following:

a. inspection of installation, maintenance, and modification of fire protection systems or features,
b. inspection of emergency lighting and communications equipment to ensure conformance to design and installation requirements,
c. inspection of the installations of penetration seals, fire barriers, and fire-retardant coating, to verify that the activity is satisfactorily completed,
d. inspection of cable routing to verify conformance with design requirements,
e. inspections to verify that appropriate requirements for room isolation (sealing penetrations, floors, and other fire barriers) are accomplished during construction,
f. measures to ensure that inspection personnel are independent from the individuals performing the activity being inspected and are knowledgeable in the design and installation requirements for fire protection, and
g. inspection procedures, instructions, and checklists that provide for the following:
    i. identification of characteristics and activities to be inspected,
    ii. identification of the individuals or groups responsible for performing the inspection operation,
    iii. acceptance and rejection criteria,
    iv. a description of the method of inspection,
    v. recording of evidence of the completion and verification of a manufacturing, inspection, or test operation,
    vi. recording of inspector or data recorder and the results of the inspection operation,
    vii. periodic inspections of fire protection systems, emergency breathing and auxiliary equipment, emergency lighting, and communications equipment, to ensure the acceptable condition of these items, and
    viii. periodic inspection of materials subject to degradation, such as fire barriers, stops, seals, and fire-retardant coatings, to ensure that these items have not deteriorated or been damaged.

Test and Test Control

Establish and implement a test program to ensure that testing is performed and verified by inspection and audit to demonstrate conformance with design and system readiness requirements. The tests should be performed in accordance with written test procedures; test results should be properly evaluated and corrective actions taken as necessary. The test program should include the following:

a. Installation Testing - Following construction, modification, repair, or replacement, the licensee should perform sufficient testing to demonstrate that fire protection systems, emergency lighting, and communications equipment will perform satisfactorily in service and that design criteria are met. Written test procedures for installation tests should incorporate the requirements and acceptance limits contained in applicable design documents.
b. Periodic Testing - The licensee should develop and document the schedules and methods for periodic testing. Periodic testing of fire protection equipment, emergency lighting, and communications equipment will ensure that the equipment will function properly and continue to meet the design criteria.
c. Quality Assurance - The licensee should establish programs for QA and quality control (QC) to verify testing of fire protection systems and features and to determine whether test personnel are effectively trained.

d. Documentation - A qualified individual or group should be responsible for ensuring that test results are documented, evaluated, and acceptable.

Inspection, Test, and Operating Status

Establish measures to document or identify items that have satisfactorily passed required tests and inspections. These measures should include identification by means of tags, labels, or similar temporary markings to indicate operating status and completion of required inspections and tests.

Nonconforming Items

Establish measures to control items that do not conform to specified requirements to prevent inadvertent use or installation. These measures should include provisions to ensure that the following occurs:

a. Nonconforming, inoperable, or malfunctioning fire protection systems, emergency lighting, and communication equipment are appropriately tagged or labelled.
    i. The identification, documentation, segregation, review disposition, and notification to the affected organization of nonconforming materials, parts, components, or services are procedurally controlled.
    ii. Documentation identifies the nonconforming item, describes the non-conformance and the disposition of the nonconforming item, and includes signature approval of the disposition
    iii. Provisions are established to identify those individuals or groups delegated the responsibility and authority for the disposition and approval of nonconforming items.

Corrective Actions

Establish measures to ensure that conditions adverse to fire protection, such as failures, malfunctions, deficiencies, deviations, defective components, uncontrolled combustible materials, and non-conformances, are promptly identified, reported, and corrected. These measures should ensure the following:

a. Procedures are established to evaluate conditions adverse to fire protection (such as non-conformance, failures, malfunctions, deficiencies, deviations, and defective material and equipment) to determine the necessary corrective action.
b. In the case of significant or repetitive conditions adverse to fire protection, including fire incidents, the cause of the conditions is determined and analysed and prompt corrective actions are taken to prevent recurrence. The cause of the condition and the corrective action taken are promptly reported to cognizant levels of management for review and assessment.

Records

Prepare and maintain records to furnish evidence that the plant meets the criteria enumerated above for activities affecting the FPP, so that the following is true:

a. Records are identifiable and retrievable and should demonstrate conformance to fire protection requirements. The records should include results of inspections, tests, reviews, and audits; non-conformance and corrective action reports; construction, maintenance, and modification records; and certified manufacturers' data.

b. Established record retention requirements exist.

Audits

Conduct and document audits to verify compliance with the FPP. Ensure that the following occurs:

a. Audits are performed to verify compliance with the administrative controls and implementation of QA criteria, including design and procurement documents, instructions, procedures, drawings, and inspection and test activities as they apply to fire protection features and safe-shutdown capability. QA personnel perform these audits in accordance with pre-established written procedures or checklists. The trained personnel who conduct the audits should not have direct responsibilities in the areas being audited.
b. Audit results are documented and then reviewed with management responsible for the area audited.
c. Follow-up action is taken by responsible management to correct the deficiencies revealed by the audit.
d. Audits are performed annually to provide an overall assessment of conformance to fire protection requirements.

The criteria shown provide a graded quality approach for implementation of fire protection programs.

ISO 9001 – 2015 QUALITY MANAGEMENT SYSTEMS – REQUIREMENTS

ISO 9001 is a generic standard used for the development of quality management systems. It's scope states:

"*This International Standard specifies requirements for a quality management system when an organization:*

- *a) needs to demonstrate its ability to consistently provide products and services that meet customer and applicable statutory and regulatory requirements, and*
- *b) aims to enhance customer satisfaction through the effective application of the system, including processes for improvement of the system and the assurance of conformity to customer and applicable statutory and regulatory requirements.*

All the requirements of this International Standard are generic and are intended to be applicable to any organization, regardless of its type or size, or the products and services it provides."

The required processes for a quality management system is defined in Section 4.4 of ISO 9001 as follows:

"4*.4 Quality management system and its processes*

The organization shall establish, implement, maintain and continually improve a quality management system, including the processes needed and their interactions, in accordance with the requirements of this international standard.

The organization shall determine the determine the processes needed for the quality management system and their application throughout the organization and shall determine:

- *a) The inputs required and the outputs expected from these processes;*
- *b) The sequence and interaction of these processes;*
- *c) The criteria, method, including measurements and related performance indicators needed to ensure the effective operation, and control of these processes;*
- *d) The resources needed and ensure their availability;*
- *e) The assignment of the responsibilities and authorities for these processes;*

f) The risks and opportunities in accordance with the requirements of 6.1, and plan and implement the appropriate actions to address them;

g) The methods for monitoring, measuring, as appropriate, and evaluation of processes and, if needed, the changes to processes to ensure that they achieve intended results;

h) Opportunities for improvement of the processes and the quality management system.

The organization shall maintain documented information to the extent necessary to support the operation of processes and retain documented information to the extent necessary to have confidence that the processes are being carried out as planned."

As noted, the requirements of ISO 9001 are generic in nature and are meant to provide the methods for developing a Quality Management System. Such items as inputs required and outputs expected, control of processes, resource qualifications, and the need to identify and implement opportunities for improvement are all parts of the quality assurance program as it applies to fire protection.

GS-G-3.1 - APPLICATION OF THE MANAGEMENT SYSTEM FOR FACILITIES AND ACTIVITIES

The purpose of the Safety Guide is provided in the Background section, and reads as follows:

"*1.1. This Safety Guide supports the Safety Requirements publication on The Management System for Facilities and Activities [11]. It provides generic guidance to aid in establishing, implementing, assessing and continually improving a management system that complies with the requirements established in [11]. In addition to this Safety Guide, there are a number of Safety Guides for specific technical areas. Together these provide all the guidance necessary for implementing the requirements of [11]."*

As such, this Safety Guide is generic in nature, providing high level requirements governing the development of processes and programs.

As the Fire Protection Quality Assurance program is considered to be a graded approach, the section for graded approach from the Safety Guide is considered to be appropriate. The process is described as follows:

"*2.41. The grading process should determine the extent of the application of the requirements of the management system to the products and activities of the organization.*

2.42. Applying controls demands resources. Resources should be applied and focused where they are necessary on the basis of aspects such as safety significance and risks. They should be applied to a lesser degree for less important products or activities. Errors in more significant products or activities could potentially lead to the diversion of large amounts of resources, could shut down a facility or production line, and could cause a threat to individuals and the environment. Introducing additional controls that may reduce or eliminate such errors is therefore highly beneficial.

2.43. It is common sense to apply tighter controls to more important products and activities. A methodology for grading should be developed that ensures that all individuals in the organization apply this common sense approach in a uniform manner."

The development of the Fire Protection Quality Assurance Criteria provided in RG 1.189 can be viewed as a method to apply this form of graded approach process.

NS-G-2.1 - FIRE SAFETY IN THE OPERATION OF NUCLEAR PLANTS

This IAEA Safety Guide provides recommendations on the elements of plant management and operation that are necessary to achieve and maintain fire safety. As such it is considered to be one of the "*number of Safety Guides for specific technical areas*" referenced in GS-G-3.1**.** Guidance on quality assurance is provided in Section 10 of the document. This section states:

"*10.2 A formal, documented quality assurance system should be established and implemented for activities affecting, and information relating to, fire safety in areas identified as important to safety.*"

Aspects of the fire protection program for which quality assurance provisions should be applied are provided in Section 10.3 of the Safety Guide. These aspects are shown in Table 3 with the relevant criteria mandated by the NRC for comparison.

Table 3 Comparison of NS-G-2.1 to RG 1.189

NS-G-2.1 Criteria	RG 1.189 Criteria
Fire Hazards Analysis	Design and Procurement Document Control
Engineering design basis, design calculations, validation of computer software, instructions and drawings for any design changes and modifications	Design and Procurement Document Control
Documentation relating to procurement, including certificates of compliance for new or modified installations, supplies and equipment	Design and Procurement Document Control Control of Purchased Material, Equipment and Services
Commissioning and installation records for new and modified work	Instructions, Procedures and Drawings
Engineering review of design changes and plant modifications	Design and Procurement Document Control
Fire safety procedures and the emergency plan and procedures	Instructions, Procedures and Drawings
The storage and use of replacement fire protection materials, systems and equipment	Design and Procurement Document Control Instructions, Procedures, and Drawings Control of Purchased Material, Equipment, and Services Inspection Test and Test Control Inspection, Test and Operating Status Nonconforming Items
Records of the combustible fire load in each area	Records
Control of combustible materials and ignition sources	Instructions, Procedures and Drawings Inspection
Documentation of completion inspection, maintenance and testing procedures and validation of emergency arrangements	Inspection Test and Test Control Inspection, Test and Operating Status
Audit, inspection and survey reports, including identified deficiencies and corrective actions	Audits

NS-G-2.1 Criteria	RG 1.189 Criteria
Technical justifications for non-compliance with specified requirements for fire safety and temporary actions implemented to compensate for deficiencies, pending completion of final corrective actions	Design and Procurement Document Control
Technical qualifications and training records of personnel	Design and Procurement Document Control Instructions, Procedures and Drawings Test and Test Control Records
Records of all fire events, large and small, including reports of investigations	Corrective Actions
Actuation of fire detectors and/or extinguishing systems: ▪ Response to actual fire conditions; ▪ False alarms and other non-fire responses	Corrective Actions
Operational failures of fire safety measures, including failures of computer software	Corrective Actions
Organization and responsibilities for fire safety	Instructions, Procedures and Drawings

CONCLUSION

The NRC identified the need to have certain quality assurance program features applied to fire protection programs after the Browns Ferry Nuclear Plant fire in 1975. The criteria that US nuclear plants follow are based on some version of these criteria.

ISO 9001 – 2015 and IAEA Safety Guide GS-G-3.1 both provide generic high-level criteria for the development of quality management systems. The US criteria can be shown to be a program developed to address the necessary elements to ensure the fire protection programs are implemented correctly.

IAEA Safety Guide GS-G-2.1 is the standard developed for fire safety during nuclear plant operation. This guide provides specific requirements for quality assurance as it is applied to a fire protection program. A comparison of the quality assurance requirements provided in the Safety Guide and the US criteria demonstrates that the US criteria can be applied to a fire protection program meeting the requirements of Safety Guide GS-G-2.1.

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"ONCE UPON A TIME …" - HISTORIC LARGE-SCALE FIRE EVENTS IN NUCLEAR POWER PLANTS AND THE LIMITS OF TRANFERABILITY OF HUMAN BEHAVIOUR

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ABSTRACT

It is a sad truth that progress in protection against catastrophic events often is made only after such events have occurred. Large-scale disasters usually lead to changes in laws and policies, according to the retrospectively identified problems responsible for the disaster. In fire protection, this usually means amending not only the requirements for structural and technical fire protection, but also the organizational measures: As human behaviour and human actions are often crucial, both when it comes to how a fire starts and develops as well as to how it is brought under control, the corresponding organizational factors and the rules that guide these actions are of the highest importance. Over time, a certain body of experience has accumulated, which describes the best ways to lead and organize all those who play a role in a fire event.

However, as general human behaviour is influenced by various factors, it tends to change over the years. E.g., the respect for authority and the willingness to follow orders has evolved over time, and corresponding to that, the authoritative leadership style prevalent in the 1950ies has at least in some places been slowly replaced by a more cooperative style. On the other hand, fire brigades still employ authoritarian structures, as these have clear advantages during a crisis. Therefore, the question has to be asked to what extent the analysis of human behaviour during a large-scale fire that lies many years in the past yields results that are still applicable today, and if a methodology for modelling human behaviour that was developed in the 1970s and 80s is still valid and applicable.

Based on a number of fire events in nuclear installations (Windscale reactor 1957, Browns Ferry power plant 1975, Krümmel power plant 2007) and – as a non-nuclear example for added perspective – the airport fire in Düsseldorf 1996, this paper will look at this question and identify crucial factors in terms of human actions that helped or hindered to control the respective event.

It is concluded that the development of an incident to a catastrophe can usually be traced back to a number of causes and influences. External influences (such as the social, political or economic situation of a country or a company) not only affect an organization as a whole, but will also shape the behaviour of each single person working in this organization. The identification of stress factors caused by these influences may help to understand and even to anticipate how personnel might react in a given situation, and in looking at the case studies of the nuclear installations, one may gain insights to the level of pressure necessary to force certain actions, may they be benevolent (e.g., a last desperate attempt at solving a problem when all other options have failed, which proves to be effective) or dangerous (e.g., taking risks with new, not well understood technology or using shortcuts to save time).

INTRODUCTION

Nuclear installations and complex industrial sites are designed in such a way that high-risk situations or disasters, e.g., a large-scale fire, are taken into account. However, such disasters, how rare they may be, cannot be conclusively prevented at all times. Examples include fire events in nuclear installations (Windscale reactor 1957, Browns Ferry power plant 1975, Krümmel power plant 2007) and the airport fire in Düsseldorf 1996. The above mentioned events show that large fires in nuclear power plants (NPPs) are very rare; this means, however, that we have to analyse old cases and check for their current applicability. The question of transferability, especially regarding human actions, is one point we look at in this paper.

In exceptional events like the ones regarded in this paper, good leadership, including a clear line of command and an established structure of authority, is important for the positive outcome of these events. For example, in case of a fire, usually the leader of the fire brigade will have the overall command. However, in case of NPPs, the shift supervisor will be responsible for avoiding harm to the environment and population that may be caused by the NPP itself, i.e. a large-scale radioactive release. Besides the leaders, there are also the employees to be considered. For them, it could be difficult in such an extraordinary event to determine and perform the correct operations and to carry them out correctly. Therefore, a clear command structure is highly important. Here the first problem that might appear becomes recognizable: There are at least two potential leaders who may give different instructions.

Today, a cooperative style of leadership is widely accepted to be the best combination of leading and participation, as well as ensuring sufficient information transfer. But in the incident structures of fire services, authoritarian structures are still used, as known for example from military services. For this there are several reasons: During fire service actions, there is less time to discuss different opportunities, so it is essential to have clear hierarchical structures and one person who makes the decisions. Ideally, the leader is well-trained and appears strong and self-confident. This behaviour of leading is accepted in this situation, if not required by the subordinate fire fighters, as it is always trained that way and as it gives the impression of safety in unusual situations.

In the daily work life, the employee however expects these days a certain measure of cooperation, self-realization and information exchange. Single persons might have special areas where they are more competent than their boss, and so it could get a bit complicated for them to deal with strict orders because they may not be used to it. On the other hand, executives change more and more from leaders to managers. And for the employees it becomes more and more important to have an equal work-life balance. Just 60 years ago, work was the most important part of life and an executive was the person who was, for the most part, professionally the best. Employees identified with their company and felt responsible for it. Bosses were in many cases more authoritarian than cooperative, and their employees supported them. An autocratic leadership style has different advantages and disadvantages, as the following table shows.

Table 1 Advantages and disadvantages of autocratic style

Advantages of Autocratic style	Disadvantages of Autocratic style
It is effective in crisis and emergency situations. The chain of command is clear and understandable Discipline is fully maintained.	Subordinates' participation in decision making process is fully ignored. It does not motivate employees. Employees work due to fear of punishment. It does not consider situational need.

As shown in Table 1 and as known from experience, the autocratic leadership style is best suited to be used in crisis and emergency situations. In fire service, this style of leadership is therefore trained, and it is accepted by all subordinates; however, frequently the fire service commander is forced to deal with involved persons who will not accept that authority and for example refuse to leave a dangerous area. So we have identified another issue, namely that people will not always follow their commander; and this is not only a problem in the autocratic style, but also in other styles during unexpected events.

Besides the type of leadership, there are other things that change during the years. Figure 1 shows that the importance of work in comparison to private life changed as well as the complexity of systems, processes and relationships and their interactions.

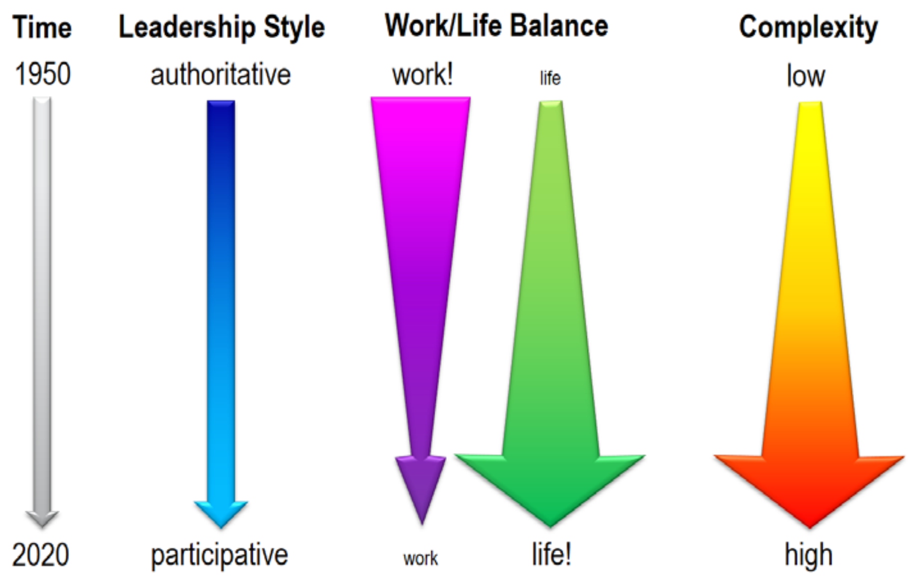

Figure 1 Changes in factors influencing human actions (Symbolic Representation)

Regarding all these issues together with changes in the cultural and political background, the degree to which today's employees would react in the same way as in the regarded cases needs to be verified.

In the following case studies, most notably the one concerning the Browns Ferry fire in the USA, exceptional events are described, where both a local fire service commander and the head of the plant were involved. Often, the fire fighters have a different approach to the fire than the employees of the plant. In addition, there are different areas of expertise, on the one hand the knowledge about the plant and the procedures in nuclear facilities and on the other hand the knowledge about fire. However, these two leaders have to work together to come to the best solution and they need their subordinates to support them.

Comprehensively, there are three questions:

- What does this mean for fire safety and emergency preparedness in nuclear power plants?
- How can we deal with new challenges and quick changes?
- What can we learn from past events?

LARGE-SCALE DISASTERS

Strategies of Disaster Prevention

Every large-scale human operation carries the risk of large-scale disasters, caused by technical failure, human error, accidents or natural events such as earthquake or weather events. (Please note that while we look only at fire events in man-made structures in this paper, the general remarks and conclusions can be applied to a much broader range of disasters.)

Strategies to prevent large-scale disasters are numerous. They start by eliminating potential causes and preventing initiators from occurring, they continue with the containing of precursors, i.e. preventing small initial incidents from developing to large events that are more difficult to mitigate, and they culminate in developing (in advance) measure to mitigate the consequences of those events. It is accepted that the higher the risk posed by a worst-case scenario is, the more diverse and robust the employed prevention and mitigation measures have to be. Therefore, possible scenarios have to be anticipated and planned for, and measures to coordinate various involved parties have to be in place.

For this reason, fire protection consists of a combination of structural, technical and organisational fire protection as well as fire defence, comprising the range from passive, preventive measures to active, mitigative measures.

Yet, it cannot be assumed that large-scale fires (or other disasters) will never occur, no matter how elaborate the measures are to prevent them. Therefore, one should be prepared for them.

However, experience shows that not every scenario can be anticipated and planned for. When things occur that were not anticipated, it is worthwhile to look at the question of why they were not: Would it have been possible to predict the occurrence of a certain event, but was it missed due to an error or a lack in foresight? Or did something happen which was genuinely impossible to anticipate? There is of course a sliding scale between the two extremes and after something has happened, it can be difficult to judge whether this should have been expected; given the benefit of hindsight, things often seem obvious that genuinely were not.

For the purpose of illustration, we will look at first at a large-scale fire that did not occur at a nuclear plant.

Düsseldorf Airport Fire

(Note: as this event did not involve a nuclear installation, it not presented together with the other case studies, and with less detail.)

Düsseldorf airport is a German international airport that has been in constant use since 1948 and has been increased in capacity a number of times.

The fire occurred on April 11, 1996. It was caused by welding work on an expansion joint above the arrivals hall of Terminal A. The airport fire brigade had not been informed about the work, so no fire watch was present. Welding spatter caused smouldering inside the dropped ceiling of Terminal A, which had been illegally insulated with flammable polystyrene. Ultimately, a flashover occurred, and dense and toxic smoke entered the arrivals hall. Terminal A was not equipped with a sprinkler system or fire doors, so the smoke could not be contained. German regulations at that time required the installation of sprinkler systems and fire doors for newly erected public buildings of this kind, but Terminal A was an older building and had been exempted from backfitting measures, so this lack was in accordance with law.

The airport fire brigade was prepared to fight fires on a runway, but had not been trained for firefighting in the terminal buildings. Therefore, their efforts were not always effective; for example, a number of people who had been waiting in a separate airport lounge inside Terminal A could not be rescued because the airport fire brigade was not aware of the exact location of said lounge. The airport fire brigade realized quickly that they were not able to control the fire alone and called fire brigades from neighbouring municipalities to aid, but coordination proved challenging as the airport fire brigade operated on a different radio frequency than the other fire brigades, who found it very difficult to operate in a location they did not know.

It took approximately 5.5 hours before the fire was extinguished; by that time, 16 people had died due to smoke inhalation, and another person died later from the consequences of smoke inhalation.

One might link the chain of events that lead to the disaster to a failure of preventive and coping measures, as introduced above in section "Strategies of Disaster Prevention"; this is illustrated in Table 2, below.

Table 2 Causes of the Düsseldorf airport fire

Disaster Prevention and Coping Strategies	Failures of Compliance in Düsseldorf Airport Fire
prevent initiators	unannounced welding work → no fire watch posted
contain precursors	illegal installation of flammable material → start and spread of smouldering
mitigate consequences	no sprinkler system or fire doors in passenger terminal → unchecked spreading of smoke
plan for scenarios	fire on the runway was anticipated, fire in the passenger terminal was not → fire brigade unprepared for scenario
coordinate efforts	airport fire brigade used different radio frequency as other fire brigades called to aid → difficulties in communication, delay in response

Influences and Causes

To reiterate: The necessity of anticipating various scenarios can be seen clearly in the airport fire in Düsseldorf, where one reason for the disastrous turn of events was later found to be the fact that the airport fire brigade had only been prepared for fires on the runway, caused by aviation accidents. A fire inside the passenger terminal simply had not been planned for, and the airport fire brigade’s answer was accordingly slower than it could have been. While this seems to be a clear lack of foresight, reducing this to the only reason for the catastrophic course of events is too simple, as other factors contributed significantly to the fire’s death toll, too. Looking at Table 2, it becomes apparent that amending even just one of the failures of compliance could have reduced the severity of the fire, if not prevented it outright.

This is in fact one point most large-scale disasters have in common: There is not one root cause for the event, but rather a web of contributing factors that accumulate, influence and aggravate each other, ultimately cumulating in a catastrophe.

To identify all these influences is a daunting task. In a typical probabilistic safety analysis, a large technical system is modelled by breaking it down to its single components and modelling their interconnected relations. A similar model could be envisioned to represent the human/organizational/political/social influences on complex organizations.

To go back to the Düsseldorf airport fire, the main purpose of the airport could be broken down into various factors contributing to it, weighing them against those which distract from it.

The first idea most people will have about the purpose of an airport might be something along the lines of punctual, undisturbed air traffic, or providing safe and comfortable travel for passengers. However, it cannot be overlooked that the purpose of an airport as a commercial operation is to turn a profit. Safety measures cost money, and a feature of large-scale disasters that comes up time and again is that costs were spared when it came to safety. In Düsseldorf, there were two major effects that belong to this type of behaviour: Firstly, the dropped ceiling in the arrivals hall had been insulated with highly flammable but cheap polystyrene sheeting, which was illegal. Secondly, the terminal building did not have fire doors or a sprinkler system, so the dense, toxic smoke generated by the fire could penetrate the whole building (it is worth noting that German codes for fire safety of buildings were extensively revised after the fire, owing to the lessons learned from the catastrophe).

While it is difficult to account for illegal activity in a model of human behaviour (the question of how likely it is that an executive is corrupt and will install sub-standard material to make profit is nearly impossible to quantify out of hand), the second effect mentioned above, that safety features are installed only to the absolute minimum required by law, is well known and can be expected with certainty. In fact, one of the most important applications of various types of safety analyses and probabilistic methods might be seen in proving the necessity to do more than laws and codes require.

Concerning the knowing violation of rules and regulations, some small effort to model this is made in current probabilistic safety analyses. For example, in probabilistic fire analyses, one of the modes for fire doors to fail is the likelihood that they have been propped up by plant personnel. This failure mode can be quantified using statistics acquired in plant walk downs and regular inspections, and as there is a lot of data available, one can assume that the resulting probability is sound.

When it comes to outright criminal behaviour which has a negative influence on the safety of complex organizations, however, there is (thankfully!) less data available. It is also nearly impossible to predict which concrete form and action this will take, so that it is not possible to determine what will be affected. Still, it could be worth investigating whether a look at recent industry scandals cannot help one to identify common patterns and allow one to get at least a qualitative measure of the degree to which safety might be compromised in human endeavours by violation of laws, codes and regulations.

Coming back to the above mentioned web of influences that accumulate to a large-scale disaster, the political situation also cannot be overlooked, both in the literal and in the figurative sense. For example, if one looks at the case study of the fire at Windscale, United Kingdom, a lot of the human actions become more understandable when one keeps in mind that both the construction of the reactor and the actual events described there took place during the Cold War, where what happened in a facility intended to produce material for nuclear weapons was considered not only to be relevant to public safety, but also to the security of the country, and political pressure to get fast results meant that the project went ahead without fully understanding what certain effects might mean.

Another example is the Düsseldorf airport fire again. Why were the additional forces not effective, even though they had been called to the aid of the airport fire brigade relatively early? Part of the problem was the already-mentioned fact that the airport fire brigade operated on a different radio frequency as the external brigades, but it has also been speculated that a certain “territorial” behaviour on part of the airport fire brigade, who were reluctant to equip the external forces with building plans and keys, contributed to the difficulties.

As with the human propensity to bend inconvenient rules territorial behaviour is a less desirable but very real human trait that needs to be taken into account when it comes to the prevention of large-scale disasters. The terms “mindfulness” and “safety culture” and all that they encompass are often cited in this context, and in the case studies for Windscale and Browns Ferry to follow, a lack of safety culture is evident in a number of aspects. Employing training cases and joint, large-scale emergency drills, which are becoming more and more commonplace, is also important, particularly when it comes to the coordination between a variety of agencies and agendas, when many different organizations are required to respond to a scenario. Again, a systematic analysis of the various influences, with a special focus on interfaces between all the personnel involved, is of great advantage.

But which scenarios should be assumed and trained for, if not every scenario can be anticipated? An added complication is that it can be difficult to determine what the “worst case” is which has to be prevented at all costs. As mentioned in the introduction above, in fire events at nuclear installations, the goal of fighting and suppressing the fire and the safety of the plant personnel and the fire fighters has to be weighed against the goal of preventing e.g. a large-scale radioactive release. The most relevant goal of fire brigade members is saving lives, while plant personnel might argue that the most relevant goal is to prevent core melt; but how should one decide whether the threat to the life of somebody in immediate danger from the fire is less relevant than the as yet potential threat to the lives of people who would be in danger after a nuclear disaster? And who should make this decision?

Various ways to identify potential catastrophes exist (e.g., hazard and operability studies, HAZOP, might be mentioned). And yet, one of the best ways to prepare for the unexpected might be to simply accept that not everything can be anticipated, that unlikely coincides will occur and the unexpected will happen. Emergency drills obviously have to model a specific scenario, and the benefit of training people to deal with exactly this scenario should not be diminished. Emphasis should however also be placed on the broader benefit of training personnel to deal with high-stress environments in general.

A flexible approach to problem-solving is necessary whenever something unexpected happens. The development of Severe Accident Management Guidelines (SAMGs) for NPPs acknowledges this. While operating procedures in NPPs are specific and detailed, describing exactly what has to be done in a given situation, SAMGs are merely “guidelines” for a reason: They leave room for interpretation, debate and decision. The task of doing this is not given to plant personnel, but to a dedicated emergency task force, who does not meet on-site and consist of experts from various groups and agencies. By this, the tasks of decision making and performing the actions decided upon is separated, and the decision making is left to people who, due to the fact that they are not on site (and therefore not under immediate threat) and the fact that they were not involved in the lead-up to the emergency, are at a lower stress and can look at the situation without prejudice and a cool head.

As the ability to deal with high stress levels, not only due to the risk people themselves face, but also due to being confronted with an unknown situation, fear for the safety of other people and the necessity of making decisions with large ramifications under pressure, in a short time or based on inadequate data, is crucial to successfully prevent, or (if that fails) to contain and mitigate large-scale disasters, a dedicated emergency task force as described above is a clear advantage in such situations.

In the following case studies we will try to identify the factors that have been described up to now.

CASE STUDIES

Windscale

The Windscale Pile 1 and Pile 2 nuclear reactors were built and operated at the northwest coast of England in the context of Great Britain's nuclear weapons program after World War II, with the specific purpose of breeding plutonium; they were never intended for power production. The reactors were graphite-moderated and air-cooled.

The reactor core consisted of a large block of graphite, penetrated by a large number of holes and channels. Cartridges made of aluminum, which contained a uranium rod of about 30 cm length, were loaded into horizontal channels at one end of the graphite core (the "charge face") at a calculated rate, with the cartridges already in the core being pushed farther back by each newly loaded cartridge. Once a cartridge had been pushed through the whole core (meaning that the uranium inside had been undergone a nuclear chain reaction for a time long enough to produce a certain amount of plutonium), it would fall out of the other end of the graphite block (the "discharge face") into a water-filled channel, from which it would be collected. The loading of new cartridges and the ensuing pushing of the already loaded ones through the reactor core was done manually. The heat generated inside the reactor core was removed by a constant flow of air generated by a large chimney, referred to as "the stack", placed at the discharge side of the reactor. In addition to the natural draught created by the stack, the airflow could be increased by various fans at the charge face and further influenced by opening or closing certain channels in the graphite core. The stack was equipped with a filter system to prevent the release of radioactive particles, as there had been some concern that a cartridge might break open, i.e. when missing the water-filled channel (the latter, in fact, happened regularly).

The fire occurred in 1957 roughly seven years after the plant had become operational. It started during a process called "Wigner[1] release", a procedure that had to be performed regularly and for which the reactor had to be shut down (the following description was put together from [1]). In a Wigner release, the graphite core was systematically heated by initiating (and then stopping) a nuclear chain reaction in the bottom level of the reactor, which heated the graphite to such a degree that the pent-up Wigner energy was released from the graphite. This released energy, in turn, heated the next layer of graphite, initiating the release of Wigner energy there. By this, the whole graphite core experienced a release of Wigner energy from the bottom layer up to the top. The procedure was necessary because it was feared that an uncontrolled release – which had happened several times during the early operation of the piles – might lead to a sudden temperature increase in the reactor, thereby creating a fire risk.

During the construction of the Windscale Piles, awareness of the Wigner effect and its possible consequences had been somewhat lacking. The Wigner releases were a mitigative effort developed well after the Piles had become operational, and therefore, instrumentation to control the temperature at all places in the graphite core was missing. The temperature inside the core could be monitored only in some select places, and the operators had to make assumptions about the temperature in the whole core based on the available readings.

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[1]- The term "Wigner effect" refers to the phenomenon that neutron radiation, as occurs in a nuclear reactor, displaces atoms in solid material, thereby causing an accumulation of potential energy in the material.

The Fire [1]

The fire was noticed on October 10th, 1957, in Pile 1; it has not been possible to determine when exactly it started, as it had been burning for some time already when the operators first realized that there was a fire. Plant personnel had started a Wigner release on October 7th, 1957, but the temperature had not risen as expected. On October 8th, a decision was made to heat up the reactor again; a sharp increase in temperature was noted at about 11.00 am, likely the time when the fire started. Plant personnel assumed that it was merely an unusual Wigner release and decided to wait for the temperature to drop. This did not happen, and at 05.40 am on October 10th, 1957, radioactivity was detected in the stack's filter, signifying that something had gone wrong. Plant personnel at first assumed that a cartridge had burst and the increase in activity at the filter was due to radioactive particles from the burst cartridge being blown out.

It took roughly another eleven hours before personnel opened an inspection hole and saw the glow indicating that a cartridge inside the reactor core had caught fire. This was something that had not been planned for, and so no procedures were in places to deal with this event. Various means were tried to contain and suppress the fire, but were not successful.

The attempt was made to push the burning cartridges out of the reactor core, but this proved to be difficult, if not impossible as a lot of them were stuck inside their channels and the steel rods used for pushing became damaged beyond repair by the heat. What proved to be helpful to at least contain the fire were the efforts to create a fire lane around the affected area by emptying the surrounding channels.

Liquid CO_2 was fed into the reactor for a time without effect (it was later assumed that the influx had been too small and that the fire by the time had had enough force to strip oxygen from CO_2).

The option of shutting off airflow was discussed multiple times, but turned down, as there were a number of reasons why a continuous airflow was needed (mainly, the continued cooling of the reactor and the necessity to keep the working conditions at the charge face bearable for the personnel working there). On the other hand, increasing the airflow in order to cool down the reactor more effectively was not possible for fear that the flow of radioactive particles might increase to such a degree that the filters would not be able to deal with it any more. Specifically plugging off the channels with the burning cartridges to shut them off from oxygen, while still being able to cool the rest of the reactor, was suggested in the early hours after the fire had been discovered, but there were no plugs available and manufacturing them on short notice was not possible (there were about 100 channels affected).

Usage of water was dismissed at first because it was feared that an explosion might occur when the water would hit the heated metal. However, with the fire continuing and the temperature inside the reactor core increasing, another problem became urgent: The reactor was housed inside a concrete building, with the concrete acting as shielding against a radioactive release. The concrete was not heat-resistant to such a degree as to withstand the temperatures reached by the fire. A collapse of the building would have meant a large radioactive release, so the decision was ultimately made to risk putting out the fire using water, as a resulting explosion would have no worse consequences than the collapse of the building. The water had some cooling effect, as evidenced by the amount of steam generated, but was not effective in putting out the fire.

Ultimately, in what might be called a desperate measure, the ventilators were switched off and by this, the airflow through the reactor was stopped or at least greatly reduced; it was felt that this had to be risked as the only possible option left to extinguish the fire (perhaps the consideration that the water was at least effective as a cooling device contributed to the decision). Deprived of oxygen, the fire started to die down, though plant personnel later theorized that the force of the fire was large enough to create a backwards suction through the stack.

A large catastrophe had been avoided largely thanks to the filters inside the stack, which at least limited the amount of radioactive particles which escaped, and due to the fact that the fire was finally extinguished. Still, noticeable contamination occurred. Pile 1 was deemed beyond repair, and as a consequence of the events, the unaffected Pile 2 was shut down only a few days later. The specific reactor technology used in Windscale has been completely abandoned.

Conclusions

We specifically draw attention to the following factors:

- The reactor had been built in a way that was assumed to be safe; the air cooling was designed to be fail-safe, as it would be available to a certain degree in any event due to the natural draught created by the stack. This was preferred to water cooling, which in case of a loss of coolant accident might have caused the reactor to go out of control very quickly.
- The Wigner effect and its effect on graphite were not well-understood in Britain at the time (in contrast to the USA and Soviet Union), leading to a reactor design requiring regular Wigner releases.
- When the necessity for Wigner releases became obvious and it became clear that the instrumentation in the core was not adequate to fully observe them, the design was neither overhauled nor amended; the operators had to make do with what had been available from the beginning. Other obvious design flaws (such as the fact that the cartridges often missed the water-filled channel when pushed from the reactor) were never corrected.
- A fire inside the graphite reactor core had not been anticipated (the Wigner releases were thought to prevent this), though the possibility of the cartridges (or the Uranium contained in them) catching fire if they missed the water-filled channel had been considered.
- In the build-up to the fire plant personnel was inactive for a long time despite indications that something was out of order because they made (incorrect) assumptions.
- A lot of the measures that prevented the accident from escalating were due to the singular actions of a number of people; for example, the stack filters had been installed at the insistence of the leader of the construction project team, Sir John Cockcroft, while the decision to use water and to switch of the air flow ultimately came from the Deputy Works General Manager Tom Tuohy, who was also the person who climbed up repeatedly on top of the burning reactor to do visual inspections of the fire's state, as this was the only way to get this information.

The following effects have been identified:

- While plant safety was considered during the planning and construction, the desire to go into production quickly apparently overrode some concerns. The context of the Cold War has already been cited as a reason for this.
- Some effects were genuinely unknown to the people involved in the project (Wigner effect in graphite), though the information would have been available elsewhere (experiences in the USA). Again, politics can be identified as the reason for the lack of information exchange. Other effects seemingly were not anticipated due to a lack of imagination or analysis (a fire inside the graphite core). It is difficult to determine why this had been the case, but it is worth noting that the attitude towards safety and pre-planning has changed very much since the fifties, so today's sensibilities might make this look more negligent than it was seen to be in the aftermath of the event.
- The complacency about the unusual Wigner release in the build-up to the fire, and the ensuing inactivity of plant personnel, might indicate a lack of safety culture (though we

wish to stress that it is difficult to judge something that took place sixty years ago, and we do not wish to fault plant personnel for their actions, especially as the concept of safety culture is significantly younger).

- The main areas of conflict were about the best way to extinguish the fire, and stemmed largely from a lack of knowledge, again due to a lack of planning and anticipating this kind of event. There does not seem to have been a lot of conflict due to matters of authority.
- The measure which finally extinguished the fire was only taken after all other possibilities had been exhausted and only as a last resort; the fear of what would happen if the fire continued had become greater than the fear of what would happen if water was used and the air flow was shut off. Whether the undoubtedly high stress levels experienced by the responsible people contributed in delaying the decision up to this point is worth considering.
- The commitment of plant personnel was crucial to the containing of the event. Tom Tuohy, without whom the fire would likely not have been extinguished and who underwent great personal risk during the events, has already been mentioned as an example. One can only speculate about the staffs' motivation; but while it would be desirable if one could always rely on such commitment, it cannot be expected.

Lessons Learned and Continuing Relevance

The main conclusion drawn immediately afterwards was that this type of reactor presents an unacceptably high risk, hence the shutdown of Pile 2 and the abandoning of this type of reactor in general.

With this radical solution, does the event still have relevance for current studies?

Two major differences between the situation in Windscale 1957 and today's nuclear power plant can be easily identified: The political situation, including the purpose of the plant, and the available knowledge about the technology used. More difficult to qualify is the difference between plant personnel's level of risk acceptance and stance on authority and leadership style then and now.

Referring back to the discussion of external influences under "Large-Scale Disasters", a plant used to breed plutonium in the context of a nuclear weapons program in the time of the Cold War is subject to a very different set of influences than a plant used for power generation in a civilian context nowadays. Still, it is worth asking whether, even if the *source* of the influence is different, the *consequences* of a certain influence or circumstance might not be the same for human actions in today's NPPs.

To illustrate this, we will discuss one aspect of the events at Windscale not yet mentioned. The public was first made aware of what had happened only after the fire was extinguished, when – as a reaction to the contamination of surrounding areas – milk was collected and destroyed. No evacuation of the area took place, not even when the personnel at Windscale started to become concerned that the concrete housing might collapse and release a large amount of radioactivity. When the decision to use water on the fire was made, the application of water was delayed until the shift change at the site (which also included the nuclear power station Calder Hall) was over, so that the majority of workers would be inside and thus better protected in case of an explosion [1]. This indicates that plant personnel were clearly aware of the danger. So why was there no effort to completely clear the site from all personnel not involved in the immediate action? A possible cause may have been a desire for secrecy, to prevent outsiders, especially hostile nations, from knowing the exact amount of the trouble.

Could this happen today? While the political situation is different, economical pressure keeps growing, and the advance of social media and the ensuing scrutiny and public discussion of every incident at a plant create a new kind of stress that has not been present in the

1950ies. It is worth asking at which point economical pressure and the fear of public backlash, especially where public opinion on nuclear power is very negative, and the ensuing loss of reputation (and perhaps revenue) might become large enough so that the desire to keep things under wraps becomes greater than the perceived duty to inform the public and the appropriate authorities about possible harmful consequences of an incident. In this context it is worth remembering that one of the key aspects of safety culture is how to encourage personnel to admit and report errors they made.

In conclusion, some aspects of the events at Windscale are still worth analysing to learn about human behaviour.

Browns Ferry

The Browns Ferry NPP consists of three boiling water reactors (units 1 – 3) which came online in 1973, 1974 and 1976, respectively. It is located in Alabama, USA. Units 1 and 2 (which were built nearly simultaneously) sharing a control room and a cable spreading room located below the control room. From the cable spreading room, a large number of cables were routed into the reactor building of unit 1, where they were spread further, with some cables belonging to unit 2 routed to unit 2's reactor building, while the cables belonging to unit 1 were routed through the rest of unit 1's reactor building.

Where the cables penetrated the wall, the walls were sealed by foamed plastic, covered on both sides with two coatings of a flame retardant paint, thus creating a fire stop. It should be noted that, though the foamed plastic itself was flammable, the combination of plastic and paint had been tested and found adequate as a fire stop. The foamed plastic was used to create an airtight seal between the buildings. A slight differential pressure between the cable spreading room and the reactor building was maintained, with the higher pressure in the cable spreading room, in order to keep radioactive particles inside the reactor building.

<u>The Fire [2], [3]</u>

The fire occurred on March 22, 1975. Due to a design change, the installation of new cables had become necessary, for which the seals/fire stops had to be breached. Their reinstallation took place by first applying the foamed plastic, then checking for airtightness; only when the foamed plastic was found to be airtight, the permanent sealing, which also acted as a fire stop, was installed.

An electrician in the cable spreading room tested the incomplete sealing to the reactor building with a candle flame. When the foamed plastic caught fire, he tried to extinguish it by himself. Only when his efforts were not successful, he informed the control room about the fire with a delay of approximately fifteen minutes. Plant personnel gave fire alarm and started to check the control panels for unusual signals, as they were aware that a cable fire might trigger both false readings and spurious actuation, as well as cause shutdowns of components.

In the meantime, the fire, drawn by the lower pressure, had spread to unit 1's reactor building and was burning freely there, as the cable insulation itself had started to burn. In this area of the reactor building, there were neither fire detectors nor automatic fire extinguishing systems installed [2]; the first sign that something was wrong there occurred when personnel working in the building noticed smoke coming from the area of the wall penetration to the cable spreading room [3].

Firefighting in the reactor building proved to be difficult, as the cable trays were located between six and nine meters above ground and could only be accessed by ladders and scaffolding. Plant personnel attempted to fight the fire using portable carbon dioxide and dry chemical extinguishers. They did not want to use water as suggested by the fire chief from Athens Fire Department which had been called in to help, as they operated under the assumption that water must not be used on electrical fires; there were apparently concerns for both fire fighter safety and the potential systems impact that might result from water-induced shorts involving the damaged electrical cables [3].

The dense smoke in the reactor building not only severely hampered firefighting efforts, but also made certain parts of the building inaccessible for manual operations necessary to keep core cooling and residual heat removal intact after the reactor shutdown had taken place. Plant personnel did not only have to constantly work around system failures due to cable damage, but also to develop alternatives when the available preventive manual and emergency measures could not be performed as planned due to the fact that, e.g., a valve that had to be closed manually in the reactor building could not be accessed. Breathing equipment was in somewhat limited supply (though it should also be noted that, as it was not as advanced as it is nowadays, it is debatable whether it would have been effective even if it had been available in larger numbers).

Ultimately, the decision was made to use water, and more than six hours after the start of the fire, water was sprayed on the burning cable trays in the reactor building. From then on, the fire was extinguished in less than an hour. With the smoke clearing in the reactor building, more options became available to plant personnel to restore and use previously unusable systems, especially as temporary jumpers were employed to establish control power to motor operators, pump controls, etc., and stable shutdown cooling was finally established about sixteen hours after the start of the fire.

The incident revealed a number of weaknesses in the fire preparedness of plant. The automatic extinguishing system in the cable spreading room had been accidentally blocked, which was realized only after the fire had started, and had to be quickly unblocked. (Afterwards, it was ultimately effective, and the fire in the cable spreading room was extinguished roughly four hours after it had started, though it took repeated attempts.) The lack of fire detectors as well as the lack of an automated extinguishing system for the cable trays in unit 1's reactor building have already been mentioned. However, a number of other factors contributed to the challenge of nuclear safety in the event, as e.g. in one case, due to erroneous routing, the separation of equipment of redundant safety trains was violated. The fact that units 1 and 2 both had been at full power operation while some of the penetration seals were still incomplete might also be cited as a somewhat questionable practice, particularly as no fire guard had been posted. Last but not least, it is worth mentioning that the plant did not have a plant fire brigade, but relied on the fire brigades of neighbouring towns.

Conclusions

- The actions and behaviour of the electrician (checking for airtightness with a lighted candle, attempting to put out the flames himself without alerting the control room) are indicative of a lack of safety culture, or to be more specific, for a lack of awareness of the possible consequences of a fire and the delay in reporting it.
- The disagreement between the fire chief from Athens Fire Department and plant personnel regarding the usage of water to extinguish the fire in the early hours is indicative of a conflict between authorities, as the plant personnel obviously did not trust the fire chief's judgement. Another contributing factor might have been that the plant personnel's training regarding electrical fires was perhaps not quite up to date. (It is recommended in [2] that, if initial attempts to put out a cable fire without the use of water are unsuccessful, water should be used immediately, as the time in which a fire is extinguished plays an important role in the amount of damage occurring due to the fire and a quick suppression of the fire is preferable; and that training for firefighters and NPP staff should change accordingly.)

- The ability of plant personnel to maintain adequate core cooling at all times, despite increasingly difficult conditions, on the other hand indicates a high level of plant knowledge and the ability to work well under high stress conditions, as long as their main duty was concerned.
- Conflicting goals also played a role in the delayed decision to use water for extinguishing the fire. The fire chief assumed that the highest goal was to extinguish the fire as soon as possible, while plant personnel wished to prevent further cable damage due to water, in order to better keep control over the plant. The decision to use water after all only came when the goal of preserving cables from short circuits caused by water became obsolete due to the extensive fire damage, and when working conditions in the reactor building became untenable, so that plant staff was afraid to lose the core cooling they had been able to establish so far. This bears some similarity to the events at Windscale; in both cases, the successful strategy was employed only after a certain point of no return had been reached.

Lessons Learned and Continuing Relevance

One lesson learned in the aftermath of the fire has already been mentioned, i.e. the recommended change in strategy for fighting electric cable fires, namely to quickly switch to water if other methods fail. Other possibilities for improvements of plant safety which the fire highlighted are e.g. equipping cable trays, especially those which are hard to reach, with automated firefighting systems, usage of fire detectors in all relevant buildings and rooms, or the physical separation of operational systems and their cables of different units. For modern plants, these measures have become standard.

Are there other lessons to learn? An interesting contrast is provided by comparing the events at Browns Ferry with the events at Windscale in the previous case study. In both cases, the question of how to extinguish the fire was raised and only answered very late in what might be called a last-ditch attempt. However, while in Windscale the reactor itself was not well known and understood, which contributed to the start and the catastrophic development of the fire, the reactor at Browns Ferry represented a technology that was very well known, and the plant personnel were able to keep on top of the situation, even though they had to resort to improvisation at a few points.

In the course of the Browns Ferry fire, core cooling was always maintained and no radioactive release occurred, even though there was a timespan when the fire burned unchecked. This is a stark contrast to the radioactive release that took place during the Windscale fire, and the main difference between these events and the cause for the difference in outcome can be traced to the different levels of understanding concerning the technology of the plants.

The question we need to ask is therefore: What level of knowledge and understanding is necessary for the safe operation of a new technology? While the new reactor types that are planned and build these days are on the whole the result of a continued development of existing and well-understood technology, in certain areas a switch from old, proven-in-use components and systems to new ones, where experience (at least in the context of NPPs) is lacking, is necessary.

A prominent example is the switch to digital I&C, both in the context of refitting older NPPs that have relied on analogue systems up to now, which creates challenges for the plant personnel who have to get used to new control panels and new routines, as well as for new-built projects, who have to take the new challenges into account during the planning phase. Questions of, e.g., how to determine the reliability of newly developed components or of ways to ensure the supply for a plant designed to last 60 years when the availability of components is limited to a few years before it is replaced by the next generation will have to be asked and answered. In these cases, a look at the past and what has happened during the introduction of new technology before may help.

Without going in further detail, we would also like to mention cyber security and computer hacking as new problem fields for NPPs. Here, one may very well ask whether plant personnel is really knowledgeable enough to understand these dangers and to act accordingly or whether the assumption that, merely because everybody owns and uses a computer daily, they will recognize e.g. a phishing email or similar threat is in reality nothing more than wishful thinking.

Coming back to the event at Browns Ferry, looking at the conflict of authority between the fire chief and the responsible plant personnel, one would assume that with better regulation, more training and an early emphasis on cooperation, e.g. in the context of disaster control exercises and emergency drills, prevention of those conflicts would be possible. However, the picture here is rather ambiguous: Referring back to the Düsseldorf airport fire, which occurred roughly 20 years later, these conflicts still seem to have played a role.

However, in the next case study, the 2007 fire at the Krümmel nuclear power plant, the plant fire brigade and other fire brigades cooperated very effectively, and it is well worth investigating why: Is this a result from ten years' worth of change in people's attitudes and "generational" effect, does this stem from lessons learned from Düsseldorf, or can this be traced to differences in work ethics and training between the nuclear and the conventional sector?

In any case, the fire at Browns Ferry shows cases that people react much better to problems in their own area of expertise than to those outside; the plant personnel who always knew what to do to combat the ever increasing loss of systems during the fire, exhibiting resilience, stress resistance and the ability to decide quickly under stress, were the same people who became unsure, delayed decisions and allowed the course of events to force their hand when it came to firefighting.

This indicates that resilience does not necessarily translate from one area to the other, and somebody who keeps calm in one type of threatening situation may well panic in another one. Therefore, one of the lessons we can still learn from the fire at Browns Ferry is a need to train people for general stress resistance rather than for specific scenarios and that in situations where multiple areas of expertise are involved, a team of experts, where each one is given the authority to decide on their own field, might be beneficial, as long as there is a way to resolve conflicts at those points where the areas intersect.

Krümmel

Krümmel NPP is a boiling water reactor which was taken into operation in 1983 and which is located near Hamburg, Germany; by now, it is decommissioned.

The Fire [4], [5]

On June 28th, 2007, one of the generator transformers caught fire after a short circuit due to an arc fault. The automatic fire extinguishing system installed at the transformer started immediately, and five minutes later the plant fire brigade arrived. With the aid of fire departments of neighbouring towns, the fire was quickly under control, and about seven hours after it had started it was extinguished. (It should be noted that – especially when compared to the events at Windscale and Browns Ferry – the fire was a fairly minor event that cannot be properly classified as a large-scale disaster.) However, while the plant was successfully shut down when the short circuit started the fire and disconnected it from the power grid, a number of operational and safety systems did not yet react in the expected manner. This resulted in some in-depth causal research in the aftermath of the event, and surveys in other German NPPs to check whether a similar sequence of events might be possible. For the purpose of this paper, we will focus only on specific aspects of the fire.

In Krümmel, the air intake for the switchgear building's ventilation system is located in the vicinity of the generator transformers. At the time of the fire, the ventilation system was running in the normal mode; that means a mixture of recirculated and fresh (outside) air was used. The fire produced a large amount of smoke and combustion gases, which were sucked into the ventilation system and ultimately made their way into the control room, which is located in the electrical (so-called switchgear) building. In addition, smoke detectors in the ventilation system were actuated. The ventilation system had been designed under the assumption that this would indicate a fire inside the electrical building, and accordingly an automatic system changed the ventilation mode of the building to exhaust mode, such that the air inside the building was blown out completely and replaced by air from the outside (environment). As the outside air was filled with smoke, this exacerbated the problem.

Soon after the fire started, as a consequence of the above-mentioned operation mode of the ventilation system, a burnt smell became noticeable in the control room. As the ventilation system was equipped with filters, soot was not transported to the control room, so control room visibility was not impaired, but it could not be excluded that combustion gases had penetrated. The shift supervisor ordered respirators to be in place in the control room. Plant personnel also changed the ventilation mode to complete recirculation, shutting off the intake of outside air completely and preventing any more smoke from entering the building. The necessity for this had not been foreseen, so there was no predefined way for carrying out these actions, and personnel had to manually override the ventilation control, which took about half an hour. After this, no additional combustion gases entered the control room.

Conclusions

We draw attention to the following human actions:

- The manual override of the ventilation system's control required personnel to do something unforeseen in the plant's operating manual, but was nevertheless done quickly. This indicates a high level of training and good knowledge of the plant. The diagnosis of what needed to be done was very quick, again indicating personnel's good understanding and command of the situation.
- The shift supervisor's decision not to evacuate the control room and to rely on respirators instead was not questioned, indicating that his staff trusted him to make the correct decision. If the decision was beneficial is difficult to determine; on the one hand, it meant that people could work in a well-known environment, and it sent the signal of "the situation is stable and under control", while an evacuation of the control room might have indicated "we are at risk, the situation is dangerous", thereby increasing stress. On the other hand, the prominent burnt smell itself might have raised fears about the staff's personal safety, though this was reduced by the available respirators.
- The close and unproblematic collaboration between the plant's fire brigade and the external forces indicates that territorial behaviour and the presence of several people with the same authority does not need to be a problem.

Lessons Learned and Continuing Relevance

It has already been mentioned that the problems uncovered in some of the plant's systems after the disconnection to the power grid led to an investigation in all other German NPPs to see if a similar effect might occur there.

Regarding human actions, the events at Krümmel showed (again) that unanticipated scenarios can and will occur. The assumption that a signal from the smoke detectors in the electrical building's ventilation system might indicate a fire inside the building was undoubtedly correct; the failure lay in not considering other possible causes, i.e. a fire outside the building. They also show that well-trained and knowledgeable personnel is able to deal with unanticipated scenarios, even under stress (though we must admit that concerning the actual threat level, the situation at Krümmel was far removed from what had happened at the fire events in Windscale and Browns Ferry).

Another insight the fire offers is that an authoritative leadership style can still be effective, as evidenced by the decision of the shift supervisor to stay in the control room, which was not contested. A further study might give more insight into the underlying reasons; one might ask, e.g. whether the shift personnel implicitly trusted their supervisor or if their motivation for following his lead was rooted in the wish not to be seen as afraid or weak by their peers.

Lastly, even though we did not go into detail about the unanticipated effects in the plant's operational and safety systems, it is worth pointing out that one reason why the possibility for these to occur had not been found in the safety analyses performed for Krümmel might be found in the highly complex and interconnected nature of the power supply system. Looking beyond the scope of nuclear installations, we can state that as technology in general tends to become more and more complex and the interconnectedness, e.g. of infrastructures, ever grows, the risk of overlooking such effects also grows, and accordingly the necessity of more in-depth analyses and better, more detailed modelling.

FURTHER DEVELOPMENTS

It is definitely possible to learn for the future from past events. Due to the fact that there is good networking in the nuclear field, it is possible to learn not only from events in one’s own country, but also from events in the international context.

However, it is necessary to analyse the information carefully to ensure that technical measures as well as human behaviour is transferable, particularly with respect to human behaviour, this always depends on the specific people concerned and the influences they are subjected to.

Due to these events, it is possible to improve the preparation for various scenarios and incorporate appropriate findings into the manuals and guides which include operating instructions for many different cases. In case of an incident in any NPP or nuclear installation, it will be examined which additional operations would have been useful in this case, and if there are any new insights, the guides will be revised. Therefore, these manuals and guides are always state of the art, so that the people who work with them trust them. This feeling of safety helps people to stay calm and not to worry unnecessarily. They are able to look up what it is they have to do and have strict instructions and orders in these manuals. Another measure that helps to keep stress levels down is the possibility to train disturbances in a simulator. With this simulator training, people experience an exceptional occurrence, so that they know that they are able to handle it. If simulator training and emergency drills take place frequently, and if working with manuals and guides becomes ingrained, this will help to prevent panicking in a true emergency.

Many studies prove that people in unexpected situations do what they are used to. Therefore, it is indispensable to train the important steps again and again. If people are panicking, there are three possible reactions: escape, fight or go rigid; for personnel in a NPP, it is vital to choose “fight”. As it is said that the fear of the unknown is the greatest fear of people, it is essential to prepare for that. Also, a well-functioning team and an accepted and established supervisor will help to handle any unexpected event.

Another point that can be seen in the above case studies is that the people in Windscale and Browns Ferry knew their plant by heart and they were willing to sacrifice themselves to save the plant and the people in the surrounding countryside. This might be explained by a comparison of generations: The generation "baby boomer" has the motto "live to work". They often stay in one company for their whole life and identify themselves with their company. Therefore, it is important for them that the company stays productive and economically sound. The following generations X and Y identify themselves less with their company. They are more self-contained and look for the right work-life-balance. It is more likely that they will change their employer during their work life. So it is more unlikely that they would risk their lives for the company [6].

For the issues discussed in this paper, this means that there is less experience concerning large-scale events in the nuclear industry and past experience cannot be fully transferred to today's situation because peoples' reactions and attitudes have changed. Windscale and Browns Ferry had comparatively light outcome because of the considered, but partially risky behaviour of the plants' personnel. In times in which only the financial and economical result is important to the employer, it is even harder to provide employee loyalty. On the other hand, people make more demands on their employer. They expect a lot from their supervisor and that their company takes care for every eventuality, while at the same time employees want to take less responsibility themselves.

So, how to show this in a risk assessment? How is a more realistic probabilistic safety analyses achievable?

The answer lies in a better modelling of human behaviour. Large-scale disasters not only in the nuclear industry, but in all fields of human endeavours, offer opportunities to further analyse human behaviour under stress. After catastrophic events, fact-finding commissions and boards of enquiry study everything that has happened in order to prevent similar events in the future. Unfortunately, their findings are not always heeded; we mention the extensive report of the Rogers Commission compiled after the explosion of the space shuttle Challenger, and the sobering realization after the disintegration of the space shuttle Columbia some seventeen years later that a lot of the same error mechanisms, especially concerning human actions, were still responsible.

A meta-analysis of as many reports and enquiries into large-scale disasters as possible with a special focus on the relevance of human actions and human factors could help to gain more insights into these processes and might even give rise to new findings. With enough data compiled, a new attempt to realistically model stress and the influence of the social environment on human behaviour could be made, including better methods for quantification of error probabilities. Of course, this would mean that these studies had to be released to the public in a usable and complete form. Here, we encounter the problem we propose to study, as national and international politics as well as business and corporate interests might prevent such a full release in certain cases.

Another option, the systematic analysis of the various influences a given employee in a high-risk situation experiences, or of the human/organizational/political/social context of a complex organization, in a similar fashion as the systematic analysis and modelling of a technical system in a probabilistic safety analysis, has already been mentioned and might be worth investigating.

Last but not least, we wish to mention that it is also beneficial not only to study what went wrong, but also to study what went right. "Why did something work, and can we make use of this in other cases? " is a sensible question to ask; looking for example at the conclusions about Krümmel fire, why did the collaboration of the several fire brigades work so well, and can the reason be replicated for other cases where many fire brigades have to work together?

CONCLUSION

Looking at the three events concerning nuclear installations described in our case studies in chronological order, it is immediately obvious that the danger they presented for the public decreased from event to event. It would be tempting to ascribe this solely to better planning, training, technology and emergency preparedness, and conclude that the likelihood for large-scale disasters is steadily going down; but unfortunately, the risk is still there, as evidenced – just to mention the most prominent recent example – by the Fukushima Dai-ichi nuclear disaster.

Still, it cannot be denied that lessons have been learned from all these accidents, as they have been learned from the events at the Düsseldorf airport fire. However, different attitudes of the public towards safety and what is considered acceptable risk, the changing behaviour and expectations of employers and employees as described above, varying outside influences such as economical pressure and the political situation, and last but not least the challenges presented by increasing complexity and new technology means that there is still considerable work to be done.

The question of how to equip people with the means to employ a successful strategy in case of a disaster, in an informed decision that considers all risks and benefits, and in a timely manner before point of no return has been reached, still needs to be answered. And as the answer might change with every new technology and every new generation, this question will have to be answered several times again.

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UK REGULATORY EXPECTATIONS IN THE ASSESSMENT OF INTERNAL FIRE AND EXPLOSION HAZARDS THROUGH THE GENERIC DESIGN ASSESSMENT PROCESS

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ABSTRACT

This paper provides an overview of the Generic Design Assessment process for new nuclear power plants in the United Kingdom (UK), and the lessons learned from the assessment of fire and explosion safety cases against expectations in ONR's Safety Assessment Principles (SAPs) and Technical Assessment Guide (TAG) on Internal Hazards.

Two reactor designs have so far successfully been taken through the Generic Design Assessment (GDA) process and received Design Acceptance Confirmation (DAC) from ONR. Hitachi-GE's UK ABWR (*A*dvanced *B*oiling *W*ater *R*eactor) design is presently undergoing the last step (4) of GDA with an expected completion date of December 2017.

As part of this paper, ONR provides a summary of typical issues and design changes resulting from the GDA assessment, which compared vendor's designs against applicable legislation and Relevant Good Practice (RGP) in the prevention, control and mitigation of fire and explosion hazards in line with the UK's non-prescriptive, goal-setting regulatory regime.

Nuclear Fire safety challenges resolved in GDA have ranged from the substantiation of novel fire barrier materials, fire protection of cables, the design philosophy applied to penetrations and dampers, hydrogen management, and the alignment of expectations with UK Dangerous and Explosive Atmospheres (DSEAR) to cite some examples. It is ONR's expectation that plant layout optimisation to minimise hazard effects and hazard elimination reduction takes place from the early stages of design. This involves for example the avoidance of large combustible inventories from nuclear safety significant areas, e.g., Emergency Diesel Generators and their associated day tanks etc. Successful resolution of the above issues has involved varying degrees of design change or additional substantiation, and in some cases these carry through GDA and into ONR permissioning activities as part of new reactor licensing.

The paper is organised in four sections. The overall process for generic design assessment (GDA) is presented first for context, followed by ONR's more detailed expectations which apply to the assessment of Fire and Explosion safety cases. Application of those expectations has resulted in challenges within GDA to reactor design and to the design substantiation via fire and explosion analysis. These are then discussed to bring out the key lessons learned. The GDA process provides for communication and graded resolution of regulatory shortfalls according to the risk gap, which are discussed together with examples of regulatory observations and issues raised upon conclusion of the GDA assessments of new reactors.

GENERIC DESIGN ASSESSMENT IN GREAT BRITAIN

As part the Energy Review conducted in 2006, the UK government concluded that nuclear new build would have a significant role in the future of the UK energy generation sector. In its contribution to the 2006 Energy Review, ONR's predecessor, the Health and Safety Executive (HSE), highlighted that previous experience with the regulation of new nuclear power stations indicated that early regulatory interactions and assessment on the design, and safety case development would reduce both the timescales for regulatory approval and the uncertainty for licensees wishing to build generic / standardised designs. The UK Government then requested the regulatory bodies, namely ONR and the Environment Agency, to develop a process to assess such designs prior to licensing and this came to be known as GDA.

GDA allows the regulators to get involved with designers at the earliest stage, where they have the most influence. By assessing at the design stage, any potential issues can be identified and highlighted so they can be addressed by the requesting parties (the companies who have submitted a design for assessment) before commitments are made to construct the reactors.

GDA follows a 4 step process with each step at increasing degrees of depth applied to the identification of key design features. This was to allow the identification and potentially the resolution of potential regulatory barriers early in the assessment process, and to minimise the chances of significant regulatory shortfalls arising later in GDA, when reactor vendors and potential licensees would have already made significant financial commitments. Specifically, the focus of each GDA step is as follows:

Step 1 – A preparatory phase in which the Requesting Party (RP) i.e. the organisation seeking their reactor design to be assessed, develops the project management structure and resource required to support the GDA process.

Step 2 – A period in which a high level assessment of the key / fundamental design features is conducted. These key fundamental features are usually captured in the "Claims" of the safety case. The assessment of claims early in the process ensures that any potentially major discrepancies between design features and regulatory expectations can be identified and addressed early, before significant resource is dedicated to the developing the evidence underpinning the case.

Step 3 – The assessment of "Arguments", with the objective of identifying whether significant design changes would be needed to meet regulatory expectations.

Step 4 – The assessment of the "Evidence" provided to underpin the design's safety case for ONR to come to a view as to whether a Design Acceptance Confirmation (DAC) should be issued.

It should be noted that issue of a DAC does not mean that permission for the construction of a nuclear station at a site in Great Britain will be granted. This remains regulated via the Nuclear Installations Act (NIA) 1965, which requires the interested party to obtain a site-specific licence and there will also be separate consents for the construction, in line with the conditions that ONR attaches to the licence. At the end of the GDA process, we will decide if the proposed designs are licensable for use in the UK. If we receive applications for development of new nuclear power stations at specific sites we will carefully consider those proposals and, take into account the work we have done on GDA, when making decisions about whether the proposals are acceptable.

In practice, GDA being outside the regulation via the NIA, means that there are not legal powers of enforcement attached to the GDA process and regulatory outcomes are effectively achieved by influencing the designers to make design changes or improve their safety case substantiation such that ONR becomes confident enough in the design to be able to issue a DAC.

As the reactor design follows the 4 stages of the GDA process, ONR inspectors identify issues and technical points that require clarification or further justification. The process of communicating these issues to the RP and resolving them is managed via a three-tiered process:

- **Regulatory Queries (RQ)** – these are low level queries, request for clarification, further information or evidence to facilitate understanding of the case put forward by the RP. In addition, ONR may issue RQs as a means to provide advice to the RP and to

inform the development of their plans and programme.
Closure and resolution of RQs does not require a dedicated work plan, but a question raised as an RQ can escalate to an RO or to an RI.

- **Regulatory Observations (RO)** – Should ONR inspectors detect the potential for a significant regulatory shortfall where action by the RP is required then issue of an RO is appropriate.
  ROs can have one or multiple actions, and usually have multidiscipline ramifications.
- **Regulatory Issues (RIs) –** RIs are raised when ONR identified a significant and serious shortfall in the design in relation to UK regulatory expectations.
  This category is reserved to those concerns which are deemed sufficiently significant to prevent the issue of a DAC unless they can be resolved before the end of the GDA process.

ONR has a policy of transparency and accountability, so ROs and RIs issued by ONR during GDA are made available to the public, together with the RP's resolution plans, via ONR's Joint Regulator website (http://www.onr.org.uk/new-reactors/assessment.htm).

As GDA of a reactor design progresses towards the end of Step 4 and the issue of a DAC, the need for closure and progression of existing regulatory shortfalls into licensing is addressed via identification of GDA Assessment Findings (AFs). These findings specifically relate to the provision of additional evidence that may be required to substantiate the case, but is not available within GDA due to a variety of reasons. A judgement is made that the safety case is however sufficient that ONR is content to issue a DAC and that it is reasonable to expect the assessment finding to be closed out within the detailed design phase.

As with our regulation of existing facilities, proposed NPPs have to show that risks have been reduced to As Low As Reasonably Practicable (ALARP) (the legal enforceable bar once the plant is built and operated). A demonstration that risks have been reduced to ALARP may include numerical risk assessments, but also include a comparison with Relevant Good Practice (RGP).

Some reactor designs have already been through design certification or licensing processes in their own countries or those of third-party nations, but may still see significant challenge to the design when they undergo GDA in the UK. This is partly due to the goal setting nature of UK Health and Safety Regulation in that there are few prescribed rules and the legally requirement is to demonstrate that the risks have been reduced to ALARP.

ONR EXPECTATIONS FROM SAFETY ASSESSMENT PRINCIPLES AND TECHNICAL ASSESSMENT GUIDES

ONR Assessment is guided by Safety and Security Assessment Principles [1] and [2], which are available in the public domain and used by ONR's Safety and Security Inspectors to come to a judgement as to whether the safety case is aligned with Relevant Good Practice and reduction of risk to ALARP has been demonstrated. ONR SAPs are benchmarked against International Guidance, including the IAEA NS-G-1.7 [3], NS-G-2.1 [4], SSR-2/1) [5] and Western European Nuclear Regulators Association (WENRA) Reference Levels [6].

Discipline-specific guidance on the application of the SAPs and assessment is available from ONR's Technical Assessment Guides (TAGs). These are also in the public domain and include an Internal Hazards Technical Assessment Guide [7] which covers Fire and Explosion from a Nuclear Safety perspective. In this paper, expectations on Fire and Explosion through the GDA process are discussed from the point of view of Internal Hazards (those that originate within the site boundary and are within the control of the licensee), and has not been extended to address External Hazards (e.g. fire and explosion hazards from aircraft crashes or forest fires, etc. which originate externally from the licensed site) or Core and Fuel issues (which deals with hazards inherent to the process or primary circuit).

Specifically, ONR's expectations in the Assessment of Fire and Explosion Hazards are by several Safety Assessment Principles, primarily:

- **EHA.13:** On the Use, storage and generation of hazardous materials: the on-site use, storage or generation of hazardous materials should be minimised, controlled and located, taking due account of potential faults.
- **EHA.14:** (Fire, explosion, missiles, toxic gases, etc. – sources of harm): Sources that could give rise to fire, explosion, missiles, toxic gas release, collapsing or falling loads, pipe failure effects, or internal and external flooding should be identified, quantified and analysed within the safety case.
- **EHA.15:** Hazards due to water: The design of the facility should prevent from adversely affecting structures, systems and components. It is therefore the expectation that the design should include provision to address fire-induced water damage e.g. as a result of activation of fire extinguishing systems.
- **EHA.16:** Non-combustible or fire-retardant and heat-resistant materials should be used throughout the facility (see Principle EKP.1).
- **EHA.17:** Fire detection and fire-fighting systems of a capacity and capability commensurate with the worst-case design basis scenarios should be provided.

These SAPs are underpinned by Engineering Key Principles, External Hazards and Fault Studies Safety Assessment Principles which are not reproduced here for conciseness but, in conjunction with the above, will determine the overall acceptability to ONR of the fire safety case.

In alignment with the SAPs, ONR expects a fire hazard analysis to be carried out within GDA to determine the potential for fire initiation and growth, and the consequences for structures, systems and components (SSCs) relevant to Nuclear Safety. Needless to say, a basic requirement which is both in ONR SAPs (EKP.3) [1] and IAEA safety standards (SSR-2/1 [5]) is to provide defence in depth. In the case of fire, this means:

- Preventing fires from starting;
- Limiting the severity of fire that start;
- Limiting the consequences of fires that start and are severe.

Preventing fire from starting by elimination of minimisation of combustible inventories is high up in the hierarchy of measures. Whilst total elimination is desirable, in many cases it is virtually impossible and, therefore, in alignment with international Relevant Good Practice, ONR's expectation is for the design, the high level claims and the fire analysis to be developed on the basis that segregation by fire compartment barriers designed to withstand full burnout is provided if practicable (the" fire containment" approach). This also stems from the expectation that SSCs relevant to safety and their components should be protected against a fire e.g. by barriers, or qualified to withstand the effect of a fire. Extensive SSC qualification requirements will place onerous requirements on the design and manufacture of numerous SSCs across the plant. On the other hand, segregation by passive fire barrier designs substantiated against the most onerous fire conditions in the compartment e.g. total burnout is therefore the favoured and expected primary claim unless segregation is not reasonably practicable.

Given the goal setting nature of the UK regulatory regime there is, however, no prescriptive requirement to provide full compartmentation by barriers or to do so for specific systems or locations. This results in a degree of variability in the level of full fire compartmentation provision, the standards and modelling tools applied for hazard characterisation and target responses by those developing fire safety cases for their generic plant designs.

Needless to say, for areas where segregation is not reasonably practicable, other measures, usually a combination of measures, are proposed by the Requesting Party (RP) to underpin the fire safety case. They are typically:

- Elimination of combustible materials / Combustible load minimisation;

- Partial barriers;
- Restricting the area of the fire by engineered or other means;
- Inert atmospheres;
- Separation of fire sources and/or SSCs by distance;
- Provision of fire detection, alarm and extinguishing systems (automatic or manual), or
- A combination of these.

The above measures are also typically applied as defence in depth measures even where segregation by fire barriers is credited in safety cases. ONR looks for hazard robustness and defence in depth against hazards because of their inherent uncertainties.

In the subsequent sections of this paper, I also discuss the degree of variability in hazard identification and characterisation techniques applied, the standards quoted in the substantiation of fire barrier withstands and typical points of attention during Generic Design Assessment.

INTERNAL FIRE CHALLENGES IN GDA

Generally, high level claims are placed on the availability to deliver Fundamental Safety Functions in the event an internal hazard including fire. As highlighted previously, safety cases for modern nuclear civil reactors will generally provide segregation between the redundant SSCs by suitably designed fire barriers which are demonstrated to withstand the full compartment fire load.

In line with the non-prescriptive approach in the UK, it is the RP's choice to select the hazard identification and characterisation tools that will be used in the fire analysis. ONR SAPs and TAGs do not prescribe or endorse specific models, other than highlighting the essential elements of fire safety which are expected to be threaded through the case put forward for assessment. It is, however, widely accepted that UK Relevant Good Practice in compartmentation is to provide 3 hr reinforced concrete barriers (or equivalent) for principal barriers between segregation divisions. Any penetrations in these should be suitably qualified such that they do not undermine the performance of the barrier, which recognises that the barrier may need to be qualified as a multi-hazard one. In the subsections below, I discuss typical approaches seen in GDA submissions for specific topics of interest:

Combustible Loading

The expectation in ONR TAG is that non-combustible materials, cabling and fluids should be used wherever is reasonably practicable to do so to minimise inventories. At the generic design stage, there will be a degree of uncertainty as to the overall amount of cabling and its exact distribution across the design.

Generally, the expectation is that the fire analysis would commence with upper bounds of combustible inventories in specific locations, provide sufficient margin to allow detailed design changes and, preferably, not take credit for defence-in-depth measures such as cabling encasement or wrapping that could restrict the combustible load input in the modelling underpinning the substantiation of the barrier. Early credit for these measures can result in challenges in detailed design (foreclosure of changes arising from C&I or Electrical supply demands) and through-life constraints on the validity of the fire case. The protective measures may be necessary for the overall safety case, but ONR's view is that including the larger combustible loading gives additional hazard robustness in design.

Local Fire Effects

Similarly to the points raised on combustible inventories above, implementation of protective, control or mitigative measures (such as the provision of bunds to contain spills and limit the area of the fire, or flange shields to prevent flammable fluids released at pressure from atomising and generating flammable mists) can be relatively low cost and are almost certainly ALARP, regardless of whether or not their provision is essential for the fire and explosion made on the substantiation of nuclear safety barriers. We would expect these to be implemented as part of the overall compliance with RGP which forms part of an ALARP demonstration and also to feature as sensible and practicable defence in depth measures.

It is also a generic design expectation that significant combustible inventories associated with emergency diesel generators, and the generators themselves, are fully segregated and so far is reasonably practicable housed in separate buildings than plant of high nuclear safety significance i.e. the reactor or control buildings building. It is ONR’s expectation that plant layout optimisation for internal hazard reduction takes place from the early stages of design.

Fire Models

A variety of tools have been used in the three GDA projects undertaken in the UK so far. The RP’s use of models has ranged from the Consolidated Fire and Smoke Tool (CFAST), developed by the U.S. National Institute of Science and Technology (NIST), quantitative methods using correlations or embedded in spreadsheets such as US NRC Fire Dynamic Tools (FDT), to various CDF modelling packages to model fire. From these, the RPs have generally extracted time-temperature profiles and compared them against the standard fire curves in BS EN 1363-1 (2012) [8] or UL 1479 [9] providing there is alignment between the design and the standard.

Challenges arise from novel construction materials and techniques for which fire tests or standards may not be available. This has been historically reflected in GDA issues which are discussed later in this paper. It is also advisable that the RP builds confidence in the use of the models in the submissions by documenting crosschecks with other tools, e.g. CDF models, and demonstrating that they are used within their ranges of validation.

Flammability Limits

In the UK Regulatory context, prevention of fire and explosion in industrial installations, are regulated by the DSEAR Regulations 2002, which transposes to UK law the expectations from the EU ATEX directives. These apply to nuclear plant, but since they are standards for life safety, may not be sufficient for cases where explosion of flammable gases could damage plant or structures which play a role in nuclear safety.

The goal setting nature of UK Health and Safety law is also evidenced from the letter of the regulations (DSEAR). Regulation 6(4a and d) of DSEAR requires that measures should be applied, subject to reasonable practicability, to reduce the quantity of dangerous substances to a minimum and to prevent the formation of an explosive atmosphere, including the application of appropriate ventilation. The hierarchy of hazard elimination, prevention, risk control and mitigation is also embedded in the regulations. As a result, ONR’s expectation (including in GDA) is that safety cases should not simply accept supplied control and mitigative measures against explosive atmospheres, but should also consider the practicality of design options in which inherent safety or preventative measures are implemented.

This has been seen in GDA in hydrogen systems (generator cooling, radwaste plant, etc.). ONR’s expectation is that a fraction of the Lower Flammability Limit (LFL) (typically 25 % LFL) is used as the threshold to determine whether a hazardous explosive atmosphere is present. This value, whilst not prescribed, comes from the DSEAR Regulations Approved Code of Practice (ACOP). DSEAR remains a goal setting, regulation and it may not be reasonably practicable to achieve 25 % of LFL, but ONR's expectation is that a robust ALARP justification will be provided as part of the GDA submissions if that is not the case. This is because the ACOP is, in simple words, a legally recognised way of complying with UK law, approved by the regulator with the consent of the Secretary of State. Outside GDA, failure to follow the ACOP is not an offence, but it is a relevant good practice and where there are grounds to consider than an offence has been committed; the dutyholder will have to prove that their approach achieved an equal level compliance than the ACOP.

High Flash Point Fluids

Within GDA, ONR's expectation is that the RPs will study the potential for combustible fluids released at pressure to form a flammable mist which could be ignited a result in flash fire or explosion hazards. This is currently an active area of research in the UK, following Joint Industry projects sponsored by the HSE, Oil and Gas and Nuclear licence holders, amongst other industry and regulatory stakeholders. Therefore an assessment of flammable mist generation potential and explosion effects on compartment barriers and SSCs will be required within GDA.

Given the nature of the generic design, and specification of oil lubricants being a matter of detail design, it is usually the case that exemplar fluids can be used as the basis for assessment, and confirmation (by an assessment of the 'Delta' with the detailed design) is carried out at the site-specific stage.

Use of Bounding Arguments

Whilst a quantitative fire analysis of fire compartments is generally expected for a safety case of a new nuclear plant, the level of information available and the timescales of GDA may direct RPs towards a reduction in scope. This may include selecting sets of representative fire compartments or individual rooms for analysis, and then providing qualitative justification as to how barriers and SSCs elsewhere in the plant are substantiated by comparison the representative case.

Whilst bounding arguments may be viewed by ONR as a sensible strategy and generally acceptable in GDA, the vendor/designer must ensure that bounding effects on barriers e.g. when shared by rooms in a compartment are captured. It is also expected that the selection of bounding rooms will follow a systematic approach aimed at capturing the effect that multiple variables influencing the progression of a fire may have on the barriers.

Penetrations through Compartment Fire Barriers

In GDA stage, ONR's expectation is that that the number of penetrations, including doors, HVAC (Heating, Ventilation and Air Conditioning) ducts, cabling, pipework through barriers of nuclear safety significance is kept to a minimum. There should be visibility and justification of the rationale for the design in this respect.

In the case of doors through Nuclear Safety Class 1 barriers, ONR's expectation from GDA submissions is that there is a robust demonstration that:

- The number has been kept to a minimum;
- They are a self-closing design;
- A lobbied-configuration (double doors) is adopted so far as is reasonably practicable;

- For single fire safety doors of high nuclear safety significance, it is RGP in the UK to provide alarms to a permanently occupied station so that degraded conditions can be detected.

Provision of fire dampers in series (on each side of the barrier) within HVAC ducts penetrating Class 1 barriers is generally recognised as good practice in the UK. An ALARP justification for alternative design of choice is therefore expected, and this should provide clear demonstration of how the needs from various disciplines (Internal Fire specialist, C&I, Electrical Engineering requirements, Radiation Protection to cite some examples) are balanced in the design of the HVAC system penetrations.

Fire Barrier Substantiation

The consequence modelling results generated in the hazard characterisation stage should be compatible with the substantiation of the fire barrier. If the barrier is designed against the requirements of an established code or fire tests, there should be cross checks of the relevance of the performance standard.

In the UK, this generally means that the standard three-hour fire test curve for reinforced concrete barriers is then assessed against barrier design criteria on parameters such as the minimum thickness or distances from the surface of concrete to the centre of the first reinforcement bar, which are specified in standards. An example is BS EN 1992-1-2 Section 5 [10], which is widely recognised within the UK nuclear industry for the design of concrete structures.

For fire loading on barriers as a result of local fires resulting in flame impingement or thermal radiation, it is generally expected in GDA that heat transfer calculations are performed to demonstrate that the temperature rise of the steel rebar and on the other side of the barrier (potentially affecting SSCs or encast items) are within advisable limits to retain the integrity of the barrier and prevent secondary fires from starting on the other side of the barrier. Specifically, criteria specified in Section 2 of BS EN 1992-1-2 [10] is that the average temperature rise over the complete non-exposed surface limited to 140 °C above the initial mean temperature. RPs have also used acceptance criteria such rebar temperatures resulting in loss of design safety margins.

REGULATORY OBSERVATIONS AND ISSUES RELATING TO FIRE AND EXPLOSION IN GDA

Having described the GDA process and discussed typical points of focus for ONR inspectors during assessment of the fire aspects of the NPP design, some of the themes relating to fire as captured in the ROs and RIs from those GDAs which ONR have performed to date.
The tiered interactions of RQs, ROs, RIs have been described earlier in this paper.

Since the Joint Programme Office between ONR's predecessor HSE and the Environment Agency was established 10 years ago, two reactor designs have completed the 4 stages of GDA and have been granted a DAC. Another two reactors are currently ongoing GDA with one of them in the last stage of and the other is, at the time of writing this paper, undergoing Step 1 of GDA. These 10 years of experience in the application of the GDA process has generated a wealth of information on generic design features and safety case methods /assumptions that resulted in the identification of regulatory shortfalls of sufficient significance to merit issuing regulatory observations or regulatory issues. The list below provide a design-neutral summary of regulatory shortfalls in the areas of Internal Fire and Explosion which were resolved via ROs and RIs as part of past GDA projects. The aim is to go through these in more detail during the presentation:

Segregation Philosophy and Fire Hazard Analysis

- Demonstration that there are design philosophies and rule sets which ensure that a systematic process is followed in the determination of segregation requirements for all C&I, electrical and mechanical SSCs.
- Assessment of the potential fire consequences on exceptions to segregation, and identification of other redundant or diverse SSCs which deliver the Fundamental Safety Functions during the operational state considered.

Fire Compartment Barriers

- Substantiation of the nuclear significant hazard barriers claimed to provide a level of fire including provision of the physical fire testing or detailed supporting analysis and the approach taken to minimise penetrations within the barriers.
- Provision of evidence in the form verification and validation analysis and/or other supporting documentation in order to prevent a single fire resulting in loss of more than one safety division. This includes the analysis supporting the claim and arguments relating to:
    - The routing and identification of protected cable trays.
    - Justification of claims and arguments made relating to geographical separation.
    - Provision of passive protection applied to cables and cable trays specifically.

Fire Dampers

- Substantiation of the approach taken to the design and installation of fire dampers; including reference to the appropriate codes and standards to demonstrate the fire dampers will meet the requirements for 3 hours fire resistance . The application of any passive fire protection to ensure that the dampers meet insulation requirements
- Definition of Appropriate Nuclear Ventilation Codes and Standards
- Demonstration that the design of HVAC systems has been adequately conceived and reduces risks SFAIRP

Hydrogen generation and ignition

- Provide substantiation of the safety case for explosion within Battery Rooms as a result of hydrogen accumulation rates during normal and fault conditions. Consideration of heating, ventilation, and air conditioning (HVAC) systems
- Demonstration that the reactor has been designed to safely manage radiolysis gases generated under normal operation.

CONCLUSION

In this paper, an overview of the Generic Design Assessment process for new nuclear power plants in the UK, and the lessons learned from the assessment of fire and explosion safety cases against expectations in ONR's Safety Assessment Principles (SAPs) and Technical Assessment Guide (TAG) has been provided. Two reactor designs have so far successfully being taken through the Generic Design Assessment (GDA) and received Design Acceptance Confirmation (DAC) from ONR. Another two designs are currently undergoing assessment.

As part of this paper, ONR summarised typical high level issues and observations raised when the generic designs are assessed against applicable legislation and Relevant Good Practice (RGP) in the prevention, control and mitigation of fire and explosion hazards.

Issues have ranged from substantiation of novel fire barrier materials, cable fire protection, the design philosophy applied to penetrations and dampers, hydrogen management and alignment of expectations with UK DSEAR to cite some examples. It is ONR's expectation that plant layout optimisation for internal hazard reduction takes place from the early stages of design and this involves the avoidance of large combustible inventories e.g. EDGs, day tanks etc. from nuclear safety significant areas .Successful resolution of the above issues has involved varying degrees of design change or additional substantiation which in cases carry through GDA and into new reactor licensing space.

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ISO/DIS 18195: A NEW STANDARD FOR JUSTIFICATION OF NUCLEAR POWER PLANTS FIRE BARRIERS

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ABSTRACT

The ISO TC85/SC6/WG3 committee is to propose a new standard for the justification of nuclear power plants fire barriers (publication planned for early 2018). This work is issued from the EPRESSI method developed by EDF in collaboration with EFECTIS-France for the EPR fleet. Significant evolutions have been included to propose an international standard soon available to the nuclear fire safety community. The aim of this method is to verify the efficiency of a fire barrier to the potential fire hazard conditions in a given location of the installation. A performance curve (time/temperature) is provided for the fire barrier, starting from the standard fire resistance performance test, and using modelling and/or supplementary test in order to obtain its fire behaviour on a long confined fire duration. On the other hand, rules for the calculation of the fire development conditions in the plant rooms, with reasonably conservative assumptions, are proposed to obtain a design fire time/temperature curve for each concerned room. The confrontation of both curves allows to validate or not the use of the fire barrier for the given location. The presentation gives an overview of the method and information on the time schedule of the ISO standard.

TC85: Nuclear energy, nuclear technologies, and radiological protection
SC6: Reactor technology
WG3: Power Reactor Siting and Design

CONTEXT AND ORIGIN OF THE METHOD

Since 2013, BNEN6 [1], a French committee in link with ISO TC85 SC 6 “reactor technology” subcommittee [2], has proposed to the community a new project work item based on the EPRESSI method [3], [4] developed by EDF in collaboration with EFECTIS - France for the EPR fleet. This project will soon result in a new ISO standard, the so called “Method for the justification of fire partitioning in water cooled NPP” at the moment identified as ISO/DIS 18195. This new standard is in its final stage and should be published at the beginning of 2018.

The confinement of fire inside an area is justified if the duration and thermal conditions of the hypothetical fires are less than what the fire barriers can resist, in other words their fire performance. This is typically based on conventional theoretical fire duration and thermal stress curves. Given the advances in the knowledge concerning the spread of fire in compartments, an improved method called EPRESSI has been developed during the 2000ies decade by EDF for EPR (*E*uropean *P*ressurized *R*eactor) type nuclear power plants. This method provides a better estimate of fire condition and duration, together with an enhanced description of fire resistance of partitioning components.

Taking profit of the feedback from the application of this method to new built reactors like FA3 (Flamanville 3, France) TSN (Taïshan, China) or HPC (Hinkley Point C, United Kingdom) the new standard proposes different enhancements that are detailed further.

JUSTIFYING THE EFFICIENT DESIGN OF FIRE SAFETY PARTITIONING

The defence in depth against internal fire hazards is typically divided into the following steps (e.g., WENRA [5]):

“ (...)providing measures:

- *to prevent fires from starting,*
- *to detect and extinguish quickly any fires that do start*
- *to prevent the spread of fires and their effects in or to any area that may affect safety.”*

The third level makes the link with the nuclear safety through fire partitioning, prevention of common mode failures and limitation of radioactive or other dangerous substance releases.

In case of a fire starting inside the installation and impacting some equipment, the role of fire partitioning is to separate and protect redundant or complementary equipment and paths in order to reach and/or maintain a safe state.

This protection/separation shall be maintained up to the end of the fire duration, which means the extinguishing of the fire by lack of combustible, by oxygen depletion or by fixed and/or manual extinguishing means.

The robustness of the safety case leads to consider prescriptive time durations (e.g., 60, 90, 120, 180 min) and to avoid as far as possible the necessity of human actions. Regarding the fire barriers, those time durations are based on the standardized fire resistance approach [6] in most of the cases using the well-known ISO 834 standard [7] to represent conservative fire conditions. Nevertheless, given the prescriptive ISO rating of a fire barrier, it is still necessary to verify that it provides a sufficient protection in regard to the potential fire conditions it is supposed to protect against, either as a part of a fire zoning partition, or as an individual equipment protection.

Different “historical” methods have been intended to assess this verification step. The method applied from the eighties on the French Nuclear fleet (57 PWR (*p*ressurized *w*ater *r*eactor) type reactors) uses a standard fire duration curve (DSN144 [8]): the surface fire load (energy/surface) of a given room, determines the required fire resistance rating of the fire barrier elements, by a simple equivalent time method. On request of the French Nuclear Safety Authority (ASN), EDF has developed for EPR FA3 the EPRESSI method in collaboration with the EFECTIS - France laboratory in order to enhance this existing approach.

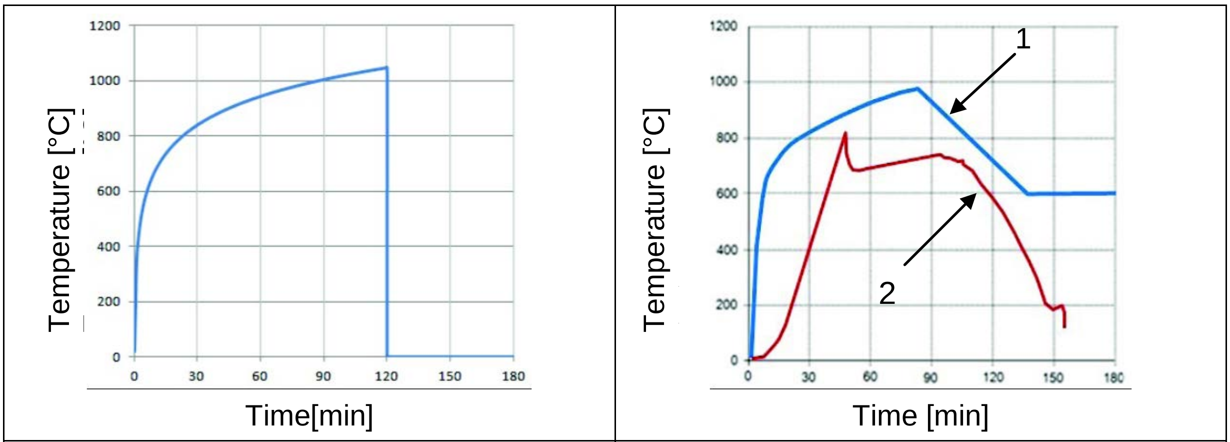
Using a single equivalent time method to verify the behaviour of the barriers exposed to fully developed fire conditions did not give a clear and definite response to a single question: what if the real fire is maybe weaker but presents a longer duration?

The aim of the EPRESSI method, now standardized in the ISO/DIS 18195, is to analyse the behaviour of the fire barrier, principally from its standard experimental qualification, and extrapolate it to longer but weaker fires, in order to obtain by a robust approach a global performance of it, with no fire duration limitation.

KEY ISSUES OF THE METHODOLOGY

The general principle of the method consists in:

- Setting up performance curves for each fire barrier (one or several curves constituting the fire performance diagram of the barrier);
- Setting up the design basis fire temperature curve for each room of a given fire area;
- Comparing the design basis fire temperature curve of a given room with the performance curves of the fire barriers in a given room.



a) ISO 834 (2 h rating)	b) EPRESSI method application

Figure 1 ISO 834 versus method application

Key issues:

1 - Room fire curve
2 - Fire barrier performance curve

A fire barrier will be qualified for a given room only if all the following criteria are met by at least one performance curve belonging to the fire performance diagram:

- The maximum slope of the fire temperature curve is less than the maximum thermal gradient of the performance curve.
- The area delimited by the fire temperature curve is smaller than the area delimited by the fire resistance performance curve. Qualitatively, this means the heat of the fire is less than the heat the element can withstand.
- The maximum temperature of the fire temperature curve is less than the maximum temperature of the fire resistance performance curve.

Note:
The presence of a classified fixed automatic fire-fighting system may be credited or not in this process in agreement with the authority having jurisdiction.

The method can be thus summarized into two main parts:

- Guidelines for determining the fire thermal effects (design fire temperature curve) to consider on fire barriers inside a given room;
- Guidelines for determining the global performance of the fire barriers based on standard test characterization.

DETERMINING A FIRE CURVE

A design temperature curve is built for each concerned room by calculation (Zone or CFD model) based on classical description of the fire source pyrolysis scenario (ignition, αt^2 growth, steady state, decay) a full inventory of the calorific load and conservative design fire growth assumptions. Oxygen depletion due to ventilation rates and confinement is to take into account with conservative assumptions. A linear decay starting after 70 % of combustible consumption is assumed (100 % for liquid fuels).

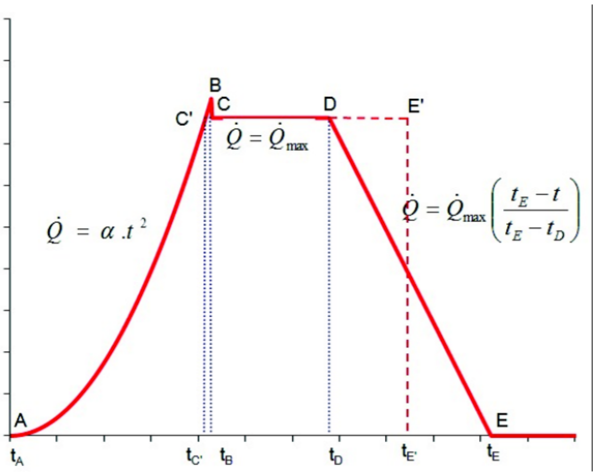


Figure 2 Design fire construction

Key issues:

- Spreading stage [AB];
- Fully developed fire [CD] or [CE'];
- Decay stage [DE].

with:

$\dot{Q}$: Heat Release Rate [kW]

$\dot{m}$: rate of pyrolysis [kg.s^{-1}]

T: time [s]

α: growth factor [kJ.s^{-3}]

ΔH_C: net heat of combustion of the fuel [kJ.kg^{-1}]

$\dot{Q}_{max}$: maximum heat release rate of the fire source

Four types of initial fire sources - typical for PWR NPP - have to be considered:

- Liquid hydrocarbon fire with fast dynamics;
- Electromechanical equipment fire;
- Cable fire;
- Fire of other materials.

Different categories of fire configuration are considered:

- Configurations with a strong probability of fire spreading (so called PFG category for probable generalized fire);
- Configurations with a significant fire, but with low risk of spreading to other sources (so called PFL category for probable localized fire);
- Configurations with moderate fire (so called neither PFL nor PFG);
- Configuration with negligible combustible load.

A minimum combustible load threshold identifies type 4 Categories. Category 3 is treated with the same assumption as Category 2. Categories 2 to 4 shall shift to Category 1, if the calculation shows temperature reaching a spread temperature threshold (STT – see further down).

PFG situations are modelled with a αt^2 growth and limitation by the oxygen depletion only, when PFL are limited with a maximum pyrolysis rate.

Inside any fire volume (cell or compartment) a fire scenario is calculated for each room. This calculation will give a fire temperature curve inside the room but also for the adjacent rooms (through openings). The overall design basis fire temperature curve assigned to a room is the curve that envelopes all of the different temperature curves obtained in the room, determined for each potential fire scenario in the fire volume.

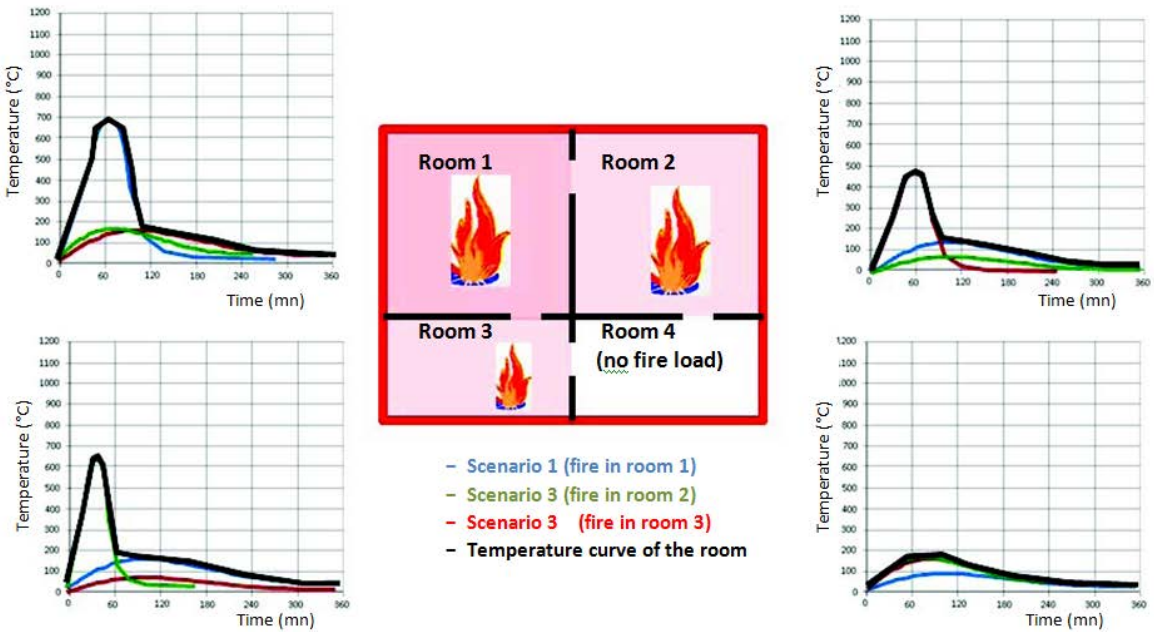


Figure 3 Determining the design basis fire temperature curve

In this process, the possibility of spreading the fire from one room to another (i.e. ignition of the combustibles of the adjacent room) will be taken into account using a spread temperature threshold (STT) with a recommended value of 350 °C (hot gas layer average).

DETERMINING A PERFORMANCE CURVE

The determination of a performance curve for the fire resistant barriers is the most innovative part of the methodology. Based on a progressive approach starting from the results and information obtained during the fire resistance tests, it proposes a modelling of the barrier behaviour to obtain a set of global performance temperature/time curves.

Global Process

The global process can be summarized as follows:

Identify the nature and the main criterion resulting in the product failure (generally: thermal). Step (1) Choice of product or equipment to be studied to plot performances curves:

Identify A, B or C way to be adopted:

Branch A: The failure of the equipment is typical for the equipment family. In this case, the performance curve is set up by numerical simulation.

Branch B: Equipment belonging to a product family that has not already been analysed. In this case, the process consists in determining a rule for the product family first, then following Branch A.

Branch C: The reference test does not easily provide a simple criterion for the failure of the product or, if this criterion cannot be simulated. One or more appropriate tests should therefore be carried out to plot the performance curves.

Modelling the Product Behaviour

A sufficiently accurate model must have been obtained first of the component behaviour (thermal modelling). This model is validated by comparison of experimental curves representative of the family criteria, or other experimental data adapted to the material properties.

Modelling will be 1, 2 or 3 D depending on the material.

Models take into account variation of thermal properties of materials, and convection/radiation boundary conditions.

Plotting the Reference Fire Curves

Three reference fire curves (CFR) are used to determine the performance curve:

$$\theta_g = 20 + 1325\left(1 - 0.324\, e^{-at} - 0.204\, e^{-bt} - 0.472\, e^{-ct}\right) \quad (1)$$

(with t [h] and θ [°C]).

The decay phases are linear with a slope β for each curve. They are initially based on parametrical fire models described in Annex B of the EUROCODE 1 [9].

Table 1 Reference fire curve coefficients

	CFR C1A	CFR C2A	CFR C3A
a	0.211	0.082	0.026
b	1.790	0.692	0.218
c	20.009	7.739	2.433
β	- 521	- 224	- 80

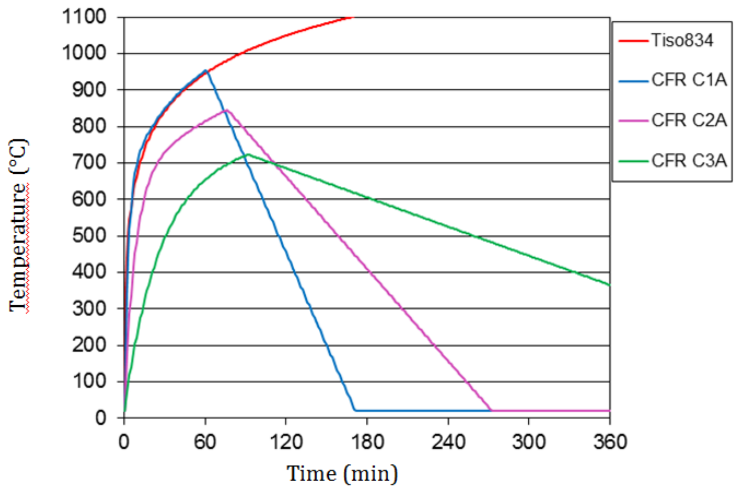


Figure 4 Reference fire curves

Plotting "Steady State" Curves

In many situations, there is a set of conditions that, even if held indefinitely, would not cause the failure criterion to be met. When the unexposed face of the element has adiabatic boundary conditions, this set of conditions is identical to the failure criterion. The duration of the steady state curve shall be limited in case of material presenting a charring and combustion effect or a specific risk of structural change at the steady-state temperature.

Determining the Performance Curves

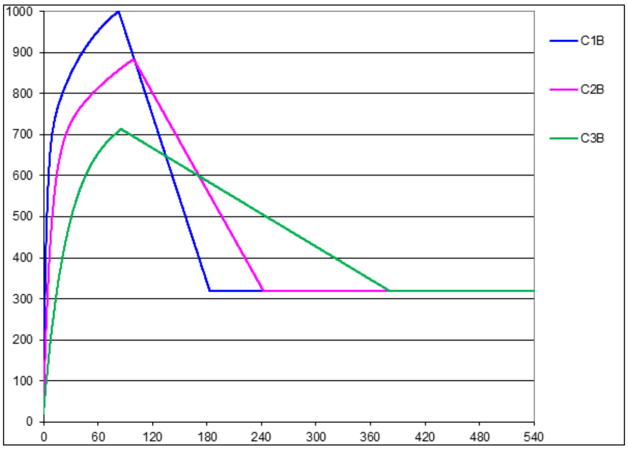


Figure 5 Example of final performance curves (2 h cable wrapping protection)

MAIN ENHANCEMENTS OF THE NEW STANDARD

Transforming a proprietary internal methodology like EPRESSI into an open standard led to necessary enhancement and adaptation to the method. The main issues in that process was to suppress the link with a specific zone model (e.g., MAGIC [10]) and to disseminate the knowledge in the fire barriers performance part.

The standard ISO/DIS 18195 includes chapter detailing the condition of using any qualified fire code in the fire curve determination process: minimum requirement concerning the code verification and validation and the management of its calculation options.

The method applicators must be fire safety engineers with an adequate knowledge of fire safety science and the applicable codes. An approved fire safety laboratory is required for section on determining barrier performance. As the method requires knowledge and experience not only in the application of standard fire tests, but also in more complex instrumentation processes and engineering models, the capability of the laboratory teams has to be confirmed. The fire laboratory shall be accredited according to ISO/IEC 17025 [11] or an equivalent national alternative for the relevant fire tests, as acceptable by the authority having jurisdiction.

The robustness of the method was reinforced through the numerous expert comments in the committee draft phase (more the 200) and a deep polishing was performed with aim to clarify the process when complex. Mandatory and informative sections have been specified and balanced in order to provide a reliable and applicable standard.

A chapter dealing with uncertainty and sensibility was added.

CONCLUSION

With the coming standard ISO/DIS 18195, ISO will provides to the community an efficient method to deal with problem of verifying the adequate design of performance barriers to respond to a given fire risk in a nuclear plant. This standard has been issued from an existing method developed for (and applied to) EPR fleet, but is available for any category of light water cooled reactor.

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FIRE PROTECTION IMPLEMENTATION AND THE RESTART OF NUCLEAR POWER IN JAPAN

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ABSTRACT

The Great Eastern Japan earthquake and tsunami of 2011 resulted in significant earthquake and tsunami related analyses, regulations, and physical plant changes. During this period, the Japan Nuclear Regulatory Authority (NRA) enacted several new requirements prior to restart including new fire protection requirements (Japan NRA fire protection rule (No. 1306195) dated June 19, 2013 [11]). In addition to compliance with the new NRA fire protection rule which is similar to US 10CFR50.48, Appendix R [2] requirements, the NRA has established an expectations that utilities will also develop Fire PRAs for each site. The Japanese have made significant improvements in this area in a relatively short period of time. This paper provides a summary of insights gained in during the last five years doing fire protection analyses at Japanese nuclear power plants, which include conducting deterministic/ restart safety evaluations, development of plant-specific fire hazards analyses, and for compliance with new Japan Nuclear Regulatory Authority rule (No. 1306195 [11]). These analyses have provided a solid foundation from which to begin Fire Probabilistic Risk Assessment (FPRA).

At this stage, Japanese plants will be expected to both deterministically comply and have a FPRA that provides an overview of plant-specific risk. This includes three fundamental tasks: detailed deterministic reviews for all operating modes, the development of Fire PRAs (FPRAs), and an assessment and disposition of variances from deterministic requirements (VFDRs). Deterministic reviews provide a baseline review of the new fire protection program against the requirements of the NRA fire protection rule (No. 1306195 [11]) and identify VFDRs. Resolutions to VFDRs can then be identified and presented to the NRA as part of the restart safety evaluation if needed.

INTRODUCTION

This paper provides a summary of insights gained in the evolution of fire protection for Japanese nuclear power plants. A summary of the regulations and insights is provided. Although this paper focuses on the impact of the new regulations and analyses, many best practices were observed as part of our reviews in Japan such as housekeeping, work practices to minimize combustibles, etc.

New Regulation

On June 19, 2013 the Japanese Nuclear Regulatory Authority (JNRA) enacted a new fire protection rule (No. 1306195 [11]) which established items to be considered in terms of securing safety functions of reactor facilities regarding the details of fire protection which applied similar deterministic protection requirements. These “deterministic” fire protection requirements are similar to the requirements of Appendix R to 10 CFR Part 50 [2]. The JNRA has also established an expectation for Fire Probabilistic Risk Assessment (FPRA) to be performed for each nuclear facility by their first periodic safety assessment. The final regulation for FPRA is still under development by the Nuclear Risk Research Center (NRRC), but is expected to strongly follow the approach defined by U.S. guidance document NUREG/CR-6850 [4]. The acceptance for the use of FPRA as a tool to disposition variances from deterministic compliance (VFDRs) has yet to be decided.

Deterministic fire protection requirements seek to establish safety margins through the post-fire survival of the systems needed to shut down the reactor. These requirements, based on a set of postulated serious fires, were developed before the staff or the industry had the benefit of probabilistic risk assessments (PRAs) for fires and other recent technical advances. For example, we now do computer simulations of how fires spread. The NRC lists these requirements in 10CFR 50.48(b) and Appendix R of 10 CFR 50 [2].

Risk-informed fire protection requirements consider risk insights as well as other factors to establish requirements that better focus attention on design and operational issues according to their importance to public health and safety. Performance-based regulations rely on a required outcome rather than requiring a specific process or technique to achieve the outcome. The U.S. Nuclear Regulatory Commission (NRC) lists these requirements in 10 CFR 50.48(c)" [2].

Implementation

The implementation of these new requirements will culminate with 3 fundamental tasks: detailed deterministic reviews for all operating modes, identification of variances from deterministic compliance (VFDR), with a plan for how to resolve non-compliances, and the development of Fire PRAs (FPRAs). The deterministic reviews provide a re-base lining and establishment of a fire protection program against the requirements of the JNRA fire protection rule (No. 1306195 [11]). VFDRs are identified where a plant does not meet the explicit requirements of the fire protection rule. FPRAs can be used to identify improvement opportunities and assess the risk significance of resolution strategies for VFDRs. For example in the US, some plants use operator manual actions (OMAs), also referred to as recovery actions (RAs), to provide for a safe shutdown path. These are local, field actions. In the "ideal" deterministically compliant plant, such RAs would not be needed. Instead automatic features would replace the function of the RA, or other design features (such as additional protection to cabling) would be included to obviate the need for a RA.

In Japan the current expectation is that plants will reach deterministic compliance, and have a FPRA that demonstrates the acceptability of compliance. As a result of these requirements being in place at the onset of the process, the Japanese have an opportunity to streamline the data collection process, since much of the information required will be used both for the deterministic and probabilistic analyses. The fundamental elements necessary to manage risk are similar, and essentially identical in actual implementation.

In addition, the expectation is that Japan FPRAs will reflect the latest state of the art methodologies including; NUREG/CR-6850 [4], ASME PRA Standard RA-Sa-2009 [13], and the various NUREGs, guidance documents, etc.

The inclusion of modern risk techniques has proven to increase plant safety within the US, and it is expected to also increase plant safety within Japan through:

- Risk insights from the FPRA;
- Risk improvements from the review of fire protection program elements.

Other benefits of the risk-informed approach include the ability to incorporate risk-informed plant changes which could reduce cost and improve safety over deterministic solutions alone.

Regardless of whether a utility is implementing a “deterministic” or “risk-informed” fire protection regulation, incorporation of risk-informed elements will result in improved plant safety and will likely result in a lower overall cost than seeking deterministic compliance alone.

METHODOLOGY

The fundamental elements of analyses for “deterministic” or “risk-informed, performance-based fire protection” are similar and should include elements found in both a Fire Hazards Analysis, and a Safe Shutdown Analysis. Japan NRA fire protection rule, section 2.3.2 [11] refers to this as the fire impact assessment:

- Fire Hazards Analysis: a review of Fire Protection Program elements, which include by area; analysis of fire barrier features, fire detection and suppression capabilities, fire loading, control of combustible materials, and fire brigade availability.
- A Safe Shutdown analysis which identifies safe shutdown means, and challenges to safe shutdown by fire area - variances from deterministic requirements (VFDRs)
    - Existing designs provide electrical separation between components to prevent a fault or failure on one train from affecting the redundant train (e.g., IEEE 384 [16] separation). The new Japan NRA fire protection rule No. 1306195 [11] now requires separation of redundant equipment and cables to provide protection from exposure fire (not limited to electrically induced faults within a cable-way).
        - Cables and components that require fire protection and are of different trains shall be separated by a wall capable of withstanding fire for more than three hours.
        - Cables and components that require fire protection and are of different trains shall be separated by at least six meters horizontally and have a fire detection and automatic suppression installed in the fire zone with no combustible material in the separating area.
        - Cable and components that require fire protection and are of different trains shall be separated by a partition wall capable of withstanding fire for one hour and shall have fire detection and automatic suppression installed in the area.

Deterministic Analyses

Deterministic analyses currently consist of:

- Fundamental Fire Protection Program reviews, to define to what extent the plant configuration meets NRA fire protection rule (No. 1306195) [11].
- Preparation of safe shutdown and fire hazards analysis (also called fire characteristics table) documentation. Figure 1 provides an illustration of the inputs required in order to develop the fire hazards analysis.

These inputs are not prepared as part of the FHA, they are inputs that support development of an FHA.

The Safe Shutdown Analysis (SSA) is an important input into the FHA, and it is one of the most critical inputs to improvements in the Japanese fire protection program. The SSA is also a major input into the Fire PRA. A primary effort of the SSA is to identify train separation issues and potential measures to resolve separation issues. The basic guidance for this is essentially the same for the U.S. and Japan.

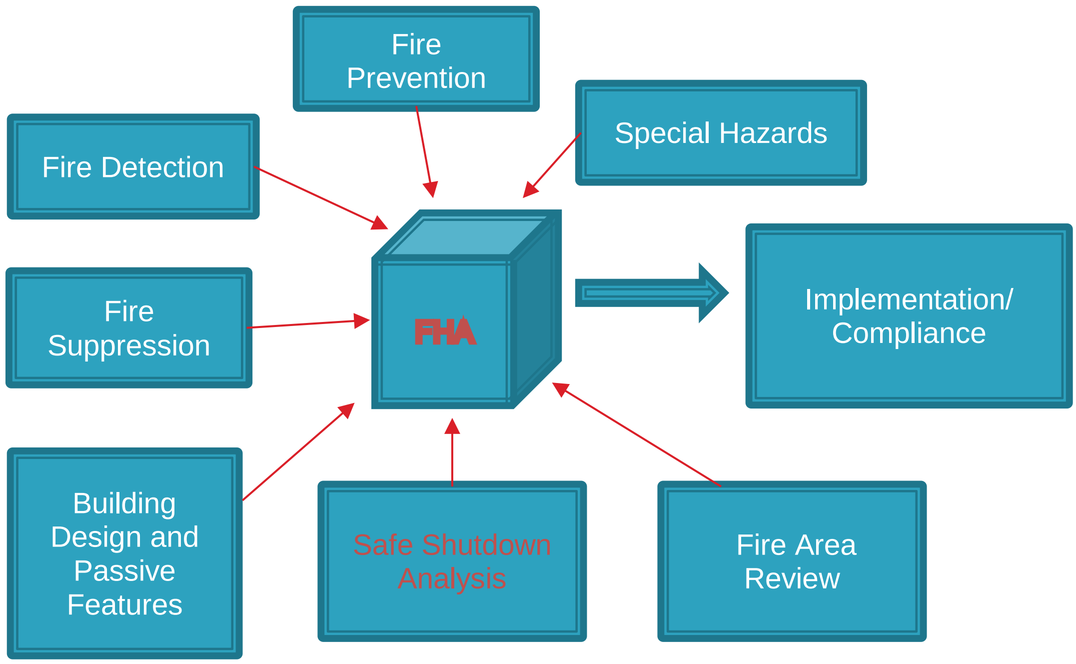

Figure 1 Fire Hazard Analysis inputs

Fire PRA

Although the specific details of a FPRA can vary, fundamentally FPRAs are expected to be performed in consonance with NUREG/CR-6850 [4], frequently asked questions (FAQs), recent Electrical Power Research Institute (EPRI) technical evaluations, and selected methods/ refinements developed by different organizations.

Examples of Challenges with the New Fire Protection Requirements

In the following, some examples of challenges with the new fire protection requirements are given:

- Fire Protection Codes & Standards – In Japan fire protection codes and standards are not defined to the extent that they are in the U.S. or in Europe. The lack of prescriptive codes and recognized international standards means that the industry has many fire protection legacy issues. This starts with the level of documentation for the design of some elements, and continues through to the monitored installation and testing of existing features.
- Fire Protection Program
  - Prior to the new Japan NRA fire protection rule, a coordinated onsite fire protection program did not exist.
  - Qualifications – nuclear fire protection engineering is an emerging skill in Japan. Prior to the new NRA fire protection requirements the sites did not recognize the need to have a qualified fire protection engineer.
  - Training – Prior to the new NRA fire protection rule fire brigades and off-site fire departments typically did not have fire response procedures and in-plant training and drills.
  - Review of modifications – Prior to the new NRA fire protection rule a review was typ-

ically was not performed by a fire protection engineer.

- Construction
    - o Fire detection devices were installed without consideration to beam pockets, and obstructions.
    - o In some cases, fire suppression devices were installed without sufficient documentation to provide confidence in their design. For example, obstructions that could have potential to obstruct sprinkler spray patterns were not evaluated. Nozzles used in this selection may also lack documentation to show adequacy for the application
    - o Barrier qualifications – in some cases credited barriers were not evaluated against recognized standards, for example the time-temperature curves from ASTM 119 [17], or ISO-834 [18]. Initial analyses resulted in a large number of apparent separation issues based on the NRA fire protection rule (No. 1306195) section 2.3.1(2) [11] separation criteria using the NEI 00-01 methodology
        - – Fire seals – documentation of installation may not reflect recognized standards for installation
        - – Fire doors – installation may not meet tested configurations for fire doors, or documentation may not provide assurance that the installed doors could withstand the now required ratings for fire endurance;
        - – Fire dampers – in some cases installation of fire dampers did not meet tested configurations, such as within ductwork within the room (and not at the barrier penetration). This means that a fire that could compromise the ductwork, would therefore negate the presence of the damper (because the ductwork assemble would have potential for a fire breach).
    - o Control of combustible materials, including storage – in some cases storage of combustible materials had been staged in close proximity to cable trays containing safe-shutdown cables.
    - o Safe-shutdown equipment and cabling in some cases were found to lack the requisite separation required by Japan NRA fire protection rule (No. 1306195 [11]).
    - o Changing environment – due to the number of additional requirements imposed on plants that must be completed prior to restart, a tremendous amount of construction and installation is occurring throughout the plant. These activities include additional security measures, as well as enhanced protections for seismic and tsunami events. This has added another level of complexity when performing fire protection assessments on what is currently a very dynamic and changing environment.

INSIGHTS

Summary of Insights

Implementation of the NRA Fire Protection Rule has resulted in significant improvements to the three layers of defense in depth:

- Prevention of fire from starting;
- Early detection and prompt suppression of fire;
- Protection of structures, systems and components (SSCs)with safety functions in order to secure hot shutdown and cold shutdown function in the event where fire cannot be suppressed promptly with a fire suppression activity.

Improvements

As part of the plan for plant restart, it is required that each plant establish a Fire Protection Program and that improvements will be made to improve plant safety with regards to fire. These improvements include significant enhancements to both administrative controls and physical modifications. The plants visited have made tremendous progress in meeting these new regulations, both programmatically and through new physical modifications to the plant.

- Fire Protection Codes & Standards – fire protection elements such as fire detection and suppression systems are being reviewed against recognized international codes and standards;
- Qualifications – specialized fire protection knowledge/ experience was not previously required in Japan. Due to the new regulation, a need has been defined to have more knowledge in nuclear fire protection, this has prompted utilities to seek out qualified personal to assist in this transition, as well as educate their own staff in this specialized field.
- Training – improvements in plant fire brigades and associated training:
  - Development of plant fire response procedures, in-plant training and fire response drills.
- Fire detection devices – regulatory requirements now require redundant fire detection systems throughout the plant, this exceeds current US and International Standards.
- Fire suppression devices – installation of new fire suppression systems throughout the plant, including extensive implementation of Halon 1301.
- Barrier qualifications – new fire barrier requirements require testing and qualification of fire barriers:
  - Fire seals are being reviewed against tested configurations, and improved as found to be necessary for compliance.
  - Fire doors are being reviewed against tested configurations, and either replaced or improved as found to be necessary for compliance.
- Control of combustible materials is being implemented:
  - For example at one plant site visited, there has been a more coordinated reduction in the presence of combustible materials within the plant (particularly in areas with safe-shutdown equipment or cables).
  - In another example, the same plant has removed all the wooden toolboxes throughout the plant, in effort to reduce the presence of potentially combustible material.
- Safe shutdown equipment and cable separation issues:
  - Additional detailed analyses have indicated that a large number of these could be resolved without plant modifications.
  - Where these detailed analyses could not provide sufficient documentation for the existing design, plant modifications have been prescribed. This has included installation of a small number of new fire barriers and limited installation of fire wrap.
  - In some cases this has even resulted in new cable routing. Insights from detailed analyses have also included enhancements to post-fire safe shutdown procedures.

CONCLUSIONS

The deterministic analyses required by the new NRA Fire Protection Rule have identified significant improvements in fire safety. Examples include the establishment of coordinated fire protection programs, development of safe-shutdown analyses, improvements to fire barriers, fire detection and suppression, and improvements in equipment (and cable) separation based on the NRA separation criteria. In addition, the insights from deterministic safe shutdown analyses have provided insights to refine post-fire safe shutdown procedures to improve fire response. Additional insights from Fire PRA are expected to identify additional cost effective improvements to fire safety.

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DEVELOPMENT OF A FIRE CONTAINMENT APPROACH IN THE FRAME OF THE FIRE HAZARD ANALYSIS FOR THE BELGIAN NUCLEAR POWER PLANTS

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ABSTRACT

Following the introduction of the WENRA Reference Levels in the Belgian regulation at the end of 2011, a comprehensive Fire Hazard Analysis (FHA) study became mandatory for all the Belgian nuclear power plants (NPPs). Seven units, representing 7500 rooms, needed to be assessed.

The FHA methodology developed is based on the IAEA's Fire Containment and Fire Influence Approaches (FCA and FIA) to demonstrate that the capabilities required to safely shut down the reactor, to remove the residual heat and contain the radioactive material are maintained in case of a single internal fire. The FCA developed is a deterministic screening approach that assesses the fire compartmentation which is the third level of the defence-in-depth concept applied to fire safety.

In the currently applied standards for the testing of the fire resistance of compartmentalization components, the normalized ISO 834 curve (temperature as function of time) is used to justify the fire rating of fire barriers. However, real fires have a different time/temperature profile. Therefore, a practical and automated method has been developed in the FCA to:

1. numerically characterize the fire barriers;
2. determine the fire curves inside a room by taking into account the different ventilation modes and the fire loads;
3. apply the fire curves to the characterized fire barriers of the room to assess possible fire propagations;
4. create a loop to reapply the step 2 and 3 in case of fire propagation(s) to adjacent rooms.

At the end of the process, for each room, all the propagation paths across the different rooms of a building are identified. The propagation paths are analysed and the impact on the loss of the safety components in the associated rooms can be assessed.

In order to cope with the large amount of data, the quantity of analyses and the imposed deadlines, a platform has also been developed to integrate all the input data (drawings, fire loads, safety equipment, etc.) and to automate as much as possible the FCA analysis.

This paper will give insights on the FCA methodology that has been developed. Its pros and cons will also be presented leading to potential pragmatic improvements.

INTRODUCTION

Following the introduction of the WENRA [1] Reference Levels in the Belgian regulation at the end of 2011 [2], a comprehensive Fire Hazard Analysis (FHA) study became mandatory for all the Belgian Nuclear Power Plants (NPPs). Seven units, representing 7500 rooms, needed to be assessed.

The FHA methodology developed is based on the IAEA's Fire Containment and Fire Influence Approaches (FCA and FIA) [3] to demonstrate that the fire safety goals are met. These fire safety goals are the capabilities required to safely shut down the reactor, to remove the residual heat and contain the radioactive material in case of a single internal fire.

The paper will introduce the principle of the defence-in-depth applied to fire safety. Then the paper will explain how the fire rating of fire barriers is assessed by numerically characterize them and how the fire (heat release rate (HRR) and temperature) and its propagation paths can be determined. Thereafter, the paper will give insights on the system analysis that is performed to assess the fire safety goals. Finally, the paper will introduce the safety tool that is used to centralize the data and to automate the fire propagation calculations.

DEFENCE IN DEPTH APPLIED TO FIRE SAFETY

To meet the safety goals, the fire safety is defined and designed according to the defence-in-depth principle which is [3] defined as follows:

- Preventing fires from starting;
- Detecting and extinguishing quickly those fires which do start, thus limiting the damage;
- Preventing the spread of those fires which have not been extinguished, thus minimizing their effects on the installation's safety and their consequences.

The developed FCA is a deterministic screening method that assesses the fire compartmentalization which is the third barrier of the fire safety defence-in-depth concept.

FIRE RESISTANCE RATING

Fire barriers and their components in Belgium NPPs are tested/verified against the Belgian standard on fire resistance (NBN 713-020 [4]), which uses the normalized ISO 834 [5] fire curve (which represents a cellulosic fire).

The fire resistance rating in this standard is the minimal time duration, for which the following criteria are met simultaneously (between bracket the almost corresponding criteria according to the EN 13501 standard [6]) when the fire barrier is exposed to an ISO 834 fire curve:

- Load bearing(R): considers the ability of a construction element to withstand fire exposure under specified mechanical actions without any loss of structural stability, typically a criterion is the maximum allowed deflection of the element;
- Integrity (E): considers the transmission of fire to the unexposed side of a construction element as a result of the passage of flames or hot gases, typically a criteria is the inflammation of a cotton prop;
- Thermal insulation (I): considers the transfer of heat from the exposed side of a construction element to the unexposed side, typically with a criteria $\Delta t_{average} > 140$ °C or $\Delta t_{maximum} > 180$ °C.

However:

- Fires can have a quicker development (higher temperatures) with a shorter duration that the ISO 834 fire curve; or
- Fires can have a slower development (lower temperatures) and last a longer time than the ISO 834 fire curve.

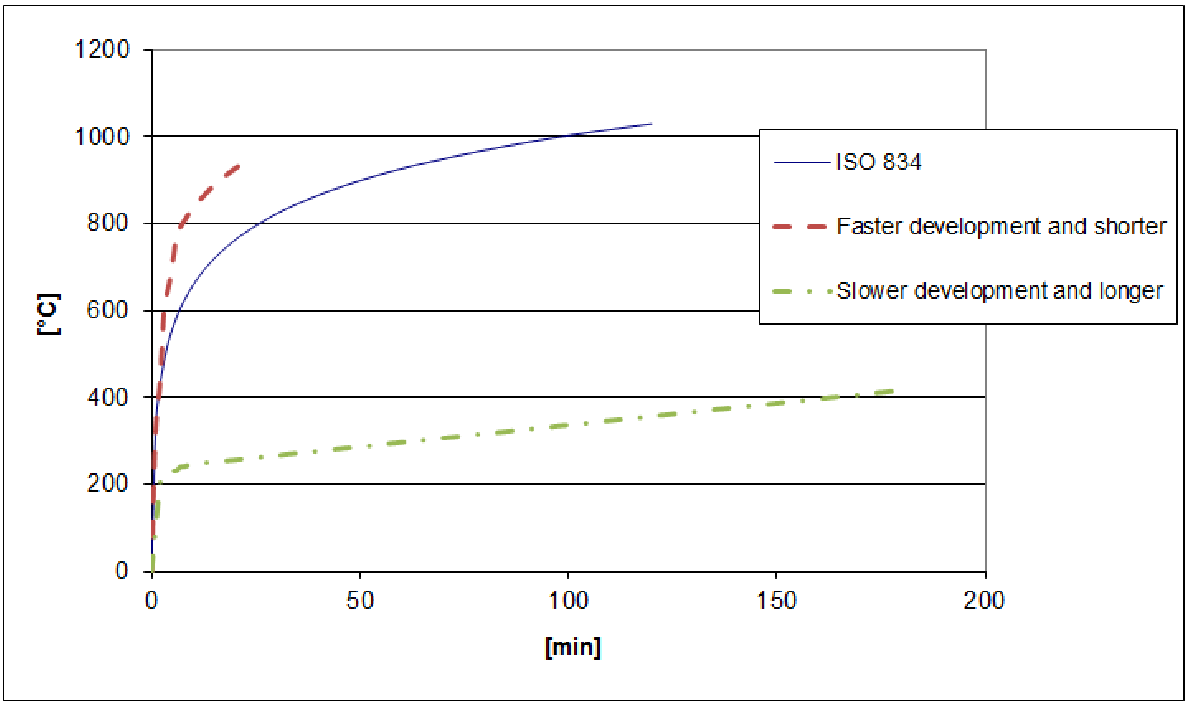

Figure 1 Fire development curves

Methods to assess the fire rating according to different fire curves were already developed such as the Ingberg "equal area hypothesis" in which it is assumed that if the areas under the temperature-time curves (above a baseline of 300 °C) of two fires are equal, the severities are equal. On this basis Ingberg developed a table from which the fire resistance of a compartment can be obtained from only the fire load [kg/m²]. But there is no theoretical justification and this method doesn't take into account the ventilation conditions. Other methods like Law, Petterson or Harmathy methods are difficult to interpret and give widely differing results [7].

Tractebel therefore developed a practical (i.e. thousands of rooms needed to be assessed) and conservative approach (the method is a screening) to assess the fire resistance rating of fire barriers if they are exposed to such fires.

The approach consists in

1. numerically characterize the fire barriers;
2. determine the fire curves inside a room by taking into account the different ventilation modes and the fire loads;
3. apply the fire curves to the characterized fire barriers of the room to assess possible fire propagations;
4. create a recursive loop to reapply the step 2 and 3 in case of fire propagation(s) to adjacent rooms.

NUMERICALLY CHARACTERIZING THE FIRE BARRIERS

The first step consisted in verifying according to the fire test reports of fire rated components in our NPPs which were the failure criteria of the components. The analysis has demonstrated that the first failure criterion was in almost all the cases the thermal insulation criterion. This means that the fire rating of the fire rated element is mainly determined by the thermal insulation properties of the element.

Nevertheless the stability and the integrity criteria shall still be assessed. For the stability criterion, it has been assumed conservatively that the criterion could be endangered if the temperature at 2.5 cm depth in a concrete wall reaches 500 °C (which represents the critical steel temperature [8]).

For the integrity criterion it has been assumed based on test reports, when this criteria was the first to be reached (mainly on double door leafs), that it was due to buckling resulting from the thermal behaviour of the components at high temperature. In order to cover this particular phenomenon, it has been verified that, in combining the criteria for the thermal insulation and the stability, excessive deformation due to buckling will never happen before the stability criterion.

THERMAL DIFFUSIVITY

In the framework of the Fire Containment Approach (FCA), the fire barriers were modelled using the Fourier-Kirchhoff equation with two thermal diffusivities parameters. One is used for thermal insulation and the other one for stability and integrity together.

To avoid that each fire barrier of the NPPs has their own thermal diffusivities parameters based on the real barrier properties (thickness, components, etc.), the thermal diffusivities parameters are determined using the designed fire rating of the considered barrier. Doing so, thermal diffusivities parameters values are only necessary for the different existing fire ratings (15 min, 30 min, 60 min and 120 min).

$$\rho \cdot c \cdot \frac{\partial T(x,t)}{\partial t} = \nabla(k \cdot \nabla T(x,t)) + q \qquad (1)$$

with:

k: thermal conductibility of the fire barrier [W/m K]);

ρ: density of the fire barrier [kg/m³];

c: thermal capacity of the fire barrier [J/kg K]);

q: internal source of heat (which is set equal to 0).

Considering the fire barriers as spatially uniform fictitious boundaries, the problem is unidimensional. The Fourier-Kirchhoff equation (Equation (1)) can then be written as follows:

$$\frac{\partial T(x,t)}{\partial t} = \frac{k}{\rho.c} . \frac{\partial^2 T(x,t)}{\partial x^2} \qquad (1.1)$$

Equation (1.1) can also be written as follows to introduce the thermal diffusivity α:

$$\frac{\partial T(x,t)}{\partial t} = \alpha . \frac{\partial^2 T(x,t)}{\partial x^2} \qquad (1.2)$$

with:

$$\alpha = \frac{k}{\rho \cdot c} \text{ [m²/s].}$$

The following assumptions are made:

- The temperature on the exposed side of the fire barrier is uniform;
- The thermal conductivity, the density and the thermal capacity of the fire barrier are kept constant;
- The fire barrier is a fictitious element with uniform thermal properties and fixed thickness(H);

- The fire barrier has the fire resistance rating of the wall element (fire door, fire damper, etc.) with the lowest fire rating;
- The Neumann condition on the unexposed side of the fire barrier is used, it means that there are no heat losses at the unexposed side of the fire barrier. This is a very conservative assumption that is used to simplify the calculations taking into account the large amount of rooms to assess.

$$\left.\frac{\partial T(x,t)}{\partial x}\right|_{x=H} = 0$$

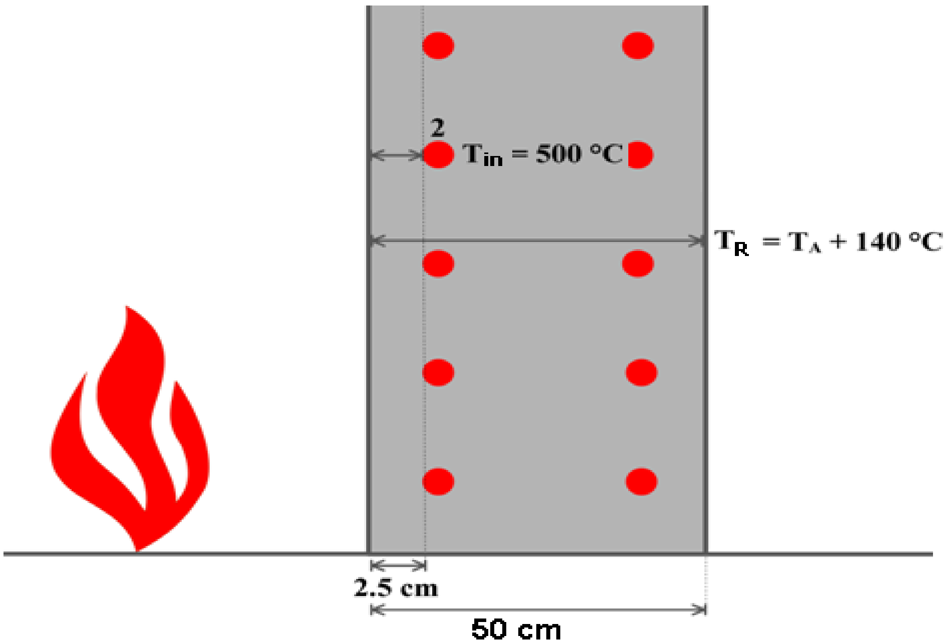

Figure 2 Assessment of the fire barriers

DETERMINE THE FIRE CURVES INSIDE A ROOM BY TAKING INTO ACCOUNT THE DIFFERENT VENTILATION MODES

Room fire curves are mainly dependant of the combustible materials and the ventilation conditions present in a room. Due to the compartmentalization, in case of fire, the ventilation conditions in the room could change due the closing of, e.g., fire doors, fire dampers, seals or the start of smoke and heat venting systems. However, it might be difficult without detailed modelling to determine the time at which the closure of some elements will happen, e.g., the closure time of fire dampers on the fresh air supply side when they are actuated by a fusible link in the damper duct. Therefore, in the FCA, it has been decided to model three distinct ventilation conditions without modelling the transitions between these conditions:

- No ventilation (“closed”): The fire is only supplied by the air present in the room.
- Natural ventilation: The fire is supplied by the air coming from adjacent rooms in the compartment trough permanent openings.
- Forced ventilation: The fire is supplied by the mechanical ventilation.

It is assumed that the “real” fire will be covered by these three ventilation configurations.

Considering the ventilation conditions of the room and the possibility to reach flashover conditions, the fire curves are governed by a set of six equations [9], [10].

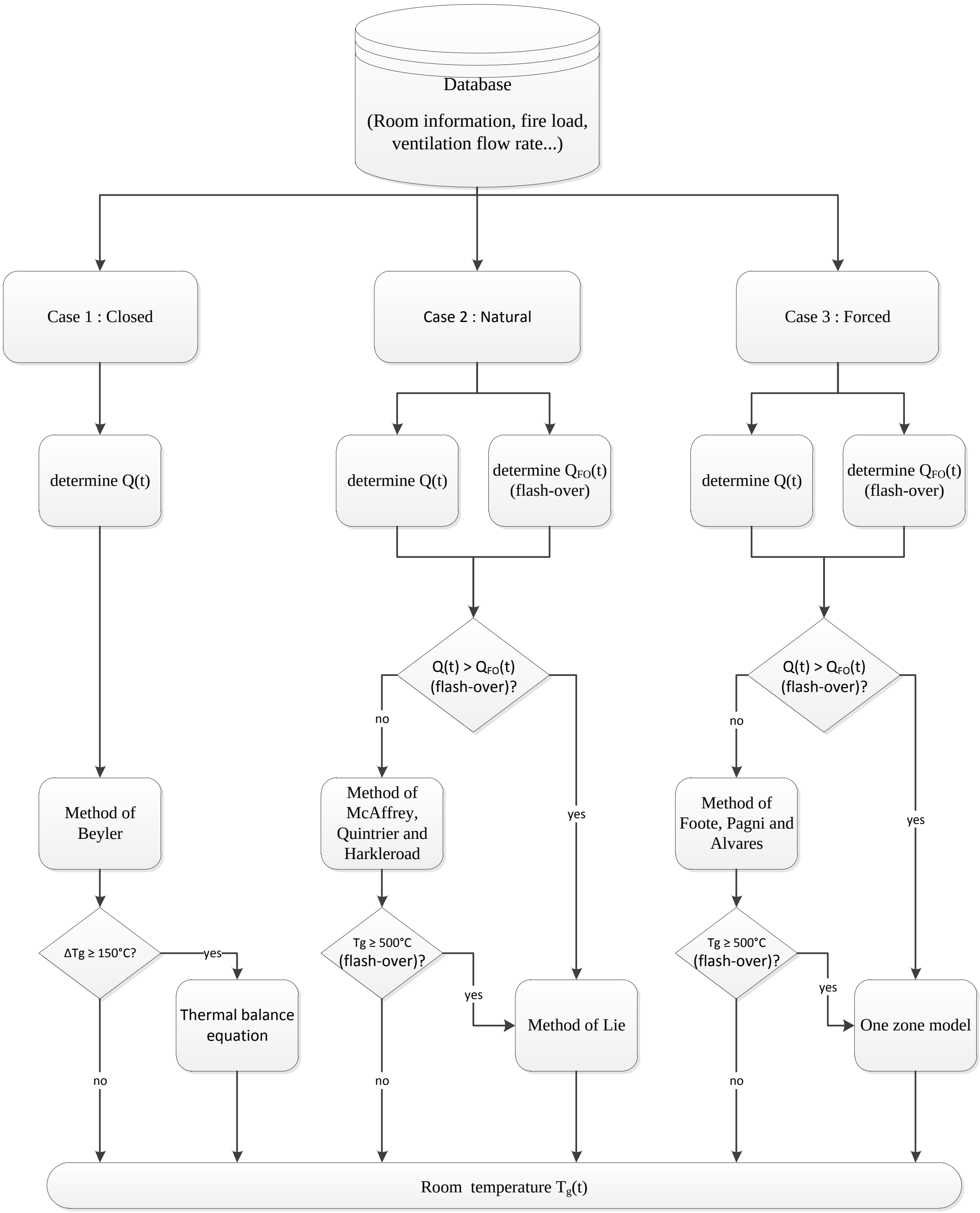

Figure 3 Determination of the room temperatures in function of the time (fire curves)

The following general assumptions and limitations are considered for all ventilation conditions:

- Calculations are performed taking into account an αt^2 growth and the maximum HRR in function of the ventilation conditions with no decrease. The HRR is maximized (and not the fire duration for instance).
- The oxygen limit is set to 0 % to compensate the air leaks in closed room configuration.

- In order to calculate the fire growth in a room, we assume that all the combustible materials (independently to their fire reaction) are involved in the fire load even if the flashover conditions are not verified[1]. The combustibles considered are the following :
  - all solid combustible materials;
  - all flammable and combustible liquids except those enclosed in pipes. However, for the diesel generators rooms, a leak is assumed on the supply pipe coming from the day tank;
  - all flammable gases (gas bottles): a constant release of gas is assumed in case of fire.

The heat release rate is corrected to take into account the position of the fire loads in the room. The fire loads can either be spread in the room, located against a wall or in a corner. A single averaged heat transfer coefficient is used for the entire inner surface of the room and the heat losses through the walls are minimized due to the use of conservative values for, e.g., the wall thicknesses, the densities and thermal capacities.

In the case that the room is protected by an automatic extinguishing system, calculations are done with and without the automatic extinguishing system. The calculation considers only one extinguishing system working at the same time. Nevertheless one extinguishing system can have an impact on several fire loads at the same time.

- For sprinkler systems, the method consists to limit the total HRR to its value after the calculated activation time of the system.
- For deluge systems, the method consists to decrease progressively the HRR of the protected fire load to zero after the calculated activation time of the system.
- For gas systems, the method consists to decrease immediately the HRR to zero after the calculated activation time of the system.

FIRE PROPAGATION ALGORITHM

Two conservative types of fire propagations have been defined:

- A direct fire propagation occurs immediately (before any fire propagation calculation):
  - A fire load is passing through a permanent hole with no fire rating between two rooms;
  - The sum of the surface opening(s) in the separation wall between two rooms is equal or greater than 1.6 m² (determined by engineering judgment (it corresponds to the surface of a door));
  - The sum of the surface opening(s) in the ceiling or floor between two rooms is equal or greater than 0.2 m² (determined by engineering judgment).

    The direct propagation process is a continuous process that only stops when the conditions listed above do not occur anymore.
- An indirect fire propagation occurs after the direct fire propagation process when one of the following conditions is met:
  - Conduction: the temperature on the non-exposed side exceeds 140 °C;
  - Instability: the temperature at 0.025 m depth in the barrier exceeds 500 °C;
  - Radiation: the gas temperature inside the burning space exceeds 500 °C[2], and

[1] The fire growth prediction depends on the flashover condition

[2] The criterion of 500 °C corresponds to the minimum gas temperature that would produce ignition of any material in the adjacent room(s) by radiation. It corresponds to a radiation of 20 kW/m² through the openings in the barrier.

- the sum of the surface opening(s) in the separation wall between two rooms is less than 1.6 m²;
- the sum of the surface opening(s) in the ceiling or floor between two rooms is less than 0.2 m².

When fire propagation occurs, a new burning space is then defined as the sum of the initial room and the room(s) where fire propagation occurred according to above mentioned criteria. Then the following actions will be performed:

- Definition of the geometrical characteristics of a new burning space by considering the room(s) adjacent to the barrier(s) where propagation occurred;
- Calculation of the fire load/energy of the new burning space;
- Calculation of the heat release rate in the new burning space;
- Calculation of the initial ambient temperature of the new burning space;
- Definition of the ventilation conditions in the new burning space;
- Definition of the initial temperature of the barriers of the new burning space;
- Calculation of the air volume available in the new burning space and in the fire cell/compartment containing the new burning space.

After each propagation, the three ventilation conditions are combined and calculated again.

The stop criteria are the conditions for which the fire propagation calculation ends. There are two types of stop criteria:

- The fixed stop criteria, which depend on the physics (occurs when the fire growth is physically no more possible):
  - There is no fire load or all the fire loads are consumed by the fire before it can propagate.
  - All the available air is consumed by the fire before it can propagate.
- The parametric stop criteria which are defined by the user:
  - the maximum fire duration;
  - the maximum volume of the burning space;
  - the maximum number of propagations;
  - the maximum number of compartments involved in the propagation.

These parametric stop criteria have been introduced in order to limit the calculation time, ensure that the calculations remain in acceptable validity range and because in most of the propagation cases, the fire findings are in the first propagations.

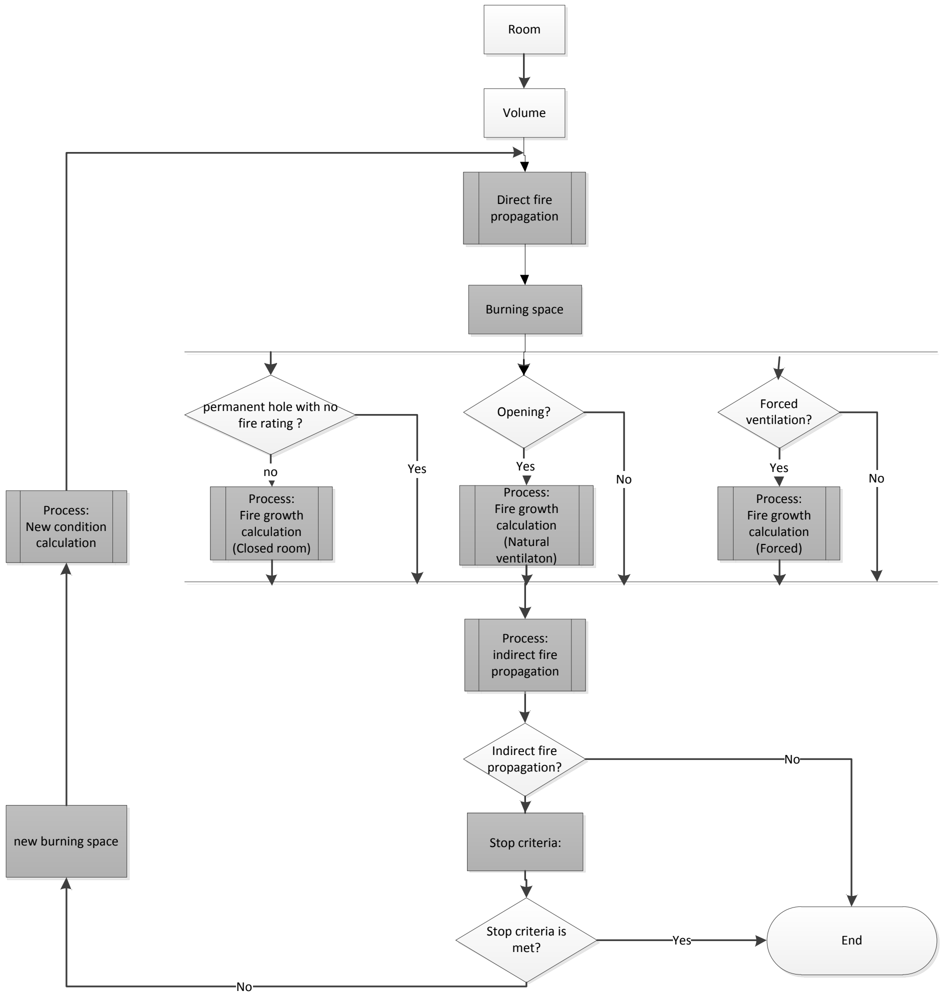

Figure 4 Propagation algorithm

SYSTEM ASSESSMENT

When all propagations are calculated then a "System Assessment" is performed. The "System Assessment" addresses the importance of the loss of different safety equipment located in the rooms potentially impacted by a fire scenario. This "System Assessment" evaluates the capability of the plant to reach the safe shutdown state. The following safety and safety support functions are required to reach the safe shutdown state:

1. Residual heat removal;
2. Support to residual heat removal;
3. Safe shutdown capacities (cool down, criticality, RCS integrity, pressure control);
4. Support to safe shutdown capacities;
5. Confinement;
6. Support to confinement;
7. Mitigation of Internal accidents in the long-term;
8. Support to mitigation of Internal accidents in the long-term.

There is no single failure criterion added to fire damages to the considered safety systems.

COMBINATIONS OF EVENTS

The analysis takes also into account combinations of independent events:

- Large Break Loss of Coolant Accident:
  Large break loss of coolant accident (LBLOCA): only the recirculation phase after a LBLOCA is taken into account as this phase duration might last approximately one year and that an independent internal fire cannot be excluded during such a long period.
- Loss of Offsite Power (LOOP):
  An independent fire cannot be excluded during a LOOP. In case of a LOOP, only the systems designed to remain operational in such conditions are credited in the FHA studies in order to meet the fire safety goals.
- Safe Shutdown Earthquake (SSE):
  Considering that the time to reach the cold shutdown state (starting from full power state) lasts few days only and considering that the probability of SSE *combined with* an independent fire during a period of 40 hours is less than 6,5 10^{-8} events/year, the combination of a SSE and an independent fire is considered as not credible.

After a SSE, an independent fire is most likely to occur when the plant is already in a cold shutdown state. In that case, it was assumed that the damages due to the earthquake were repaired before the fire occurs.

SAFETY ASSESSMENT TOOLS

In order to perform the study and to be able to update it in the future, a software has been developed in cooperation with IOS international to allow:

- the data acquisition;
- the calculation;
- the assessment;
- the reporting.

The data acquisition is done by two complementary ways:

- Complete the FHA database based on available building database;
- Complete and verify data in the field by walk downs with a dedicated input tool.

All the data is geo-localized and structured by categories (type of fire loads, safety equipment, detection means, etc.) per room in a graphical user interface and on drawings of the plants.

Typical data are [3]:

- General information of the room (geometry, layout, etc.);
- Fire loads characteristics;
- Location and characteristics of the fire loads;
- Walls/floors/ceiling characteristics such as the fire rating, the openings, etc.;
- Location and type of the fire detectors;
- Location and type of the manual and automatic fire suppression systems;
- Presence and identification of FHA safety equipment and/or cables parts;
- Ventilation flow rates.

The collect of the data has constituted a large effort.

The geo-localisation allows also identifying all interconnection between the rooms, which is essential to determine the propagation paths.

When the data acquisition is complete, calculations are run automatically for each room in order to determine the possible propagations path. Calculations are using a set of Matlab routines that where developed by Tractebel.

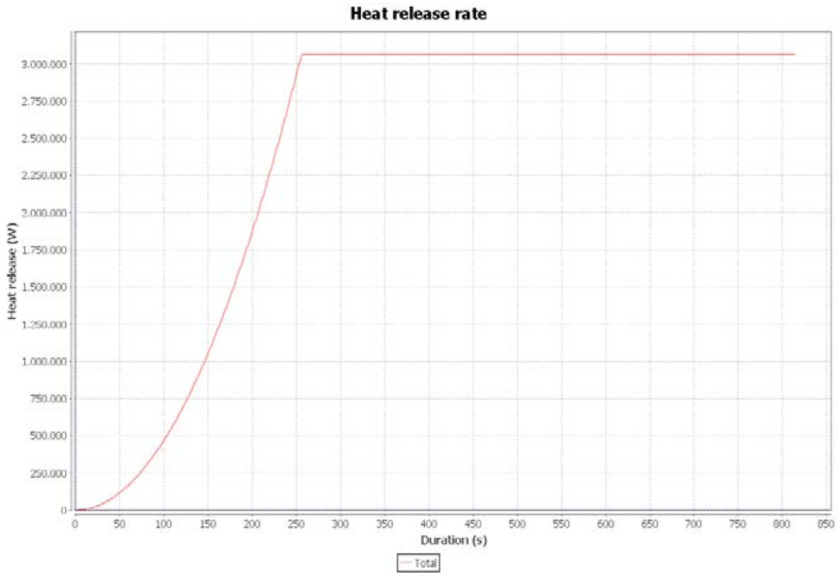

Figure 5 Example of heat release rate

In parallel, the tool allows to assess the adequacy of the fire detection, manual (hydrants, portable extinguishers) and automatic extinguishing means using algorithm provided by Tractebel. The tool assesses automatically some criteria based on prescriptive requirements (e.g., the required quantity of portable extinguishers according to the floor area and their type according to the type of fire load) or generates visual helps to perform, e.g., the adequacy of the fire detection (see figure 6 on which the hatched area corresponds to the surface covered by one detector and the red circles to the maximum distance allowed between detectors).

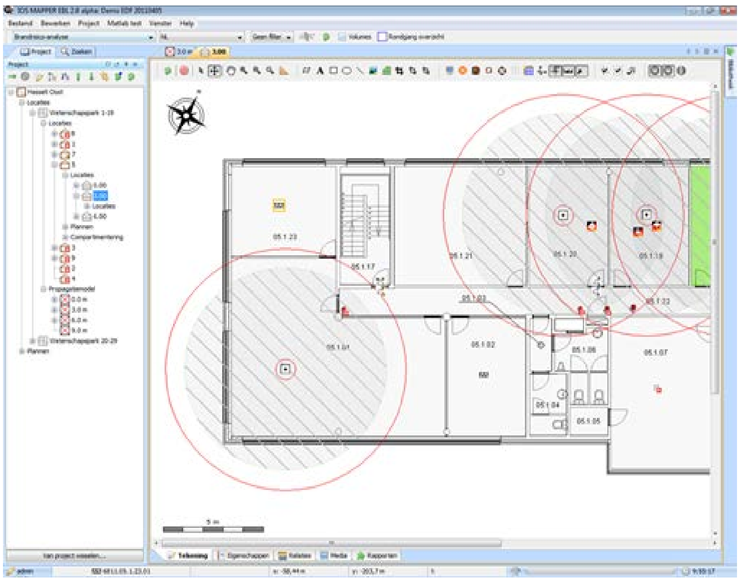

Figure 6 Example of fire detection assessment

Finally, the tool can generate automatic reports with all useful data's and results.

PROS AND CONS

Advantages of the method:

- Assessments depend only on the global fire rating of the fire barriers and not on the specific characteristic of each element (e.g., fire doors, seals, fire dampers, etc.).
- Assessment is not user dependent.
- Assessment is largely automatized.
- All data is centralized and allows to keep the study up to date.
- Available data and model (e.g., propagation model) are used for other projects (e.g., Fire PSA, Flooding PSA, etc.).

Disadvantages:

- The method is very conservative (because it is used as a screening).
- The method is only usable if the assessed building is divided in fire compartment with physical boundaries. The method is not appropriate if separating distance between redundant SSC is used as segregation means. In such case, the FIA approach or specific fire risk analysis have to be used to demonstrate that the fire safety goals are met.
- The assessment is data quality dependent although this is not specific for this method.
- It requires a large effort to initially collect and introduce the data in the database.

CONCLUSIONS

The FCA methodology developed is a new and simplified method which allows assessing and screening the compartmentalization of nuclear power plants in the framework of Fire Hazards Analysis. The methodology is in line with the IAEA expectations and has been used for the Fire Hazard Analysis of all the Belgian Nuclear Power Plants.

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ASSESSEMENT OF HAZARDS COMBINATION INCLUDING INTERNAL FIRE

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ABSTRACT

Lessons learned from the accident affecting Fukushima Daiichi highlighted the importance of considering an NPP's robustness against the challenges from combined and consequential hazards. This includes that designers and licensees should understand the multi hazard effects on key safety systems. This provides challenges to the licensees/vendors relating to consequence assessment and engineering substantiation. This paper provides a regulatory perspective on these issues and discusses and outlines ONR's developing expectations for the assessment of multi-hazards.

UK REGULATORY CONTEXT

The Office for Nuclear Regulation (ONR) is the United Kingdoms' (UK) independent regulator of nuclear safety and security. A key principle of UK's law and ONR's regulatory approach is the requirement that licensees build, operate and decommission nuclear sites in a way that ensures that risks are kept as low as reasonably practicable. This is referred to as the ALARP principle and requires licensees to demonstrate that they have done everything 'reasonably practicable' to reduce risks. Demonstration of risks is ALARP may include numerical risk assessments – including potential risks from hazards, optioneering studies but also generally includes a comparison with "relevant good practice".

The UK generally operates a goal-setting regime rather than the more prescriptive, standards-based regimes. To ensure an effective an efficient regulatory approach ONR sets out its regulatory expectations and requires licensees to determine and justify how best to achieve them. ONRs regulatory expectations are outlined within the Safety Assessment Principles (SAPs) [1] and associated technical assessment guides – all of which are published and are freely available on the internet.[1]

ONR's goal setting approach allows licensees to be innovative and achieve the required high levels of nuclear safety by adopting practices that meet its particular circumstances.

The UK's approach is benchmarked against international standards, and in some cases compliance with an international standard may be viewed as relevant good practice. We also take account of national standards from other countries as potential good practices. This allows us to look at designs which may have come from a variety of different countries and be open to the underlying design approaches that protect against hazards. Relevant standards may include IAEA standards [2] to [5], but the flexibility of our approach also allows us to consider safety cases which relate to U.S. Nuclear Regulatory Commission Regulation (NU-

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[1] Other ONR presentation to this SMiRT Post-Conference Fire Seminar gives more details of ONR's assessment approach and quotes several of our SAPs.

REGs), European Utility Requirements (EURs) and national standards (e.g., French or German).

MANAGING THE RISK FROM COMBINED HAZARD EVENTS

To minimise the effects of combined hazards, and to ensure that they do not adversely affect the reliability of safety systems design to perform essential safety functions, items important to safety (i.e. safety systems and safety related systems) should be either qualified to withstand the effects of combined hazards or protected against the hazards, i.e. this required the appropriate use of equipment qualification, redundancy, diversity, separation or segregation.

For each combined hazard sequence that cannot be eliminated a “defence in depth” approach should be adopted. The safety case should demonstrate how the “defence in depth” philosophy has been applied to each hazard combination and identify the appropriate control measures.

- Prevent the hazards occurring;
- Limit the severity of the hazard should it occur;
- Limit the consequence of the hazard should it occur and be severe.

To prevent the hazard occurring all reasonable practicable means commensurate with good engineering practice should be adopted in the design and layout of the plant, and through the use of SSCs (*s*ystems, *s*tructures, and *c*omponents) of appropriate capacity and capability, to reduce the likelihood of hazards and to mitigate against consequences.

Hazard severity should be minimised as far as is reasonably practicable. Hazardous inventories should be removed, reduced or isolated. Measures should be adopted to segregate and isolate hazards reducing their influence on each other. Items important to safety that are to be used for hazard control and mitigation should be protected from the accumulative effects of a combined hazard sequences. Any safety related SSC should be rated and have withstand against all hazards individually and against combined hazard sequences, such that the barrier could contain the event and prevent spread to other facilities.

Where there are constraints on systems and a full segregation cannot be deployed due to conflicts with other plant design requirements, separation of items important to safety could be achieved using an appropriate combination of safety measures. This could include options such as adopting local protection systems, wraps, shielding, increasing standoff distances, implementing local passive barriers, and installation of active systems such as fire suppression systems, drainage and ventilation.

Hazard combination sequences could be caused by maloperation, and therefore human factors can be significant. Activities that could affect nuclear safety should be designed such that the important aspects of operation and management required for maintaining safety are identified and implemented.

COMBINED AND CONSEQUENTIAL HAZARDS ASSESSMENT

The internal hazards assessment involves some discrete steps including identification of hazards including combined and consequential events, identification of Systems, Structures and Components(SSCs) potentially affected by the hazards, analysis of the consequences and identification of safety measures. This process is briefly discussed below.

Combined and Consequential Hazards Identification

Safety assessments should demonstrate that the threats from hazards are either removed or tolerated and minimised. This is done by demonstrating that items important to safety are appropriately designed to meet the required performance criteria. Safety assessments are necessarily plant specific.

A key element in determining performance criteria for SSCs related to the safety of Nuclear Power Plants (NPPs) is to identify and characterise those hazards to which it could be subjected. Hazards, such as fire and other internal hazards, by their nature cannot be treated in isolation and often will give rise to further hazards, thus plant may be exposed to the challenges from multiple hazards. Consideration should therefore be given to the effects of combined hazards.

The potential for a combination of hazards to affect safety should take account of the potentially widespread effects of external (and some internal) hazards (including concurrent and consequential hazards) which may challenge multiple safety functions and locations simultaneously. In addition, the hazard may affect multiple facilities, as well as the local and national infrastructure. In considering the risks from a site, and whether they are ALARP, consideration on a site-wide basis will be needed for credible combinations of internal or external hazards and or plant faults.

The approach taken to identify a combined hazard event should be systematic and comprehensive. Determination of the combination sequence should take into account hazard effects, plant/facility design, locations and the operating environment as well as essential services (to and from the facility).

Some guidance for hazard identification has been developed either at a company or a national level, but there is not very much coverage of combined and consequential hazards in international guidance.

Many of the approaches include categorising the types of hazard combinations to be considered. A widely used taxonomy has three types of combinations:

- **Consequential Hazards**: The consequences of an internal hazard induce one or more additional hazards – e.g. an exploding gas bottle generating fragmentation and fire. This may equally lead to a cascade of events.
- **Concurrent Hazards**: A common initiating event (including external hazards) results in multiple internal hazard(s) occurring – e.g. seismic event leading to both fire and flood challenges.
- **Independent Hazards**: An initiating event (including hazards) occurs independently from, but simultaneously with an internal hazard, e.g., a fire on a standby diesel when responding to a plant-trip caused by a weather-related loss of heat sink event.

The interaction of external and internal hazards should also be assessed; external hazards can be an initiator for multiple internal hazards to occur. For example, a fire could occur at the same time as an earthquake or flood. No one facility is the same and therefore every facility will have a unique hazard fingerprint.

The complexity of combined hazards and the potential permutations calls for an effective process to be applied to identify and characterise and screen the candidate hazard combinations. Hazards should be identified in terms of their severity and frequency of occurrence. Consequential and correlated events should be characterised as having either a discrete frequency of occurrence (discrete hazards), or a continuous frequency-severity relation (non-discrete hazards). For independent events an identification process should be adopted to include all foreseeable independently occurring hazards. ONR recognise the risk that hazard identification processes could lead to long lists of potential combinations and encourage pragmatic approaches that provide bounding assumptions and lead to a clearer presentation of the challenges.

Company and national guidance may include some guidance on which combinations are credible. For example, some guidance combines frequencies to identify that some combinations can be excluded from study. This is particularly of interest to regulators, and ONR looks for robust arguments. Guidance often includes a cut-off frequency for hazard combinations, but this is artificial and potentially misleading if the coupling between the contributing hazards are not fully understood. Another area for care is to assess the frequency of a hazard combination (for this example, fire and flood) and to recognise that although it may not be credible that the maximum fire and the maximum flood occur in the same event, there may be a credible combination of fire and flood which is onerous to the plant and which is credible.

For each internal or external hazard or combination which cannot be excluded on the basis of either low frequency or insignificant consequence, a design basis event should be derived. ONR would prefer licensees and vendors to adopt a more permissive approach to screening such that the challenges to their safety cases from low frequency combinations are understood and to consider if it is reasonable to enhance their design robustness with this knowledge. In most cases, satisfactory decision making on design robustness can be made by bounding analyses, but this should also include bounding analyses for hazard combinations.

ONR's experience of assessing hazards safety cases from differing NPP designs suggest that it is often easier to make compelling safety cases if designers are "hazard aware" at the early concept stage of a design. This can lead to a simpler and more robust set of "hazard informed" layout decisions, with improved alignment between the rooms in differing floors, with simpler near-monolithic primary hazard barriers, and with a reduced number of penetrations though primary hazard barriers. Many designs, however, appear to have hazards considered as an afterthought and although acceptable safety cases can be constructed these may be more complex, and potentially less robust.

The design of SSCs to withstand the effects of combined, consequential and concurrent internal hazards is a multi-disciplinary task. This should start at the stage of the derivation of the hazard as close integration and coordination of the engineering and internal hazards disciplines is important for the delivery of a safe, efficient and effective design solution.

Combined and Consequential Hazards Analysis

Once a hazard or hazard combination is identified as requiring further analysis there are two separate parts to analysis. One looks at the hazard progression (e.g. for a fire, what temperatures, pressures, smoke concentrations can be present), the other looks at the ability of plant or structures to withstand these challenges. Key to the plant challenges may be layout decisions and how hazard barriers segregate plant.

Care needs to be taken when conducting combined hazard analysis. Combined hazards can occur at the same time, or can occur at later intervals. It is therefore important to determine a hazard combination sequence. A hazard combination sequence should determine the loading/ magnitude of the hazard, the duration it is applied, and sequencing of the occurrence of other hazards. As an example, fire may be associated with the consequence of a pressure part failure which can lead to immediate effects such as blast, jet impact, missile impacts and pipe whip dynamic and environmental impacts, followed by the slower developing effects of the fire. A challenge for the substantiation of the withstand capability of barriers is to assess whether the sequence and timing of these demands on the barriers affect their integrity. This type of analysis is complex and may require input from a number of disciplines such as structural integrity, civil engineering and mechanical engineering to mention but a few.

For each identified hazard combination sequence, the analysis should also take into consideration any deterioration or damage to safety related SSCs after being subjected to each of the various hazards and determine how its performance and subsequent withstand is affected. For example a structure that has been subject to a blast load could have reduced withstand as a result of damage to load bearing elements, if this structure was then subjected to a design basis vehicle impact (even if withstand had been demonstrated for a vehicle impact) it could ultimately result in a failure of the structure. Therefore, for a combined hazard event it is the net effect of the hazards that could result in a failure of a system or structure, even if individual withstands can be demonstrated.

Some internal hazards will always be a sequence initiator and therefore demands an assessment of a combined hazard sequence. For example a blast will generate a shock and in most cases fragmentary missiles. Interaction of both shock and fragments should be considered when the timing of the shock fragmentation is sufficiently close to one another. Changes in the materials state as a result of the shock wave interaction could affect the fragment withstand claims, and therefore should be accounted for.

The combination of two or more hazards occurring at the same time, coincidently or following one another could cause cumulative damage sufficient to undermine the safety claims. All elements of a safety related SSC should be identified and their potential contribution to failure assessed. This should include consideration of, but not limited to, the performance of fixtures and fittings, joints, paint/coating systems, claddings, penetrations, sealants and ventilation systems. For example, an explosion event could damage both fire protection claddings and ventilation systems, thus if a fire was to start there would be loss of fire containment and ultimately a potential escalation of event. A non-nuclear example was seen at the World Trade Centre at New York, where the Towers withstood the initial impacts but failed following the subsequent fire. Analysis suggested that the consequences of fire were exasperated by loss of fire protection to structural steelwork, so the structure may have withstood either the impact or the fire but not the combination.

Another feature of combined hazards is the potential for translation of effects beyond the initial location as the hazard effects are realised. Within the UK, ONR has seen several safety cases which have looked at whether an oil fire coincident with a flood (e.g. caused by a turbine disruptive failure) could lead to translation of burning fire to another location where it may have more significant effects. A relevant international event was at the Vandellos NPP where burning lubricating oil from a failed turbine was carried by water in the culverts underneath the turbine to the area below the reactor.

The hazards and consequences arising from combined hazard events, where either single or multiple measures are designed to prevent their escalation, should be quantified and assessed to verify the adequacy of the measures, e.g., for preventing fire spread and maintaining the integrity of the safety systems.

Most established design standards contain standard load combinations that should be considered for generic design purposes. It is important that, in any particular circumstance, the actual load combinations and sequences arising from the hazards are used for the design with relevant factors applied to provide an appropriate level of conservatism. The methodologies used for analysis and design should be appropriate to the safety function of the SSC. Measures should be applied to provide assurance of the validity of data and models used in safety case analysis work, including engineering substantiation and verification carried out to demonstrate that any numerical models are correctly implemented and accurately represent the design specification. As part of the verification, the measures should be allocated an appropriate safety category (A-C) and safety classification (1-3) to clearly identify their role in ensuring nuclear safety.

The design should be developed to ensure that any potential conflicts in the design to meet nuclear safety, nuclear security, conventional safety and fire requirements are considered and implemented in an integrated manner so that they do not compromise one another.

Combined hazard analysis may also contain various levels of uncertainty. Analysis should therefore determine the sensitivity of analytical results to the assumptions made. This should include the assumptions for the hazard load; sequencing of events and duration the hazard is applied as well as the data used and the methods of calculation in order to identify the potential of cliff edge effects. The analysis should also identify all the limits and conditions necessary in the interests of safety.

CONCLUSION

The effects of combined hazards should be considered as part of the nuclear safety case. This paper has discussed key principles for the identification, analysis and mitigation of combined hazard sequences, and given some regulatory insights. These will be supplemented by examples in the supporting slides.

Nuclear plants are complex and have many areas that could give rise to multiple hazards. Therefore, combined hazard sequences should be determined for credible hazards that could occur concurrently, coincidently or independently together. The analysis of the cumulative effects of a combined hazard sequence is complex and should account for any degradation of performance as a result of each hazard sequence.

Combined hazard sequences should be mitigated as far as is reasonably practicable utilising safety measures that either eliminate the hazard, reduce the severity or frequency. By identifying and quantifying the combine hazard sequence adequate safety measures can be implemented and therefore demonstrate that the risks from a combined hazard sequence are as low as is reasonably practicable.

Guidance on both the identification of combined hazard combinations, the characterisation of the behaviour of the combined event and the effects on plant and structures is scarce; there is some national guidance, but this is more on the identification of credible combination than on the effects. ONR has adopted a consistent approach to these issues for some time now. ONR intends to capture its current practice in a forthcoming update to the ONR technical assessment guide for internal hazards. ONR is also keen to influence international guidance towards improved consistency on the treatment of combined and consequential hazards.

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AFCEN RCC-F: A NEW STANDARD FOR FIRE PROTECTION OF WATER COOLED NUCLEAR POWER PLANTS

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ABSTRACT

Before the end of 2017, AFCEN will publish a new code for fire protection of water cooled nuclear plants, named RCC-F. This code, evolved from former ETC-F code which has been applied to different EPR plants under construction (Flamanville 3 (FA3, France), Hinkley Point C (HPC, United Kingdom), Taïshan (TSN, China)) presents significant enhancement and evolutions resulting from eight years of work involving different contributors from the nuclear field (AREVA, CEA, EDF, CNNC, CGN, etc.). It is now open to any type of PWR (*p*ressurized *w*ater *r*eactor) type of nuclear power plants and not any longer limited to EPR(*E*uropean *P*ressurized *R*eactor) plants. The presentation gives an overview of the code specifications and focuses on significant improvements.

INTRODUCTION OF AFCEN ORGANIZATION AND RCC-F

AFCEN "Association Française pour les règles de conception, de construction et de surveillance en exploitation des matériels des chaudières électro-nucléaires" (French society for design, construction and in-service inspection rules for nuclear island components [1]) founded in 1978 is now an international association whose primary purpose is to produce up-to-date codes offering accurate and practical rules for the design, construction and in-service inspection of components for use in industrial or experimental nuclear facilities (RCC codes) and ensure certified and readily-available training programs enabling code users to achieve a high level of expertise, knowledge and practical skills in using AFCEN codes. AFCEN's editorial groups, currently feature over 650 experts. More than 110 nuclear power plants and experimental reactors are currently designed and/or built using AFCEN Codes The association proposes at the moment three codes for mechanical components: RCC-M (fabrication), RSE-M (in-service inspection) and RCC-MRx (high temperature reactors, experimental reactors and fast neutron reactors); one code for electricity and I&C systems (RCC-E); one code for nuclear fuel (RCC-C); one code for civil engineering works (RCC-CW) and one code for fire protection systems (ETC-F).

Before the end of 2017, AFCEN will publish a new code for fire protection of PWR type nuclear plants, named RCC-F (Design and Construction Rules for Fire Protection of Water Cooled Nuclear Power Plants). RCC-F is an evolution of the AFCEN ETC-F produced in two versions (2010 and 2013). This new release avoids EPR specificities and has been adapted to PWR reactors in general.

ORIGIN AND FEATURES OF RCC-F

RCC-F is a full fire safety standard for PWR NPP covering the different aspects of design (partitioning, egress, detection, extinction, etc.) and making link to equipment qualification specification and standards, risk analysis methodologies, operation, intervention and firefighting. It is consistent with relevant high level standards such as IAEA NS-G-1.7 [2] or the WENRA Safety Level "S" [3].

RCC-F has been derived from ETC-F used on EPR projects such as FA3, HPC, and TSN. It beneficiates from the long-term French experience on fire safety in NPP, started in the eighties with codes like RCC-I [4].

Many updates, enhancements clarifications and optimisations have been introduced by the dedicated sub-committee at AFCEN, taking profit of the FA3, OL3, HPC and TSN feedback. Not only EDF but other industrials and actors from the fire safety field have been participating to those developments. A mirror committee CSUG is active in China.

RCC-F code provides a great flexibility for the use of local standards or practices. It gives an introduction to advanced risk analysis methodologies such as the EPRESSI method, with potential benefits in the cost of the technical solutions.

RCC-F has been chosen in France for new built projects like EPR NM, considering that the code represents a "best available practice" in the nuclear fire safety field.

RCC-F STRUCTURE

The structure of the code starts classically from high level consideration to practical rules. Technical specifications, applicable standards and references are provided in the appendixes.

Chapters B to C provide a systematic methodology for the establishment of the fire safety strategy in the scope of the nuclear safety case: starting from safety objectives to assessment rules (§ B), and practical method for the fire zoning and common modes identification, functional confirmation and treatment (§ C). § D gives general construction provision (and some link with the operator prevention) when § E goes more in details into practical considerations: relevant technical solutions, rules of design and installation of equipment related with fire.

The code chapters are organised as follows:

A 2000 GENERAL POINTS
- A 2100 OBJECTIVE OF THE RCC-F
- A 2110 GENERAL OBJECTIVE
- A 2120 NUCLEAR SAFETY PRINCIPLES
- A 2200 APPLICABILITY OF THE RCC-F
- A 2300 DEFINITIONS

A 5000 QUALITY ASSURANCE

B 1000 GUIDELINE OF NUCLEAR SAFETY DESIGN PRINCIPLES
- B 1100 MAIN SAFETY OBJECTIVES
- B 1200 DESIGN NUCLEAR SAFETY REQUIREMENTS AND ANALYSIS RULES
- B 1300 APPLICATION OF RANDOM FAILURE PRINCIPLE
- B 1400 FIRE AND EVENTS

C 1000 FIRE PROTECTION DESIGN BASES
- C 1100 PREVENTION OF FIRE START
- C 1200 QUICK DETECTION AND EXTINCTION
- C 1300 LIMITATION OF AGGRAVATION AND PROPAGATION

D 1000 CONSTRUCTION PROVISIONS
- D 1100 PREVENTION
- D 1200 FIRE CONTAINING

MAIN IMPROVEMENTS PROVIDED BY RCC-F

RCC-F takes profit of the four decades feedback and operational experience of the EDF PWR fleet and proposes an up-to-date guideline for building new plants with regard to fire safety prevention and protection.

The fire protection approach is based on the classical defence in depth approach [2], [3]:

- Prevention of fire occurrence (selection of materials with low reaction to fire level, prevention of ignition, electrical protection, limitation of fire loads, etc.);
- Quick detection and extinguishing of fires having started (automatic fire detection and fixed fire extinguishing and suppression systems, manual means of firefighting);
- Limitation of aggravation and propagation of fire (called fire mitigation, by fire barriers, prevention of common mode failures, limitation of environmental releases).

Each level is detailed and leads to equipment or construction requirements, material qualification and controls.

The nuclear safety approach is based on the state-of-the-art principles for internal hazards, taking into account the relevant safety principles: random failure, plausible internal hazards or accidental conditions combinations, habitability of the main control room, etc.

In comparison to the FA3 ETC-F, the main improvements of RCC-F are resumed in the following.

Enhancements, Clarifications and Optimisations of the Code

Starting from the ETC-F FA3 (Rev. G) text, many clarifications and enhancements have been proposed to obtain a more clear and more comprehensive code. It has to be noted that the reference AFCEN version is in English (French version to be published further) and a significant editorial language polishing was part of the work.

The code provides a better identification of nuclear safety requirements, by differentiation between life safety, environmental and investment protection. A better balance between requirements (“shall”) and recommendations (“should”) improves the applicability of the code.

In the same objective, more flexibility has been introduced in the technical solutions (e.g., credited numerical codes and methods, smoke control, damper technology) in agreement with the different teams and entities represented in the working group.

Integration of Two National Regulation Appendices (France and United Kingdom)

Life safety is an important issue in fire risk assessment and its complementarity (and sometimes potential conflicts) with nuclear safety has to be correctly assessed. A significant work has been carried out on this issue during the HPC application of ETC-F, starting from a code dedicated to specific French applications and including many links to French life and environmental safety regulations. All along the main body an identification of the issues potentially impacted by local regulations has been introduced in the code (e.g., egress, alarm, prevention requirements, etc.). A link is made with two practical applications (France and United Kingdom) in Appendix A. It does not mean that the code is not applicable to other countries: In those cases, chapters A to E will be directly applicable, but the link to national regulation shall be assumed by the user, with much support from the two illustrations already given in Appendix A.

Avoidance of EPR Specificity

To propose a more general PWR standard, it was necessary to identify and analyse EPR specificities potentially present in the ETC-F code.

First of all, the vocabulary was inspected to eliminate specific wording such as RRC, PCC (FA3) and substitute it by more relevant wording from high level references (DBC, DEC (WENRA)). Classification terms (F1, F2) were changed by general formulas like: "*systems allowing to reach and maintain a Safe Shutdown State*", or "*safety classified systems*", as far as there is no international consensus on those terms.

Mentioning design specificities concerning for instance reactor or other building design, the 4-train concept, or the severe accident approach, was pursued and suppressed.

Then, most important of all, the safety principles issued from ETC-F FA3 were reviewed and updated in consistency with the state-of-the-art and the most usual practice worldwide. Considering that the detailed corpus of safety principles adopted to manage an internal hazard like fire are assumed by each new built project - in agreement with the authority having jurisdiction - the set of principle presented at § B is not any more mandatory, but can be modified or completed by each project. Complementary explanations are provided in Appendix H to adapt the common mode identification process in such cases.

OTHER ISSUES

Environmental Issues

The new French regulation [5], [6] with respect to nuclear safety now includes an evaluation of environmental impacts in case of internal hazards, including fire. This new regulation is integrated in the French appendix and the code has been modified to be easily compliant with it. Modifications of FA3 ETC-F resulting from these investigations have been incorporated in RCC-F.

EPRESSI Method

EPRESSI is a method developed by EDF to control the adequacy of a fire barrier to the potential fire hazard conditions in a given location of the installation. A short summary of the method and a link to the detailed specification document is proposed in RCC-F. The method is suggested as a good practice to assume this necessary step of the fire hazard analysis (FHA). It has to be noted that an ISO standard is about to be issued, based on this method (see [7]). The next versions of RCC-F may probably shift to this ISO standard.

Electrical Cables

Recent EU (*E*uropean *U*nion) CPR (*C*onstruction *P*roducts *R*egulation*)* is changing the panorama for the specifications of reaction to fire for electrical cables in Europe. In France the C1 category is now transposable into Euroclasses. The RCC-F code will propose different solutions in that context in order to specify cables with a satisfactory fire reaction:

- NF standard C 32070 [8] test no. 2 (class C1) and standard IEC 60332-3 [9] category B, regarding their fire behaviour, IEC 61034-2 [10] for smoke density test, EN 50267-2-3 [11] for corrosivity, based on PH and conductivity tests;
- IEC 60332-3-23 [9] (flame spread test) and IEC 60754-2 [12] (corrosivity test) and IEC 61034-2 [10] (smoke density test);
- Euroclass cables from minimum class Cca, s1, d1, a2, according to EN 13501-6 [13].

In all cases halogen free cables are required.

PERSPECTIVES

The upcoming new RCC-F standard has been adopted as design code for EDF new built projects such as EPR NM (EPR *N*ew *M*odel). Licensing proceedings are to start with French TSO IRSN on the code.

Furthermore, a design code as RCC-F is necessarily subject to evolution to remain actual with respect to the state-of-the art and the operating experience. The upgrade period of AFCEN codes is either two or three years at the time being. During that time, modifications are collected through detailed modification forms. Interpretation forms allow getting good understanding or examples of application of the code.

Thus, the AFCEN RCC-F subcommittee work is going on. The main trends of the future developments are to enhance § D and § E introducing the feedback from China, United Kingdom and technological watch. Issues like beyond design basis hazards considerations, non-thermal effects of fire, detailed fire analysis guidelines, are on the menu.

CONCLUSION

AFCEN RCC-F is a coming new standard for the design of fire protection of NPP. In line with former codes like RCC-I or ETC-F, the code benefits from the long-term French nuclear industry experience in the field and the recent feedback from EPR projects such as FA3, HPC, TSN or OL3. Not limited to EPR designs, it provides a relevant and flexible guideline applicable to all types of PWR reactors.

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U.S. NRC ACTIONS AND PATH FORWARD AS A RESULT OF INTERNATIONAL HIGH ENERGY ARCING FAULT PHASE 1 TESTING RESULTS

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ABSTRACT

International nuclear power plant (NPP) operating experience has shown electrical distribution equipment (e.g., switchgear, bus ducts, etc.) can be subject to a failure mode that causes extensive damage known as High Energy Arcing Faults (HEAF). Equipment failures that result in HEAFs cause a rapid release of electrical energy in the form of heat, vaporized metals such as copper and aluminum, plasma, and explosive mechanical force. The energetic fault typically consists of two distinct phases, each with its own damage characteristics. The first phase is characterized by the short, rapid release of electrical energy. The second phase is characterized as the ensuing fire and modelled using classical fire-modelling tools.

Due to the potential safety significance of HEAF events, the Nuclear Energy Agency (NEA) Working Group on Integrity and Ageing (WGIAGE) initiated a task on HEAF events in 2009 to provide an in-depth investigation. The results of this test program identified the interaction with aluminum materials to be a potential exacerbating contributor to the extent of damage, commonly referred to as the zone of influence (ZOI). The test program also revealed a previously unidentified failure mechanism whereby conductive aluminum products of combustion are discharged to distances that greatly exceed current ZOI boundaries.

In light of these recent findings, the U.S. Nuclear Regulatory Commission (NRC) has taken additional steps to assess the potential safety impacts including the issuance of generic communication to alert licensees of the potential vulnerability associated with HEAFs involving aluminum components. The NRC has entered the aluminum HEAF safety concern into its congressionally mandated Generic Issues (GI) program. The GI program required three technical evaluation phases: screening, safety assessment, and regulatory response. As part of this process, the NRC staff will systematically evaluate plant safety, obtain additional data, and use expert judgement where necessary to assess the safety impact of aluminum HEAFs on NPP operation and inform future agency actions.

INTRODUCTION

The Working Group on Integrity and Ageing (WGIAGE) under the Organization for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) defined a "High Energy Arcing Fault (HEAF)" as (cf. [2]):

- *"High Energy Arc Faults (HEAF) are energetic or explosive electrical equipment faults characterized by a rapid release of energy in the form of heat, light, vaporized metal and pressure increase due to high current arcs between energized electrical conductors or between energized electrical components and neutral or ground. HEAF events may also result in projectiles being ejected from the electrical component or enclosure of origin and result in fire.*

  The energetic fault scenario consists of two distinct phases, each with its own damage characteristics and detection/suppression response and effectiveness.

  - *First phase: short, rapid release of electrical energy which that may result in projectiles (from damaged electrical components or housing) and/or fire(s) involving the electrical device itself, as well as any external exposed combustibles, such as overhead exposed cable trays or nearby panels that may be ignited during this energetic phase.*
  - *Second phase (i.e., the ensuing fire[s]): is treated similar to other postulated fires within the zone of influence.*

  An arc is a very intense abnormal discharge of electrons between two electrodes that are carrying an electrical current. Since arcing is not usually a desirable occurrence, it is described as an "arcing fault." The arc is created by the flow of electrons through charged particles of gas ions that exist as a result of a vaporization of the conductive material."

International nuclear power plant (NPP) operating experience data clearly show that a significant number of HEAF events have occurred worldwide in operating plants. A report published by the OECD/NEA in June 2013 [1] documents 48 different HEAF fire events reported by the 12 member countries of the OECD/NEA Fire Incidents Records Exchange (FIRE) Project. This number, which has further increased in recent years, represents about 10 percent of all fire events reported to the FIRE database.

In analysing relevant operating experience, it becomes readily apparent that HEAF events tend to create challenges that complicate the plant's ability to safely shutdown the reactor and maintain it in a safe condition. The electrical disturbance that initiates the HEAF often causes loss of essential electrical power, while products of combustion tend to create challenges that complicate the plants' ability to safely shutdown the reactor and to the operators and fire brigade members handling the emergency. For many plants in the United States, fires are a dominant contributor to plant risk. HEAF-initiated scenarios were found to be significant contributors to the overall fire risk on a preliminary assessment of 10 U.S. National Fire Protection Association (NFPA) 805 NPP's risk assessment information. The range of fire risk contributed by HEAF-initiated fire scenarios ranged from 1 percent to 27 percent on a per-unit basis. The average per-unit risk contribution was about 15 percent [3].

INFORMATION NOTICE

The U.S. NRC issued information notice (IN) 2017-04, "High Energy Arcing Faults in Electrical Equipment Containing Aluminium Components" on August 21, 2017, to inform the industry of operating experience and recent NRC testing results pertaining to the magnitude of arcing fault hazards in electrical equipment containing aluminium components [4]. The NRC expects the information notice addressees to review the information for applicability to their facilities and consider actions, as appropriate. This information notice was based on U.S. NPP operating experience and an NRC-led international HEAF testing program performed through the OECD NEA.

As part of the testing program, a total of 26 tests were performed consisting mostly of electrical equipment with copper conductors. The equipment with copper components exhibited similar damage states to those postulated in the current methodology presented in NUREG/CR-6850, Appendix M [5]. However, results obtained for equipment containing aluminium components exhibited damage states well beyond those postulated in current HEAF damage models.

The increased physical damage to the test specimens, measurement devices, and the testing facility observed during tests involving aluminium components was attributed to the presence and interaction of aluminium with the arc during the HEAF. Aluminium in the components, subcomponents, or parts that form part of the normal current carrying pathway caused more energetic plasma development when involved in the electrical arcing process. The increased energetic plasma caused a larger amount of cabinet damage and/or the transport of gaseous high energy particles/plasma farther than was assumed in the current zone of influence (ZOI).

Another observation made during testing was the deposition of aluminium products on most surfaces within the electrical enclosure (i.e., cabinet) including electrical equipment external to the electrical enclosure tested. This aluminium by-product layer caused shorting problems in the test facility's electrical power supply and required significant repair. The extent of damage observed from the electrical enclosures containing aluminium components far exceeded that of the electrical enclosures which did not contain aluminium components.

In addition to the evidence from testing, the Information Notice also compiled relevant operating experience that demonstrates that the hazards from a HEAF may be substantially greater for electrical equipment that contains aluminium components than for those with copper components. The operating experience also documents the spread of electrically conductive aluminium by-products that could lead to additional failures. A summary of the aluminium impact from operational experience is stated below:

- Fort Calhoun Station, Unit 1, June 7, 2011: This event illustrates the adverse effects caused by large quantities of conductive aluminium by-products in the smoke produced by HEAF events involving aluminium which can adversely affect adjacent equipment. The event further resulted in significant unexpected system interactions (specifically, loss of power to both train A and train B buses). The event also resulted in grounds on both trains of safety-related DC power used for breaker operation and electrical protection. The fire resulted in a loss of power to six of nine safety-related 480 VAC electrical distribution buses, one of two safety-related 4160 VAC buses, and one of two non-safety-related 4160 VAC buses. The event resulted in the loss of the spent fuel pool cooling function [6], [7].
- Columbia Generating Station, August 5, 2009: This event involved aluminium bus bars enclosed in aluminium ducts. The event vaporized about 1.2 m (4 ft.) of each of the three buses and 2.4 m (8 ft.) of the bus duct enclosure, and smoke and heat effects were observed at all metal joints and covers for a distance of 6 m (20 ft.) south and about 3 m (10 ft.) north of the missing section [8], [9].
- Diablo Canyon Nuclear Power Plant, Unit 1, May 15, 2000: This event damaged both the 12 kV bus duct and the 4 kV bus duct. Conductors from both bus ducts were made of aluminium. The event led to the loss of both offsite electrical sources and the reliance on emergency diesel generators [10].
- Zion Nuclear Power Station, Unit 2, April 3, 1994: This event initiated a fire that the onsite fire brigade could not control without offsite brigade assistance. The bus duct was made of aluminium. The Phase A and B isophase bus ducts showed signs of excessive arcing. The licensee found extensive aluminium spatter in the general area of the fault as well as large amounts of white powder that was later determined to be aluminium oxide. In addition, the licensee stated that the physical damage observed during inspections was greater than other documented failures of this nature [11].

- Shearon Harris Nuclear Power Plant, Unit 1, October 9, 1989: This event damaged over a 15.2 m (50 ft.) section of the phase A bus. The bus duct enclosure was made of aluminium. The event also destroyed the neutral grounding bus and caused three fires: (1) an oil fire at the B main power transformer, (2) a hydrogen fire underneath the main generator, and (3) a third small oil fire in the generator housing [12].
- Kewaunee Power Station, July 10, 1987: This event damaged a 9.1 m (30 ft.) section of the bus bar, and the licensee observed the spread of a metallic dust. The bus bar conductors were made of aluminium [13].

GENERIC ISSUES PROGRAM

In addition to the issuance of an information notice, NRC staff submitted the issue to the NRC's Generic Issue Program on May 6, 2016 [14]. The NRC defines a generic issue (GI) as a well-defined, discrete, technical or security issue, the risk/or safety significance of which can be adequately determined and which: (1) applies to two or more facilities; (2) affects public health and safety, the common defines and security, or the environment; (3) is not already being processed under an existing program or process; and (4) can be resolved by new or revised regulation, policy, or guidance or voluntary industry initiatives. A GI may lead to regulatory changes that either enhance safety or reduce unnecessary regulatory burden.

The agency's Generic Issue Process (GIP) for resolving GIs is described in MD 6.4 [15]. It includes five distinct stages that may be exercised:

1. Identification; (Completed [14])
2. Acceptance Review; (Completed [16])
3. Screening; (Completed [19])
4. Safety / Risk Assessment; (Pending)
5. Regulatory Assessment; (Pending)

During each stage, NRC staff determines if more information is needed, if the issue should proceed to the next stage, or if the issue should exit the GIP. When issues exit the GIP, the possible outcomes include no action, further research, transfer to appropriate regulatory programs, or possible industry initiative. In any case, the GIP provides feedback to the person proposing the GI (requestor) of the outcome at each stage. Issues that proceed through all five stages result in regulatory solutions being provided to program offices for implementation and verification.

The issue was officially entered into this process on May 12, 2016, and an initial safety evaluation was performed that determined this issue does not represent an immediate safety concern to operating NPPs based on several mitigating factors including, but not limited to, contingency plans for loss of large areas due to fire and explosions [16], [17]. On May 20, 2016, a generic issue review panel (GIRP) was formed, and an initial screening evaluation was performed [18], [19]. The GIRP members concluded that the proposed GI met all seven screening criteria outlined in Management Directive (MD) 6.4, “Generic Issues Program.” Therefore, the GIRP recommended that this issue continue into the Assessment Stage of the GI program.

Specifically, the staff identified that a potential issue exists for plants having electrical equipment containing components made of aluminium in areas subject to HEAF conditions. A HEAF event involving aluminium may cause greater damage to structures, systems, and components than previous analyses indicated. This decision is based on recent test results indicating that the ZOI around the initiating fault location may be larger than postulated in the current methodology for HEAF.

In addition, a HEAF event involving aluminium may challenge the technical basis of the current deterministic fire protection physical separation requirements described in 10 CFR 50, Appendix R “Fire Protection Program for Nuclear Power Facilities Operating Prior to January

1, 1979". Section III.G.2.b of Appendix R, states in part: "*Separation of cables and equipment and associated non-safety circuits of redundant trains by a horizontal distance of more than 20 feet with no intervening combustible or fire hazards. In addition, fire detectors and an automatic fire suppression system shall be installed in the fire area.*"

The GIRP also reviewed the initial evaluation and determined that no immediate safety concerns were evident and found that it continues to remain valid.

GIRP ACTIONS GOING FORWARD

The GIRP proposed a series of short-term and long-term actions to systematically determine how to resolve this proposed GI [20]. The GIRP will lead the staff's efforts on this GI, with resources and support from the Office of Nuclear Regulatory Research (RES) and the Office of Nuclear Regulatory Regulation (NRR).

The short-term actions are anticipated to occur during the assessment stage and include:

1. Determining the extent of condition (e.g., use of aluminium in electrical components in areas subject to potential HEAFs). Based on an NEI (*N*uclear *E*nergy *I*nstitute) - performed survey [21], aluminium components were found to be prevalent in some HEAF-susceptible equipment located in areas of the plants evaluated in fire analyses.
2. Developing an interim zone of influence for NPPs with aluminium components in areas where HEAFs are postulated to occur using either expert elicitation or appropriate operational experience.
3. Determining electrical fault characteristics which correspond to HEAF events as defined in fire frequency documents such as fault current, voltage and duration [22].
4. Developing a risk/safety determination by identifying appropriate pilot plants to assess the risk to operating NPPs with aluminium in the areas where HEAFs can occur.
5. Developing a plan for future testing using the phenomenon identification and ranking table (PIRT) exercise to focus on parameters and phenomena.
6. Determining whether the issue needs to proceed to the next stage, Regulatory Office for Implementation. It is in this stage that changes to regulations would be addressed.

The Long-Term actions are possible actions that NRR may consider during the Regulatory Implementation Stage, including:

1. Issuing generic communications, requests for information, or orders, as deemed necessary.
2. Revising technical guidance documents to reflect potential changes to methodology based on the new information.
3. Assessing risk through long-term performance monitoring. This will be accomplished through training for inspectors on the hazards from a HEAF involving aluminium and identification and revisions to NRC procedures, as necessary, for inspecting licensees' Fire PRA during fire protection inspections.

GIRP RISK EVALUATION PLAN

To determine an approximate risk profile for HEAF events involving aluminium, several factors need to be considered. First, the staff intends to develop an interim increased ZOI using either expert elicitation or appropriate operational experience. This interim ZOI will be used to calculate a potential increase in plant risk. Second, the staff will also evaluate the characteristics of HEAF events that may affect frequency values used in PRAs. In current modelling approaches, HEAF events are treated with a one-size-fits-all model that assumes all HEAF events will reach a deterministic ZOI or damage profile. The staff believes the best approach to evaluate these risk impacts will be to solicit pilot plants and use their existing HEAF scenarios and fire PRA plant modelling techniques. These scenarios would be evaluated for the presence of aluminium and modified to account for an increased ZOI using the existing fire PRA internal plant risk model.

This approach will require cooperation from several pilot plants that have configurations possibly reflecting an increase in risk from the increased ZOI. In particular, the pilot plants should verify that targets of significance (i.e., cables and electrical equipment) are out of the ZOI in the existing models but within the increased ZOI. The additional damage estimates, once incorporated into their existing and modified models, will enable calculation of the change or delta in core damage frequency (CDF) or large early-release frequency (LERF). This exercise would be most successfully as a joint activity between the Electric Power Research Institute (EPRI) and the U.S. NRC's Office of Nuclear Regulatory Research (RES) working under the terms of the NRC/EPRI Memorandum of Understanding (MOU) and accompanying Fire Risk Addendum.

Based on the step-by-step approach outlined above, the staff should be able to effectively conclude what the risk and safety significance is from the presence of aluminium in HEAF. The staff believes this evaluation can be performed in a timely manner if detailed plant information is available.

PHASE 2 OECD/NEA INTERNATIONAL HEAF TESTING

The NRC is collaborating with our international partners (in the frame of a common OECD NEA project) to conduct a second set of full-scale experiments to further explore the damage conditions created by HEAF events. The second phase of testing is scheduled to begin in 2018, and the results from this experimental series will report on the thermal and mechanical damage caused by HEAF events. The data collected from the experimental series will support updating and advancing methods to characterize and assess the risk of HEAF events. Previous work in Phase 1 examined electrical cabinets with a wide variety of manufacturers, manufacture dates, materials, and configurations. Although the tested cabinets provided an important view of the performance of available equipment, too many uncontrolled variables exist to fully understand their significance on the severity of the HEAF.

To prioritize the parameters and phenomena in need of further study, the NRC conducted a phenomena identification and ranking table (PIRT) exercise with the international partners. A PIRT is a facilitated expert elicitation designed to identify the important phenomena and parameters of a given subject and to prioritize them for future study. The results of the PIRT exercise suggest a focus on electrical characterization of the arc, the material of components, and mitigation strategies. To increase the repeatability of tests, the electrical enclosures and bus ducts will be uniform and carefully specified. The enclosure configuration will be chosen based on typical plant design, and preliminary tests will be performed to ensure the arc will not extinguish until the power supply to the cabinet is turned off. The bus bar material and configuration will be chosen based on the desire for a known and repeatable arc location and plasma ejection direction. Real-time measurements of voltage and current during the arc will provide data for calculation of arc energy and arc power for comparison to thermal and pressure measurements. The use of a common NPP electrical cabinet and bus duct should increase repeatability between experiments.

The NRC has developed a preliminary draft test plan and is currently in the process of dispositioning comments from international partners and the public. The draft test plan was submitted to the *Federal Register* on August 8, 2017, for a 30 day public comment period under the agency docket number NRC-2017-0168 [23].

CONCLUSIONS

For many NPPs, fire is a dominant contributor to plant risk. HEAF-initiated scenarios can contribute significantly to fire risk, and operational experience shows that HEAFs continue to occur despite the comprehensive electrical protection designed to mitigate such events. Operational experience also suggests that significant complications to shutting down the plant can occur during and after a HEAF [1].

Like most major fire events, HEAF normally generate large quantities of dense smoke, cause significant equipment damage, and in many cases, challenge operators with scenarios that they are unlikely to have been trained on. These conditions contribute to the likelihood of human errors, which can greatly complicate the plant response to these events.

The OECD NEA HEAF testing program identified a potential issue where existing regulations, guidance, and analytical models used for PRA applications may not bound the hazard if aluminium is present. Under these conditions, the ZOI of damage could be substantially larger than indicated in the current guidance. Also, recent HEAF testing and operating experience identified a new potential failure mode (the spread of electrically conductive aluminium by-products in the smoke of HEAF events involving aluminium). This by-product has the potential to damage sensitive electronics beyond the ZOI such as in the Fort Calhoun fire event in 2011. It is possible that an enlarged ZOI accounting for the presence of aluminium could result in loss of redundant equipment during a HEAF event. The severity and risk impact of these events and potential consequences highlight the need for a greater understanding of the underlying phenomena and treatment of HEAF events to provide adequate NPP safety.

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EXPERIMENTAL STUDY ON HIGH ENERGYARCING FAULTS (HEAF) TO ASSIST FIRE SAFETY REGULATION

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ABSTRACT

Recently, large-scale electric discharges called high energy arcing faults (hereinafter referred to as "HEAF") occurred in electric equipment in domestic and overseas nuclear power plants. If a HEAF occurs in electric equipment, the pressure and temperature in and around the equipment rise rapidly causing an explosive phenomenon with destructive force that results in serious damage to the equipment. In addition, a HEAF may cause a fire, which would have a serious damage on cables and other components around the equipment.

In Japan, due to the Great East Japan Earthquake of March 11, 2011, an explosion in metalclad switchgears (hereinafter referred to as "M/C") at Unit 1 of Onagawa nuclear power station (hereinafter referred to as "NPS") of the Tohoku Electric Power Company Co., Inc., which presumably resulted from a HEAF event and was accompanied by a fire. The significant thermal energy released from a HEAF event spread to adjacent M/Cs and burnt many pieces of electric equipment and cables connected to the M/Cs.

In order to investigate the HEAF event progression and to understand well the phenomena involved, S/NRA/R conducted a series of HEAF tests. The test results indicated that the condition of initiating ensuing fires i.e. threshold arc energies are different between distribution panel (hereinafter referred to as "DP") and M/Cs. The values of arc energy which can cause ensuing fires were between 26.3 and 28.6 MJ for the DP and between 42.6 and 57.2 MJ for the M/C. These energy thresholds are considered to be dependent on the characteristics of individual electric cabinets such as internal volume and containment level. If the arc discharge duration is reduced, the arc energy can be decreased and consequently the occurrence of ensuing fires may be prevented.

On the basis of the knowledge obtained by the test results, measures for prevention of ensuing fire and mitigation of explosion are proposed as a new requirement for fire safety regulation of domestic NPSs. Amendment of the regulatory requirements were issued on August 8, 2017 and enforced on the same day.

This study summarizes the information on the S/NRA/R test results and the new HEAF requirements based on the test results.

INTRODUCTION

When the high energy arcing occurs between energized conductors, such as breakers, switchgears, and other components, and between such a conductor and the ground, in an electric cabinet, a damage, failure and/or other abnormalities may be caused due to a release of heat and/or light, metal evaporation, and/or an explosion accompanied by a rapid pressure excursion. The phenomena are followed by an ensuing fire (a fire breaking out by the component high temperature due to the effect of heat resulting from the arcing), by which the component damage and other consequences may be expanded. These phenomena are called high energy arcing faults (hereinafter referred to as "HEAF"). Other electrical cabinets connected to the HEAF-occurred cabinet would be damaged and the fire spreads to the neighbouring cabinets simultaneously, which may affect the safety function of the nuclear power station (hereinafter referred to as "NPS").

On the basis of such circumstances, the U.S. Nuclear Regulatory Commission (hereinafter referred to as "NRC") has conducted a case analysis [1] on HEAF events that occurred in the U.S. since the early 2000s. In addition, the Committee on the Safety of Nuclear Installations (hereinafter referred to as "CSNI") of the Organization for Economic Co-operation and Development Nuclear Energy Agency (hereinafter referred to as "OECD/NEA") set up a working group on HEAF events in 2009 and has been advocating the importance of discussing HEAF events to ensure the safety of nuclear facilities. HEAF events are drawing attention around the world as there is a need to develop a method for evaluating the impact of HEAF events from the viewpoint of nuclear safety regulations [2].

In Japan, due to the Great East Japan Earthquake of March 11, 2011, an explosion occurred in the metalclad switchgears (hereinafter referred to as "M/C") at Unit 1 of Onagawa NPS of the Tohoku Electric Power Company Co., Inc. (hereinafter referred to as "Unit 1 of Onagawa NPS"), which presumably resulted from a HEAF event and was accompanied by a fire [3]. The fire spread to adjacent M/Cs and caused many pieces of electric equipment and cables to burn. Therefore, the Regulatory Standard and Research Department of the Secretariat of the Nuclear Regulation Authority (S/NRA/R) conducted a series of HEAF tests on electric cabinets since 2013 as a research effort toward the sophistication of regulatory standards concerning fire protection in nuclear facilities aimed at obtaining knowledge mainly about how HEAF events, like the one that occurred in the M/Cs at Unit 1 of Onagawa NPS. At these HEAF tests, high-current arc discharges expected to occur in actual equipment were generated in M/Cs with medium voltage (7,000 V or so), distribution panel (hereinafter referred to as "DP") and motor control centre (hereinafter referred to as "MCC") with a relatively low voltage (480 V), which are commonly used at nuclear facilities.

This study summarizes the information on the S/NRA/R test results such as knowledge about how HEAF events develop, how much arc discharge energy generates, and under what conditions a fire occurs, which are compiled into the new HEAF requirement.

OVERVIEW OF S/NRA/R HEAF TESTS

Purpose of S/NRA/R HEAF Tests

Current HEAF test projects that are ongoing are three : the S/NRA/R HEAF test project (Japanese regulatory side tests) [4], the OECD/NEA HEAF test project lead by the NRC [5], and the CRIEPI HEAF test project (Japanese utilities side tests) [6].

The purpose of S/NRA/R HEAF tests is to obtain technical knowledge about the development of HEAF events (to understand what occurred in the Onagawa HEAF event), the arc energy level at which a fire is caused by a HEAF, developing regulatory guidance for fire hazards analysis methods for HEAF, and so on. For this purpose, the S/NRA/R has been conducting HEAF tests since 2013 at the KEMA laboratories in the U.S., which have large-current generators, in collaboration with the NRC under the accordance with cooperation agreement for research.

Selection of Test Devices

Figure 1 shows the outline of the S/NRA/R HEAF tests with three types of electrical equipment used in a typical nuclear power plant. While the reactor is in operation, a part of the power from the main generator is passed through a transformer to lower the voltage and is used as the power for motors and such to run the plant. The power for plant operation is supplied via M/Cs (around 7,000 V), DP (480 V), and MCC (480 V), which are considered to be typical electrical equipment at nuclear power plants, were used as the test devices.

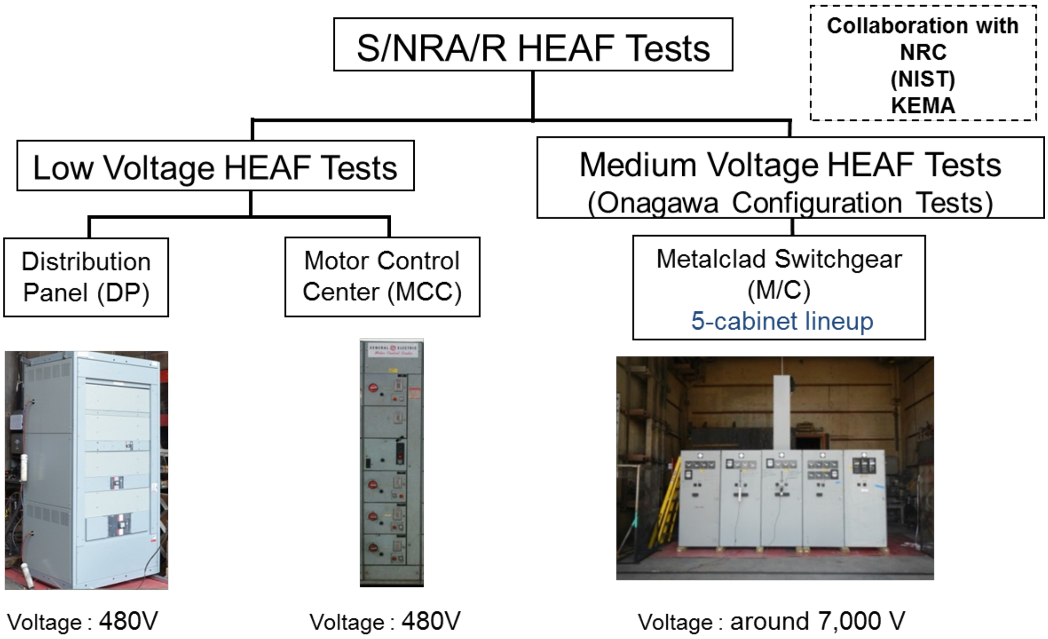


Figure 1 Three types of electrical equipment in a typical nuclear power plant

Target Value of Short-circuit Current (Arc Current)

There is a need to set a short-circuit current as a target current value by which arc discharge is generated in an electric cabinet (M/C, DP, and MCC) in a HEAF test. The short-circuit value of each electric cabinet is set when the electric system of the nuclear power plant is designed, and it is calculated based on the impedance of the upstream transformer and the rated current of the secondary-side transformer. The method for calculating the short circuit current value is as follows:

First, the rated current I_0 of the secondary-side transformer can be calculated from the three-phase power W and the rated voltage V_0 as follows:

$$I_0 = W / (\sqrt{3} \times V_0) \qquad (1)$$

The theoretical maximum three-phase short-circuit current I_b can be calculated with the short-circuit impedance (or the product-specific percent impedance of the transformer) Z and the rated current I_0 as follows:

$$I_b = I_0 \text{ x } 100 / Z \qquad (2)$$

In this equation, the short-circuit impedance Z represents as a percentage the ratio of the primary-side voltage and the secondary-side rated voltage when a voltage is applied to the primary side with the secondary-side transformer short-circuited and the secondary-side current has reached the rated current.

For the metalclad switchover (M/C), the three-phase power W is 26,000 kVA and the rated voltage is 7,100 V. The Z of the transformer located upstream of the metalclad switchover is 9.5 %. Accordingly, the short-circuit current $I_{b\_M/C}$ can be calculated by Equations (1) and (2) as follows:

$$I_{0\_M/C} = 26{,}000 / (\sqrt{3} \times 7{,}100) = 2.1 \text{ kA}$$

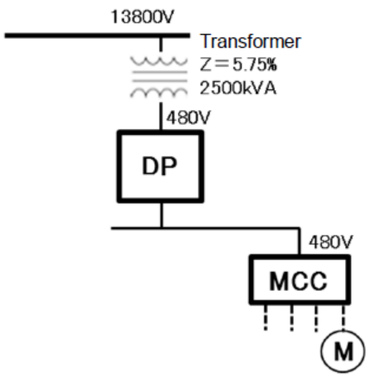
$$I_{b\_M/C} = 2.1\ \text{kA} \times 100/9.5 = 22.3\ \text{kA}$$

Figure 2 shows the connections and values of a DP with a relatively low voltage and a MCC in standard electric equipment. The short-circuit current I_{b_DP} of the DP can be calculated with the standard design conditions in Figure 2 in the same manner as for the M/C as follows:

$$I_{b\_DP} = 52.3\ \text{kA}$$

In addition, when a short-circuit occurred in the MCC, the connection with the DP and the increment of the short-circuit current due to the current from the motors connected to the MCC (motor contribution) were taken into consideration. Assuming that four motors are connected, a current four times larger than the rated current of a motor at 2.8 kA is regarded as the maximum current that flows when a short-circuit occurs, and the short-circuit current I_{b_MCC} of the MCC is calculated by the equation below as the short-circuit current increment:

$$I_{b\_MCC} = 52.3 + 4 \times 2.8 = 63.5\ \text{kA}$$



DP: Distribution Panel
MCC: Motor Control Centre
M: Motor

Figure 2 Distribution diagram between DP and MCC (+Motor)

Table 1 shows the target short circuit current values for each electric cabinet as calculated above.

Table 1 Current and voltage in HEAF tests

Electrical Cabinet	Power W [kVA]	Rated voltage V_0 [V]	Short-circuit impedance Z [%] (Product-specific percent impedance of transformer)	Target short circuit current I_b [kA]
Metal clad switchgear (M/C)	26000	7100	9.50	22.3
Distribution Panel (DP)	2500	480	5.75	22.3
Motor Control Centre (MCC)	2500	480	5.75	52.3

Electrical Circuits Used for the Tests

Figure 3 shows the electrical circuits used to simulate arc discharges generated in the actual equipment.

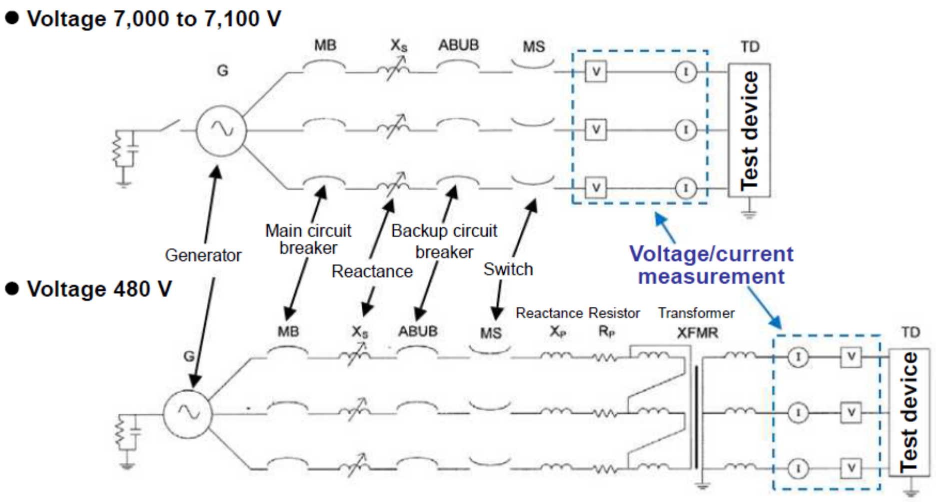


Figure 3 HEAF test circuit

Different circuits were used in the test. One is with the voltage of 7,000 V to 7,100 V for the M/C and the other is with the voltage of 480 V or the DP and the MCC. The tests were conducted by setting up corresponding electric cabinets to the test device in the figure. In the tests, the voltage and current were measured upstream (on the generator side) from each electric cabinet.

In these HEAF tests, arc discharge was generated in accordance with C37.20.7-2007 [7] of the Institute of Electrical and Electronics Engineers (hereinafter referred to as "IEEE"). As shown in Figure 4, the short-circuit currents (large current) listed in Table 1 were applied to a bus bar with a conductive wiring to generate arc discharge.

Measurement

It is thought that there are three items that need to be measured to evaluate HEAF events and their impacts: the voltage and current waveforms of arc discharge, which are used to understand the arc power and arc energy, the pressure in the electric cabinet when arc discharge occurs, which is used to obtain knowledge related to the impact on the inside of the electric cabinet, and the heat flux around the electric cabinet, which is used to obtain knowledge related to the impact on the area surrounding the electric cabinet (ZOI: Zone of Influence).

Table 2 shows the measurement items in the HEAF tests. The arc power and energy were calculated based on the measured voltage, current, and duration of arc discharge. The pressure in the electric cabinet was measured with piezoelectric air pressure transducers. The heat flux around the electric cabinet was measured with slug calorimeters.

Table 2 Measurement items in HEAF tests

Measuring item	Purpose of measurement	Method
1. Voltage/current waveform	Calculating the arc power and arc energy	Recording and analysing the voltage and current wave-forms
2. Pressure in electric cabinet	Obtaining knowledge related to the impact on the inside of the electric cabinet	Measuring the pressure in the electric cabinet with a piezoe-lectric air pressure transducer
3. Heat flux around electric cabinet	Obtaining knowledge related to the impact of arc discharge in an electric cabinet on the out-side of the cabinet	Measuring the heat flux with slug calorimeters

Configuration of M/Cs and Short Circuit Location

M/Cs equipped with magnet blast circuit breakers manufactured by General Electric were used for the tests. They were slightly modified so that their configuration is almost the same as those used at Unit 1 of Onagawa NPS. At Unit 1 of Onagawa NPS, HEAFs occurred at some of the M/Cs in ten line-up M/Cs, but five line-up M/Cs were used in the tests because of the limited space in the laboratory.

Figure 4 shows the configuration of a M/C (Depth: 2,133 mm, Width: 914 mm, Height: 2,286 mm) and the arcing point. The rated voltage and current of these M/Cs are 6,900 V and 2.3 kA, respectively. However, the HEAF tests were conducted with the assumption that the rated voltage and current were 7,000 to 7,100 V and 2.3 kA, respectively. Power to the M/Cs was supplied from outside of the switchgears via the horizontal bus bars. The horizon-tal bus bars were connected to the vertical bus bars in the switchgears, from which power was supplied to the primary side of the circuit breaker.

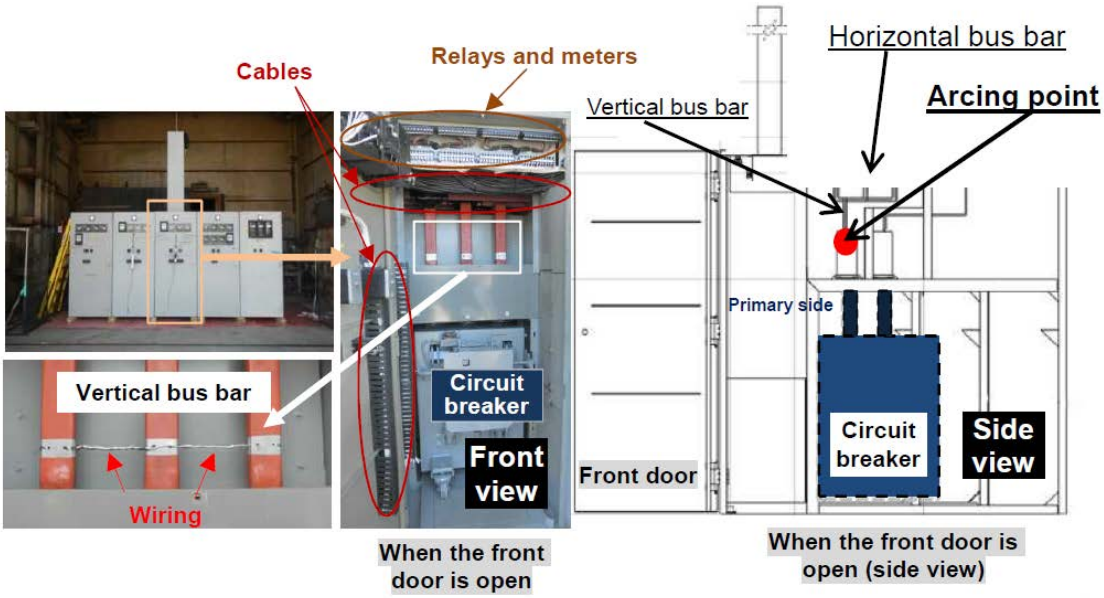


Figure 4 M/C used in the test [4]

Flammable materials are used in the switchgears: plastic parts and cables for the relays, meters, and other components of the switchgears. Arc discharge was generated on the aluminum vertical bus bars on the primary-side circuit breaker in the M/C. As mentioned in Figure 3, in the electrical circuits, arc discharge was generated in accordance with the IEEE guide by wiring a conductive wire to the vertical bus bar and then applying a large current under the test conditions given in Table 1 to cause a three-phase short-circuit.

Configuration of DP and Short Circuit Location

An APN-B, which is manufactured by General Electric and is commonly used at nuclear power plants, etc. in the U.S., was used as a DP for the tests. Figure 5 shows the configuration of the DP (depth: 889 mm, width: 1,143 mm, height: 2,286 mm) and the arcing point.

The rated voltage and current of this DP are 480 V and 3.0 kA, respectively. Power to the DP was supplied from outside the cabinet via the horizontal bus bars. The horizontal bus bars were connected to the vertical bus bars in the cabinet and power was supplied from the vertical bus bars to three circuit breakers.

Flammable materials used in the cabinet include plastic parts used in the circuit breakers and cables. Arc discharge was generated on the copper vertical bus bar on the back of the circuit breaker installed at the bottom. Arc discharge was generated in the same manner as the M/Cs.

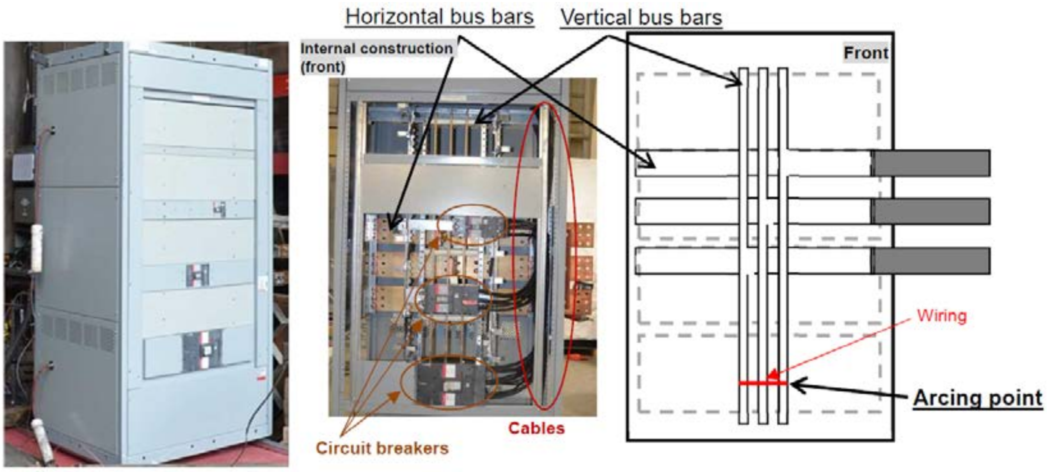


Figure 5 DP used in the test [4]

Configuration of MCC and Short Circuit Location

A Series 7700 MCC, which is manufactured by General Electric and is commonly used at nuclear power plants, etc. in the U.S., was used as a MCC for the tests. Figure 6 shows the configuration of the MCC (depth: 508 mm, width: 508 mm, height: 2,324 mm) and the arcing point.

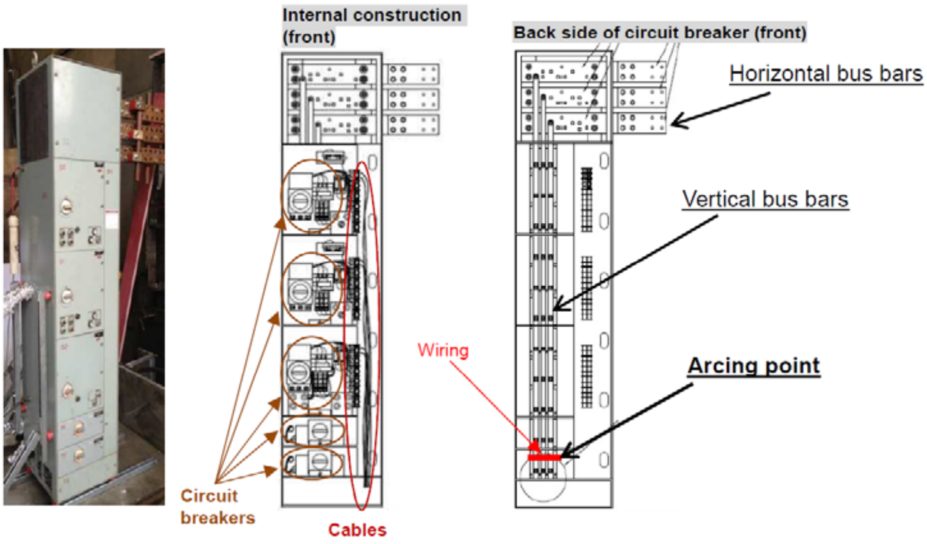


Figure 6 MCC used in the test [4]

The rated voltage and current of this MCC are 480 V and 0.6 kA, respectively. Power to the MCC was supplied from outside of the control centre via the horizontal bus bars. In addition, the horizontal bus bars were connected to the vertical bus bars, from which power was supplied to five circuit breakers.

Flammable materials used in the centre include plastic parts used in the circuit breakers and cables. Arc discharge was generated on the copper vertical bus bar on the back of the circuit breaker installed at the bottom. Arc discharge was generated in the same manner as the M/Cs.

Target Duration of Arc Discharge

The duration of arc discharge in the HEAF tests, or the setting value of the short-circuit time, was set to 2.0 seconds, which is the same as the setting value for the over-current relays (hereinafter referred to as "OCR") in the circuit breakers used at Unit 1 of Onagawa NPS. For some tests, it was set to 3.0 seconds taking into consideration of the possibility of delay in interruption due to failure of circuit breakers. For the M/Cs, the additional tests were conducted with target values of 1.0 second and 2.5 seconds in order to survey the threshold value of the ensuring fire. The measured duration of arc discharge given in the test results indicates the time during which arc discharge continued.

Calculation of Arc Discharge Energy

The arc discharge energy (J) in the HEAF tests was obtained by multiplying the arc power (W), which was obtained by multiplying the voltage (V) and current (A) measured upstream from the test device (generator side) during arc discharge, and the duration of arc discharge (s) and then summing the values for the three phases.

HEAF TEST RESULTS

Metal Clad Switchgear (M/Cs)

The HEAF test was conducted six times using five line-up M/Cs with the voltage, short-circuit current, and short-circuit time set to 7,000 to 7,100 V, 22.6 to 25.0 kA, and 1.0 / 2.0 / 2.5 / 3.0 seconds, respectively (arc discharge generation conditions). Figure 7 is a group of photos illustrating the HEAF test of the M/Cs. Photo (1) shows the M/Cs before the test. Photo (2) shows the moment when arc discharge occurred (after approximately 0.2 seconds). Photo (3) shows the generation of metallic fumes, etc. (after approximately 2 seconds). Photo (4) shows the ensuing fire (after approximately 10 minutes). These photos are arranged in chronological order. Photo (2) shows that part of the arc discharge and metallic fumes came out of the switchgear from the opening on the top. Photo (3) shows that large quantities of metallic fumes were generated. The ensuing fires occurred several minutes after the arc discharge, which caused the adjacent M/Cs and cables in the vertical tray to catch fire (secondary fire). In the M/Cs HEAF tests, ensuing fire occurred in four out of six tests. Arc power was approximately 20 MW for four tests and larger than 20 MW for two tests.

	
(1) Before the test	(2) Moment when arc discharge occurred (after approximately 0.2 seconds)
	
(3) Metallic fumes, etc. were generated (after approximately 2 seconds)	(4) Ensuing fire occurred (after approximately 10 minutes)

Figure 7 HEAF test of M/Cs [4]

Distribution Panel (DP)

The HEAF test was conducted three times under the same conditions using DP with the voltage, short-circuit current, and short-circuit time set to 480 V, 52.3 kA, and 2.0 seconds, respectively (arc discharge generation conditions).

Figure 8 is a group of photos illustrating the HEAF test of the DP. Photo (1) shows the DP before the test. Photo (2) shows the moment when arc discharge occurred (after approximately 0.1 seconds). Photo (3) shows the generation of metallic fumes, etc. (after approximately 1 second). Photo (4) shows the ensuing fire (after approximately 10 minutes). Photos (2) and (3) show that some of the metallic fumes, etc. blasted out of the DP. The ensuing fires occurred several minutes after the arc discharge and lasted approximately 20 minutes. In addition, when the ensuing fire occurred, large amounts of smoke and soot were emitted. In the DP HEAF tests, ensuing fire occurred in two out of three tests. Arc power was approximately 20 MW for all the tests.

(1) Before the test

(2) Moment when arc discharge occurred (after approximately 0.1 seconds)

(3) Metallic fumes, etc. were generated (after approximately 1 second)

(4) Ensuing fire occurred (after approximately 10 minutes)

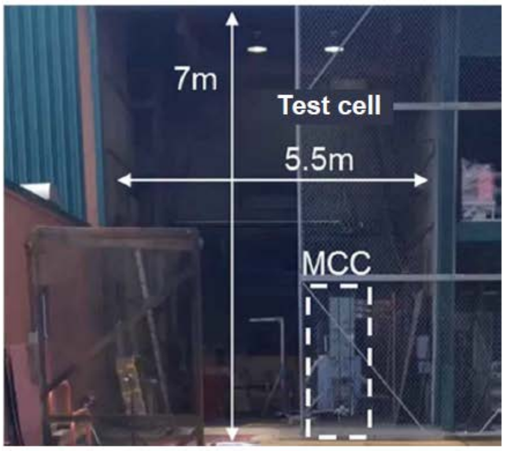
Figure 8 HEAF test of a DP [4]

Motor Control Centre (MCC)

The HEAF test was conducted four times under the same conditions using MCC with the voltage, short-circuit current, and short-circuit time set to 480 V, 63.5 kA, and 2.0 seconds, respectively (arc discharge generation conditions). Figure 9 is a group of photos illustrating the HEAF test of the MCC.

Photo (1) shows the MCC before the test. Photo (2) shows the moment when arc discharge occurred (after approximately 0.2 seconds). Photo (3) shows the blowout of arc discharge and metallic fumes, etc. (after approximately 0.5 seconds). Photo (4) shows the generation of metallic dust, etc. (after approximately 2 seconds). Photo (3) shows that the MCC chassis was damaged and large quantities of metallic fumes, etc. blew out. Photo (4) shows that a large amount of metallic dust, etc. spread throughout the test cell (width 5.5 m × height 7.0 m).

In the MCC HEAF tests, arc power was approximately 20 MW for all tests. However, the ensuing fire did not occur for all four tests. This is presumably because the amount of heat generated by the arc energy was too small due to the short duration of arc discharge (0.9 seconds or less in all four tests). In addition, the fragile chassis of the MCC was damaged when arc discharge occurred and almost all the heat energy was released out of the MCC, thereby keeping the temperature in the MCC below the point at which a fire occurs.



(1) Before the test

(2) Moment when arc discharge occurred (after approximately 0.2 seconds)

(3) Metallic fumes, etc. blew out (after approximately 0.5 seconds)

(4) Metallic dust, etc. were generated (after approximately 2 seconds)

Figure 9 HEAF test of a MCC [4]

DISCUSSION

Occurrence of a Fire Caused by Arc Discharge

Thirteen HEAF tests were conducted in which six times with M/Cs, three times with DP, and four times with MCC. An ensuing fire occurred in six of the thirteen tests: four times with M/Cs and twice with a DP. This section summarizes the relationship between the occurrence of a fire and the arc energy, evaluation of occurrence of a fire, and discusses a concept of fire prevention.

Relationship between Occurrence of a Fire and the Arc Energy

Figure 10 shows the relationship between the arc energy and arc discharge duration required for causing ensuing fire. It is shown that the more the arc duration increases the more the arc energy does. The tests where an ensuing fire occurred are marked with red.

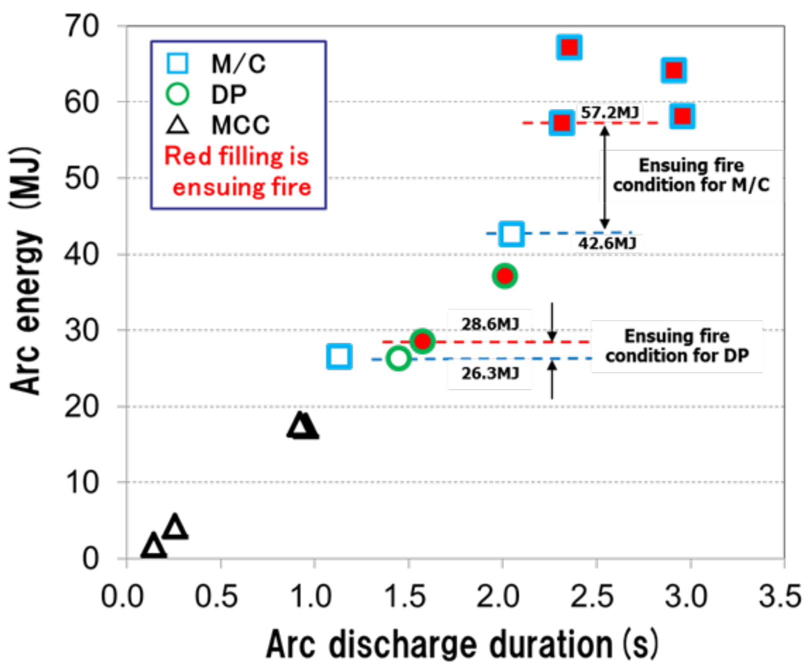


Figure 10 Arc energy required for causing ensuing fire [4]

As previously mentioned, the values of arc energy which can cause ensuing fires were between 26.3 and 28.6 MJ for the DP and between 42.6 and 57.2 MJ for the M/C. From these test results, it is said that an ensuing fire can be prevented by decreasing the arc discharge duration and the arc energy. The ensuing fires caused by HEAF events did not occur immediately after an arc discharge was generated but, were observed several minutes after an arc discharge was generated (see Figure 7 (4) and Figure 8 (4)). An ensuing fire occurs presumably because the generated arc energy heats up the cables and other components in the electric cabinet, thereby causing flammable materials to catch fire.

Evaluation of Occurrence of a Fire and a Concept for Fire Prevention

The arc energy necessary for causing an ensuing fire differs between the DPs and M/Cs. As mentioned in relationship between occurrence of a fire and the arc energy, the M/Cs and DP have different chassis sizes (internal volumes) and different levels of containment such as tightness and strength of chassis, etc. Therefore, the arc energy necessary to cause an ensuing fire is thought to depend on the internal volume and openings (containment level) of each electric cabinet. For example, an electric cabinet with a smaller internal volume will have a higher internal temperature and is more likely to cause the cables and other flammable materials in the cabinet to burn at a lower arc energy than electrical cabinets with a larger internal volume. An electric cabinet with a higher containment level releases less energy and is more likely to cause the cables and other flammable materials in the electric cabinet to burn at a lower arc energy than electric cabinets with a lower containment level. These facts are clearly shown in the test results for the M/Cs and DP in Figure 10. That is to say, because the M/Cs have a larger internal volume than the DPs and have a lower containment level with vents in their tops, more energy is needed in the M/C to cause an ensuing fire than the DPs by at least 20 MJ. Therefore, in evaluating the generation of an ensuing fire, there is a need to confirm the internal volume and containment level of each electric cabinet and properly take them into consideration in the evaluation.

The results of the HEAF tests show that an ensuing fire can be prevented by decreasing the duration of arc discharge, or decreasing the arc energy.

HEAF PROTECTION MEASURES (MEASURES FOR PREVENTING ENSUING FIRE)

Consideration of Practical Protection Measures for HEAF

HEAF is a phenomenon where a large current arcing occurs, resulting a rapid release of energy (explosion) accompanying heat, light, metal vaporization, and a pressure increase in the first phase, and a fire may break out due to the accumulation of heat in the second phase.

Although the detailed understanding of the phenomena and evaluation methods of explosion in the first phase are still under study in safety research, the knowledge about fire occurrence in the second phase has been accumulated, and as a result, for example, it is becoming clear that if arc duration can be shortened by operating the protective relay of a power supply board in a short time or by other ways, as a measure for preventing fire, it is possible to prevent fire and to decrease the impact of explosions.

Protective Relays of an Over-current of Distribution Lines of NPS

The following two types of protective relays are available that intercept the distribution line to protect the electric equipment when an over-current of the distribution line of NPS occurs [8].

1) Over-current relays (OCR)
   It operates at approx. 200 % of full load current, but it is not an instantaneous operation. It is a time-limit operation (order of several seconds) to avoid the operation of motors with large starting current.
2) Short-circuit relay
   It operates instantaneously (approx. 0.1 seconds) at approx. 650 % of full load current.

Figure 11 shows the conceptual drawing of operation of OCRs and short-circuit relays.

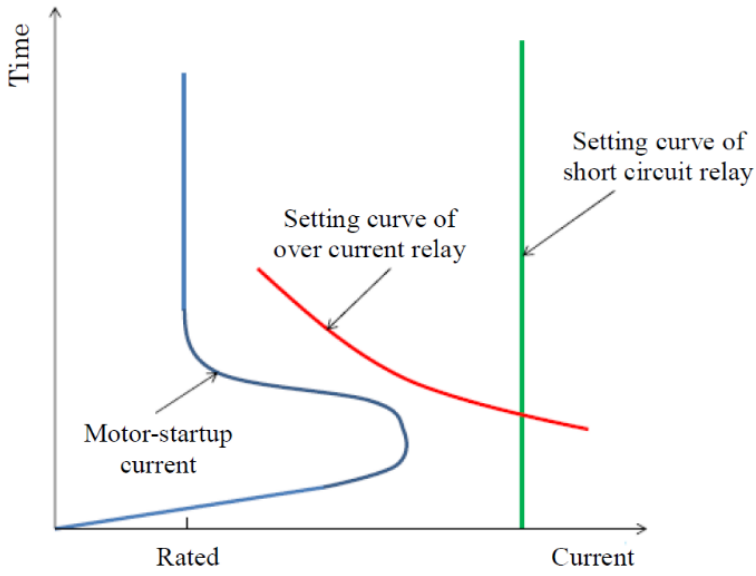


Figure 11 Conceptual drawing of operation of OCRs and short-circuit relays [8]

When short-circuit occurs, the breaker operates instantaneously by the short-circuit relay to isolate the accident point. In general, only the OCR is provided in the upstream of the M/C bus, and the short-circuit relay that operates instantaneously is not equipped. This is because short-circuit is not supposed to occur since the load equipment is not provided in the upstream of the M/C bus, and when the short-circuit relay is activated in the upstream of the M/C bus, the electric outage spreads instantaneously to a broader area, which is not a safer.

As shown by the M/C failure accident of the Onagawa, Unit 1 at the Great East Japan Earthquake, an arc discharge occurred in the M/C load breaker itself, and when it was damaged, there was no other mean to avoid an arc discharge other than intercepting with the breaker in the upstream of the M/C. In such a case, as the relay that operates the breaker is an OCR of time-limit operation, an arcing of approx. 2 seconds will continue.

On the other hand, S/NRA/R HEAF tests obtained so far shows that arcs of which duration is less than about 1 second did not cause the breakout of an ensuing fire (see Figure 10). Therefore, it is considerably possible that an occurrence of ensuing fire can be restrained when short-circuit relays are installed in the upstream breaker of M/C buses to intercept the line current within 1 second at the time of an arcing.

For the present situation of OCR, the digital upgrade of equipment is advancing with the periodical equipment renewal of power centres and other components. In the case of the Higashidoori, Unit 1 in which digital type protective relays are installed, since the operation setting range is more flexible than before and the setup time of OCRs of the upstream breakers of M/C buses is one second or less, the plant is substantially designed to restrain an ensuing fire even if short-circuit relays are not installed [8]. For existing plants, not only for new plants, renewal of protective relays from analogue to digital types is expected according to the future plant renewal plan. At the renewal opportunities, the setup time of OCRs in the upstream of M/C buses is expected to be one second or less and ensuing fire is considered to be prevented.

Actual Examples of OCR

Figure 12 shows the conceptual drawing of the distribution line of a NPS. OCR 1 and OCR 2, the upstream breaker of M/C buses, are set to operate in as short a time as possible in the range that satisfies the following conditions:

1) The relay does not operate under the bus rated current in the steady state.
2) The relay does not operate under the starting current of the bus peak load.
3) The relay operates within the overload capacity of the start-up (or site) transformer.

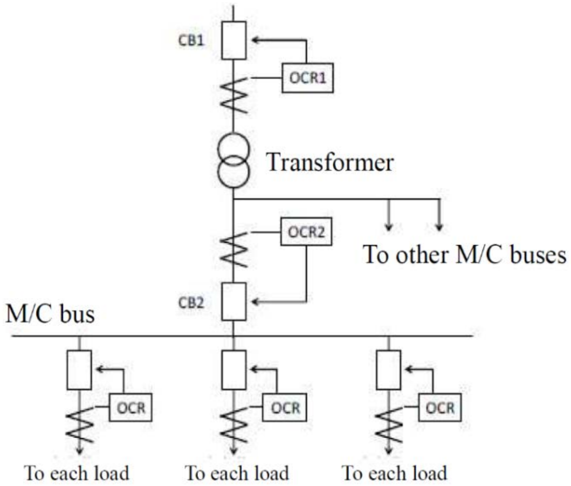


Figure 12 Conceptual drawing of the distribution line of a nuclear power station [8]

Figure 13 shows the conceptual drawing of transformer secondary current at the time of motor start up, and OCR 2 setting curve. As an actual example, since OCR 2 of the Onagawa Unit 1 was an analogue type OCR, approx. 1.7 seconds was the limit at the time of a transformer overload capacity equivalent current (it becomes lower than the transformer current limit at the time of motor start-up). But, since the OCRs of Higashidoori, Unit 1 is a digital type and the slope of the setting curve can be changed, the flexibility has improved to shorten the operating time to 0.8 seconds [8].

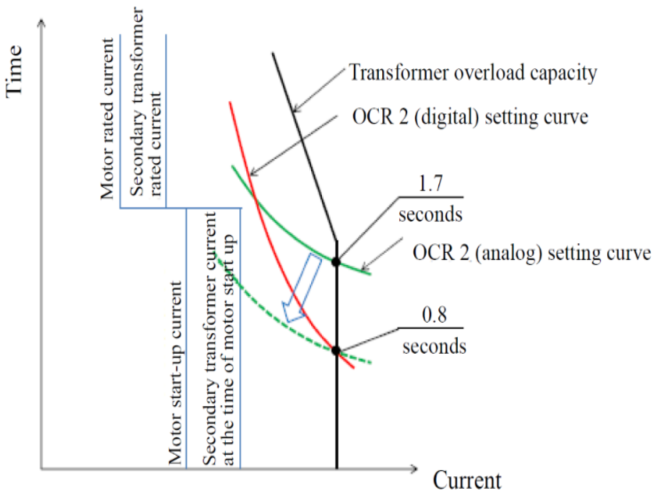


Figure 13 Conceptual drawing of transformer secondary current at the time of motor start up, and OCR 2 setting curve [8]

JAPANESE REGULATORY REQUIREMENTS

Concept of HEAF Regulatory Requirements

The concept by which regulatory requirements for strengthening protection for damages of electric cabinets due to a HEAF according to the abovementioned background is as follows [9]:

1) Objectives

   Decreasing the consequences of an explosion, reduction of heat generation, and prevention of damage expansion due to a high energy arcing of concerned electric cabinets.

2) Concerned facilities and equipment

   Concerned electric cabinets of commercial nuclear power reactor facilities, research reactor facilities, and reprocessing facilities (hereinafter referred to as "commercial power reactors and other facilities")

3) Requirements

   Regarding the concerned electric cabinets, it is required to decrease the consequences of an explosion and to set the interrupting time of breakers appropriately so that an ensuing fire does not break out.

Outline of the HEAF Review Guide

1) Scope of application

   The guide is applied to the design of the electric cabinets used in commercial nuclear power reactor facilities. For research reactor facilities and reprocessing facilities, the guide is applied as a reference.

2) Positioning of the guide

   The guide provides an example for reviewers who judge the adequacy of appropriate setting for the interrupting time of breakers to reduce heat generation of the concerned electric cabinets and to prevent expansion of damage by decreasing the consequences of an explosion due to an arcing.

3) Confirmation of tests and evaluations

   It should be confirmed that the test to generate arcing and the evaluation based on the test results are performed appropriately.

   a) Contents of the tests

      It should be confirmed that the target of the short-circuit current of generating an arcing is set up appropriately, the test that generates an arcing is performed, and the conditions that do not cause an ensuing fire are obtained.

   b) Evaluation of an ensuing fire breakout

      It should be confirmed that the arc energy is computed using appropriate data and the threshold energy that causes an ensuing fire is calculated.

4) Criteria of adequacy

   It should be confirmed that the interrupting time of the breaker of the concerned electric cabinets is set to a smaller duration time of an arcing than that of the threshold that causes an ensuing fire (in addition, measures for not only the breaker in the concerned electric cabinets but also the upstream breakers outside the concerned electric cabinets are confirmed, if necessary). Moreover, it should be confirmed that the function of fire detectors is maintained and firefighting is prepared even when an explosion occurs at HEAF.

Transitional Measures

The enforcement date is the proclamation date, and the transitional measures taken are as follows [10]:

1) For existing commercial power reactors and other facilities, the rules are not applied until the date of completion of the first periodic inspection of the facility after the enforcement:
    a) 2 years for electric cabinets other than the electric cabinets connected to emergency diesel generators
    b) 4 years for electric cabinets connected to emergency diesel generators
2) For commercial power reactors and other facilities under construction, the rules are not applied until the day before the commissioning date after the enforcement.
3) The application according to the amended rules in the abovementioned term is not rejected, and the approval and related matters follow the amended rule.

Schedule in Regulatory Standards

1) Implementation of the invitation of opinions: from February 23 to March 24, 2017
2) Decision by the Nuclear Regulation Authority: July 19, 2017
3) Proclamation (Official Gazette Public Notice): August 8, 2017
4) Enforcement: August 8, 2017

SUMMARY

The HEAF tests were conducted in order to obtain technical knowledge about the development of high energy arcing fault (HEAF) events, the arc energy level at which an ensuring fire occurs, and the impact of arc discharge.

The approximate arc energy necessary for causing an ensuring fire was confirmed. The values of arc energy which can cause ensuing fires were between 26.3 and 28.6 MJ for the DP and between 42.6 and 57.2 MJ for the M/C. The energy necessary for causing an ensuring fire is thought to depend on the internal volume of each electric cabinet and containment level.

The knowledge about ensuring fire occurrence in the second phase of HEAF has been accumulated, and as a result, for example, it is becoming clear that if arcing time can be shortened by operating the protective relay of a power supply board in a short time or by other ways, it is possible to prevent fire and to decrease the impact of explosions.

In the new Japanese HEAF regulatory requirements, prevention of ensuing fire and mitigation of explosion are required. One of the possible counter measures is replacement of analogue type OCR to digital type OCR. The response of the digital type OCR is much faster than that of old analogy ones.

In addition, concerning the degree of the HEAF impact and other factors, safety research and investigations are to be continued, and when new knowledge is obtained, the results will be reflected in the regulatory standards further, as necessary.

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PROPOSAL FOR EVALUATION METHODOLOGY ON TOTAL ARC ENERGY DURING HEAF (HIGH ENERGY ARCING FAULT) EVENT FOR HIGH AND LOW VOLTAGE SWITCHGEARS

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ABSTRACT

High energy arcing faults (HEAF) have the potential to cause extensive damage to the failed electrical components and distribution systems along with adjacent equipment and cables within the zone of influence (ZOI). Furthermore, the significant energy released during a HEAF event can act as an ignition source to other components within the area of the HEAF. In Japan, during the Great East Japan Earthquake that occurred in 2011, the seismically induced HEAF fire event, which caused wholesale damage to multiple high-voltage switchgears, was observed in Onagawa nuclear power plant (NPP).

In response, in August 2017, the NRA (*N*uclear *R*egular *A*uthority) in Japan amended the safety requirement for the power supply to consider the influence of subsequent fire due to a HEAF event (hereinafter called HEAF fire event). Therefore, it is urgently necessary to establish design criteria to prevent a HEAF fire event and to enhance the experimental data on a HEAF fire event. In order to estimate the total arc energy during a HEAF event and obtain the threshold value to prevent HEAF fire for existing non-arc-proof electrical cabinets, several series of three-phase internal arc tests with high (6.9 kV class) and low (480 V class) voltage electrical cabinets were conducted. CRIEPI carried out internal arc tests with full-scale high/low voltage metal-enclosed switchgear components (non-arc-proof type, copper bus conductor), and evaluated the arc energy, the mechanical damage to the cabinet and the surrounding equipment due to the impulsive pressure, and the possibility of subsequent fire occurrence. In case of high voltage switchgears, when the arcing energy exceeded 27 MJ, subsequent fire was identified. In particular, in the case where the arc flash was discharged in the circuit breaker room, a two-second arc duration in a three-phase short-circuit current with 18.9 kA (measured arcing energy over 40 MJ) caused subsequent fire that required extinguishment. On the other hand, in case of a low voltage power center, when the arc energy exceeded 19 MJ, subsequent fire was identified. According to these demonstrative tests, this paper presents an evaluation method to estimate total arc discharge energy during HEAF events for high and low voltage electrical cabinets.

INTRODUCTION

Large electrical discharges, referred to as HEAF, have occurred in the switching components of NPPs throughout the world [1]. In general, HEAF in electrical equipment are initiated in one of three ways: poor physical connection between the switchgear and the holding rack; environmental conditions; or the introduction of a conductive foreign object (e.g., a metal wrench or screwdriver used during maintenance). According to a report from the OECD FIRE Database Project [2], 11.5 % of the fire events collected in the OECD FIRE Database [3] represents HEAF fire events as shown in Figure 1. In particular, in Japan, the Great East Japan Earthquake occurred on March 11th, 2011, causing HEAF in two of ten sectors of the non-emergency high voltage switchgears and resulted in a seismically induced HEAF fire event in Onagawa NPP.

In response, in August 2017, the NRA in Japan amended the safety requirement concerning technical standards for commercial power generation nuclear reactors and their attached facilities, especially for power supply, to consider the influence of HEAF fire events as shown in Table 1 [4]. Therefore, it is urgently necessary to establish design criteria to prevent HEAF fire events and enhance the experimental data with respect to HEAF fire events.

In order to estimate the arc energy during a HEAF event and obtain the threshold value to prevent the HEAF fire for the existing non-arc-proof electrical cabinets, CRIEPI carried out several series of three-phase internal arc tests with high (6.9 kV class) and low (480 V class) voltage electrical cabinets.

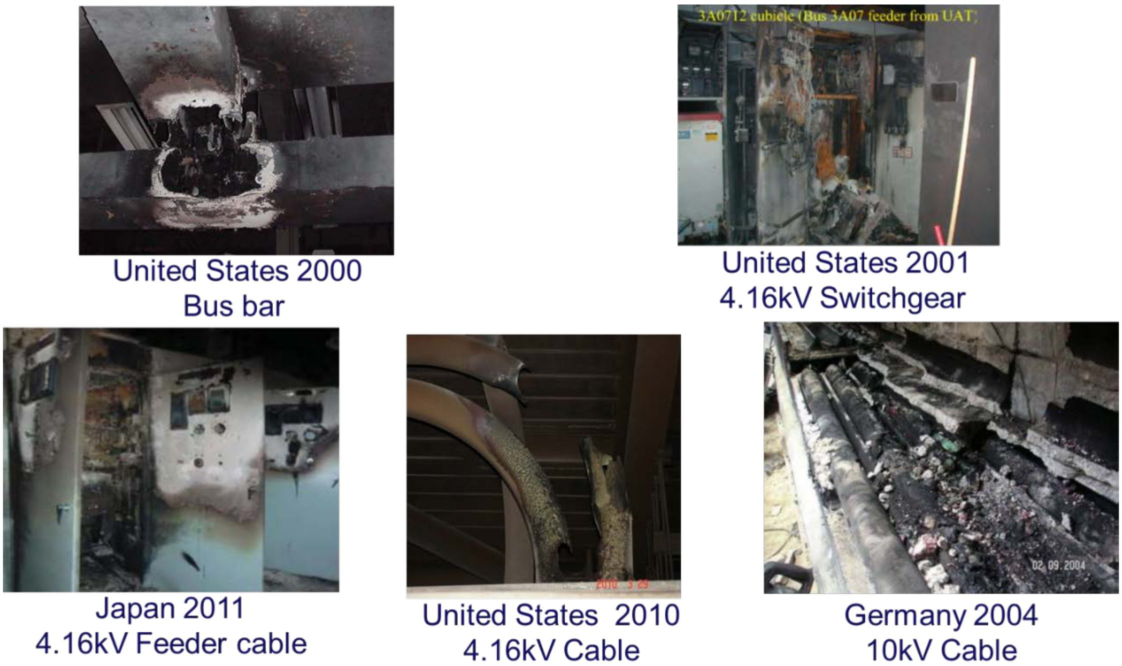


Figure 1 HEAF fire events [1]

Table 1 Current status of the amended requirement in Japan (as of August 2017) [4]

Technical standards for commercial power generation nuclear reactors and their attached facilities	
Article 45	Safety power supply facility
Term 3	For safety power supply facilities (facilities for supplying electricity to safety facilities), to secure the electric power supply to the equipment necessary for ensuring the safety of the nuclear power reactor facility from the designated power lines, generators constantly used in power generation nuclear reactor facilities and emergency power supply facilities, the following measures shall be taken.
Item 1	Measures necessary to prevent the spread of damage to the electrical cabinets due to HEAF
Item 2	In addition to what is listed in the preceding item, measures necessary to detect equipment damage, failure or other abnormality and prevent its expansion

INTERNAL ARC TEST PROGRAM

Internal arc tests using high and low voltage switchgears were conducted at the High Power Testing Laboratory of the CRIEPI at the request of the Federation of Electric Power Companies of Japan [5], [6]. The HEAF test program consisted four phases as follows. The equipment considered in our study consists of high/low voltage non-seismic-proof and seismic-proof switchgears as shown in Table 2.

- Phase-I: Ten HEAF tests using non-seismic, non-arc-proof 7.2 kV switchgears
- Phase-II: Three HEAF tests using seismic, non-arc-proof 7.2 kV switchgears
- Phase-III: Four HEAF tests using seismic, non-arc-proof 480 V switchgears
- Phase-IV: Five HEAF tests using non-seismic, non-arc-proof 480 V switchgears

Table 2 HEAF test program

Test Items	Phase I	Phase II	Phase III	Phase IV
Cabinet type	Non-seismic / 7.2 kV max. 4 cabinets	Seismic / 7.2 kV 2 cabinets	Seismic / 480 V 2 cabinets	Non-seismic / 480 V 2 cabinets
				
Phase number	Three phases			
Test frequency	50 Hz			
Test voltage	6.9 kV	8.0 kV	504 V	504 V
Test current	18.9 kA	40.0 kA	45.0 kA	45.0 kA
Target duration	0.1 - 2.0 s	0.2 - 0.6 s	0.2 - 1.5 s	0.4 - 1.4 s
Arc discharge point	cable room circuit breaker room	cable room circuit breaker room	circuit breaker room	circuit breaker room

TEST FACILITY

The Electric Power Engineering Research Laboratory of CRIPEI, located about 65 km south from the centre of Tokyo, was established in 1963 to make an important contribution to the progress of power transportation technology and conducted research and tests on the short-circuit performance of power equipment and materials using its high power short-circuit testing facility as shown in Figure 2.

The High Power Testing Laboratory was newly established in 2001, and laboratory accreditation was granted by the Japan Accreditation Board for Conformity Assessment (JAB) in compliance with ISO/IEC17025. As a laboratory meets international standards, there is a variety of test activities that include publishing test reports and issuing certificates. In this test facility, short-time withstand current and peak withstand current tests for circuit-breakers, disconnectors, grounding switches, load break switches, metal-enclosed switchgears and gas-insulated switchgears can be conducted with a test capacity of current up to 60 kA and duration up to 2 s.

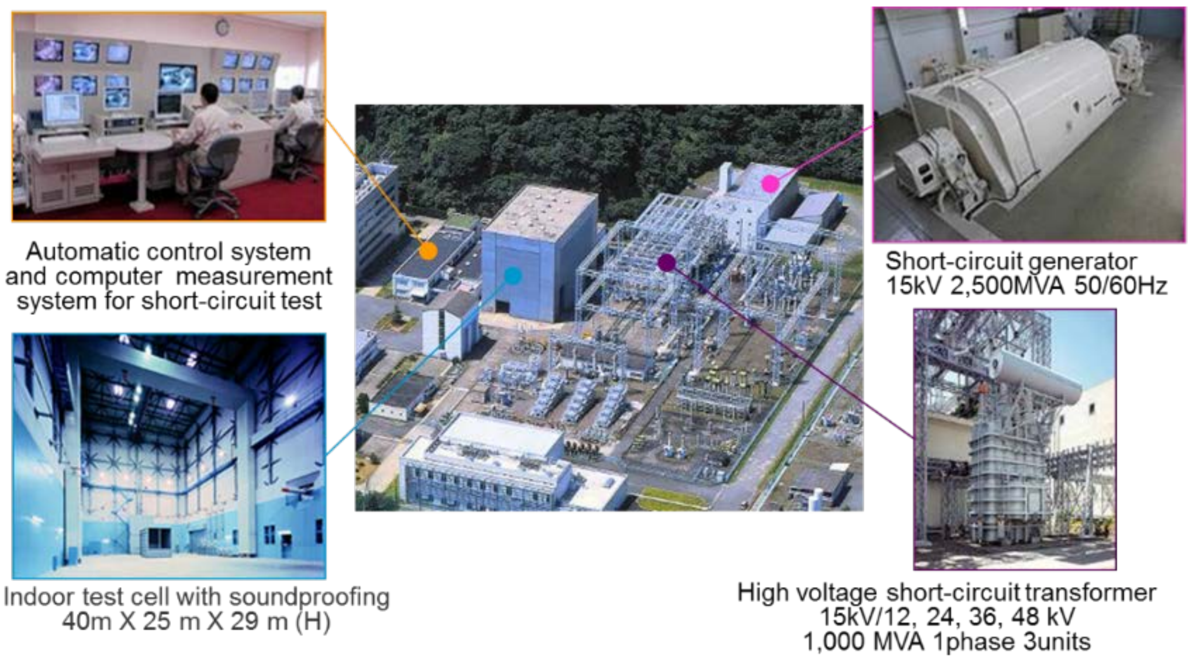


Figure 2 High Power Testing Laboratory (Yokosuka-shi, Chiba-ken, Japan)

Figure 3 shows the internal arc test circuit for a high voltage switchgear.

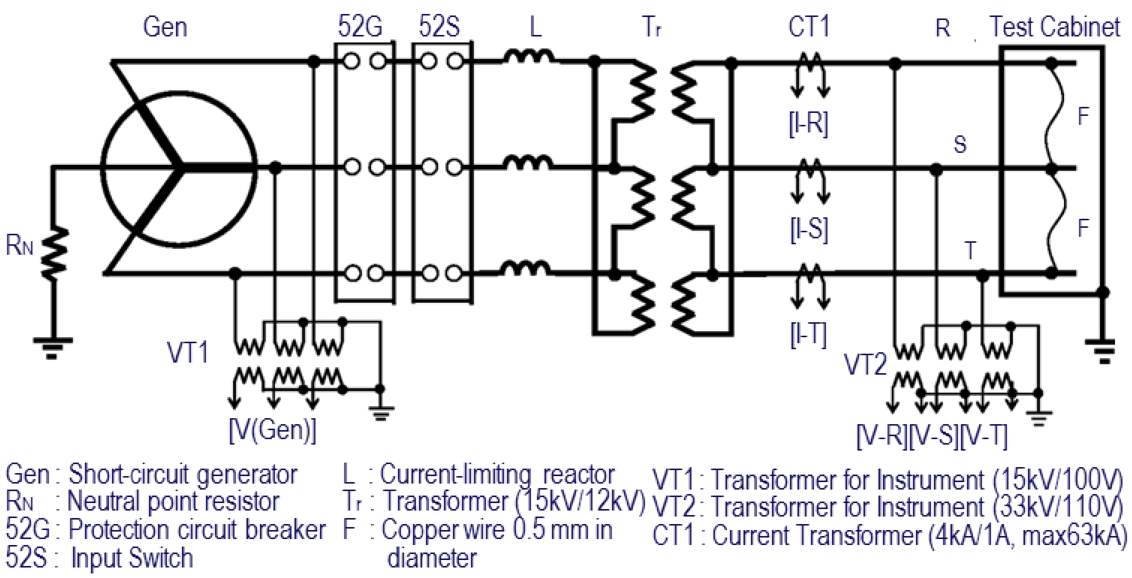


Figure 3 Internal arc test circuit for a high voltage switchgear

TEST MATRIX

The total number of HEAF tests was thirteen, varying the type of switchgears, rating voltage, current, and arc discharge locations as shown in Table 3. The test matrix was setup referring to “JEM1425-2011, Appendix A - Internal Fault” [7].

For internal arc tests, seismic/non-seismic and non-arc-proof 7.2 kV switchgears and 480 V power centres were tested in the unloaded condition (no primary load attached to them). The arc current was set to 20 kA – 45 kA considering the maximum three-phase short-circuit current from the designated power system. Referring to the standard of JEM1425-2011, the arc duration was set to the range between 0.1 s and 1.0 s. Moreover, from a safety point of view, a longer arc duration of 2.0 s was also considered. As arc discharge points, the secondary bus in the cable room and the VCB/ACB terminal in the circuit breaker room were selected and the arc was initiated by means of a copper wire 0.5 mm in diameter. The cabinet doors were closed to represent events that may occur under normal operation.

The test cabinets included the associated electrical equipment to provide a representative configuration. Moreover, secondary combustibles such as cables were also included in the test setup to verify the occurrence of the ignition.

TEST EQUIPMENT

In the Phase I test program, a total eight units of non-seismic-proof and non-arc-proof “3 - 6.9 kV metal-clad switchgears” were prepared and four series of HEAF tests were carried out. In Test Series 1, Series 2, and Series 3, cabinets A+B, cabinets C+D and cabinets E+F+G+H were used, respectively as shown in Figure 4. In Test Series 4, cabinets A+B were reused by reconditioning after Test Series 1.

In the Phase II test program, two units of seismic-proof and non-arc-proof “3 - 7.2 kV metal-clad switchgears” were prepared and Test Series 5 was carried out using cabinets I+J.

In the Phase III program, two units of seismic-proof and non-arc-proof “3 – 480 V power centres” were prepared and Test Series 6 was carried out using cabinets K+L.

In the Phase IV program, two units of non-seismic and non-arc-proof “3 - 480 V power centres” were prepared and Test Series 7 was carried out using cabinets N+O+P.

MEASUREMENT

During the tests, the arc intensity (e.g., arc power, rated current and voltage), arc duration, inner pressure inside the cabinet by pressure sensors, surface temperature of the cabinets by thermography, and passive temperature within the ZOI were measured. Additional instrumentation included high-speed video cameras. In case of Test Series 5, instrumented cable trays were placed in the vicinity of the switchgear to investigate the thermal damage or the potential fire resulting from the arc event.

Moreover, in case of Test Series 7, a hood calorimeter with a scrubber to mitigate the smoke effect on the surrounding environment was placed above the test cabinets to measure the incident and heat release rate and to assess the occurrence of subsequent fire resulting from the arc event as shown in Figure 5.

Table 3 HEAF test matrix and test results

Test Case	Arc Discharge Location			Voltage [kV]	Current* [kA]	Duration [s]	Arc Energy [MJ]	Fire
	Cabinet	Room	Location					
Phase-I: Use of eight non-seismic-proof, non-arc-proof 7.2 kV switchgears								
1-1	A	upper	secondary bus	6.9	18.9	0.103	3.09	no
1-2	B	upper	secondary bus			0.302	8.17	no
2-1	C	upper	secondary bus			0.527	12.9	no
2-2	D	upper	VCB terminal			0.526	10.4	no
3-1	E	upper	secondary bus			1.23	24.7	no
3-2	F	upper	VCB terminal			1.23	20.3	no
3-3	E	lower	secondary bus			1.23	27.6	yes**
3-4	F	lower	VCB terminal			2.18	41.8	yes***
4-1	A	lower	VCB terminal			2.39	44.6	yes***
4-2	B	Lower	VCB terminal			1.23	17.7	no
Phase-II: Use of two seismic-proof, non-arc-proof 7.2 kV switchgears								
5-1	I	upper	secondary bus	8.0	40.0	0.22	12.8	no
5-2	I	lower	VCB terminal			0.21	8.68	no
5-3	J	lower	VCB Terminal			0.63	25.3	no
Phase-III: Four HEAF tests using seismic, non-arc-proof 480 V switchgears								
6-1	K	upper	ACB terminal	0.504	45.0	0.20	2.49	no
6-2	K	middle	ACB terminal			0.51	6.34	no
6-3	K	lower	ACB terminal			1.53	19.8	yes***
6-4	L	middle	ACB terminal			0.18	2.91	no
Phase-IV: Five HEAF tests using non-seismic, non-arc-proof 480 V switchgears								
7-1	N	upper	ACB terminal	0.504	45.0	0.43	5.76	no
7-2	O	upper	ACB terminal			0.07	0.88	no
7-3	O	middle	ACB terminal			0.02	0.34	no
7-4	O	lower	ACB terminal			1.32	18.5	no
7-5	P	upper	ACB terminal			1.43	18.9	no

Remarks:
* Arc current: Max. three-phase short-circuit current from the designated power system
** Self-extinction observed after 20 min
*** Suppression work executed by portable water spray after ignition

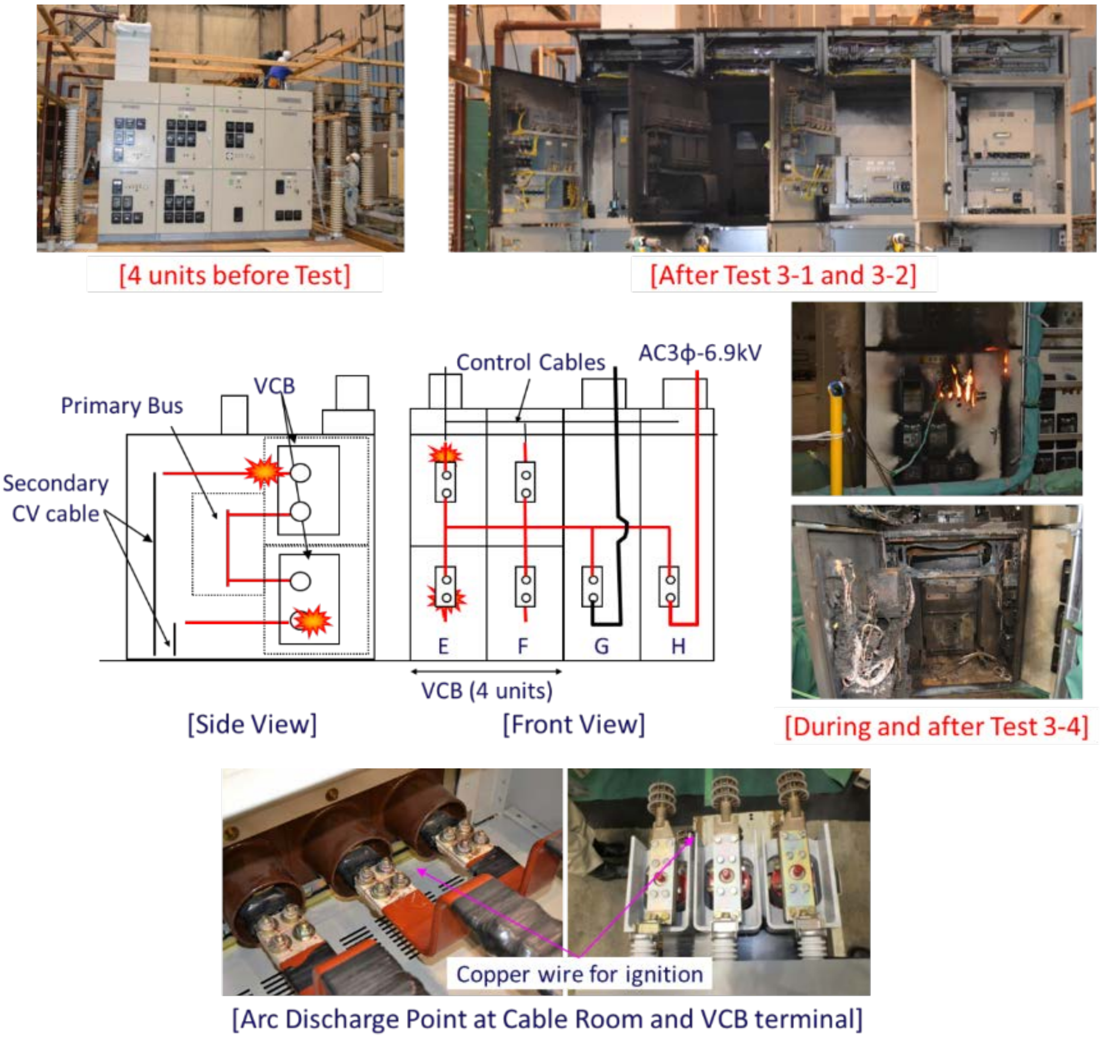


Figure 4 Typical damage of a test cabinet observed in Phase I

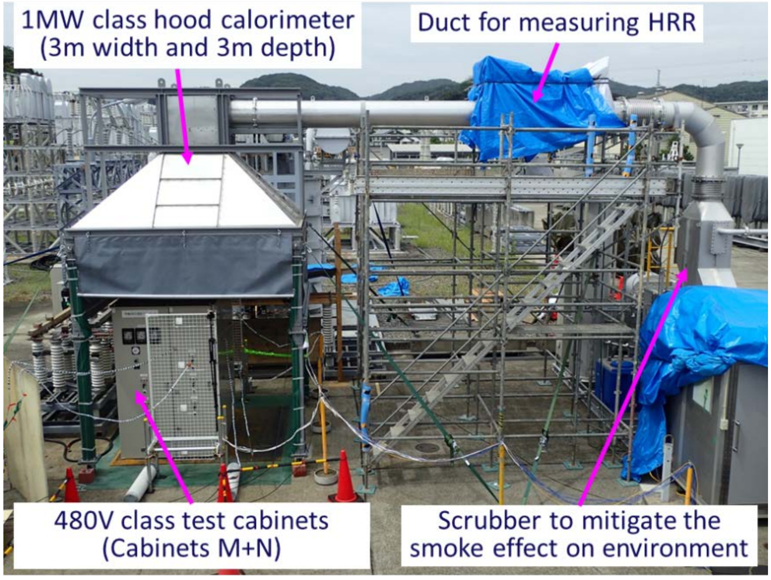


Figure 5 Internal arc test equipment layout for Test Series 7

HEAF TEST RESULTS

Figure 6 shows the arc flash and smoke generation observed in the Phase I (tests 3-4, 5-1). In test 3-4, as the arc was ignited at the VCB terminal located in the lower circuit breaker room with a duration 2.0 s, door opening due to the high pressure and the melting of the front panel of the VCB were observed. After 15 min, the fire was actively extinguished by portable water spray according to the safety procedure of the test facility.

Figure 7 shows the damage to the components observed in test 5-1. As the arc was ignited in the upper cable room with a duration of 0.2 s, the roof and rear panels came off and the cable tray was remarkably deformed due to the impact of the detached roof panel. However, there was no remarkable thermal damage to the cables on the tray despite exposure to extremely hot arc ejecta gas.

In the Phase-III, we measured the arc energy using 480 V class electrical cabinets (three-phase three-wire system) under a condition with a short circuit current around 45 kA and durations from 0.2 to 1.5 s. As a low voltage electrical cabinet with relatively low content volume rather than a high voltage metal-clad switchgear, a subsequent fire was identified when the arcing energy exceeded 19 MJ. Figure 8 shows the arc flash and the subsequent fire observed in Test 6-3. This subsequent fire was immediately suppressed by portable water spray according to the safety procedure of the test facility.

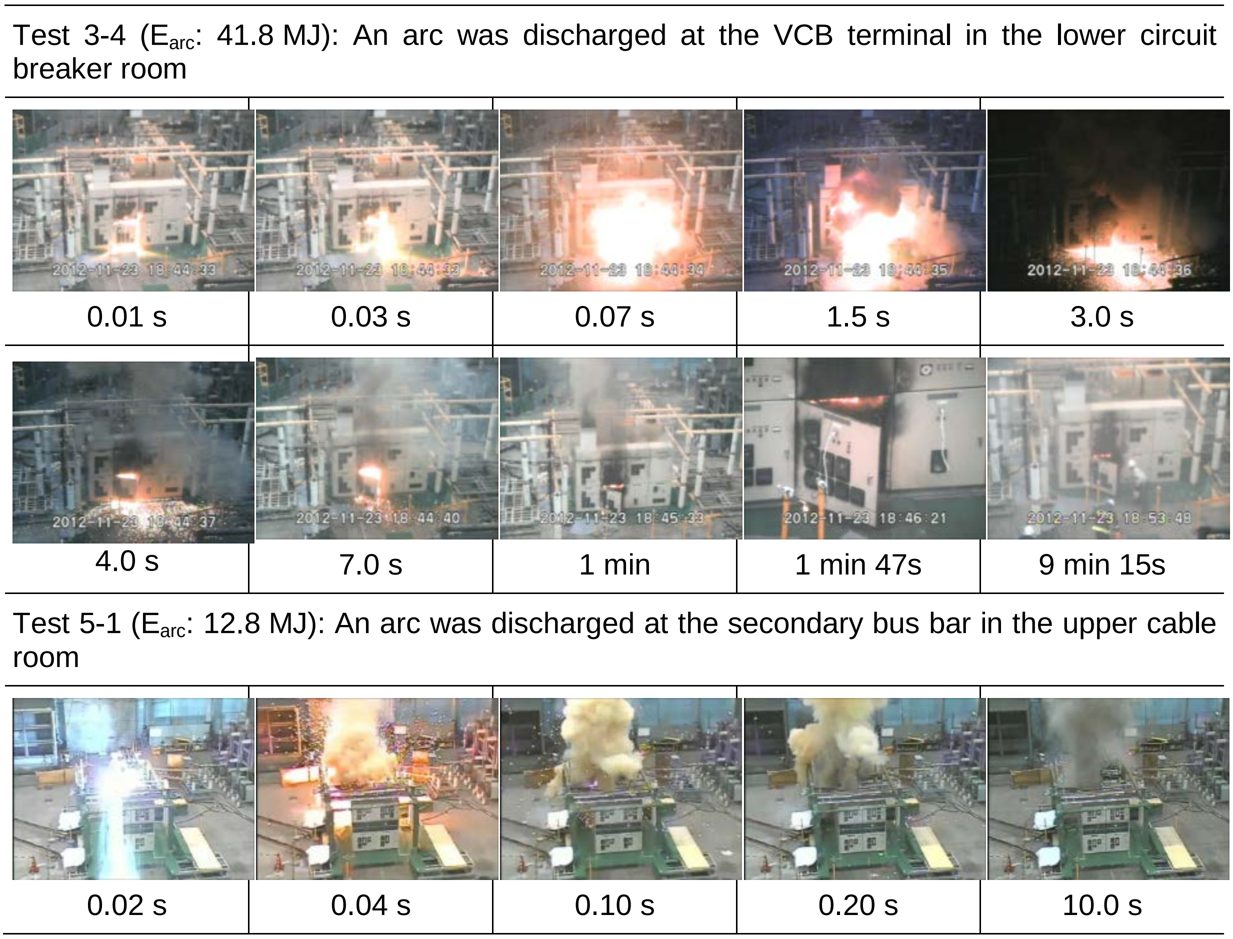


Figure 6 Arc flash and smoke generation observed in tests 3-4 and 5-1

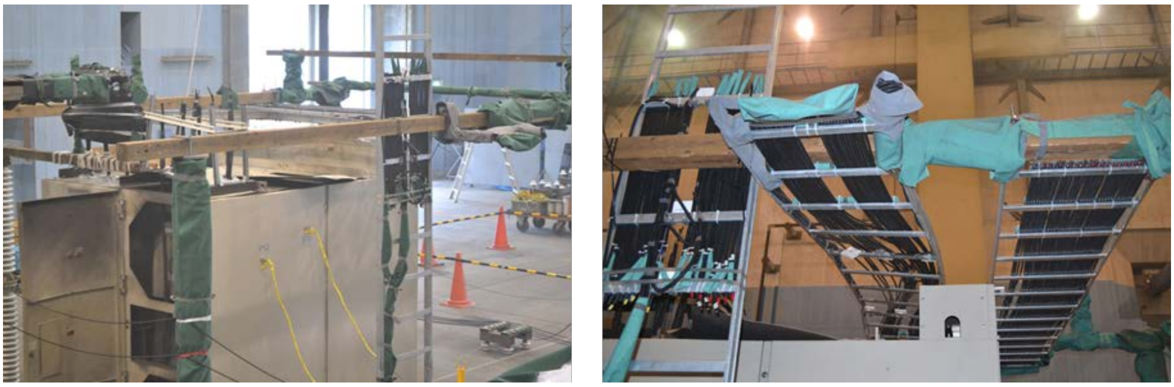


Figure 7 Damage to the equipment observed in test 5-1

<table>
<tr><td colspan="4">Test 6-3 (E_{arc}: 19.8 MJ): An arc was discharged at the ACB terminal in the lower circuit breaker room</td></tr>
<tr>
<td>
0.2 s</td>
<td>
0.6s</td>
<td rowspan="2">
A subsequent fire was observed in the lower circuit breaker room after the inner arc test.</td>
<td rowspan="2">
After the test, there was no significant impact to the adjacent cabinet or cable box above the cabinet.</td>
</tr>
<tr>
<td>
1.6 s</td>
<td>
5.0 s</td>
</tr>
</table>

Figure 8 Arc flash and subsequent fire observed in test 6-3

Figure 9 shows the HRR (*H*eat *R*elease *R*ate) and TTC (*T*hermal *T*ransfer *C*oefficient) measured in the Phase IV (tests 7-1, 7-4 and 7-5). This coefficient is obtained by dividing the thermal energy obtained by integrating the HRR by the arc energy, which is well-known as k_p value that represents the fraction of energy that goes into raising the gas pressure. In these tests, as no subsequent fire occurrence was observed, the HRR declines immediately after peak occurrence and the measured TTC value was saturated at a value of 0.5 or less and seems to be less than the value in the literature (copper bus bar $k_p = 0.53$ [8]) since it does not contain a certain amount of smoke flowing out of the hood.

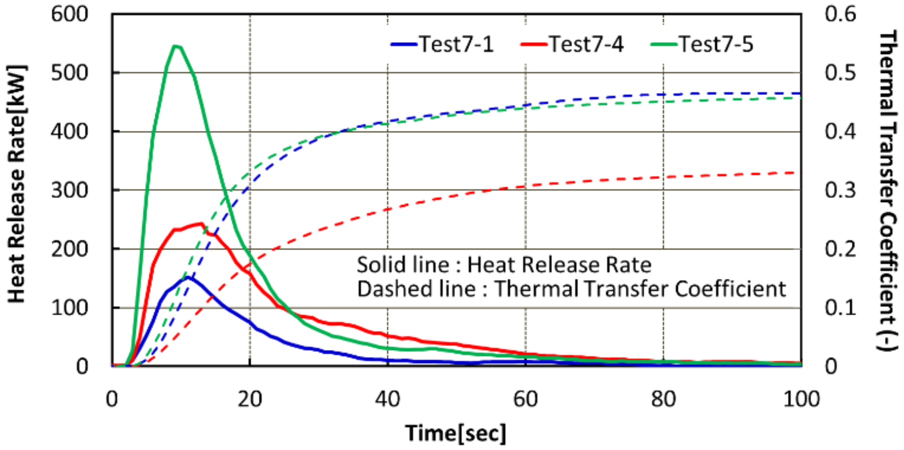


Figure 9 Heat release rates measured in tests 7-1, 7-4 and 7-5

ARC ENERGY

Arc energy E_{arc} for three-phase inner arc occurrence can be calculated by Equation (1):

$$\mathrm{E}_{3\emptyset} = \int V_R \cdot I_R dt + \int V_S \cdot I_S dt + \int V_T \cdot I_T dt \tag{1}$$

where three-phase arc energy $\mathrm{E}_{3\emptyset}$, the arc voltage for the R-phase V_R, the arc voltage for the S-phase V_S, the arc voltage for the T-phase V_T, the arc current for the R-phase I_R, the arc current for the S-phase I_S, the arc current for the T-phase I_T.

Here, we assume that the arc current of each phase is identical as shown in Equation (2):

$$I = I_R = I_S = I_T \tag{2}$$

As arc voltage V_{arc} (sum of V_R, V_S, V_T) may be constant not depending on the bias of the arc current, $\mathrm{E}_{3\emptyset}$ can be derived by Equation (3):

$$\mathrm{E}_{3\emptyset} = (V_R + V_S + V_T) \int I\, dt = V_{arc} \int I\, dt \tag{3}$$

As the integrated value of arc current $\int I\, dt$ represents the product of the average current value and the arc duration, $\mathrm{E}_{3\emptyset}$ can be rewritten by Equation (4):

$$\mathrm{E}_{3\emptyset} = V_{arc} \times I_{average} \times t_{arc} \tag{4}$$

where the mean value of current I $I_{average}$, the arc duration t_{arc}.

When the current waveform is assumed to be a sinusoidal wave, $I_{average}$ can be derived as follows:

$$I_{average} = {}^{2}/_{\pi} \cdot I_p = 0.637 \cdot I_p \tag{5}$$

$$I_{rms} = I_p/\sqrt{2} = 0.707 I_p \tag{6}$$

$$I_{average}/I_{rms} = 0.637/0.707 = 0.9 \tag{7}$$

$$I_{average} = 0.9 \cdot I_{rms} \tag{8}$$

where the symmetrical component peak value I_p, the current effective value I_{rms}

Therefore, $\mathrm{E}_{3\emptyset}$ can be rewritten using I_{rms} by Equation (9):

$$\mathrm{E}_{3\emptyset} = V_{arc} \times (I_{rms} \times 0.9) \times t_{arc} \tag{9}$$

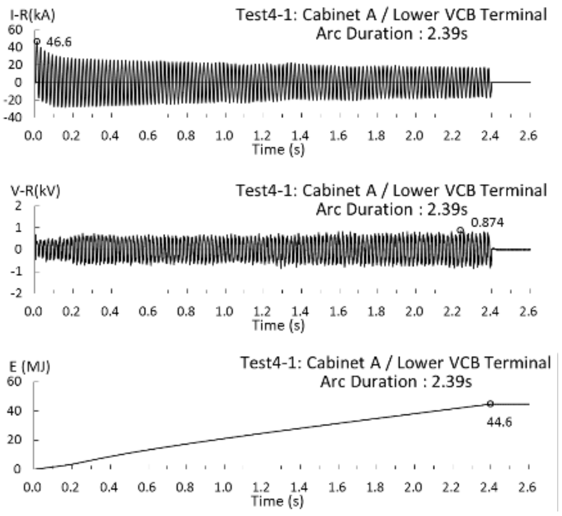
Figure 10 shows an example of the measured arc current, voltage and energy. Figure 11 shows the measured arc energy and voltage for high/low voltage switchgears. It is found that the measured arc voltage seems to be constant regardless of the arc duration, and their mean values for high/low voltage switchgears were 1.344 kV and 425 V, respectively.

Accordingly, applying the measured arc voltages values to equation (9), the estimation formula for the arc energy can be proposed as follows:

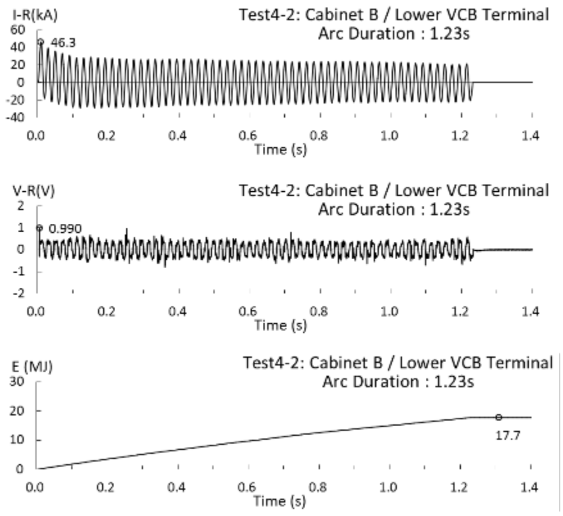
$$\mathrm{E}_{3\emptyset/High\ Voltage} = 1.344kV \times (I_{rms} \times 0.9) \times t_{arc} \tag{10}$$

$$\mathrm{E}_{3\emptyset/Low\ Voltage} = 0.425kV \times (I_{rms} \times 0.9) \times t_{arc} \tag{11}$$

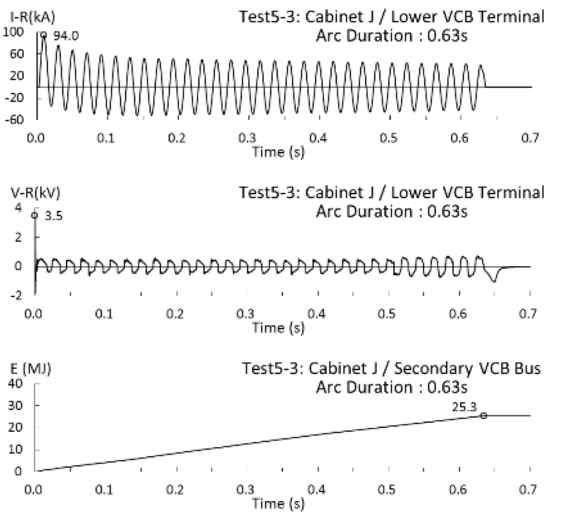
Figure 12 shows the estimation lines of the arc energy for high/low voltage switchgears. As the scattering of the experimental data seems to be not very high, these equations will be practical during practical design activities. Moreover, it is found that the lower limit values to prevent subsequent fire after a HEAF event for high/low voltage switchgears can be set to 27.6 MJ and 19.8 MJ. However, to assure these threshold values, enhancement of the experimental data is highly recommended.



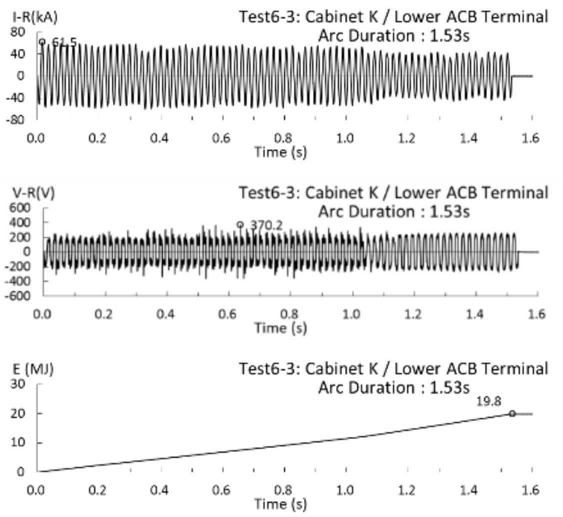
Test 4-1, lower / VCB terminal



Test 4-2, lower / VCB terminal



Test 5-3, lower / VCB terminal



Test 6-3, lower / ACB terminal

Figure 10 Examples of the measured arc current, voltage and energy

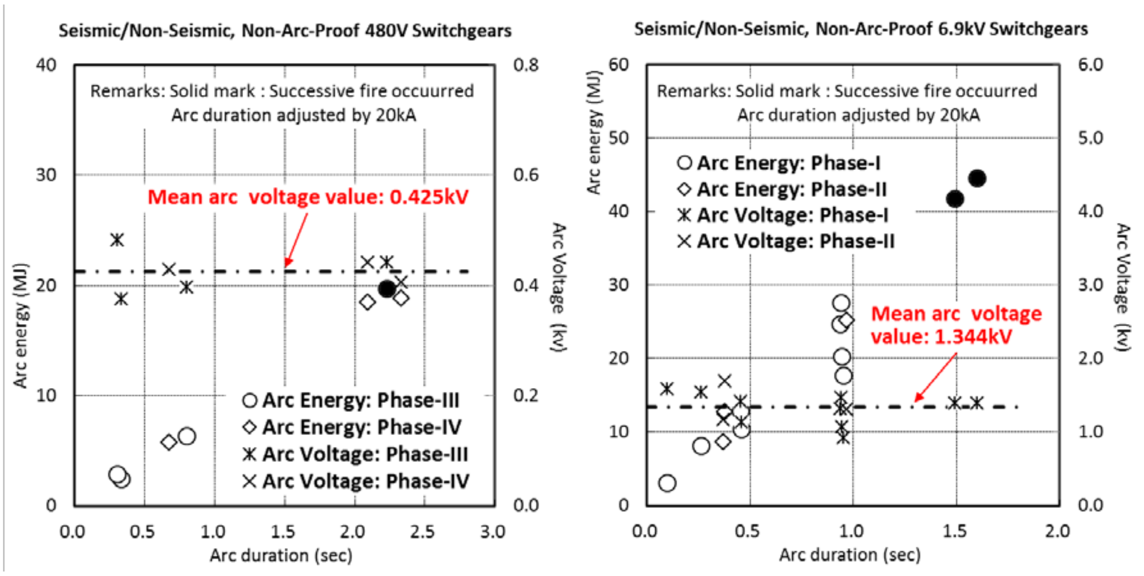


Figure 11 Relationship between arc duration and measured arc energy/voltage

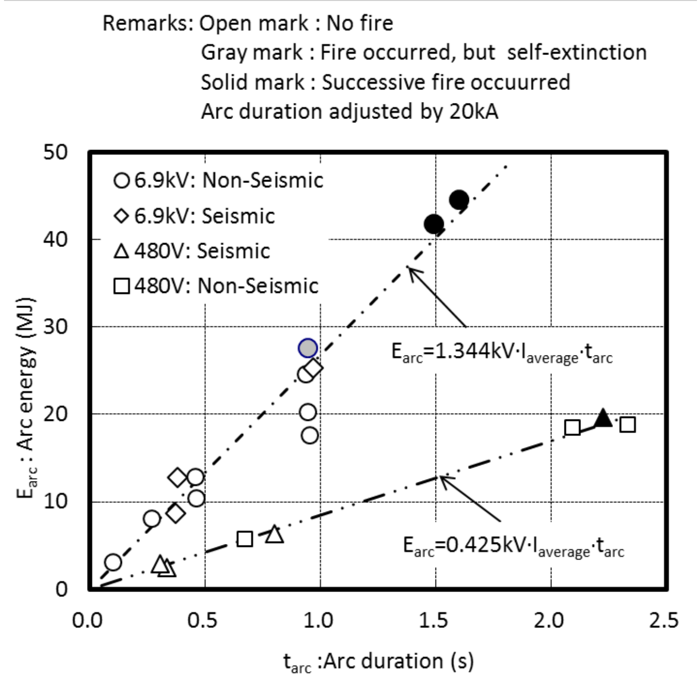


Figure 12 Estimation lines of arc energy for high/low voltage electrical cabinets

CONCLUSIONS

Successive fire due to the HEAF event in a high voltage metal-clad switchgear was identified at the Onagawa NPP after the Great East Japan Earthquake in March 2011. During the HEAF event, hot gas heated in the metal enclosure due to the arc flash will be emitted out of the enclosure or to adjacent enclosure, and has a potential to damage the surrounding equipment. In light of this, we executed internal arc tests with full scale high/low voltage electrical cabinets (non-arc proof type, copper bus conductor), and evaluated arc energy, the mechanical damage of the cabinets and the surrounding equipment due to the impulsive pressure and the possibility of successive fire occurrence. As a result, we proposed the empirical formula to estimate the total arc energy during HEAF event for high and low voltage switchgears.

Moreover, the threshold values to prevent the HEAF fire vent were also discussed. In case of high voltage switchgears, when the arc energy exceeded 27 MJ, successive fire was identified. Particularly in the case where the arc flash was discharged in the circuit breaker room, a 2-second arcing duration in a three-phase short-circuit current with 18.9 kA (measured arc energy over 40 MJ) caused successive fire which required extinguishing. On the other hand, for low voltage electrical cabinets (power center) with relatively low content volume, it could be confirmed that the arc energy above 19 MJ induced the HEAF fire.

ACKNOWLEGMENT

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GLOVE BOX FIRE BEHAVIOUR IN FREE ATMOSPHERE

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ABSTRACT

In nuclear facilities as fuel processing or waste reprocessing plants, glove boxes (GBs) are frequently used to handle radioactive materials in containments for safety conditions. Furthermore, they can be especially designed to prevent radiation exposure to operator by using leaded panels providing biological shielding. These panels are often made of Kyowaglas (70 % of methyl polymethacrylate (PMMA) and 30 % of lead) with a thickness of 50 mm. Despite a wide use of such devices in nuclear industry, few results are available, describing the global behaviour of a GB fire, for fire safety analysis. Thus, the aim of this study is to present the main fire characteristics of 1 m^3 GB using PMMA panels instead of Kyowaglas as surrogate of biological protection for safety reason. The experimental facility and the design of fire tests conducted in free atmosphere are presented in detail and main outcomes concerning fire properties of GBs are given. The analysis of the experimental results presents the effect of the combustible loading, as the GBs are equipped from 1 to 5 polycarbonate panels, used for the containment and from 1 to 2 PMMA working sides. The results show a maximum heat release rate ranging from 1.7 to 4.1 MW, depending of the number of combustible panels. In addition, a high internal gas temperature, almost common to each fire tests, is measured to be greater than 1000°C. The effect of the ignition process on the fire behaviour is also presented and shows an identical fire scenario both for a 50 kW and a 0.1 kW gas burner device. Several GB fire tests under identical conditions have also been performed and indicate a good repeatability of the experimental results.

INTRODUCTION

A fire in a basic nuclear installation, such as a laboratory or a plant, may result in the release of radioactive material to the environment. In order to avoid and, if necessary, limit this release, appropriate prevention, protection and fire-fighting measures must be put in place. To do this, estimating the radiological consequences of a fire on the population and the environment is necessary. The total activity corresponding to the release of nuclear materials, also called "fire source term", is an input to the calculation of the radiological consequences. Moreover, in addition to the radiological consequences on the population and the environment, the health impact on workers and emergency response teams must be taken into account. As a result, it is necessary to study the radioactive releases inside the concerned rooms of the nuclear facility. However, high disparities are often found in the estimates of the fire source term. These can have significant consequences in terms of decision making during a crisis situation, such as the geographical perimeter to be secured and, more broadly, in the field of the nuclear safety.

Historically, a number of accidents following a fire start in a GB were recorded in the 1950s and 1960ies, but relatively little information is available on the existence of more recent events [1]. A guide of the Factory Mutual Research Corporation [1] lists 24 fires and 19 explosions between 1956 and 1965 on laboratory GBs operated by the United States Atomic Energy Commission. We can also cite the fires that occurred in the GBs of the Hanford Atomic Products Operation in the 1960s [3]. The most significant contamination resulting from a GB fire occurred at the Rocky Flats plant in the USA in 1957 [4]. September 11, 1957, plutonium shavings in a GB located in the Plutonium Recovery and Fabrication Facility building spontaneously ignited. The fire spread to the flammable GB materials, including PMMA windows and rubber gloves. The fire rapidly spread through the interconnected GBs and ignited the large bank of high-efficiency particulate air (HEPA) filters located in a plenum downstream. Within minutes the first filters had burned out, allowing plutonium particles to escape from the building exhaust stacks. The building exhaust fans stopped operating due to fire damage, which ended the majority of the plutonium release. Another major fire occurred in the Rocky Flats plant on May 11, 1969 in the Plutonium Processing Facility building [5]. As for the fire of 1957, the spontaneous combustion of plutonium shavings in the GB is at the origin of this disaster. While the fire bore marked similarities to the 1957 fire, the level of contamination was less severe because the HEPA filters in the exhaust system did not burn (after the 1957 fire, the filter material was changed from cellulose to non-flammable fiberglass). A third GB fire occurred again at Rocky Flats Environmental Technology site on May 6, 2003, in a GB during decommissioning [6]. For the French basic nuclear installations, 14 incidents related to a fire start on a GB were recorded over the period 1970-2010; 12 led to a loss of integrity of the GB. The consequences of the two other incidents were not mentioned.

For the previous reasons, The Institut de Radioprotection et de Sûreté Nucléaire (IRSN) has initiated a program aimed at improving knowledge on the potential release of the nuclear particles due a GB fire source. In particular, it is worthy to determine the quantity of radioactive material involved in a GB fire and the quantity of plutonium dioxide to be suspended to the environment. The first step in this program consists to collect information on the behaviour of GB fire source. The BAG_CSS test campaign is the first phase of the program carried out by IRSN. It consists in characterizing a GB fire source without surrogate of radioactive material in order to determine the main characteristic of GB fire (mass loss rate, heat release rate, etc.) and to assess the thermal, chemical and aeraulic stresses that the radioactive particles could undergo during the fire. After a brief description of the experimental facility, this paper presents the main results of seven GB fire tests conducted in free atmosphere under the SATURNE device.

GLOVE BOX FIRE TESTS DESCRIPTION

Glove Box Fire Source

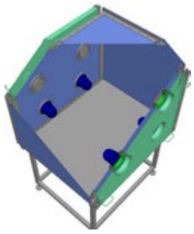
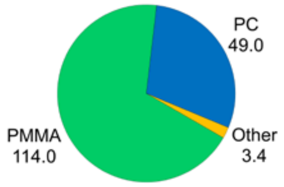
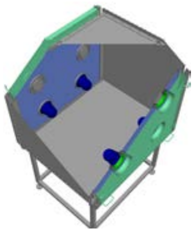
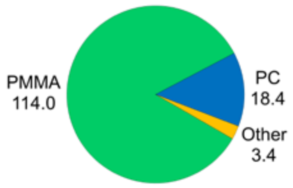
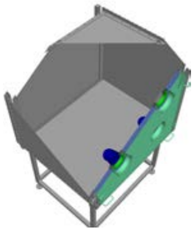
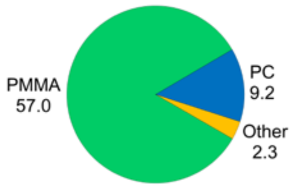
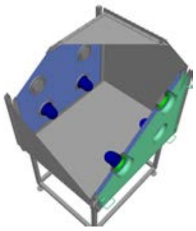
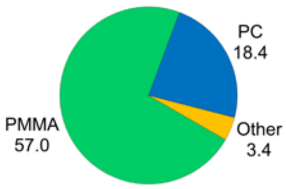
The analysis of the safety reports handled in recent years by IRSN has made it possible to collect a database on the different types of GBs available in French basic nuclear installations. This information was used to define a representative GB for the needs of BAG_CSS experimental program.

The GBs used as fire source have the same size for all the seven tests. The internal dimensions of the GB are 0.9 x 1.2 x 0.9 m^3 (depth x width x height), i.e. an approximately 1 m^3 in volume. These GBs are said to be "analytical" since they are devoid of their specific ventilation system, suppression system and all internal equipment. The GBs' containment panels are either made of polycarbonate (Lexan brand PC), 10 mm thick, or of 2 mm thick stainless steel sheet. The biological protection in Kyowaglas (70 % of PMMA and 30 % of lead), equipping usually the GBs' working sides, are simulated by sheets of PMMA with a thickness of 50 mm. A 30 mm air gap separates the PC containment walls from the PMMA protection panels. The working sides of the 1 m^3 GB have two glove holes in the top part and two glove holes in the bottom part, with the two rows spaced 360 mm apart (see Figure 1). The glove holes have a diameter of 170 mm in the PC containment panels and 200 mm in the PMMA panels. The glove holes in the lower part are spaced 500 mm apart, while those in the upper part are 600 mm apart. The glove holes in the upper part, allowing occasional access for handling the GB's filters (as in a complete GB), are fitted with polyethylene (PE) plugs.

Gloves in polyurethane (PUR) are fitted into the glove holes in the lower part. They are held in place by stainless steel containment rings and polypropylene (PP) immobilisation rings.

Four GB configurations are tested with a variable number of PC containment panels and PMMA protection panels (see Table 1). The full combustible load corresponds to the BAG_CSS_1.1 test configuration with two working sides, with PC and PMMA panels on each working side, and with PC panels on the TOP and lateral sides of the GB. Only the top and lateral sides in PC are replaced by stainless steel panels for the second configuration. For the third GB configuration, only one working side was installed with a single PC panel and a single PMMA panel. The last GB configuration was the same as the second configuration but with no PMMA panel on one of its working side. The combustible load varies from 68.5 to 166.4 kg depending on the GB configurations.

Table 1 Combustible load for each GB configuration

GB Configuration[(1)]	Tests concerned	Combustible load [kg]	
		Total	Distribution
	BAG_CSS_1.1	166.4	
	BAG_CSS_1.2 BAG_CSS_1.5 BAG_CSS_1.6 BAG_CSS_1.7	135.8	
	BAG_CSS_1.3	68.5	
	BAG_CSS_1.4	78.8	

(1) Grey, blue and green colours respectively for the stainless steel, PC and PMMA panels.

System of Ignition

In order to study the effect of the ignition method, two types of gas burner supplied with commercial propane are used to ignite the GBs externally along the PMMA panel: a rectangular sand burner and a point burner. The rectangular sand burner with an area of

0.2 x 0.8 m² is located at the bottom of one of the GB's working sides and on its axis of symmetry. The uniform distribution of the flame of the area of the burner ignited GB's biological protection over almost all its length. The heat release rate delivered by this system is 50 kW (see Figure 1a). The point burner comprised a 4/6 stainless steel tube terminating in a Swagelok 1/16 reducer. This system produced ignition at a point, similar to a "cigarette lighter flame" in size, at the bottom of the PMMA biological protection and on its axis of symmetry. The heat release rate delivered by this system is 0.1 kW (see Figure 1b).

(a) (b)

Figure 1 Ignition phase with (a) a 50 kW wide rectangular burner and (b) a 0.1 kW point burner

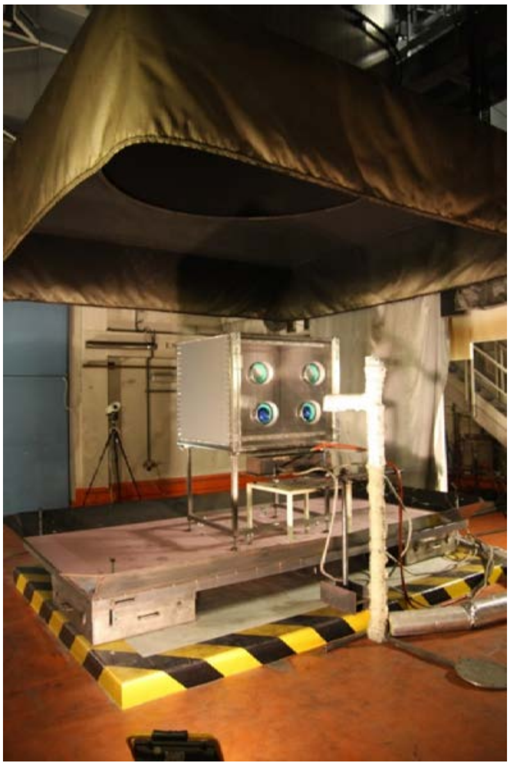
The ignition is piloted by an electric spark system. The durations of the supply of propane are similar for all the tests and are of the order of 4 min. The tests using each type of ignition system are detailed in Table 2 below.

Table 2 Ignition system for each GB fire test

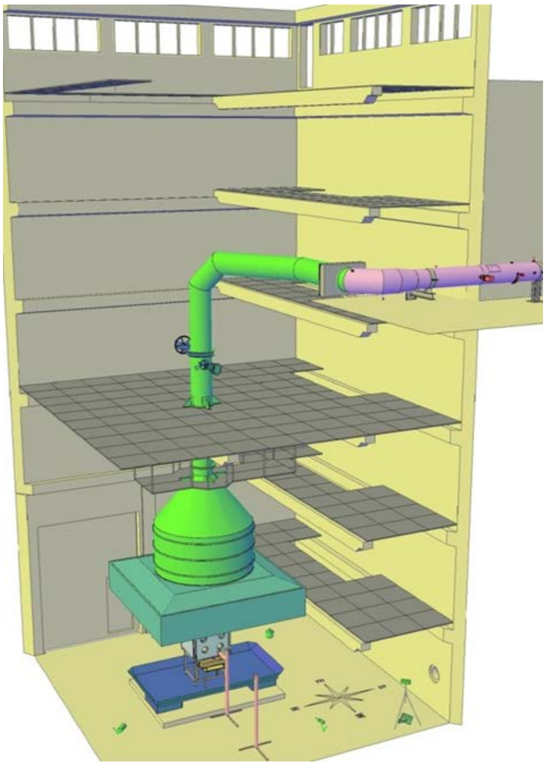
System of ignition	Tests concerned	Ignition characteristics
Rectangular sand burner	BAG_CSS_1.1 BAG_CSS_1.2 BAG_CSS_1.3 BAG_CSS_1.4 BAG_CSS_1.7	Ignition over a wide area 50 kW during 4 min
Point burner in 4/6 stainless steel tube	BAG_CSS_1.5 BAG_CSS_1.6	Local ignition 0.1 kW during 4 min

SATURNE Facility

The tests are conducted in free atmosphere in a large well-ventilated enclosure, namely SATURNE, which has been designed as a large-scale calorimeter and used in IRSN to study various large fire sources as in [7], [8], [9], [10], [11]. The SATURNE facility is 10 x 10 m^2 in area and 20 m in height. This installation comprises three areas: the platform where the fire source is placed on (see Figure 2a), the hood and its exhaust duct (see Figure 2.b), the ventilation network. The GB fire source to be characterised is placed on the platform centred under the hood in the SATURNE facility. The hood capturing the smoke and hot gases is 4.5 x 4.5 m² in area and is connected to an exhaust duct. This latter is then connected to a ventilation network fitted with a dilution line, a full HEPA filtration system and fans. Openings at the top of the SATURNE facility on each of its four sides allow sufficient air to be taken in to maintain the fire source in a stable air environment with a constant oxygen concentration of 21 % in volume.



(a)



(b)

Figure 2 SATURNE facility (a) GB fire source under the hood and (b) overview of the calorimeter

Instrumentation

The instrumentation of SATURNE facility is typical of calorimeters with measurement of the fuel mass of the fire source and measurements in the smoke exhaust duct such as pressure, temperature, gas flow rate and oxygen, carbon monoxide, carbon dioxide and soot concentrations.

Specific instrumentation is also added nearby the GB fire source. The incident heat fluxes radiated by the GB fire source are measured at 0.5, 1 and 3 m from the surface of the burning PMMA panel and at respective heights of 0.3, 0.6 and 0.9 m from the floor of the GB. A video system of four cameras located all around the GB fire source allows following the fire evolution. From the second test, thermocouples are added in the GB in order to measure the internal temperatures at three heights, i.e. 0.225 m, 0.45 m (mid height in the GB) and 0.675 m from the GB floor. These temperatures do not only indicate the convective heating of gases but also include the flame radiation.

EXPERIMENTAL RESULTS AND DISCUSSION

Scenario of the Glove Box Fire Development

The seven BAG_CSS tests conducted in free atmosphere all show a similar fire development scenario. Indeed, the time evolution of fire may be described as four successive phases.

The first phase, lasting 4 min, corresponds to the external ignition of the GB. Depending on the gas burner system described above, the PMMA protection panel is ignited over a wide area with the rectangular burner (see Figure 1a) or a narrow area with the point burner (see Figure 1b) during this ignition phase.

When the burner is stopped, the flames spread slowly over the internal and external faces of the ignited PMMA protection panel. The duration of this fire incubation phase is variable and depends on the power of the burner. This phase takes much longer time for tests BAG_CSS_1.5 and BAG_CSS_1.6, for which small point ignition is used.

At the end of the fire incubation phase, the heat flows coming from the combustion of the PMMA protection panel coupled with the heating of the gases in the GB reach a sufficient high thermal level for affecting significantly the PC containment panels and accelerating their pyrolysis. This additional contribution of the PC to the combustion process increases rapidly the heat release rate of the fire. At this stage, and where applicable, the second PMMA protection panel opposite to the fire side is also consumed. The fire then reaches its full power during this third rapid combustion phase.

At this stage, the combustible plates (initially vertical) are, partly consumed over their height or melted at the bottom of the GB resulting in a reduced combustible material/flame exchange area. This reduction of the exchange area and the reduction in the available combustible load result in a decrease in the fire intensity. This decrease of fire power continued until the fire stopped.

Fuel Consumption and Fire Duration

In free atmosphere, whatever the GB's configuration, the fire stops by lack of fuel. The rate of consumption of the fuel, τ_{fc} Eq. (1), is always close to 100 % (see Table 3). The duration of the fire, d_f, is considered as the duration of the pyrolysis and varies from 2 hr 14 min to 3 hr 11 min for the BAG_CSS tests. Pyrolysis process ends when the fuel mass loss rate, $\dot{m}_f$ Eq. (2), becomes zero. The maximal value of $\dot{m}_f$ varies from 56 to 140 $g.s^{-1}$ for the seven BAG_CSS tests.

$$\tau_{fc} = \frac{m_{fc}}{m_{f,0}} \quad (1)$$

where $m_{f,0}$ is the initial total mass of the fuel before GB ignition and m_{fc} is the mass of fuel consumed.

$$\dot{m}_f = \frac{dm_f}{dt} \quad (2)$$

Heat Release Rate of the Fire

The power of the fire, $\dot{Q}$, also called HRR for "Heat Release Rate", expresses the quantity of heat released by the combustion reaction per unit of time. The heat release rate of the fire source is an essential input data when defining the fire source [12]. In a free atmosphere, the heat release rate of the fire is assessed from the products consumed or produced during the combustion reaction [13][14]. The formulations of this so-called "chemical" method are written below in Eqs. (3) and (4) respectively for the oxygen consumption (OC) method and the carbon dioxide generation (CDG) method. CDG is the preferred method for estimating the heat release rate of fire for the BAG_CSS tests, with the exception of the test BAG_CSS_1.1 for which the OC method is used due to the saturation of the CO_2 production measurement.

$$\dot{Q}_{OC} = E_{O_2}^{C_nH_m}\dot{m}_{O_2}^{C} - \left(E_{O_2}^{CO} - E_{O_2}^{C_nH_m}\right)\frac{M_{O_2}}{2M_{CO}}\dot{m}_{CO}^{G} - \left(E_{O_2}^{C} - E_{O_2}^{C_nH_m}\right)\frac{M_{O_2}}{M_C}\dot{m}_{C}^{G} \quad (3)$$

$$\dot{Q}_{CDG} = E_{CO_2}^{C_nH_m}\dot{m}_{CO_2}^{G} + E_{CO}^{C_nH_m}\dot{m}_{CO}^{G} + E_{C}^{C_nH_m}\dot{m}_{C}^{G} \quad (4)$$

The time evolution of the heat release rate of the fire, shown in Figure 3, illustrates the four different phases of the GB fire growth defined above: an ignition phase, a fire incubation phase, a rapid combustion phase and an ending phase until the stop of the fire. In addition to the rapid kinetics of the heat release rate increase, the GB fires reach very high powers with maximum values between 1.7 and 4.1 MW. The fire power remains high in spite of the reduction in the number of combustible walls. For instance, the GB fire reaches a heat release rate of 1.7 MW in BAG_CSS_1.3 test, although this GB has only two combustible panels. It should also be noted that the fire power is maintained at a high level for a long time, for example in BAG_CSS_1.2, BAG_CSS_1.5, BAG_CSS_1.6 and BAG_CSS_1.7 tests. Indeed, in these tests, the fire power remained above 2 MW for more than 20 min.

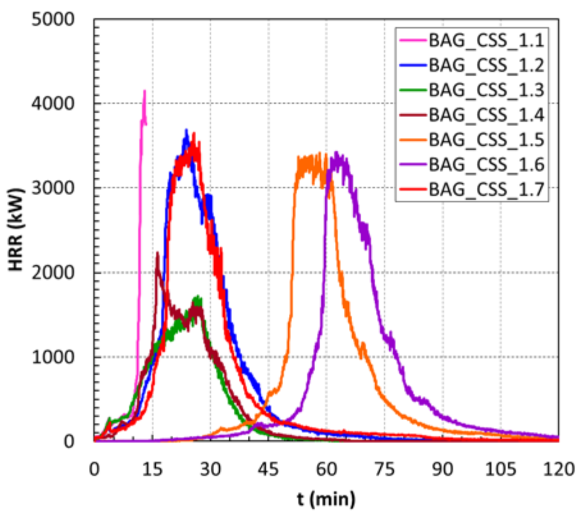


Figure 3 Development over time of the fire heat release rate for the seven BAG_CSS tests

The total energy, E_{tot}, released during the fire tests is obtained by integrating the time evolution of heat release rate over all the duration of the fire, as showed in Eq. (5). This total energy is corrected for the energy released by the combustion of the propane used to ignite the GB, $E_{C_3H_8}$, in order to reach the actual energy released during the combustion of the GB combustible materials, E_{net}. Thus, by applying the relationship (6), it is possible to estimate a mean effective heat of combustion for the duration of the fire.

$$E_{tot} = \int_0^{t_{end\,fire}} \dot{Q}(t)\,dt \quad (5)$$

$$\Delta H_{c,eff,net} = \frac{E_{net}}{m_{fc}} = \frac{E_{tot} - E_{C_3H_8}}{m_{fc}} \quad (6)$$

Whatever the configuration of the GB and the type of ignition tested, $\Delta H_{c,eff,net}$ is of the same order of magnitude, i.e. 29.4 ± 1.0 MJ.kg^{-1} (see Table 3). This mean value is in the range of the heat of combustion indicated by the two main fuels which compose a GB, i.e. PMMA and PC ($\Delta H_{T,PMMA} = 25.2\ MJ.kg^{-1}$ and $\Delta H_{T,PC} = 31.6\ MJ.kg^{-1}$ [15] respectively), resulting in near complete combustion involving a combustion efficiency close to unity.

Table 3 Duration of the fire, mass of fuel consumed, rate of consumption of the fuel, maximum of fuel mass loss rate, maximum of heat release rate and mean effective heat of combustion of the seven BAG_CSS tests

Tests	d_f	m_{fc} [kg]	τ_{fc} [%]	$\dot{m}_{f,max}$ [g.s^{-1}]	$\dot{Q}_{max}$ [kW]	$\Delta H_{c,eff,net}$ [MJ.kg^{-1}]
BAG_CSS_1.1	-(2)	-(2)	-(2)	140(3)	4149(3)	-(2)
BAG_CSS_1.2	2 hr 47 min	133.5	98.3	115	3687	30.1
BAG_CSS_1.3	2 hr 14 min	66.4	96.9	56	1723	28.4
BAG_CSS_1.4	2 hr 21 min	71.0	90.1	68	2228	30.4
BAG_CSS_1.5	3 hr 11 min	133.8	98.5	115	3416	29.3
BAG_CSS_1.6	3 hr 07 min	132.0	97.2	113	3424	29.9
BAG_CSS_1.7	2 hr 44 min	131.2	96.6	118	3650	28.9

(2) Value unknown due to an unexpected stop in data acquisition following a general loss of power supply.
(3) Maximum value measured before the unexpected break in data acquisition.

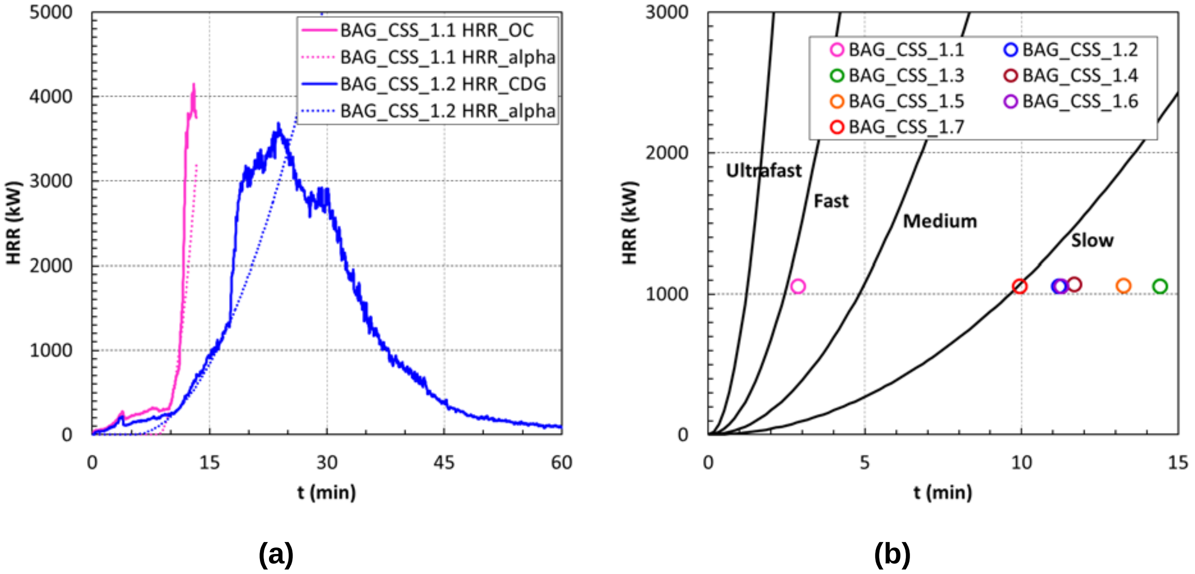
Fire Growth Rate

The growth rate, α, of a fire source allows the spread of a fire on a material to be characterised simply and classified according to the speed of propagation obtained in tests under a calorimeter hood [16], [17], [18]. The fire growth rate is determined using Eq. (7) by supposing that the spread of a fire on a combustible material changes with the square of the time. By convention [18], the fire growth rate, α, is determined by measuring the critical time, t_{crit}, necessary to reach a fire power $\dot{Q}_{crit} = 1055\ kW$ after the actual ignition of the fire source at the initial time, t_{ini} see Eq. (8).

$$\dot{Q}(t) = \alpha(t - t_{ini})^2 \tag{7}$$

$$\alpha = \frac{1055}{(t_{crit} - t_{ini})^2} = \frac{1055}{(\Delta t_{crit})^2} \tag{8}$$

For each of the seven BAG_CSS tests, the heat release rate of the fire measured as close as possible to 1055 kW is determined and the associated critical time t_{crit} is evaluated. From this point, the pair (α, t_{ini}) is determined by adjusting the curve from the relationship (7) as closely as possible to the experimental data. By means of an example, the heat release rate thus obtained by Eq. (7) is compared in Figure 4a to the heat release rate obtained experimentally for BAG_CSS_1.1 and BAG_CSS_1.2 tests. Using this approach, the growth rates α are obtained from all the GB tests allowing the GB fire sources to be classified according to the NFPA standard [18] (see Figure 4.b). So, the GB fire source with a top made of combustible material (test BAG_CSS_1.1) is classed as "fast" whereas the other six GB fire sources with a steel plate top are classed as "slow".



(a) (b)

Figure 4 Rate of growth (a) determination for BAG_CSS_1.1 and BAG_CSS_1.2 tests and (b) all GB fire sources compared to the NFPA classification [18]

The NFPA standard applied here classifies a fire source according to the fire growth rate. But this approach does not allow predicting the maximum value of heat release rate for the fire source. In all the tests with steel roof, the burning of the PC material occurs always above the 1.055 MW HRR. Indeed, as soon as the PC panels begin to burn, the fire power increases significantly with a fire growth rate well beyond the previous phase. This point is illustrated in Figure 4a (t > 18 min) for the BAG_CSS_1.2 fire test.

Well-stirred Reactor

The GBs tested have two rows of glove holes on their working sides (see Figure 5a). As soon as the beginning of fire, this specific geometrical configuration favours the flame spread along the vertical panel and finally the development of fire on both sides of the PMMA protection panel (see Figure 5b). Very quickly, the plugs and gloves in the glove holes in the PC containment panels melt. Thus the openings created allow the flames to spread into the GB and swirling flames appear inside the GB itself. The lower openings make easy the air to enter into GB and to feed the fire with ambient air (see Figure 5c). Moreover, the upper openings make easy the combustion products to go out the GB and the fire to expand outside of GB (see extended flames above GB on Figure 5d).

In addition to the presence of holes, the development of the fire on the two faces of the burning PMMA protection panel is facilitated by the 30 mm space separating that panel from the GB's containment panel in PC. The large thickness of the PMMA protection panel (i.e. 50 mm) allows it to keep its initial shape for many minutes (see Figure 5d). The PC containment panel is then exposed for a long time to sufficiently large heat fluxes due to the burning of the close PMMA protection panel. So, it ends up melting, mainly falls down on the floor of GB and, in turn, contributing to the total heat release rate of the fire source. At that stage, the fire power rises quickly. The heat fluxes inside the GB then lead to the combustion of the other panels (the other PC containment panels and secondary PMMA protection panel if present). The fire then reaches its maximum heat release rate as seen in Figure 3.

Therefore, due to its specific configuration, a GB can be similar to a well-stirred reactor, in which combustion would be almost perfect. The high temperature inside the GB (details hereafter) and the measurement of the smoke indicating almost no CO or C_nH_m (see Table 4 and the paragraph below) confirm this hypothesis of quasi-perfect combustion.

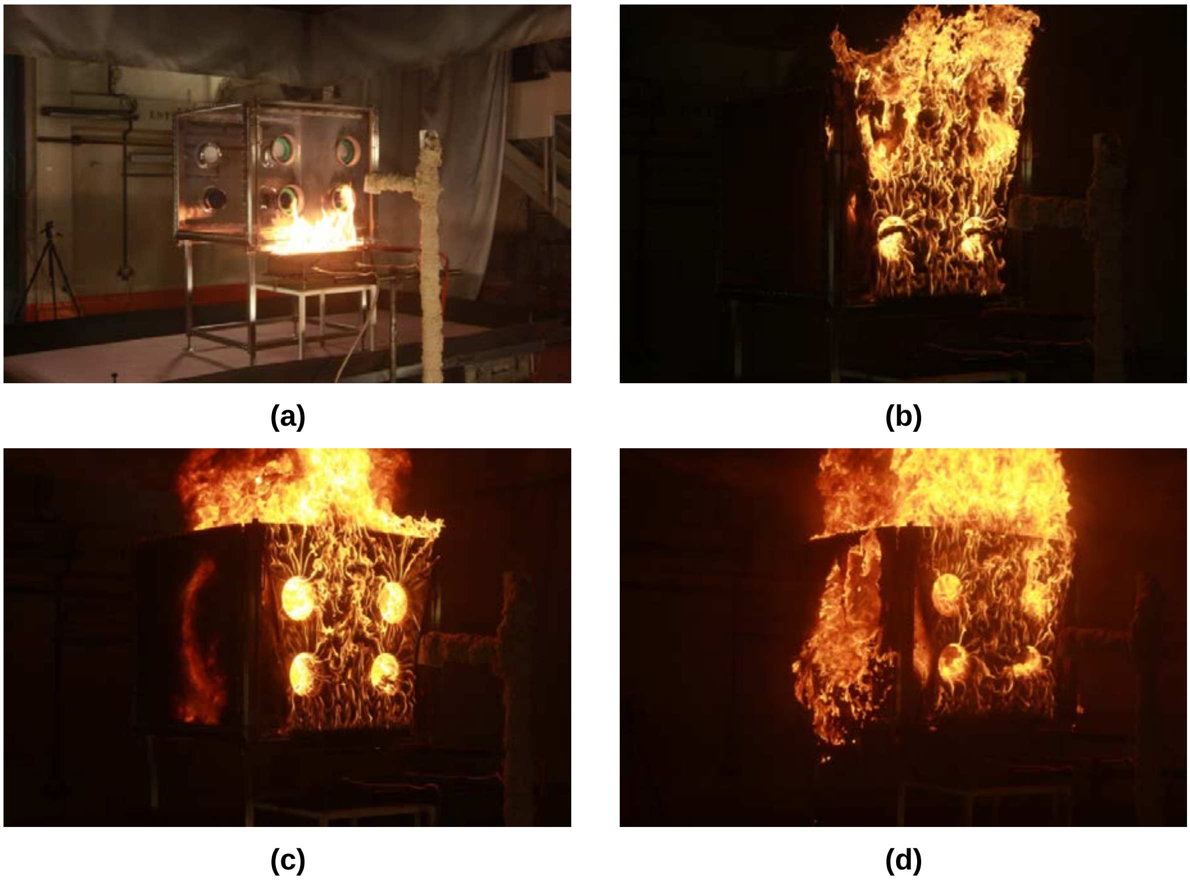


Figure 5 Fire growth during test BAG_CSS_1.1 at (a) t = 0, (b) t = 10 min, (c) t = 11 min 30 s and (d) t = 14 min after ignition

Glove Box Internal Temperature

At the beginning of the fire, the three thermocouples, located inside the GB, show a stratification of internal gases. The internal temperatures become homogeneous within the GB from about 15 min after the GB ignition. From these three thermocouples, the mean temperature inside the GB shows a maximum value between 1000 and 1200 °C for the seven tests (see Table 4). These mean temperatures appear much higher than for typical diffusion flames of a fire in free atmosphere (about 800 to 900 °C [17]), and may be similar to the particular combustion conditions operating inside a well-stirred reactor.

Species Produced by the Combustion

Species produced by combustion are assessed from measurements made in the smoke exhaust duct. The gases measured are expressed as a volume fraction of the volume of dry air sampled, X, whereas soots are measured as a mass concentration, C_s. The mass flows of gaseous species i, $\dot{m}_i$, and soot, $\dot{m}_s$, are determined from relationships in Eq. (9). The total mass of species j, m_j, is obtained by integration of the mass flow measured in the calorimeter's exhaust duct during the duration of the fire. The yield of the species j, y_j, must then be determined from Eq. (10).

$$\dot{m}_i = X_i \frac{M_i P}{RT} \dot{v} \quad and \quad \dot{m}_s = C_s \dot{v} \tag{9}$$

$$y_j = \frac{m_j}{m_{fc}} = \frac{\int_0^{t_{end\,fire}} \dot{m}_j(t)\,dt}{m_{fc}} \tag{10}$$

For the seven BAG_CSS tests, the yield of each species appear to be of the same order of magnitude, whatever the configuration of the GB (see Table 4) with, on average, $y_{CO_2} = 2.191\ g.g^{-1}$, $y_{CO} = 0.013\ g.g^{-1}$, $y_{C_nH_m} = 0.002\ g.g^{-1}$ and $y_S = 0.019\ g.g^{-1}$. The absence of the species CO and C_nH_m confirms the hypothesis of quasi-perfect combustion.

Table 4 Maximum of the mean temperature inside the GB, yields in the smoke of the dioxide carbon, oxide carbon, unburned gases and soot and maximum of the incident radiative heat flux of the seven BAG_CSS tests

Tests	$\overline{T}_{max}$ **[°C]**	y_{CO_2} **[g.g^{-1}]**	y_{CO} **[g.g^{-1}]**	$y_{C_nH_m}$ **[g.g^{-1}]**	y_s **[g.g^{-1}]**	$\dot{q}''_{r,max}$ **[kW.m^{-2}]**		
						$d\ (0.5\ m)$ $h\ (0.3\ m)$	$d\ (1.0\ m)$ $h\ (0.6\ m)$	$d\ (3.0\ m)$ $h\ (0.9\ m)$
BAG_CSS_1.1	-(4)	-(5)	-(5)	-(5)	-(5)	31	28	7
BAG_CSS_1.2	1212	2.234	0.013	0.002	0.018	112	> 56(6)	11
BAG_CSS_1.3	1090	2.122	0.014	0.002	0.012	95	53	8
BAG_CSS_1.4	1001	2.274	0.016	0.005	0.012	53	33	5
BAG_CSS_1.5	1245	2.165	0.014	0.002	0.024	71	51	9
BAG_CSS_1.6	1216	2.217	0.011	0.001	0.019	75	52	10
BAG_CSS_1.7	1209	2.132	0.012	0.002	0.031	80	54	11

(4) Temperature inside the GB not measured.
(5) Value unknown due to an unexpected stop in data acquisition, following a general loss of power supply.
(6) Saturation of the measurement.

Repeatability of Fire Tests and Effect of the Glove Box Ignition System on the Fire Growth

The two ignition systems (50 kW wide rectangular and 0.1 kW point burners) are tested on the same GB configuration for 4 tests: BAG_CSS_1.2 and BAG_CSS_1.7 tests with the rectangular burner (50 kW), and BAG_CSS_1.5 and BAG_CSS_1.6 tests with the point burner (0.1 kW). For all tests, the ignition duration is 4 min for the two burners.

Comparing the time evolution of the heat release rate of these four tests (see Figure 3), only the fire incubation phase is affected by the type of ignition device. The rapid combustion and ending phases until the fire stop are identical for both the fire development kinetic and for the maximum fire powers achieved. The 0.1 kW point ignition results in a lengthening of the incubation phase to 33 and 41 minutes compared to the ignition with the 50 kW burner. The difference of 8 min in this phase between tests BAG_CSS_1.5 and BAG_CSS_1.6 shows that the initial development of the fire using this point ignition depends greatly on the environmental conditions, such as air flows and initial temperature in the experimentation hall.

Outside the incubation phase, the GB fire source in a free atmosphere behaves in a completely repeatable manner as shown by the time evolution of the heat release rate (see Figure 3) and the main magnitudes (see Table 3 and Table 4) characterising the tests.

Effect of the Combustible Load in the Glove Box

The ignition method and configuration of the GB used in tests BAG_CSS_1.2, BAG_CSS_1.7, BAG_CSS_1.3 and BAG_CSS_1.4 are identical except that the two last tests show a different combustible load on the second working side of the GB (i.e. in the opposite location from the ignited working side, see Table 1). A PMMA protection panel is removed from the GB configuration of the tests BAG_CSS_1.2 or BAG_CSS_1.7 to that of the BAG_CSS_1.4 test. Test BAG_CSS_1.3 repeats the configuration of test BAG_CSS_1.4 but replaces the PC containment panel with a solid steel sheet one. This change of configuration in the second working side has the effect of modifying the GB's combustible load. The combustible load of 135.8 kg for tests BAG_CSS_1.2 and BAG_CSS_1.7 is then reduced to 78.8 kg for test BAG_CSS_1.4 then to 68.5 kg for test BAG_CSS_1.3.

The fire growth rates for these four tests (see Figure 3) are comparable for the first 15 min of fire and subsequently allow the contribution to the fire of each of the combustible materials on the second face to be separately appreciated. Test BAG_CSS_1.3 compared to test BAG_CSS_1.4 particularly identifies the contribution to the fire of the PC panel on the second face by an increase in the fire power between 15 and 23 min. The comparison of test BAG_CSS_1.4 to tests BAG_CSS_1.2 and BAG_CSS_1.7 points out a significant increase in the heat release rate of the fire and of its duration due to the presence of the additional PMMA panel on the second face.

A reduction in the combustible load naturally leads to a decrease of fire duration and fire power (see Table 3). The absence of a PMMA panel on the second face results in a significant reduction in the heat release rate of the fire and the temperature inside the GB. In spite of this significant reduction, the maximum heat release rate of the fire remains high, of the order of 1.7 MW, in test BAG_CSS_1.3 where only 68.5 kg of combustible material is present and where no air can be supplied to the second face (solid steel plate). The other characteristic values ($\Delta H_{c,eff,net}$ and y_j) shown in Table 3 and Table 4 remain overall similar for the four tests, also showing that a change in the supply of air via the second working side has a little or even no influence on those magnitudes.

Radiative Heat Fluxes

In general, the incident radiative heat fluxes, $\dot{q}_r''$, are very high with maximum values at $d = 1.0\ m$ and $h = 0.6\ m$ systematically higher than 20 kW.m^{-2} for all tests (see Table 4). Theses radiative heat fluxes remain with high values at 3 m from the GB, typically ranging from 5 to 11 kW.m^{-2}. Such high heat fluxes can lead to the surface thermal degradation (up to the ignition of combustible materials) of the GB assemblies. For instance, some PMMA materials can be ignited for critical heat fluxes coming from 6 to 23 kW.m^{-2} under cone calorimeter [15].

Although the heat release rate of the fire was much higher for BAG_CSS_1.1 test compared to the other tests conducted in SATURNE (see Table 3), the incident radiative heat fluxes appear to be clearly lower at the three measuring points (31, 28 and 7 kW.m^{-2} for BAG_CSS_1.1 versus a mean of 81, 50 and 9 kW.m^{-2} for the 6 others tests). This paradox is due to a different flame shape between BAG_CSS_1.1 test where the top of the GB is made of PC and the other tests where the top of the GB is made of sheet steel. The presence of the steel roof is an obstacle to the flame and forces this latter to get out of the GB by the vertical sides. The distance from flame to radiometer decreases and the incident radiative fluxes are then measured significantly higher. From a safety point of view, in the event of a fire, GBs with a sheet steel top present a greater risk of high thermal stress on the neighbouring targets at the same height.

CONCLUSIONS

As part of the programme undertaken by IRSN on the topic of radioactive materials being able to raise into suspension in GB fires involving PuO_2, seven tests were conducted during a first test phase known as BAG_CSS program. The BAG_CSS test series consisted of characterising a 1 m^3 GB fire source in free atmosphere under the SATURNE calorimeter and in the absence of radioactive material surrogate. The study focused on two main parameters: the number of combustible panels of the GB and the ignition process on an external fuel panel (i.e. a rectangular burner or a small point burner).

All the seven BAG_CSS tests conducted in a free atmosphere show a similar fire development scenario with four successive phases: ignition, incubation, rapid combustion and the decrease of the fire until it stops by lack of combustible material. The seven 1 m^3 GB fires reach very high powers up to 4.1 MW. The maximum fire powers remain high despite a reduction in the number of combustible panels. Indeed, the GB fire source with only two combustible panels reaches a heat release rate as high as 1.7 MW. It is also notable that the fire power remains high for a significant time. Whatever the configuration of the GB and the ignition method tested, the mean effective heat of combustion is of the same order of magnitude at 29.4 ± 1.0 $MJ.kg^{-1}$. This mean value is within the range of the heats of combustion of the two main combustible materials in the GB, i.e. PMMA and PC, resulting in quasi-complete combustion (i.e. with a combustion efficiency close to unity). This quasi-complete combustion is due to the GB's configuration being similar to a well-stirred reactor, with swirling flames being observed inside the GB fire source. The mean temperatures inside the GB fire source vary between 1000 and 1200 °C for the seven BAG_CSS tests. These mean temperatures appear much higher than those of typical turbulent diffusion flames (about 800-900 °C) and may be similar to the particular combustion conditions operating inside a well-stirred reactor. The quasi-perfect combustion is also deduced from the quasi-absence of CO and C_nH_m species in smoke. The growth rate, as defined by the NFPA standard, allows the GB fire source with a roof made of combustible material to be categorised as "fast", while the other six GB fire sources with the roofs made of sheet steel were classed as "slow". The repeatability of the GB fire source is demonstrated in the BAG_CSS campaign. The 0.1 kW point ignition (comparable in size to a cigarette lighter flame) results only in a longer incubation phase of 37 ± 4 min compared to the more powerful 50 kW ignition method, but the other phases are identical, both from the point of view of the kinetic of the fire's development and from the point of view of the magnitude of the main values. The presence of the sheet steel top is an obstacle to the flames and forces them out of the vertical sides of the GB. The distance from the flames to a target on the face of the GB is then reduced and, therefore, the radiative heat flux to which the target is exposed is higher than for a fire in a GB with a top in combustible material.

The results of the seven BAG_CSS tests allow progress to be made in the characterisation and knowledge of the combustion of a GB but they raise a set of questions. In particular, these questions concern the major effect of confinement on the heat release rate of the fire and the use of a real Kyowaglas biological protection panel, which requires that additional data are acquired. One essential component of such additional research work will be based on an analytical approach aimed at developing a model for this very particular type of fire source. Then the future work will concern also the assessment of the potential release of particles during GB fires.

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INSIGHTS FROM RECENT FIRE TESTING – CURRENT TRANSFORMERS AND INSTRUMENTATION CIRCUIT RESPONSE TO FIRE

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ABSTRACT

Fire testing has played a pivotal role in advancing the knowledge-base and state-of-the-art methods for quantifying fire-induced electrical circuit failures. These advancements have supported revisions to regulatory guidance and risk assessment methods. While much is known on the response of control and power circuits to the effects of fire, recent collaborative efforts have identified several areas where additional research via testing could provide justification for updating guidance and methods. Under two separate efforts, the U.S. Nuclear Regulatory Commission (NRC) has sponsored limited scope testing efforts to understand the failure modes of current transformers and instrumentation cables from thermally damaging conditions.

Secondary fires caused by fire-induced failure of current transformers (CTs) were postulated in the 1980s and are assumed to occur in industry guidance. While theoretically possible, differing views exist on the possibility of such phenomena actually occurring. In an effort to fully understand this concern and to resolve long standing debate of the issue, the NRC, in cooperation with the Electric Power Research Institute (EPRI) working under a Memorandum of Understanding (MOU), sponsored Brookhaven National Laboratory (BNL) to perform a series of experiments involving CTs. Sixty-three test configurations were performed. These experiments confirmed that the open secondary crest voltage was dependent on CT core design, primary voltage, primary current, and the CTs turns ratio. None of the experiments demonstrate the possibility of an open CT secondary resulting in a secondary fire. In no instance overheating or arcing were observed on any portion of the CT or secondary cable's insulating system. Given the nature of this testing, these results provide a strong technical basis that the postulated safety concern does not pose a secondary fire risk.

The failure behaviour of instrumentation cables and circuits from the effects of fire is not well understood. A handful of tests performed by the NRC as part of a nuclear industry testing program in 2001 demonstrated mixed results. To better understand instrumentation circuit failure modes, the NRC sponsored Sandia National Laboratories (SNL) to perform a limited set of experiments on instrumentation cables and circuits. A total of 39 small-scale tests were conducted. Ten different instrumentation cables were tested, ranging from one conductor to eight-twisted pairs. Three test circuits were used to simulate typical instrumentation circuits present in nuclear power plants: a 4 – 20 mA current loop, a 10 – 50 mA current

loop, and a 1 – 5 VDC voltage loop. A regression analysis was conducted to determine key variables affecting signal decay time. The tests provided evidence that instrumentation cable can experience slow signal decay under fire-exposure conditions. The signal decay times ranged from 0 to 2 minutes for one cable type and 0 to 21 minutes for another. Findings from this research also identified key variables that influence the signal decay time to be time to failure (dependent variable) and number of conductors (independent variable).

INTRODUCTION

The U.S. NRC conducts experimental investigations to support successful regulation and oversight. Over time, the purpose of testing has changed to meet the specific needs of the NRC. Early fire research focused on confirming the correctness of regulatory requirements (1975 - 1987). Next came a period of time where select topical areas were evaluated to support fire-risk analyses being performed at several nuclear power plants (NPPs) (1987 - 1993). Subsequent research focused on specific fire-induced safety hazards such as the effects of smoke on digital equipment, performance of penetration seals, turbine building risk, and fire-related operational experience review (1994 - 1998). The 1995 Commission Policy statement on the use of probabilistic risk assessment (PRA) shifted the focus of fire research to fill gaps in the four functional areas of Fire PRA, namely prevention, detection and suppression, mitigation, and quantitative evaluation of fire safety (1998 - 2005). This research culminated with the development of the keystone document describing the methodology to perform fire PRAs for nuclear facilities (i.e., NUREG/CR-6850, "Fire PRA Methodology"). As the methodologies have matured and been applied in regulatory application, a need for additional research has risen to bridge knowledge gaps.

Recently, the NRC performed a series of research projects involving expert judgement in the area of fire-induced circuit response [1], [2]. One insight from this work was a need for additional research to address a knowledge gap related to current transformers and to better understand the failure modes of instrumentation cable damaged under severe fire conditions. This paper summarizes the results from these two programs. Each program is described separately with a discussion of the background of the issue, experimental approach, and conclusions presented.

CURRENT TRANSFORMERS

Background and Safety Concern

Current transformers (CTs) are used in NPPs to monitor current in electrical distribution systems. Different types of CTs are available including wound, bar, window, bushing, auxiliary, and ground sensor types. However, the window-type dominates the types of CTs used in NPP's AC power distribution system applications and is the focus of this research. The window-type CTs considered here have a laminated core of high-permeability steel with a secondary winding insulated from and permanently assembled on the core. The window-type CTs have no primary winding as an integral part of the CT structure. The primary winding (bus bar or cable) is located through the window of the CT. Figure 1 shows typical window-type CTs installed on three-phase conductors inside an electrical enclosure.

Under normal operating conditions, a CT reproduces a scaled-down current waveform of the current flowing in the primary circuit. This scaled-down current can then be used by protective relays, metering, and other applications. The alternating current in the primary winding (known as excitation current) produces an alternating magnetic field in the core, which then induces an alternating current in the secondary winding circuit. The primary and secondary circuits are magnetically coupled so that the secondary current is linearly proportional to the primary current over an intended normal operational range.

Figure 1 Window-type CTs shown with bus bar as primary circuit [3]

Electromagnetic principles establish the importance of operating the CT core in a specific zone of its excitation curve. Figure 2 shows the excitation curve and associated zones of operation. Normally the CT operates in the linear portion (Non-saturated Zone 1) of the excitation curve (i.e., primary current = secondary current x turns ratio); while under open secondary condition, it operates near or above its knee (Intermediate Zone 2 or Saturated Zone 3). However, under this abnormal condition, the CT still attempts to maintain the current ratio (i.e., primary ÷ secondary). Under open-circuit conditions on the CT secondary circuit, a high crest (or peak) voltage on the secondary circuit would occur. The high crest voltage is due to the electromagnetic coupling of the CT, which causes the CT to attempt to maintain the current relationship dictated by the CTs turns ratio. Provided that current is flowing in the primary circuit, this condition can result in CT damage, potentially generating voltages that may exceed the dielectric strength of the CT's insulating materials and may cause arcing to connected or nearby components.

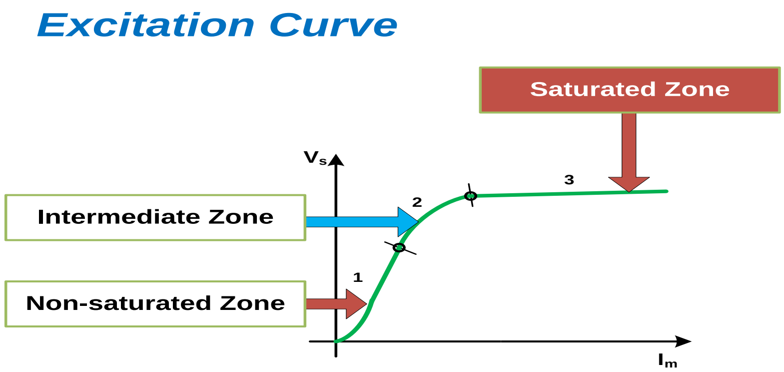

Figure 2 Excitation curve [3]

In a letter to the NRC dated July 21, 1983 [4], Brookhaven National Laboratory (BNL) raised a potential concern associated with fire-induced open-circuit in a CT's secondary circuit. The letter postulated the scenario in which potentially high voltage induced on the secondary winding of a CT as a result of open-circuiting the CT's secondary circuit due to a fire ultimately causes the CT and/or the connected components to fail in a manner that could potentially start a secondary fire. A secondary fire, as used in this report, refers to a fire at a location remote from the original fire that is responsible for the initial open-circuit in the CT's secondary circuit. This secondary fire would defeat the design fire assumption of a single fire occurring.

From the CT's physical location in the plant to the main control room instrument indications, the secondary circuit may consist of long (e.g., hundreds of feet) instrument wires whose insulation is susceptible to both initial and secondary fires. The resulting high voltage condition in the secondary from an open-circuited CT introduces a potential concern for fire protection strategies in NPPs. Because the post-fire safe shutdown analysis is based on postulating a fire in one fire area at a time, the possibility of a second fire in a separate fire area can impact the final outcome of the fire protection strategies. Currently, NRC-endorsed [5] industry guidance [6] for conducting a post-fire safe shutdown circuit analysis identifies circuit failures due to an open circuit. An example provided in Section 3.5.2.1 of NEI 00-01, Rev. 2 [6] includes: *Open circuits on a high voltage (e.g., 4.16 kV) ammeter current transformer (CT) circuit may result in secondary damage, possibly resulting in occurrence of an additional fire in the location of the CT itself.*

Joint research performed by the NRC collaboratively with the Electric Power Research Institute (EPRI) concluded that this safety concern is not credible for CTs with turns-ratios of 1200:5. Although a belief was held by most that this conclusion could be extended to CTs with larger turns ratios, data were not available. As such, the group of experts recommended that testing was warranted to the range of CT turns rations found in the plant electrical distribution system [1], [2]. This work was subsequently performed by BNL in 2016 under NRC and EPRI direction.

Approach

The testing evaluated the possibility of larger turns ratio CTs (i.e., > 1200:5) to create a secondary fire when the CTs secondary is operating under open-circuited conditions with current flowing in the CT primary. The testing focused on characterizing the transition of the exciting (or magnetizing) current from the very low magnitude under normal operating conditions to an open secondary condition with no current in the secondary but high voltages that could act as a fire ignition source. The testing assumed that an open-circuit condition of an energized CT occurred (due to fire damage); however, the open was created mechanically rather the from fire damage. The open-circuit is expected to cause abnormally high voltages in the secondary circuit, provided that the flow of the primary current continues.

Two scenarios were postulated that could be affected by the saturation of the CT's magnetic core and the high voltage in the open secondary circuit:

1. The open secondary crest voltage in the secondary circuit exceeds the breakdown voltage of the cable's insulating system.
2. The CT itself gets overheated after being exposed to a very long core saturation period, or an arcing occurs at the CT's secondary taps that may need over 20 – 40 kV crest voltage for an air gap of 1 - 2 inches [7].

Test variations included:

- Primary voltages: 500 V, 250 V, 125 V;
- Two AMRAN CT types: fixed-ratio 2000:5 CT; multi-ratio 4000:5 CT;
- Primary current 60 A to 4,000 A for fixed-ratio of 2000:5 CT;
- Turn ratios of 500:5 to 4000:5 for multi-ratio CT;
- Fast, intermittent opening, and arcing simulations for open circuit configuration.

Testing was conducted at a BNL facility equipped with configurable three-phase low-voltage power sources and state-of-the-art high-speed data acquisition systems. Figure 3 shows the testing power supply used for the CT testing. The power supply was configured as a three-phase delta/wye source connected to a variable load bank to control the amount of current flowing in the test circuit. The CT under test was connected to one leg of the supply.

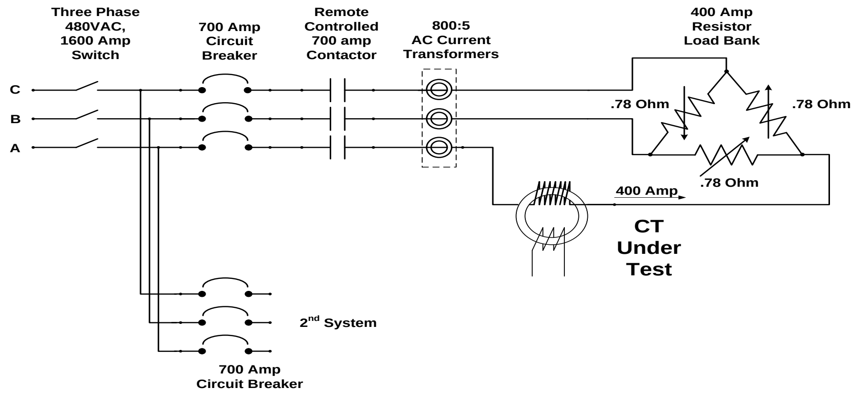

Figure 3 Test power supply configuration

Two different models of AMRAN CTs were tested. A 2000:5 CT (identified as "AM2CT") was of the fixed-ratio type, while the 4000:5 CT (identified as "AM4CT") is a multi-ratio CT. Both CTs meet the ANSI/IEEE C57.13 Standard, and their outer encapsulations were enclosed in plastic-cases.

Numerous measurements were made during each test. Figure 4 illustrates the instrumentation and test setup used. The 'A' phase of the power supply serves as the primary circuit of the CT. The secondary side of the CT is connected to a high-voltage relay, a shunt, and an ampere meter. The burden resistor (i.e., an ammeter) and about 100 feet of secondary cable were used to simulate an actual plant's typical configuration. The CT's secondary side was instrumented with a relay to create the open circuit configuration. The increase in the secondary voltage and decrease in secondary current was recorded via high-voltage isolation modules connected to a high-speed data acquisition system. Other parameters monitored during testing included primary current (harmonics and RMS values) and primary voltage and the surface temperature of the CT. A high-speed video camera also was used to capture the arcing and fire formation (if any) at several strategic locations. These cameras were synchronized with the high-speed data acquisition system to get secondary circuit characteristics during the arcing process (if any).

Baseline tests were performed using the 2000:5 CT without creating an open circuit. The baseline tests were used to verify the correct voltage and current configuration. Following successful baseline testing, 51 open secondary test configurations were performed using both fixed-ratio CT 2000:5 (AM2CT) and multi-ratio CT 4000:5 (AM4CT). Table 1 presents the test matrix. Additional tests of certain test configurations were performed to simulate the effects of long duration, test repeatability, intermittent relay opening, time step optimization, and other conditions such as arcing. Thus, a total of 63 tests involving two CTs

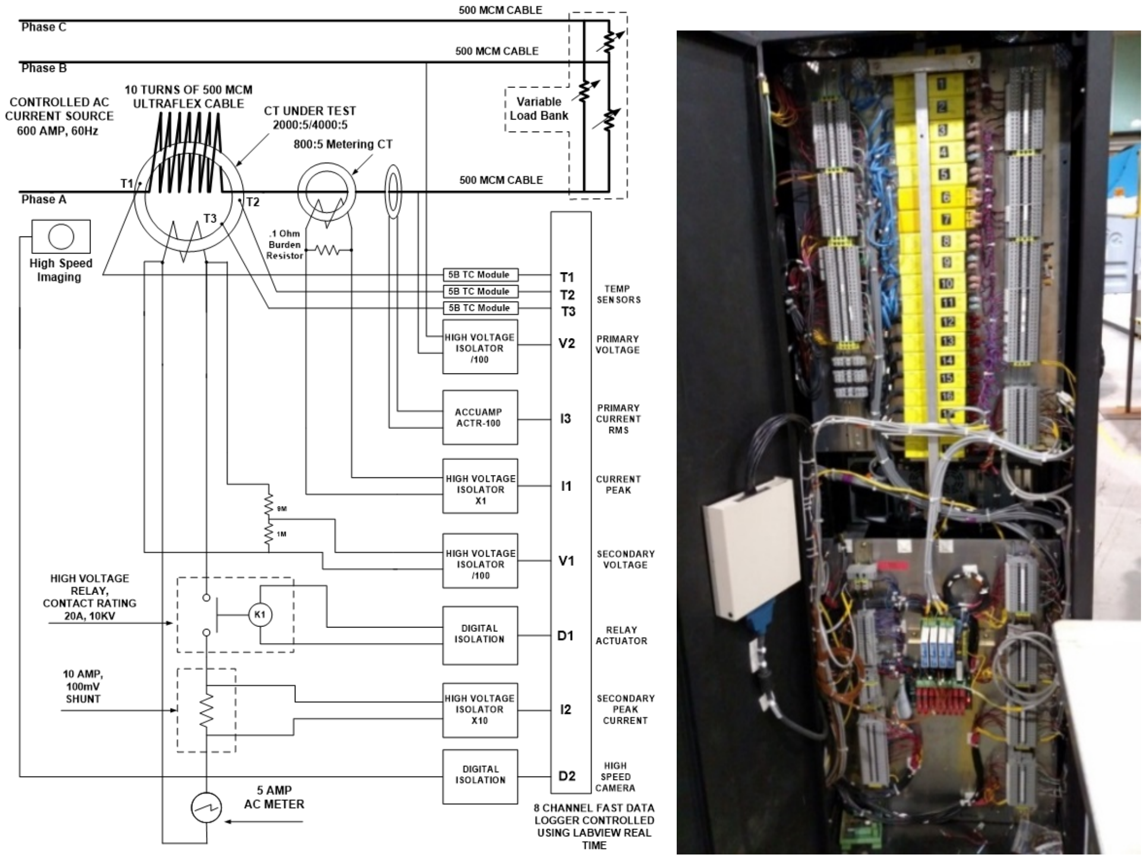

Figure 4 Illustration of instrumentation used for CT tests (left) and photo of instrumentation system (right)

Each open secondary test typically lasted for 30 seconds. The opening relay remained open for about 5 - 6 seconds during which the data logger registered the “TRANSIENT” data. As soon as the secondary circuit was opened, the secondary current becomes zero and the secondary voltage increases. The primary circuit remained constant for the entire 30 seconds. Another set of “CONTINUOUS” data also was recorded each second for the entire 30 seconds (or 10 minutes, in a few tests) to capture the temperature rise in the CT. All relay opening and data collection sequences were automated using LabVIEW real-time programming computer code.

During each test, observations of the secondary tap connections were made for any electrical arcing or fire damage and the CT’s core for its temperature rise. The high-speed camera also recorded the CT’s secondary taps for the entire test duration. In addition, periodic condition monitoring tests were performed periodically to assess the condition of the CT’s secondary winding after it had been subjected to crest voltages during open secondary testing. The condition monitoring included DC resistance test, impulse test, and for the cable – HiPot dielectric withstand test.

Several additional tests were repeated varying other test parameters (e.g., with the relay open in the secondary for about 5 and 10 minutes to obtain the effect of the high secondary voltage and core saturation on the secondary cable’s insulation resistance, the temperature rise in the CT, and the change in the CT’s winding resistance). Several other tests involved arcing simulation at the relay opening, intermittent opening of the relay, and examining the repeatability of each test.

Table 1 Test Matrix

Test #	CT Turns Ratio	Primary Voltage	Primary Current	Secondary Current	Test #	CT Turns Ratio	Primary Voltage	Primary Current	Secondary Current
2CT01	2000:5	480-500	2000	5.00	**4CT06**	1500:5	480-500	1500	5.00
2CT02	2000:5	480-500	1500	3.75	**4CT07**	1000:5	480-500	1000	5.00
2CT03	2000:5	480-500	1000	2.50	**4CT08**	500:5	480-500	500	5.00
2CT04	2000:5	480-500	500	1.25	**4CT09**	2000:5	220-250	2000	5.00
2CT05	2000:5	480-500	250	0.62	**4CT10**	1500:5	220-250	1500	5.00
2CT06	2000:5	480-500	125	0.31	**4CT11**	1000:5	220-250	1000	5.00
2CT07	2000:5	220-250	2000	5.00	**4CT12**	500:5	220-250	500	5.00
2CT08	2000:5	220-250	1500	3.75	**4CT13**	1000:5	110-125	1000	5.00
2CT09	2000:5	220-250	1000	2.50	**4CT14**	500:5	110-125	500	5.00
2CT10	2000:5	220-250	500	1.25	**4CT15**	4000:5	480-500	4000	5.00
2CT11	2000:5	220-250	250	0.62	**4CT16**	4000:5	480-500	3000	3.75
2CT12	2000:5	220-250	125	0.31	**4CT17**	4000:5	480-500	2000	2.50
2CT13	2000:5	220-250	62	0.15	**4CT18**	4000:5	480-500	1000	1.25
2CT14	2000:5	110-125	1000	2.50	**4CT19**	4000:5	480-500	500	0.62
2CT15	2000:5	110-125	500	1.25	**4CT20**	4000:5	480-500	2500	0.31
2CT16	2000:5	110-125	250	0.62	**4CT21**	4000:5	480-500	125	0.16
2CT17	2000:5	110-125	125	0.31	**4CT22**	4000:5	480-500	62	0.08
2CT18	2000:5	110-125	62	0.16	**4CT23**	2000:5	480-500	4000	10.0
2CT19	2000:5	480-500	2500	6.25	**4CT24**	2000:5	480-500	3000	7.50
2CT20	2000:5	480-500	3000	7.50	**4CT25**	2000:5	480-500	2000	5.00
2CT21	2000:5	480-500	4000	10.00	**4CT26**	2000:5	480-500	1000	2.50
4CT01	4000:5	480-500	4000	5.00	**4CT27**	2000:5	480-500	500	1.25
4CT02	3500:5	480-500	3500	5.00	**4CT28**	2000:5	480-500	250	0.62
4CT03	3000:5	480-500	3000	5.00	**4CT29**	2000:5	480-500	125	0.31
4CT04	2500:5	480-500	2500	5.00	**4CT30**	2000:5	480-500	62	0.16
4CT05	2000:5	480-500	2000	5.00					

Results

Out of 51 test conditions, 21 tests on 2000:5 CT (AM2CT) and 30 test conditions on 4000:5 CT (AM4CT) were conducted. In each test, the primary voltage and primary current remained constant and independent of what was happening in the secondary circuit (i.e., from a closed secondary circuit to an open secondary configuration). When the relay opened the secondary circuit, the secondary current dropped to zero amperes, and the secondary voltage increased from zero to several thousand volts. Figure 5 presents a typical current and voltage waveform response. Temperature measurements made on the CT demonstrated minimal temperature rise (less than 5 °C increase per test).

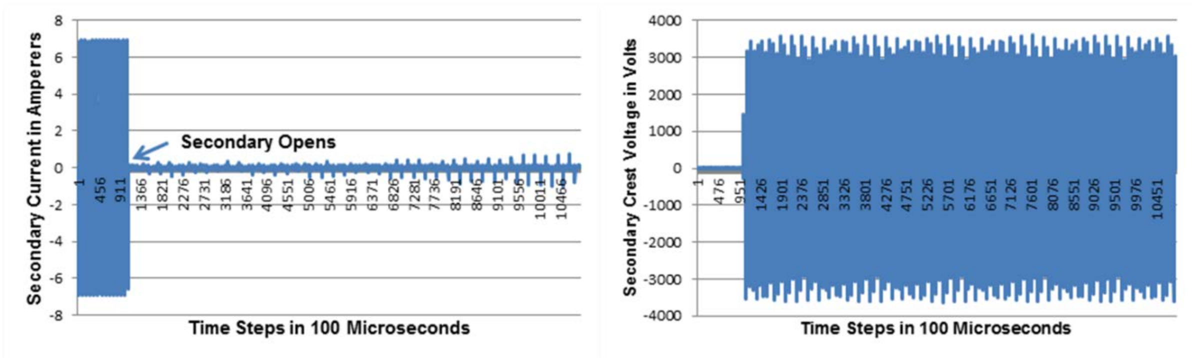

Figure 5 Typical waveforms for secondary circuit current (left) and voltage (right)

Unlike a voltage transformer (VT), under normal conditions, CT's primary voltage has a minimal effect on its operation. However, because of the CT's inherent turn ratio the primary current level has significant effect on the instrumentation readout of the secondary current. The primary voltage, along with the primary current and the turn ratio, has an effect on the CT's behaviour under an abnormal open secondary condition. Figure 6 illustrates the dependencies of the open secondary crest voltage with the primary voltage and primary current levels keeping the turn ratio constant. The results presented here are taken from the AM2CT tests. This clearly indicates that the open secondary crest voltage is dependent on the primary current as well as the primary voltage.

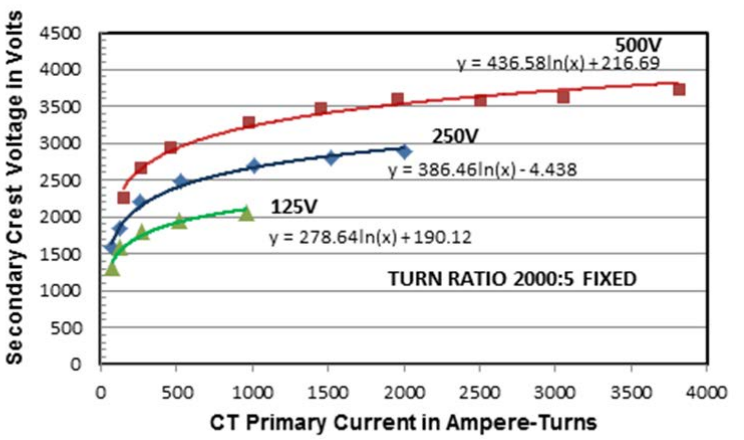

Figure 6 Open secondary crest voltage versus primary voltage/current (2000:5 turns ratio)

Based on the testing performed under this effort, no single test produced signs of arcing or explosive failure nor was there sufficient temperature increase to cause ignition of surrounding materials. The testing clearly demonstrated the initial assumed fire protection guidance to postulate a secondary fire caused by an open circuit in a window-type CT secondary circuit is unsubstantiated.

INSTRUMENTATION CIRCUITS

Background and Project Need

Development and maintenance of a fire probabilistic risk assessment (PRA) involves performing circuit analysis and circuit failure mode likelihood analysis to support realistic estimates of plant risk from fire. Significant research efforts have been performed in this area since the early 2000s [8], [9], [10], [11]. The results from these efforts provide a strong technical basis for the different modes of failure of power and control cables exposed to fire conditions. Instrumentation circuit on the other hand are less understood with regard to their response to fire damage. Of the several hundred tests performed in recent times, less than 10 have focused on the circuit response of instrumentation circuits. That test series was performed by the Nuclear Energy Institute (NEI) and the Electric Power Research Institute (EPRI) in 2001 [8]. For instrumentation circuits, these early tests concluded that thermoplastic (TP) insulated cables generally displayed no characteristics of signal degradation prior to complete loss of signal and thermoset (TS) insulated cables displayed up to 10 minutes of signal degradation prior to complete loss of signal.

Instrumentation circuits provide critical information to operators regarding the status of plant conditions. Circuit fault effects on instrument systems are unique and can be more complex than power and control circuits. Instrument sensors typically convert process variable values (temperature, pressure, level, flow, etc.) to an electric signal (e.g., voltage and current) for transmission to a remote readout or display. Instrumentation readings can also be used to actuate an automatic plan response because instrumentation circuits can be tied to process equipment such as the reactor protection system and the engineering safeguard feature actuation system.

The chaotic nature of fire and the lack of empirical data in this area have resulted in the use of worst-case assumptions for circuit analysis of instrumentation circuits. In addition, operator response may be impacted for some response conditions if fire-induced damage results in signal degradation that causes inaccurate indication. Better understanding of the failure modes and effects of instrumentation circuits could support a stronger basis for performing a more realistic fire PRA and operator response procedures for fire scenarios involving instrumentation cable and circuits. To evaluate these phenomena, the NRC sponsored SNL to perform a scoping study to better understand the fire-induced failure modes of instrumentation cables. This research is intended to better quantify the cable failure modes (i.e., leaks in current) that may occur before catastrophic failure in instrumentation circuits. This work included initial bench-scale testing necessary to identify focus areas for further study to fully address the research question and to support refinement/development of implementation guidance.

The Typical Instrumentation Circuit

Current loops typically used in nuclear power plants exist in two forms: 10-50 mA (old standard) and 4 - 20 mA (new standard). In either case, the principle of operation is the same: current produced by the loop power supply is sent around the loop, flowing through every device and load or burden device in the circuit. The current is modulated into a process variable by a transmitter, which converts a sensor's measurement into a current signal and amplifies and conditions the output. A sensor typically measures parameters such as temperature, humidity, flow, level, or pressure. The current loop has a receiver, a device that interprets the current signal into units that can be easily understood by the operators. The receiver converts the 4 – 20 mA current back into a voltage that can be displayed, or can actuate another component based on its start/stop logic. In this example, 4 mA represents 0 percent of the measurement, and 20 mA represents 100 percent; when the current is between 4 mA and

20 mA the voltage across the resistor is in direct proportion to that current. Figure 7 presents a simplified instrumentation current loop circuits.

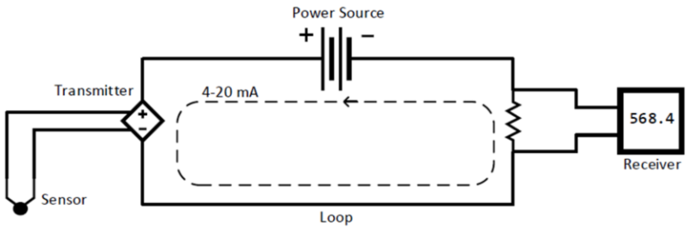

Figure 7 Illustration of 4 - 20 mA current loop

Current loops are extremely robust systems; they are impervious to electrical noise, and routing the signal through shielded, twisted-pair cables further reduces noise. Grounding the negative of the power supply to the shield provides additional noise protection. It is ideal for long distances because current does not degrade over long connections unlike voltage which can degrade. It is also simple to detect a fault in the system. For example, a loss of power would indicate 0 mA instead of the expected 0 percent output of 4 mA for a typical 4 - 20 mA design.

Approach

To meet the project goals, a fairly large number of tests were performed involving varied arrays of cable types, heating conditions, and circuit types.

A variety of cable types and configurations were included in this test series. The variations included conductor insulation type (TP, TS), number of twisted pair(s) or conductors(s) per cable (2 - 8), and the use of a shield around conductor pairs. Table 2 provides a list of instrumentation cables evaluated under this effort.

Three test circuits were used to simulate instrumentation circuits similar to what can be found in industry. The 4 – 20 mA current loop was selected as it is the most popular instrumentation circuit given its insensitivity to electrical noise and its designation as the standard output signal, according to ANSI/ISA-50.00.01-1975 (R2012), “Compatibility of Analog Signals for Electronic Industrial Process Instruments” [12]. The 10 - 50 mA control signal circuit design began back in the days of vacuum tubes where high line voltages were required to power up the circuitry. Because transistor circuits have become more widely used (and are more stable and accurate), the 10 - 50 mA current loop is not as prevalent in industry; however, these types of circuits may be present in older NPPs and were therefore included in testing. Finally, a 1 - 5 VDC instrumentation circuit was also included in the testing to understand how a voltage loop reacts in response to a fire. Each cable type was tested three times for the three different test circuit configurations. Figure 8 shows the 4 - 20 mA and 1 - 5 VDC instrumentation circuits used during testing. The 10 -50 mA circuit is not shown, but is similar to the 4 - 20 mA with a larger current source (37.5 mA) and a small burden resistor (100 ohm instead of 250 ohm).

Table 2 Cable list

Manufacture	Insulation / Jacket Material	TS	TP	# of twisted Pairs or Conductors	Overall Shield	Shielded Pairs	Notes
Rockbestos Firewall III	XLPE/CSPE	x		2/c	x		From the Firewall III product line, a nuclear qualified cable brand. Equipment qualification certificates were not requested.
Rockbestos Firewall III	XLPE/CSPE	x		4/c	x		
Rockbestos Firewall III	XLPE/CSPE	x		2	x	x	
Rockbestos Firewall III	XLPE/CSPE	x		4	x	x	
Belden	PVC/PVC-Nylon		x	2	x		Industrial-grade cable
Belden	PVC/PVC-Nylon		x	8	x		
Belden	FR-EPR/CPE	x		2	x	x	
Belden	FR-EPR/CPE	x		8	x	x	
Belden	XLPE/LSZH	x		1	x	x	
Belden	XLPE/LSZH	x		8	x	x	
General Cable	PVC/PVC		x	2/c	x		CAROLFIRE Test Cable 4
Rockbestos-Surprenant	XLPE/CSPE	x		2/c	x		CAROLFIRE Test Cable 7

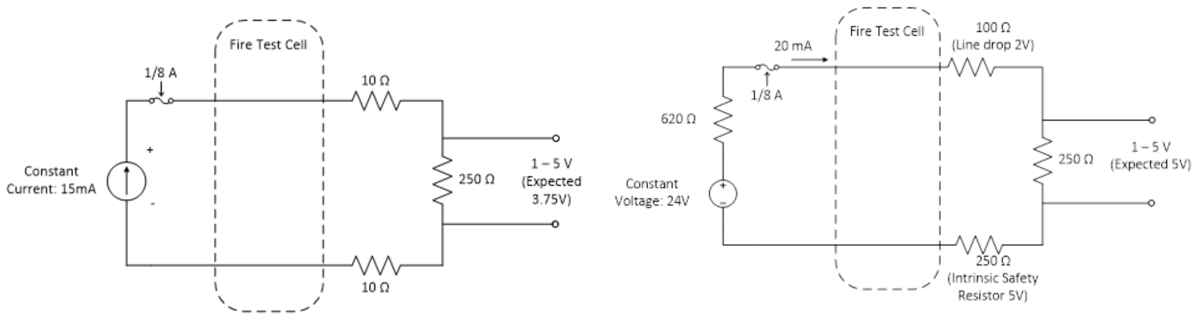

Figure 8 Instrumentation test circuits; 4 - 20 mA (left), 1 - 5 VDC (right)

Testing was conducted using a small-scale, radiant heat testing apparatus. The ceramic heater allows for well-controlled heat exposures that are beneficial for comparison purposes. The ceramic fiber heater is constructed of ceramic fiber insulation, which isolates the heating chamber from the outside. The heater is light weight, and its low-density properties make it ideally suited for high-temperature applications requiring low thermal mass. The heater size was customized with the same cylindrical ring configuration that the Penlight heating apparatus used in previous testing [9]. The ceramic fiber heater has an inner diameter of 0.41 m (16 in), is 0.6 m (24 in) long, and transfers heat radially onto the surface of the cables.

The exposure temperature was controlled and monitored by thermocouples (TCs) mounted on the inner surface of the shroud. This created a radiant heating environment analogous to that seen by an object enveloped in a fire-induced, hot gas layer or in a fire plume outside the flame zone. The ceramic fiber heater simulates these conditions with shroud temperature and heat flux, assuming a constant emissivity of 0.85 from the application of a high emissivity coating. Figure 9 shows photographs of the ceramic heater.

Figure 9 Picture of cable test setup (left) and ceramic heater (right)

Tests were conducted using paired cable lengths supported on a 30 cm (12 in) wide ladder-back style cable tray suspended through the center of the ceramic heater. Conduit or air drop configurations were not performed. The cable tray and other physical test conditions are effectively identical to those used in CAROLFIRE and DESIREE-Fire programs [9], [11]. In each test, two cables were placed on the cable tray shown in Figure 10. One of the cables was used for thermal monitoring and the other for electrical monitoring. The thermal monitoring was performed by placing a Type-K TC just below the cable jacket. The cable tray was then placed inside the heating apparatus.

Figure 10 Representative cable setup

Two ramp-and-hold heating profiles were used for the majority of the tests, and both used the same heating ramp slope but with different hold temperature. The TS-insulated cable hold temperature was 470 °C; while the TP-insulated cable hold temperature was 325 °C. A total of 40 tests plus 4 preliminary tests were performed during this series.

Results

Of the 39 tests, 13 tests showed signal degradation of 3 seconds or less. The 26 other tests experienced a signal degradation duration that ranged from 31 seconds to over 21 minutes. Results from TS-insulated cables demonstrated that 12 out of 32 tests experience signal degradation of less than 1 minute, while 4 tests experienced durations in excess of 10 minutes. One TP-insulated cable experienced signal degradation that lasted for 2 minutes and 36 seconds. Figure 11 presents the results from Test 4A where the signal duration lasted about 10 minutes. In this figure, the signal (voltage across burden resistor) is shown in blue while the cable and ceramic heater shroud temperatures are shown as green and red, respectively.

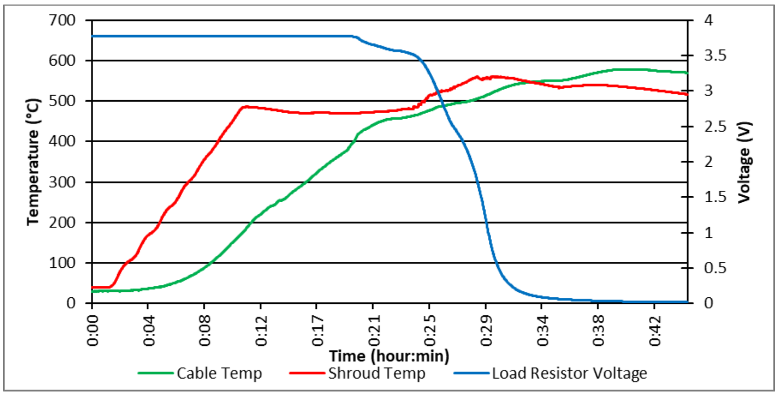

Figure 11 Test 4A temperature and voltage measurement.

Figure 12 presents the results showing signal leakage duration by cable material.

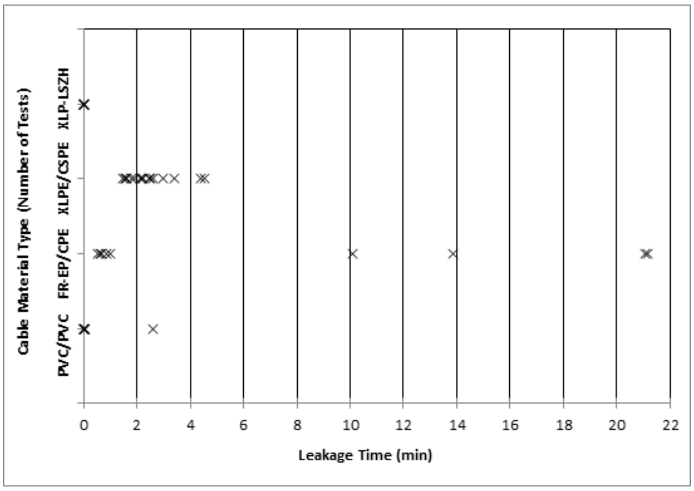

Figure 12 Signal leakage time by cable material

For TP-insulated cables, the signal degradation duration was not always instantaneous as previously identified during the industry test series [8]. However, the limited number of tests performed in this series could not conclude the prevalence of TP-insulated cables experiencing signal degradation. To provide some insight on the variable that may affect signal degradation, a regression analysis was performed. Variables evaluated included:

- Manufacturer;
- Insulation/jacket material;
- Thermoset or Thermoplastic;
- Number of conductors;
- Shielding;
- Circuit type;
- Circuit grounding;

- Shield grounding;
- Circuit fusing.

Quantitative regression analysis was only able to identify with statistical confidence that a relationship exists between the number of conductors and the signal leakage time. Qualitative regression analysis via a decision tree indicated that insulation/jacket cable material was a key variable with the highest four leakage current times all occurring with cables with fire retardant ethylene-propylene rubber insulation and chloro-sulphonated polyethylene (FR-EPR/CPE) jacket material. The decision tree regression analysis did not find the cables insulation type (i.e., TS vs. TP) to be a key variable.

This research provides insights into the signal degradation and performance of low-voltage instrumentation circuits in fire conditions. A total of 39 small-scale tests were conducted, primarily on TS cables because the earlier testing indicated significant signal delay time was not seen in TP cables. The tests provided evidence that, under the appropriate circumstances, instrumentation cables can have a slow signal leakage time under fire-exposure conditions. The signal leakage time varied from 0 seconds to over 2 minutes for TP cables. The signal leakage time for TS cables ranged from 0 seconds to over 21 minutes. At first glance, the FR-EPR/CPE 8-twisted pair cable had a significant signal leakage time compared to the other cables. However, a regression analysis was performed to better understand the key variables that drove signal leakage time.

From this testing, three note-worthy general observations on the performance of instrumentation cables can be drawn:

- The results from the testing of TP cables contradicted the findings from prior, limited testing that stated TP cables had no signal leakage characteristics prior to signal loss. TP cables were found to have a smaller leakage time on average with TS cables; however, one TP test experienced a leakage time of 2.6 minutes. Therefore, TP cables may have some signal degradation prior to failure.
- The main focus of this series of testing has been on TS cables. Industry testing conclusions stated that TS cables displayed some amount of signal leakage before the signal failed. During this series of testing, 12 out of the 32 tests had less than 1 minute of signal leakage before failure. Only 4 of the tests had a signal leakage longer than 10 minutes. Therefore, it is difficult to conclude that TS cables will always experience signal leakage before failure, contrary to what was concluded in earlier testing.
- A regression analysis was performed on the test data to determine key variables that contributed to longer leakage times. The dependent variable for this analysis is the time it takes for the cable to lose signal below a certain threshold (signal leakage time). The key independent variable was the number of conductors, which aligns with an increase in cable mass per unit length.

CONCLUSIONS

Fire science, engineering principle, and sound judgement are some of the main tools that fire protection engineers can use to solve complex technical problems. However, gaps in knowledge and the unique fire protection applications found in nuclear facilities necessitate the use of empirical approaches. This paper has presented two cases where experimental work was performed to address specific applications. In the case of current transformers, the research demonstrated the difficulty in developing conditions that support ignition of materials and components in a secondary location from the induced open circuit fault. This evidence, along with electrical engineering principles and expert judgement, provides a strong technical basis to support revisions to current guidance. These revisions would eliminate the consideration of secondary fire as a result of open circuit, fire-induced failures for most window-type current transformers. The second case confirmed that the slow degradation of instrumentation cables is a credible failure mode and is applicable to both thermoset-insulated and thermoplastic-insulated instrumentation cables. These results could subsequently be used to focus additional testing or to support revision to fire protection methods.

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EXPERIMENTAL CHARACTERIZATION OF A FORKLIFT FIRE

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ABSTRACT

In the frame of facilities and equipment maintenance in nuclear area, the forklifts (and more specifically those powered by electrical power) are commonly used to lift and transfer the heavy loads around and inside the nuclear installations. As all type of electric vehicles, some electrical failure can occur and lead to ignite a fire for instance close to the battery compartment or close to the electric motor. From that, the flame can propagate from the initial ignition spot to the whole vehicle and then could involve significant thermal stress to some surrounding materials (such as cables, electrical cabinet, etc.) taking part in the safety of the facility.

A forklift fire source is considered as a complex combustible due to the different nature (liquid, solid) and composition of materials (type of polymers, hydraulic liquid, etc.) and due to the complex geometry of a forklift. So, the best and simple approach to determine the fire properties of such complex fuel is to use a large-scale calorimeter allowing the burning of this actual and full-scale fire source. In the paper, it is proposed to study the fire behaviour of an electrical forklift (FENWICK model, type E15Z-02) and to determine its fire characteristics (heat release rate, mass loss rate, etc.). After a comprehensive description of the forklift and of the fire tests (facility, experimental design, type of sensors, etc.), the main experimental outcomes are presented with details and discussed in the paper. Further, these experimental data provide the thermodynamic and chemical characteristics of a forklift fire, which can be used as input data in fire modelling for performing safety analysis in nuclear facilities.

INTRODUCTION

In order to carry out maintenance tasks in nuclear facilities (power plants, reprocessing plants, etc.) some electrical vehicles, such as forklifts supplied by battery power, are often used for transporting the heavy materials. Even if such vehicles are considered as relatively more safe concerning the potential fire hazard compared to forklifts running with petrol or gas engines, an electrical malfunction can however occur and involve a fire ignition of the forklift. For illustrating such fire events (see [1]), the National Fire Protection Association (NFPA) estimates that, in 2003 - 2006, U.S. fire departments responded to an estimated total of 1340 structure and vehicle fires per year in which industrial loaders, forklifts or related material handling vehicles were directly involved in ignition. From these 1340 fires, 1220 incidents (91 %) were coded as vehicle fires (for all type of lifting trucks). This report indicates also that almost two thirds of loader or forklift fires (65 %) started in the vehicle engine area, running gear or wheel area and that the main factors contributing to ignition of these vehicles were:

- unclassified mechanical failure or malfunction (27 %),
- electrical failures or malfunctions (26 %), and
- leaks or breaks (14 %).

In 2002 [2], He et al. proposed to demonstrate the feasibility of a performance-based solution for providing adequate life safety levels for the occupants of an industrial warehouse and focused their evaluation on the performance of a smoke venting system and the exit distribution in an industrial warehouse. For carrying out this study, the computer model FAST (based on a zone modelling [3]) was used to simulate physical conditions inside the warehouse during a set of predetermined fire scenarios. In this paper, the principal sources of ignition were considered to arise from electrical faults and accidental sparks from machinery and tools, including the potential for ignition through forklift fires. But no data was available to characterise the fire behaviour of such a fire source, which was only an assumption to start the development of the fire in the warehouse.

To our knowledge, very few data about the behaviour of forklift fires are available in open literature. Consequently, their fire properties needs to be determined properly in order to be able to perform relevant fire safety analysis for assessing the potential fire risk of such events in the nuclear installations.

This paper focuses on the determination of the thermodynamics and chemical characteristics of a forklift fire. First, the description of the forklift (FENWICK model, type E15Z-02) is given in detail as well as the experimental facility and the measurements (type of sensors, location) involved in the fire tests. After a brief presentation of the different ways for the forklift ignition, the experimental data are described in detail and the main outcomes are analysed thoroughly. Finally, this work provides an original set of data determining the main properties of a forklift fire (heat release rate, mass loss rate, chemical reaction, etc.).

DESCRIPTION OF FIRE TESTS

Large-scale Calorimeter

For safety and security purposes, the fire tests are performed in the large-scale hood in open atmosphere belonging of the EFECTIS FRANCE Company [4] located in Maizière-Lès-Metz (France). This calorimeter hood (cf. Figure 1) is about 8 x 8 m² in area and 4 m in height. It can carry out some real scale fire tests up to a fire power of about 10 MW. The smoke and hot gases from the fire are exhausted by a large duct (about 1 m in diameter) under natural ventilation condition. The air inlet coming from free atmosphere (cf. Figure 2) supplies the fire source by seven openings (1.0 x 0.7 m² in area) located on three sides of the facility and the fourth side being the wall adjacent to the control room. All the walls are made of cellular concrete.

Figure 1 Hood (outside and inside top views) gathered the smoke by natural ventilation

Side view (right) of the forklift | Rear view of the forklift

Figure 2 Experimental facility showing the location of the forklift

Description of the Fire Source

The forklift (see Figure 3) is a common FENWICK model (type E15Z-02) powered by re-chargeable storage batteries located in a compartment just below the driver seat. This lifting truck has a lifting capacity of 1500 kg and its external dimensions are 1.8 m in length (disregarding the forks), 1.05 m in width and 1.95 m in height. The hydraulic system (pump, pipes, hydraulic cylinders, oil, etc.) are located under the front floor. About 15 l of oil are available in the hydraulic circuit. The main electrical systems (engine, cables, etc.) are located in a compartment behind the driver seat. For safety reasons, the batteries are removed but the boards of plastic holding them are left in place. The vehicle cab is composed mainly with different types of polymer (seat, wheel, dashboard, cables, etc.). The windshield and roof of the cab are simple plates of polycarbonate (PC) screwed onto the steel structure of the forklift. The front and rear tires are solid and made of materials in rubber compounds.

The forklift (cf. Figure 2 and Figure 3) is placed on a large steel plate of 3.0 m in length, 1.8 m in width and 0.15 m in height. This spillage retention tray is designed to capture the liquid oil and the pieces of materials (PC, plastics) falling down onto it. Its bottom is fully recovered with a gypsum plate.

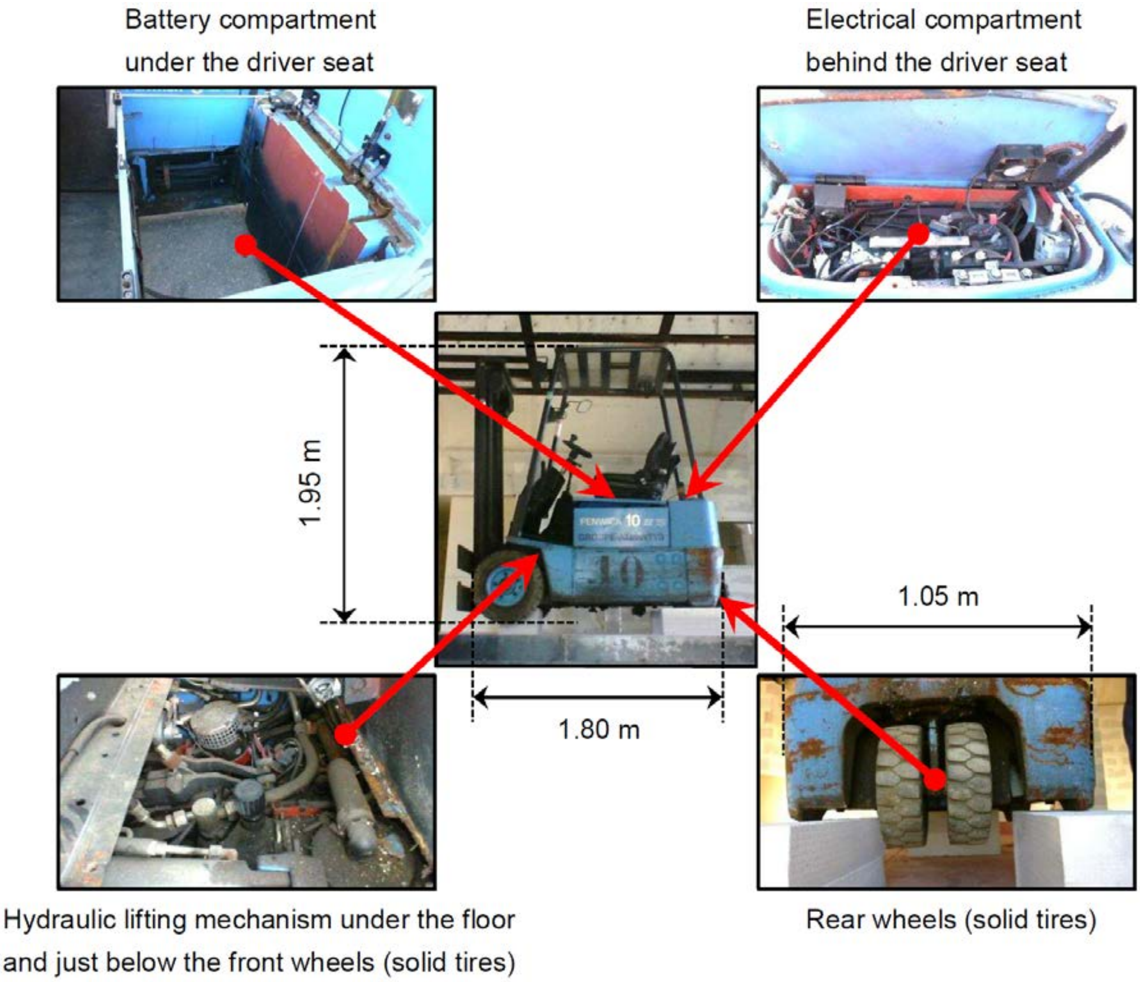

Figure 3 Detailed description of the forklift fire source (FENWICK model, type E15Z-02)

Instrumentation

This large scale calorimeter is equipped with several sensors located in the smoke exhaust duct:

- A pitot tube with a pressure transducer and a thermocouple (K-type) for measuring the mass flow rate flowing in the duct;
- Two gas analysers for determining the amounts of combustion products (O_2, CO_2/CO) released by the fire;
- A bank of filters allowing to assess the soot concentrations during the fire.

Moreover, a weighting system located under the steel retention tray is set up in order to measure the mass loss by the forklift. Also, a video system of several cameras located on the left side of the lifting truck allows following the evolution of the forklift fire.

System of Ignition

The ignitions of the forklift are performed by means of steel square pans filling with heptane fuel. Two different pans are used as described in Table 1: a medium pan of 0.065 m² in area, and a large one of 0.25 m² in area. Three fire tests were carried out with the experimental parameters based on the pool fire size, its location beside the truck and the initial quantity of heptane (see Table 1 hereafter):

- the medium pan in the battery compartment with an initial mass of combustibles of 1.76 kg,
- the large pan under the front left tire with an initial mass of combustible of 1.71 kg, and
- the medium pan under the front left tire with an initial mass of combustible of 1.53 kg.

Table 1 Main characteristics of heptane pool fire for igniting the forklifts

Combustible: **Heptane (C_7H_{16}, Heat effective of combustion: 44.4 MJ/kg)**				
Test Number	**Surface [m²]**	**Location of the pan [-]**	**Initial mass of fuel [kg]**	**Duration [min]**
1	0.25 x 0.25 = 0.0625	Battery compartment (driver seat is down)	1.76	~ 21
2	0.5 x 0.5 = 0.25	Under the front left tire	1.71	~ 8
3	0.25 x 0.25 = 0.0625	Under the front left tire	0.53	~ 6

For the first test (see Figure 4 below), the duration of the heptane pool fire is due to the fact that the driver seat is returned to its initial position before ignition and so the air supplying the fire source is quickly reduced involving a well-known under-ventilated regime [5], [6]. Consequently, the mass loss rate of heptane decreases allowing the duration of the heptane pool fire to be as long as 21 min.

Determination of the Heat Release Rate and the Effective Heat of Combustion

The heat release rate of the fire source (namely HRR or $\dot{Q}(t)$) in an open atmosphere is determined by the usual chemical methods, i.e. by the assessment of the oxygen consumed (OC method) or CO_2/CO produced (CDG method) during the combustion reaction. The detailed formulations of these chemical methods are well-known and can be easily recovered in [8], [9] or [10]. For this study, the two methods are used to determine the fire power and, whatever the fire test, they provide closely the same results. The total energy, E_T, released by the fire source during the tests is determined by integrating the time evolution of heat release rate over the full duration of the fire. The detailed calculation is obtained as:

$$E_T = \int_0^{t_{end}} \dot{Q}(t)\, dt \qquad (1)$$

The total energy obtained in this work for each fire source (see Table 2) does not consider the heptane pool fire used for the forklift ignition. The effective heat of combustion $\Delta H_{c,eff}$ of the fire source is determined by the following relation:

$$\Delta H_{c,eff} = \frac{E_T}{M_c} \qquad (2)$$

Here, M_c is the total mass loss of combustible measured by the weighting system during the forklift fire.

EXPERIMENTAL RESULTS AND DISCUSSION

Description of the Fire Scenarios

Despite the different ways to ignite the lifting trucks (i.e. battery compartment or under the front left tire), the three fire tests performed under the large scale calorimeter in open atmosphere show very similar behaviour of the forklift fires, except the initial stage of the fire growth rate. All the scenarios are illustrated in Figure 4 for test 1 (ignition in the battery compartment), in Figure 5 for test 2 (ignition under the front left tire with a large pool) and in Figure 6 for test 3 (ignition under the front left tire with a medium pool). In total, three successive stages during the forklift fires can be determined by the analysis of the video recordings and fire power:

- After the ignition of the heptane pool fire, the fire propagates to the vehicle cab more and less quickly depending on the type of ignition. So, the compartment of the hydraulic system, the plastic board, the driver seat and the solid front tires (except test 1) burn together involving a high thermal stress on the windshield and roof made of PC material. This last melt and fall down on the lower part of the cab. During this stage, the fire power can be as high as 420 kW, 800 kW and close to 1 MW for the fire tests 1, 2 and 3 respectively. Moreover, the gas temperature inside the compartment of hydraulic system is so high that the oil pipes begin to leak. Thus, the hydraulic liquid runs down and flows in the spillage retention tray. Thereafter, the fire decreases and the heat release rates are observed to be ranged from 100 kW to nearly 300 kW depending on the fire test. In the same time, the radiant heat fluxes from the flame preheat the hydraulic liquid.
- When the temperature of oil is high enough (just below the compartment of the hydraulic system), the oil suddenly ignites and the flame spread from the front part to the rear part of forklift. For test 1, the front tires are then ignited. The flame reaches the rear part of the truck inducing the burning of the rear solid tires and the cables in the engine compartment. The fire power consequently increases up to about 800 kW, except for test 2 with only 300 kW due to the fact that the gypsum plate was slightly wet. Then, it decreases quickly with the progressive extinction of the oil pool fire leaving only the tires burned.
- After that, the tires continue to burn for a very long time, the heat release rate diminishing slowly until extinction. The total duration of the forklift fire is assessed about 4 h.

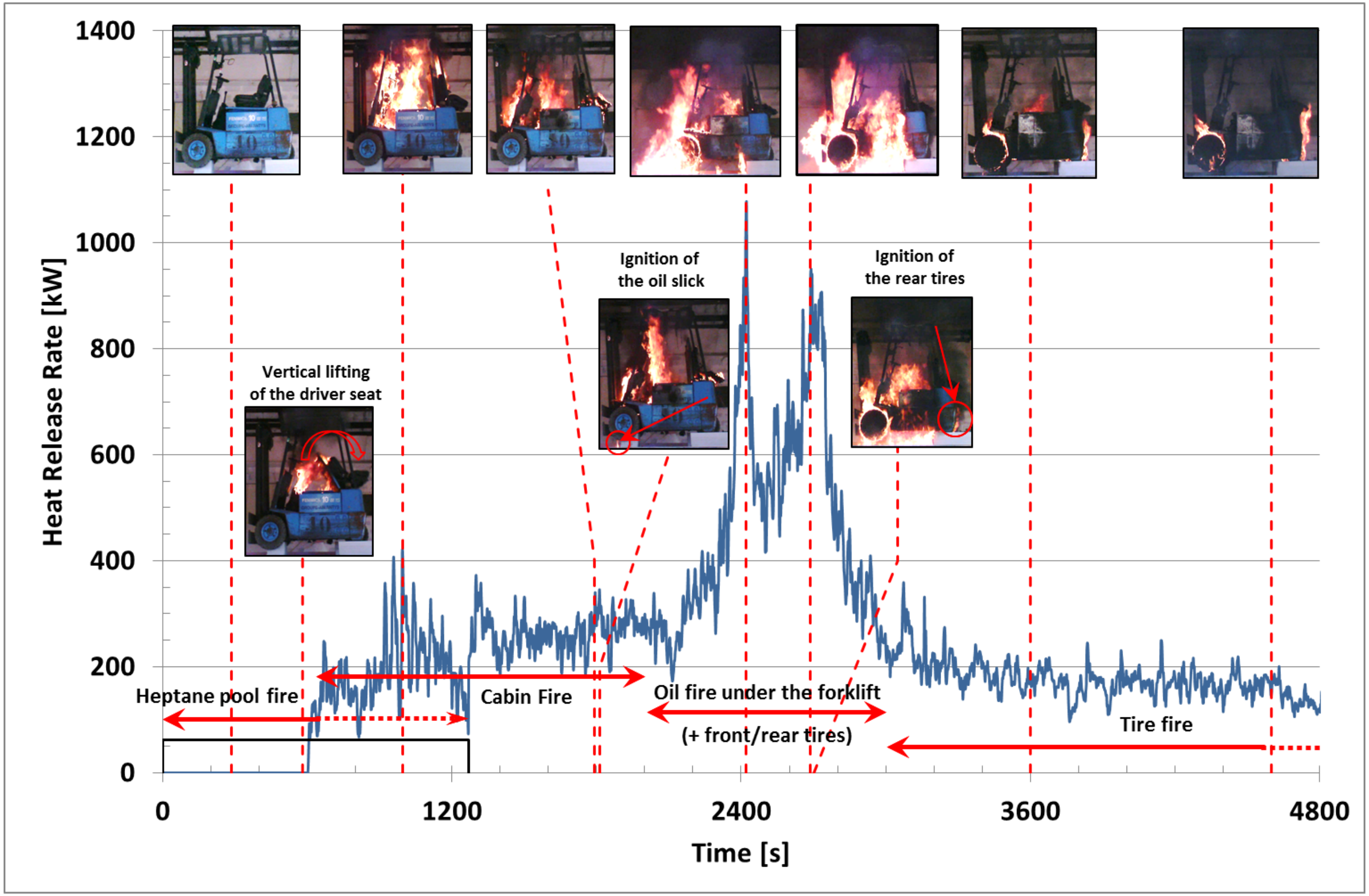

Figure 4 **Development of the f**ire power over time in test 1 (ignition with a medium heptane pool fire under the driver seat)

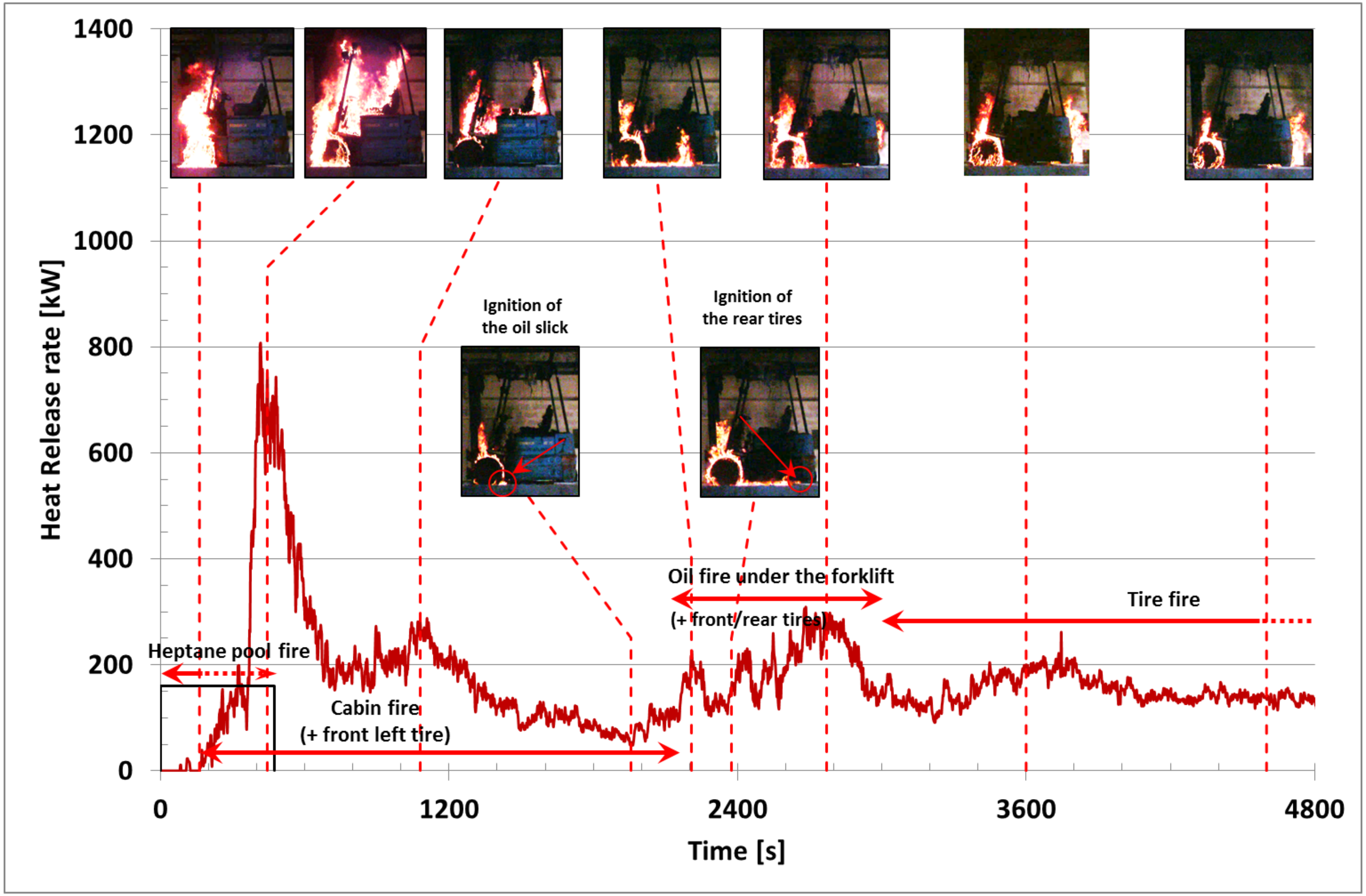

Figure 5 Development of the fire power over time in test 2 (ignition with a large heptane pool fire under the front left tire)

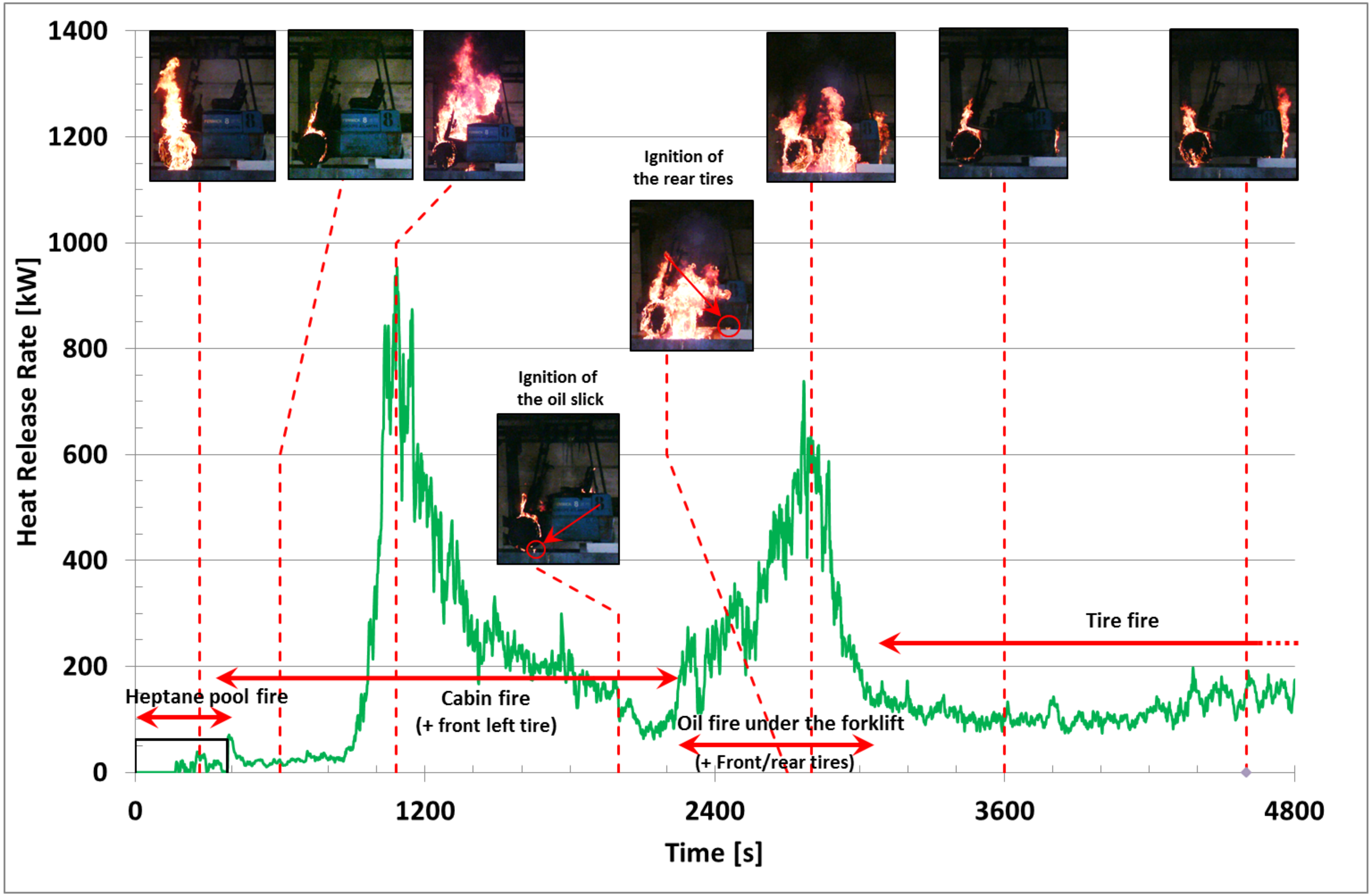

Figure 6 Development of the fire power over time in test 3 (ignition with a medium heptane pool fire under the front left tire)

Fire Growth Rate versus Type of Fire Ignition

In the frame of a design fire, the fire growth rate α (see Figure 7) is commonly used to characterize the fire propagation on a combustible and provides a simple way for ranking the potential fire hazard for a combustible material. This empirical approach [11], [12] assumes that the heat release rate of the combustible increases as the square of time as:

$$\dot{Q}(t) = \alpha(t - t_{ini})^2 \quad (3)$$

By convention, the fire growth rate is assessed by measuring the time necessary to reach a fire power of 1055 kW as soon as the incubation time t_{ini} is over, and the heat release rate increases significantly. But, this value is not reached for the first peak of HRR in all the tests. Consequently, in the same way that the NFPA standard [12], it is proposed to fit the previous expression by considering the maximum HRR $\dot{Q}_{max}$ at the time t_{max} for the first HRR peak and thus to determine the fire growth rate as:

$$\alpha = \frac{\dot{Q}_{max}}{(t_{max} - t_{ini})^2} \quad (4)$$

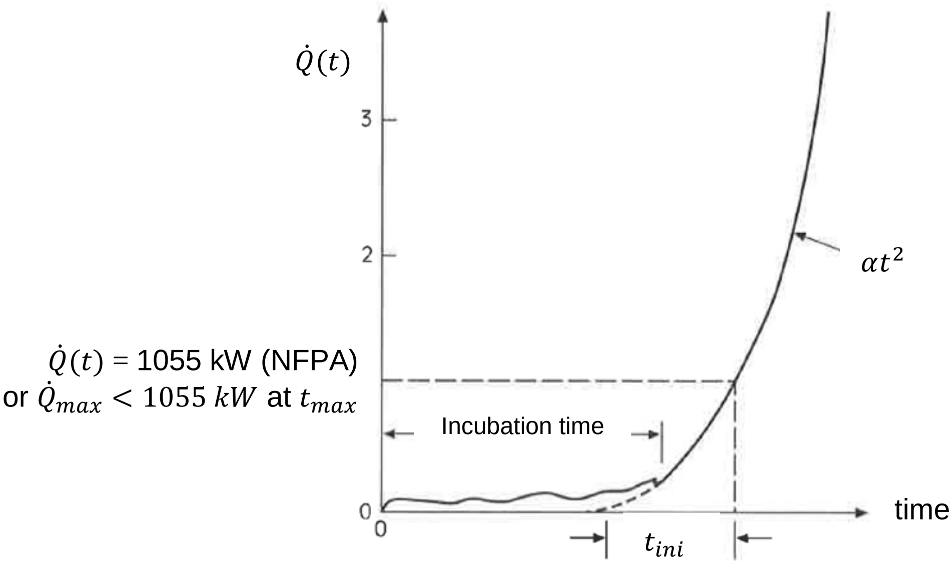

Figure 7 Principle for the assessment of the fire growth rate (extracted from [11])

Figure 8 summarizes the fire growth rates obtained during the fire forklift fires. The tests 2 and 3 using a heptane pool fire under the front left tire are quite close with values for α of 0.029 and 0.017 kW/t² respectively, ranking them between medium and fast. The test 1 is significantly lower with a value for α of 0.003 kW/t², ranking it as a slow fire source. Indeed, as the heptane pool fire is located on the bottom of battery compartment and its HRR is limited by the air incoming inside it, the surrounding combustible materials (i.e. the lower part of the seat driver) undergoes weakly the thermal stress due the flame. Thereafter, the seat driver ignites and then the fire spread to other combustible parts of the truck as described for the two other tests.

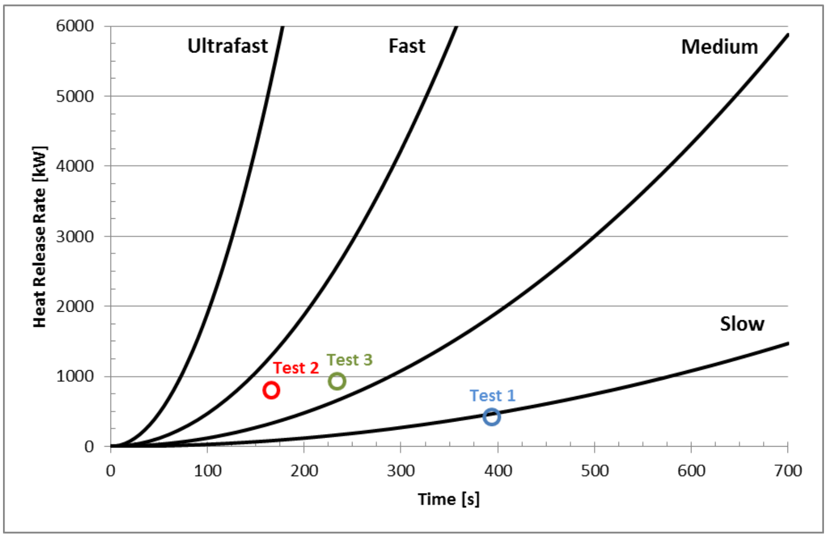

Figure 8 Fire growth rates obtained for the forklift fires

Heat Release Rate

The time histories of heat release rates for all forklift fires are presented in Figure 4, Figure 5, and Figure 6. By a time integration of these results on the full time (about 4 h) and by averaging on all the tests, the average fire power is estimated as 116 kW and the mean mass loss as 92.3 kg. The value for the HRR seems quite weak, but the most part of the time is due to the burning of the solid tires, which is quite weak for a long duration (i.e. about 3 h). For comparison, the mean HRR assessed from 0 to 4800 s (i.e., 1 h 20 min) is of 200 kW and the mean mass loss of 56 kg. Thus, 60 % of mass loss by the forklift fire source is released during the first hour and 40 % during the last three hours.

Based on the full time of the fire tests, the average total energy is of 1649 MJ and the mean effective heat of combustion of 17.8 MJ/kg. Whatever the thermodynamic properties, the standard deviation is less than 12 % showing, in the whole, a quite similar behaviour and consistence for the three forklift fires, even if such a fire source is complex (various types of fuels, geometry, etc.). All these outcomes are gathered in Table 2.

Table 2 Mean thermodynamic properties of the forklift fires

Fire Test	M_c [kg]	$\dot{Q}_{moy}$ [kW]	E_T [MJ]	$\Delta H_{c,eff}$ [MJ/kg]
Mean	92.3	116	1649	17.8
Standard deviation (σ)	± 7.0 (± 8 %)	± 13.4 (± 12 %)	± 192 (± 12 %)	± 1.2 (± 7 %)

Chemical Reaction

The same work can be performed with the combustion products in order to determine a mean chemical reaction for a forklift fire. This chemical reaction (see Table 3) is expressed as the mass ratio of mass of released products and fuel mass loss (burn or unburnt), and the results from fire tests are detailed hereafter:

$$F + 1.290\ O_2 \Longrightarrow 1.452\ CO_2 + 0.040\ CO + 0.775\ H_2O + 0.023\ soot$$

Table 3 Mean combustion products released by the forklift fires

Fire Test	$y(O_2)$ [g/g]	$y(CO_2)$ [g/g]	y(CO) [g/g]	$y(H_2O)$ [g/g]	y(S) [g/g]	ΔH_c [MJ/kg]
Mean	1.290	1.452	0.040	0.775	0.023	17.8
Standard deviation (σ)	± 0.088 (± 7 %)	± 0.025 (± 2 %)	± 0.005 (± 13 %)	± 0.009 (± 9 %)	± 0.068 (± 39 %)	± 1.2 (± 7 %)

For the gaseous products, the experimental results are consistent between the fire tests with a maximum standard deviation of 13 % for CO. Nevertheless, a quite large discrepancy is observed for the soot concentration (standard deviation assessed as 39 %), probably explained by the fact that the number of filters was not sufficient (only ten filters) compared with the duration of the fire tests (about 4 h).

CONCLUSION

Based on three tests performed in a large-scale calorimeter in open atmosphere, this study determines the behaviour of a forklift fire and assesses the main thermodynamic and chemical properties of such fire source. This forklift powered by rechargeable storage batteries is a FENWICK model (type E15Z-02) equipped with solid tires made of materials in rubber compounds. The ignition is carried out by heptane pool fires (medium and large size) and the location of the pan is either in the battery compartment just below the seat driver or either under the front left tire.

The major outcomes of this study concern more especially: the time history of this truck fire showing three major successive stages (cab fire, oil pool fire and tire fire), the determination of fire characteristics of such fire source (mean mass loss, mean heat release rate, average chemical reaction) and the effect of ignition on the fire growth rate. In the whole, the behaviour for the three tests is quite similar except for the beginning of the fire (i.e. incubation time and fire growth rate).

This work provides an experimental database that can be used as input data in a safety analysis concerning fire scenarios involving similar electrical forklift.

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EFFECTS OF SMOKE AND THERMAL STRESS ON ELECTRICAL EQUIPMENT FAILURE

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ABSTRACT

Fire constitutes a major risk in the safety assessment of nuclear facilities. In particular, one of the risks is the consequences of heat and combustion product transfers from the fire room to adjacent rooms. To this end, knowledge of the impact of these combustion products on the electrical or electronic material should constantly be updated and assessed on new equipment ensuring a safety function and conducts IRSN to carry out its own research studies on this topic, to support and enhance safety analysis.

In this sense, an experimental campaign called CATHODE was conducted by IRSN and aimed to study the electrical failure on electronic relays by thermal impact. This first campaign, carried out in a convection furnace called SIROCCO, allowed the determination of the malfunction appearance times as a function of the ambient temperature, as well as the critical temperature of malfunction. The CATHODE campaign was followed by the CATHODE SUIES test campaign. This second campaign aimed to study the impact of smoke on the malfunction occurrence, was conducted in a large-scale facility (DIVA), using the same equipment tested in the CATHODE campaign, without smoke. In particular, this equipment was submitted to the smokes from electrical cabinet fire. Main results of this campaign show that smokes from a real fire weaken the functioning of the equipment, causing malfunctions at temperatures much lower than the critical temperature determined in CATHODE campaign. Indeed, in purely thermal mode, the critical ambient temperature determined in CATHODE is around 160 °C, for considered equipment, while this critical temperature fall around 75 °C for the same equipment exposed to smoke in a real fire scenario (CATHODE SUIES results). Results highlight that, combined with thermal effect, smoke behave like aggravating agents which favour the malfunction occurrence.

INTRODUCTION

When conducting a fire risk analysis, it is important to know the critical temperature of electrical equipment in critical situations. The technical characteristics of this equipment generally indicate a limited temperature of operation in the normal use. However, when a fire develops in a room, the gas temperature becomes significantly higher than the operating temperature recommended by the manufacturer. In this case, the electrical equipment may malfunction after a certain time due to different thermal transfer processes. As shown by the experience feedback of real fires mentioned in the DOE Handbook [1], a fire can have serious consequences on equipment, both for short and long duration. The short duration effects are attributed to heat and smoke and include short circuits and electrical malfunctions that make equipment inoperable or initiate unwanted actions. In the long-term, the degradation effect is related to the corrosion of the conductive elements by the smoke. The reliability of the equipment is reduced, resulting in sporadic and unpredictable behaviour.

According to the DOE handbook [1], thermal damage to electronic equipment may always be permanent and results in irreversible electrical malfunction. In 1993, Factory Mutual showed that electronic equipment damage is significant for exposures of 79 °C and malfunction occurs as early as 60 °C [1] are reached. However, there is no indication of the time taken to obtain the malfunctions or their durations. In 2001, Keski-Rahkonen and Bjorkman [2] carried out an experimental study in order to determine the delay to obtain a failure at a given ambient temperature. This study deals with electromechanical equipment: a pressure transmitter consisting of a unit of measurement and electronics, and a valve actuator with its electric motor. The results of these tests show that the pressure transmitter is not damaged for the maximum operating temperature (i.e. 70 °C), but intermittently for an ambient temperature of 140 °C and then permanently at 250 °C. In an experimental study on electrical equipment malfunction, of nuclear installations [3], Gay et al. showed that the thermal criteria for failures defined by the safety regulations were not sufficiently realistic in view of the critical temperatures determined on electronic and electromechanical equipment tested in analytical tests (95 °C for electronic boards and 130 °C for electromechanical equipment). The conclusion of Gay et al. therefore clearly shows the robustness of some of its equipment to thermal aggression, compared to the default criteria set out in the regulations.

However, it is clear that heat is not the only agent in a fire that damages electrical and electronic equipment. The smoke emitted by the fire cannot be excluded in experimental studies on the equipment malfunction, in order to guarantee the representativeness of the fire exposure. The aggressive agents contained in the fire smoke are soot particles and corrosive gases. The malfunctioning mechanisms associated with these products are, on the one hand, the disturbance of the electrical properties of the equipment, attributed to the conductive soot particles, and, on the other hand, the chemical degradation of the components and their connections by the corrosive gases. The quantity of these gases and particles around the equipment determines the intensity of the caused damage. The evaluation of the products concentrations in the fire room, but also in the adjacent rooms, is therefore fundamental in a study on electrical malfunction. The smoke corrosivity on electrical equipment was evaluated in a large-scale fire test on PVC cable fires [4]. In this test, the sedimented particles measured in the fire room contained 33 % of the chlorides responsible for the corrosivity, and only 2 % of these chlorides had been released outside this room. The authors explain that the residence time of the smoke in a large room is long enough for the chlorides to bind with the particles and then sediment into the room where the fire takes place. Data from the literature on this subject include, first, the numerous results of several series of tests obtained by SNL between 1994 and 1999, reported in the detailed NUREG reports [5], [6], [7], the main results of these studies being gathered in [8]. All these SNL tests are carried out with the same type of device consisting of a combustion cell connected to an exposure chamber; the measurements and the operating protocol are similar.

These SNL tests [5] to [7] clearly show that smoke significantly disrupt electrical circuits. In general, the digital systems fail intermittently, due to a disturbance of communication between the various components of the circuit. The failure of a digital system is mainly due to the increase in leakage currents and the appearance of short circuits. The leakage currents are due to the soot particles, which are attracted by the electrically charged surfaces and which are deposited by forming conductive carbon bridges. The leakage current can be maintained at a high level after the smoke extraction, when the deposition of soot has previously formed on the component surface (on a printed circuit, for example). The SNL tests [5], [6] to [7] also allowed to measure the electrical conductivity of the smoke as a function of their density. The amount of smoke required to cause equipment failure varies depending on the type of signal (analogue or digital), the sensitivity of equipment mainly depends on the impedance of its circuits. On this subject, Tanaka et al. [9] specify that the conductivity directly expresses the quantity of leakage currents or short circuits generated between the conductive elements of the exposed circuits. The more the measured conductivity increases (which corresponds to a decrease in the insulation resistance), the more chaotic the equipment becomes. Thereafter, Tanaka elaborates some mechanisms of soot-circuit interactions that could explain the observed conductivity variations. In the first instance, the soot particles are attracted by the surfaces under tension and build more or less fragile conductive carbon bridges between conductors that are normally insulated from one another (increase in conductivity and therefore in leakage currents). Another issue is that high humidity levels increase the conductivity of the circuit, that is, the increase in leakage currents. It should be noted that the strength or fragility of the conductive bridges created depends on the nature of the soot and on the bias voltages applied to the circuits. As long as the concentration of soot particles and humidity remain high enough around the equipment, the conductive carbon bridges, which destroy themselves with the convective movements of the air, are regenerated by the continuous deposition of new particles.

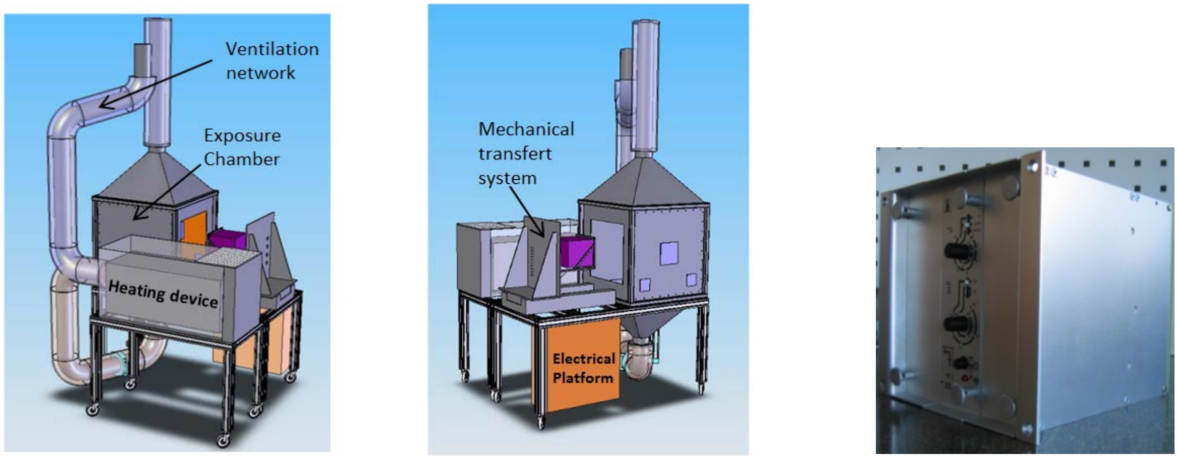
For about ten years, IRSN has based its research programs on electrical malfunction on real equipment located in installations interesting nuclear safety. At the end of the 2000s, the first experimental approach consisted in carrying out an analytical study of thermal impact dysfunction on real equipment relevant to nuclear safety (CATHODE program). The experimental protocol of CATHODE consists in exposing this equipment to different temperature ranges in a convective heating device with controlled temperature (device called SIROCCO). The purpose of the CATHODE characterization is to determine the critical operating temperature in a steady-state temperature regime as well as to develop the time curve for thermal failure (i.e. the time required to obtain the malfunction as a function of ambient temperature). The second phase of this experimental program on electrical equipment malfunction is a global approach and was carried out in the large-scale facility DIVA. This second phase, called CATHODE SUIES, has involved real fires to test the operating conditions of a VIGIRACK relay. These demonstrative tests aim to measure the impact of smokes on the operation of the equipment, in addition to heat (combined mode of aggression), in particular in the sub-critical temperature range, from the thermal point of view; determined in CATHODE tests.

The article presents the main results associated with these two electrical equipment malfunction campaigns. A mapping of the relay VIGIRACK operating states, as a function of the ambient temperature and the volume concentrations of the soot contained in the smoke from fire is presented in the last section of this paper. First, the experimental devices SIROCCO, the operating conditions and the associated results are presented.

MALFUNCTION CAUSED BY THERMAL STRESS IN STEADY STATE

Description of the Experiment

The device used to carry out the CATHODE analytical tests is called SIROCCO (see Figure 1a) and consists of three main functional elements. The first corresponds to an exposure chamber (about 1 m^3) in which the samples are heated (up to 300 °C). The second one consists of a heating device (coiled heating resistors) associated to a ventilation network (variable flow rate up to 300 m^3h^{-1}). The third element corresponds to the mechanical system for the automated transfer of equipment within the exposure chamber. A dedicated electrical platform for power supply and wiring of the tested equipment is added to these three functional blocks.



(a) **(b)**

Figure 1 The SIROCCO device (a) and the VIGIRACK relay (b)

The equipment tested in CATHODE, which can be installed and used in some electrical network of nuclear power plants, is an overcurrent protection relay called VIGIRACK, associated with the A326E electronic card (see Figure 1b).

The operating principle of the VIGIRACK relay is the following: monitoring an electrical network, the output relays automatically switch their contacts when at least one of the three phases exceeds a threshold of current (set to 4 A for our study). In situ, the contact receiving the switchover can be dedicated to the transmission of an alarm to alert of a malfunction on the network. In order to test the operation of the relay experimentally, a periodic overcurrent (equal to 6 A) is created from a current generator (every 3 min), at the input of the relay tested, on its phase numbered C (see Figure 2 and Figure 4).

During normal operation, the output relays switch their output contacts when the current injected at Phase C (set at 3 A before and after the overcurrent, as on the other two inputs) exceeds the value of the internal trip threshold (4 A), during the entire duration of the overcurrent.

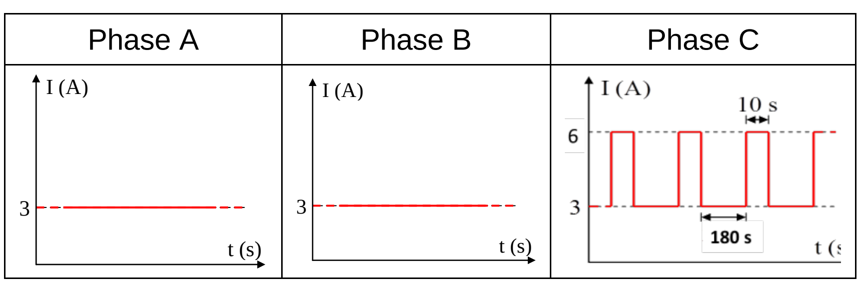


Figure 2 Current injection sequence for CATHODE tests

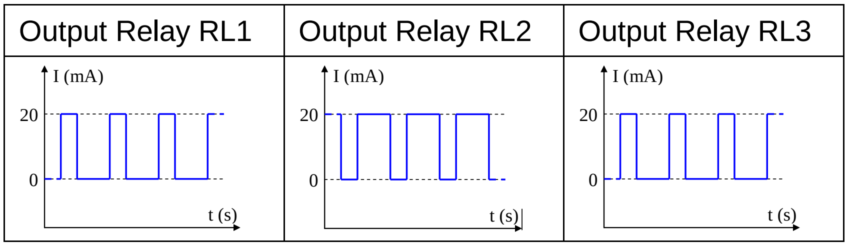


Figure 3 Output responses to input loads when the relay is operating correctly

Thus, the VIGIRACK is considered to function correctly as long as relays RL1, RL2 (0 A, loop normally open) and RL3 (20 mA, loop normally closed) change state (20 mA for RL1 and RL2, 0 mA for RL3) synchronously with the rhythm of the exceeding current (see Figure 3).

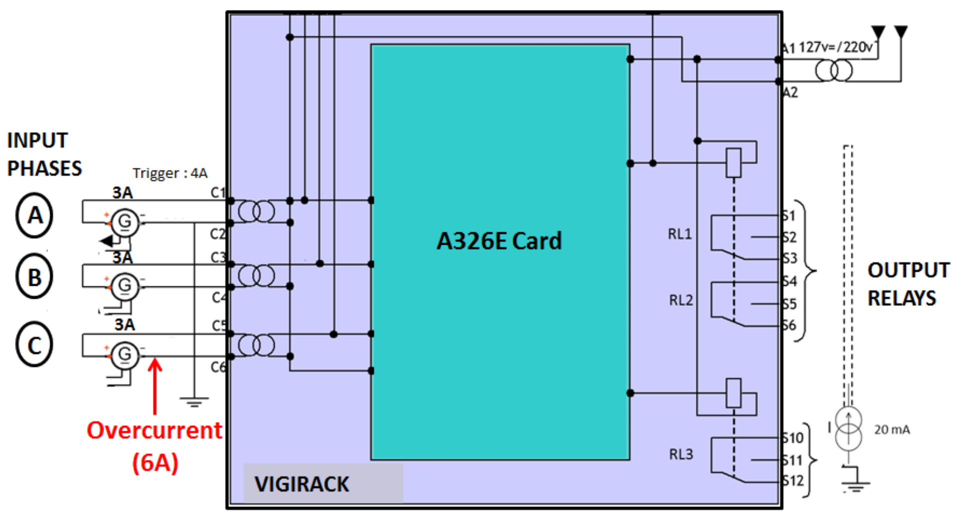


Figure 4 Wiring diagram of the VIGIRACK relay

Analysis of Malfunctioning Temperatures

Three tests (CAT-VIG.1 ; CAT-VIG.2 ; CAT-VIG.3), corresponding to three ambient temperature levels in SIROCCO device (251 °C, 200 °C, 171 °C), led to three malfunctions, occurred at different times. The last two tests (CAT-VIG.4 and CAT-VIG.5), carried out respectively at an ambient temperature of 160 °C and 165 °C did not lead to malfunction. Table 1 summarizes the results of the five tests, giving the mean ambient temperature, T_a (average ambient temperature over time of exposure), Tc_{max}, the maximal temperature of the electronic board obtained during the test (equal to T_f at the malfunction time, in case of equipment failure), as well as the duration of exposure to have the failure, named t_f. Note that the maximum exposure time has been fixed to one hour, except for test CAT-VIG.3, for which an additional time has been allowed to reach the thermal threshold of malfunction determined on the electronical card in the first two tests (about 160 °C).

Table 1 Characteristic times and temperatures of CATHODE tests

Test	T_a [°C]	Tc_{max} [°C]	t_f [s]
CAT-VIG.1	251	160 (= T_f)	630 ± 90
CAT-VIG.2	200	160 (= T_f)	1170 ± 90
CAT-VIG.3	171	161 (= T_f)	3880 ± 90
CAT-VIG.4	160	150	no malfunction
CAT-VIG.5	165	155	no malfunction

As an example, the type of signals for the relay's electrical inputs and outputs, are given below on Figure 5, for the CAT-VIG.3 test. After 3880 s of exposure, the output relay RL1 does not respond to the solicitation of the input overcurrent, applied in phase C: the VIGIRACK is then considered inoperative from this moment, due to a thermal degradation of its components.

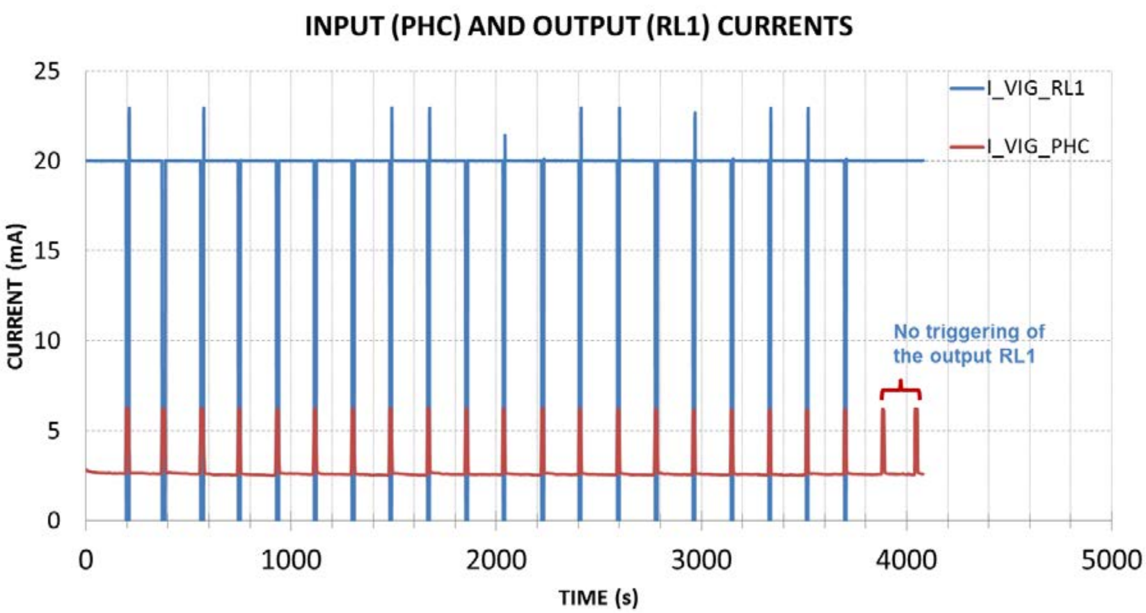


Figure 5 Electric signal curves from the tested VIGIRACK (input/output, CAT-VIG.3 test)

The failure obtained in this test is a “clean break” of the triggering function of output relay. The mean ambient temperature is 170 °C around the relay in the exposure chamber (see Figure 6), and the surface temperature on the electronic board, obtained at the malfunction time, is 161 °C (see Figure 7).

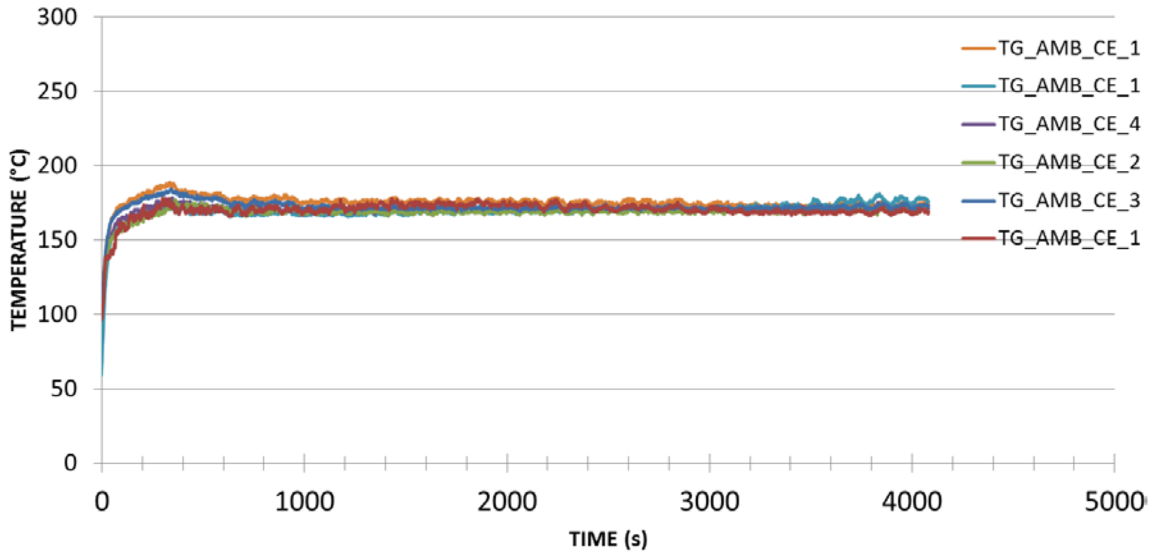


Figure 6 Ambient temperatures in exposure chamber (CAT-VIG.3 test)

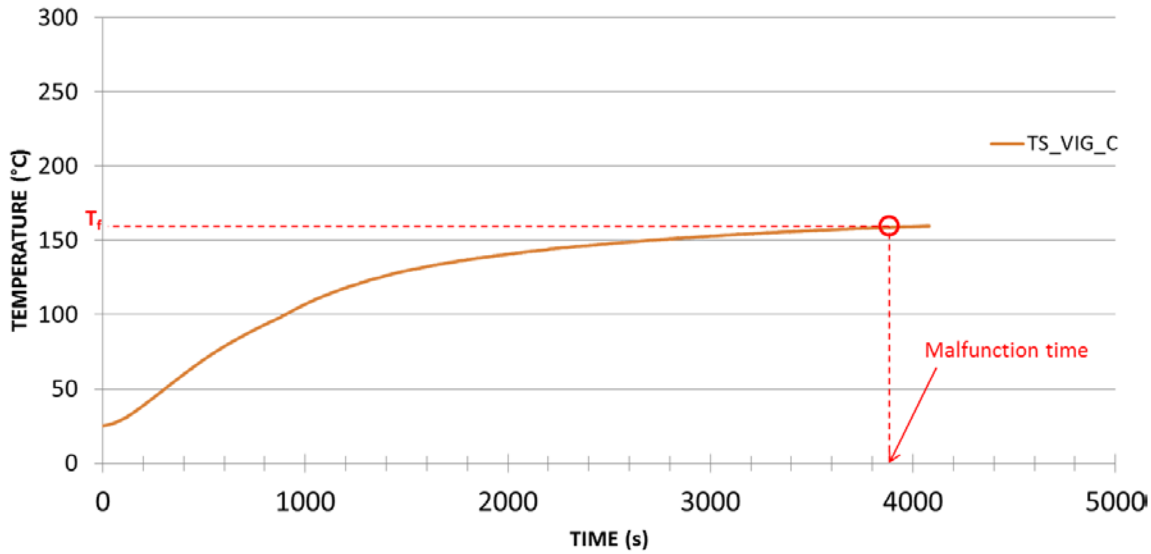


Figure 7 Surface temperature on the electronic board (CAT-VIG.3 test)

The malfunction curve of the VIGIRACK relay can be used to link the ambient temperature around the relay to the time required to obtain the equipment failure. Figure 8 presents the different results obtained with SIROCCO and an empirical formulation has been determined with a power law function.

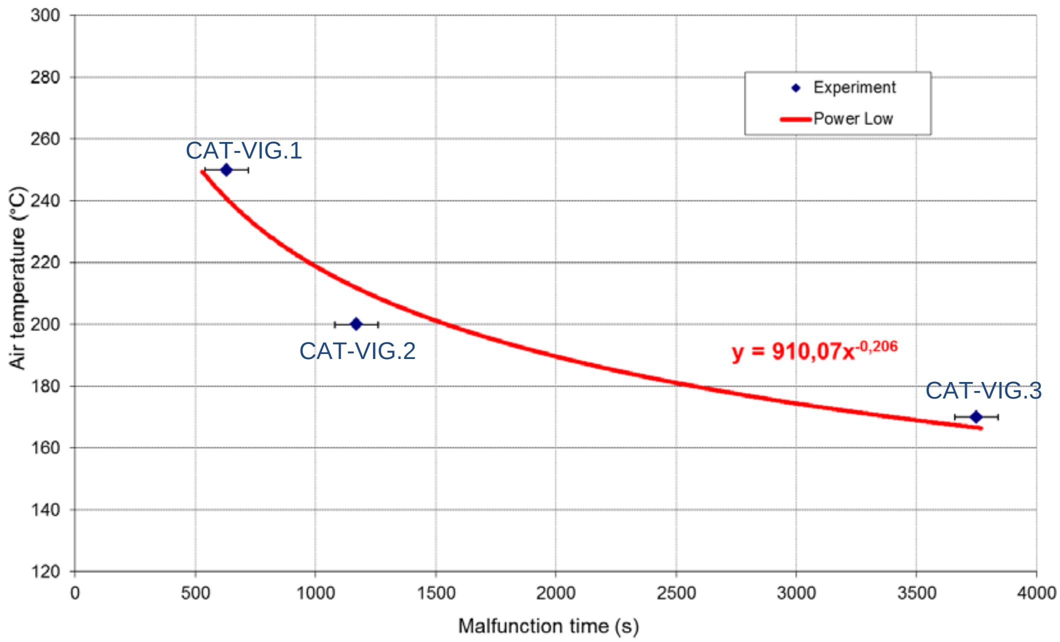


Figure 8 Experimental malfunction curve of the VIGIRACK relay (CATHODE)

Critical Threshold of a Pure Thermal Failure

Since the VIGIRACK relay is a low power electronic equipment, the internal heat flux emitted by the functioning of components is low compared to that provided by the ambient air in the SIROCCO device. Moreover, only the heating coil delivers a convective air flow into the exposure chamber to heat the equipment. There is no other source of external heat.

By these assumptions, the equilibrium between the external temperature and the internal temperature of the VIGIRACK relay is reached for an infinite time. The critical temperature is defined as the smallest ambient temperature leading the relay to malfunction for an infinite exposure time. Due to the above, this ambient critical value will be equal to the surface temperature of the electronic board, measured at the time of the malfunction (i.e. T_f). The average value of T_f is about 160 °C (see Table 1). The critical ambient temperature at thermal equilibrium, for an infinite time, will therefore be taken equal to this value.

MALFUNCTION CAUSED BY SMOKE PROPAGATING FROM A REAL FIRE

The analytical campaign CATHODE was followed by the CATHODE SUIES campaign, the objective of which was to provide concrete answers on the malfunctioning of the VIGIRACK relay subjected to a real fire atmosphere, and to appreciate in particular the deviations of its behaviour compared with the purely thermal exposure mode. To do this, the VIGIRACK relay and its instrumentation have been installed in the DIVA multi-room large-scale facility and submitted to an electrical cabinet as fire source [10].

Test Characteristics of CATHODE SUIES Campaign

The CATHODE SUIES campaign includes four tests called CATS-VIG.1, CATS-VIG.2, CATS-VIG.3 and CATS-VIG.4 (see Table 2). The main characteristics of the DIVA tests and results have already been described and presented in [10] and intended to test the influence of a fire door and different ventilation dampers on the development of the fire of an electrical cabinet. For all the CATHODE SUIES tests, the relay VIGIRACK is positioned in the south-west corner of the fire room [10]. This position of the VIGIRACK relay against the electrical cabinet significantly limits the direct flame radiation on it. Two heights, tested twice (see Table 2), are retained for the position of the relay in the fire room (0.55 m and 1.80 m from the ground) in order to access different levels of temperature and concentration of soot.

Table 2 Main characteristics of the four tests CATHODE SUIES

Test name	Height of the relay in the DIVA room	Test objectives
CATS-VIG.1	1.80 m	Fire door without dampers
CATS-VIG.2	0.55 m	Fire door + dampers (inlet)
CATS-VIG.3	0.55 m	Fire door + dampers (inlet and outlet)
CATS-VIG.4	1.80 m	CATS-VIG.3 characteristics with another damper type

The electrical settings are typically the same type as those used in CATHODE (see Figure 9), except for the triggering threshold and the applied overcurrent, set respectively to 4.5 A and 7 A for the CATHODE SUIES tests (instead of 4 A and 6 A for the CATHODE tests). The value of the overcurrent has been increased in order to ensure that the tripping output threshold is exceeded. In order to be in operating conditions similar to those of the CATHODE tests, only the phase C input was solicited. For CATHODE SUIES tests, the period between two consecutive solicitations was reduced to 20 s (instead of 180 s during the CATHODE tests). This higher frequency of overcurrent makes it possible to better monitor continuously the operation of the relay in an unsteady environment, characteristic of a real fire.

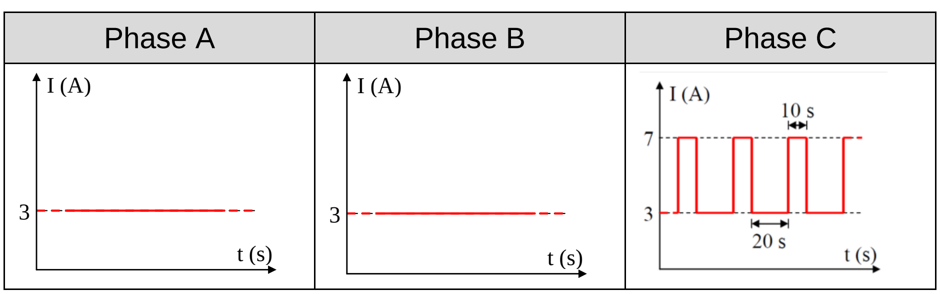
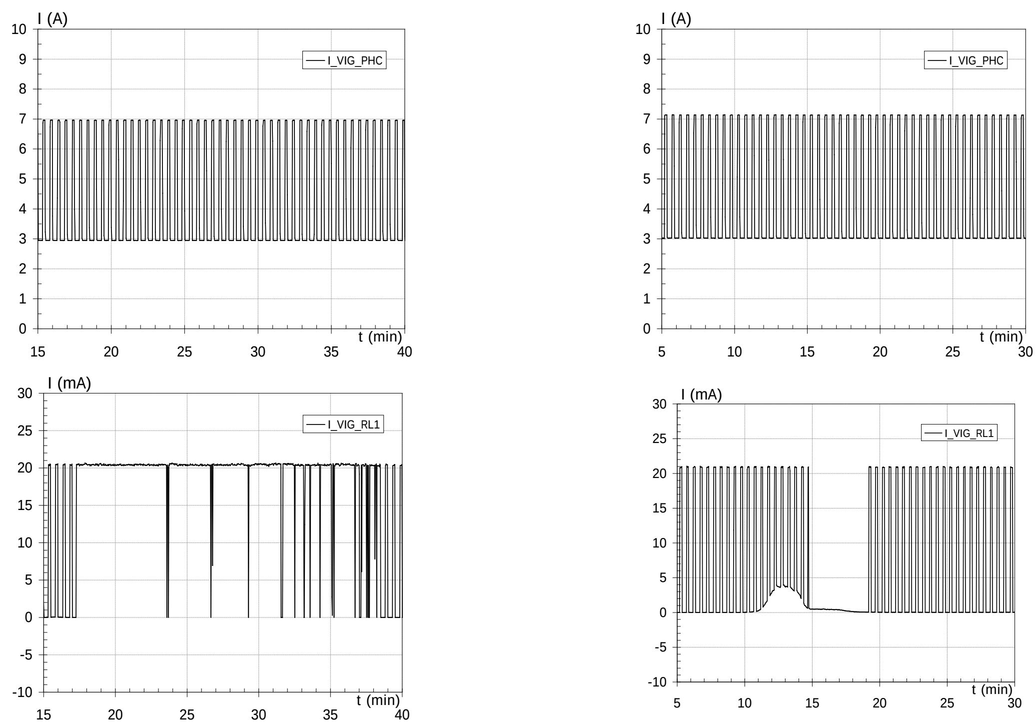


Figure 9 Current injection sequence for CATHODE SUIES tests

Analysis of Temperatures during Malfunction in CATHODE SUIES

The responses of the VIGIRACK relay enable to identify a phase of malfunction of the equipment during the fire phase of the electrical cabinet, for the two CATS-VIG.1 and CATS-VIG.4 tests, for which the relay was located at the upper part of the room (1.80 m from the ground). No malfunction was observed on the VIGIRACK relays located at 0.55 m from the ground during the CATS-VIG.2 and CATS-VIG.3 tests.

In contrary to the purely thermal malfunctions observed in CATHODE, where failures were a sharp and abrupt interruption of the output signal, malfunctions observed in real fire situations, having an origin related to the impact of the smokes, show sporadic, partial and temporary alterations of the output signal. A focus on the malfunctioning phase allows observing different modes of failure according to the test (see Figure 10). For the CATS-VIG.1 test (see Figure 10a), the equipment malfunctioned abruptly and then resumed functioning sporadically to operate normally again continuously. For the CATS-VIG.4 test (see Figure 10b), a first "partial" malfunction occurs during which the current loops did not fully open. This phase was followed by a complete malfunction of the equipment and then by a sudden and continuous restart of the relay VIGIRACK.



(a) (b)

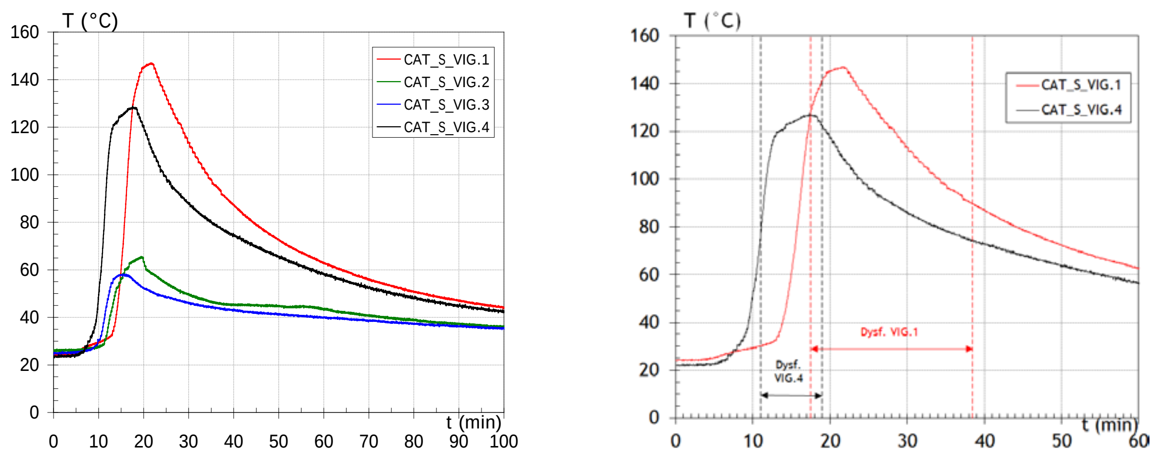
Figure 10 Electrical solicitations and responses of output relay RL1; (a) CATS-VIG.1 test ; (b) CATS-VIG.4 test

In the time base originating from the electrical cabinet ignition, the malfunctioning times noted in Figure 10 are synthesized in Table 3.

In addition to the different modes of malfunction discussed above, the time and duration of failures are also different between the two tests. In contrary, time evolution of temperatures (see Figure 11a) for the two malfunction tests have a similar shape, attesting to a certain thermal reproducibility between the CATHODE SUIES tests.

Table 3 Synthesis of the malfunctions phases obtained in CATHODE SUIES tests

Name of test	Appearance time of malfunction	Duration of malfunction	Types of malfunctions
CATS-VIG.1	17 min 30 s	21 min	- Total malfunction between 17 min 30 s and 23 min 30 s - Sporadic signals between 23 min 30 s and 38 min 30 s
CATS-VIG.4	11 min	8 min	- Partial malfunction between 11 min and 14 min30s - Total malfunction between 14 min30 s and 19 min



(a) (b)

Figure 11 Gas temperature developments over time around VIGIRACK relay for the 4 tests; (a) occurrence time and duration of the malfunction projected on the temperature curves in CATS-VIG.1 and b) CATS-VIG.4 tests

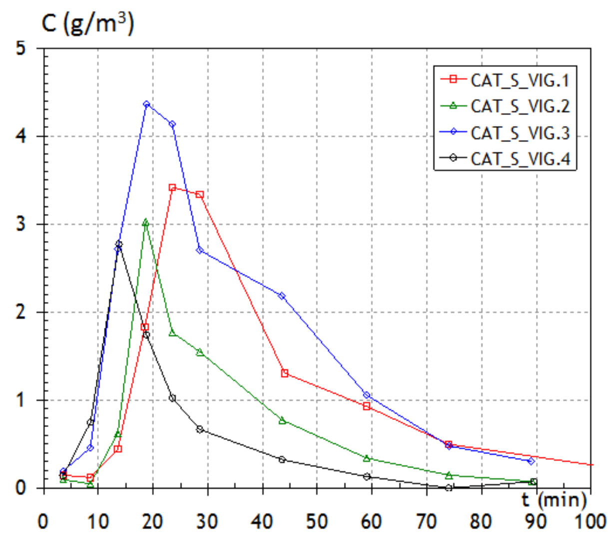
In Figure 11a, the maximum temperatures occur between 15 min and 22 min after the cabinet ignition and reach 57 °C and 65 °C, respectively for CAT_S_VIG.3 and CAT_S_VIG.2 (tests with the VIGIRACK relay at 0.55 m height) and 127 °C and 147 °C respectively for CAT_S_VIG.4 and CAT_S_VIG.1 (testing with the VIGIRACK relay at 1.80 m height). For these two last tests, the malfunction occurred respectively at 75 °C and 128 °C (see Figure 11b). The return of a normal functioning is obtained for 90 °C (CAT_S_VIG.4) and 122 °C (CAT_S_VIG.4). It is therefore difficult to link the malfunction phase with a temperature threshold of the surrounding gases, in the situation of unsteady state real fire.

Recall that the CATHODE tests made it possible to evaluate a critical ambient temperature of malfunction around 160 °C. The CATHODE SUIES test results show clearly that, in real fire conditions of exposure, the malfunction of the same equipment (VIGIRACK relay) occurs at much lower ambient temperatures (75 °C).

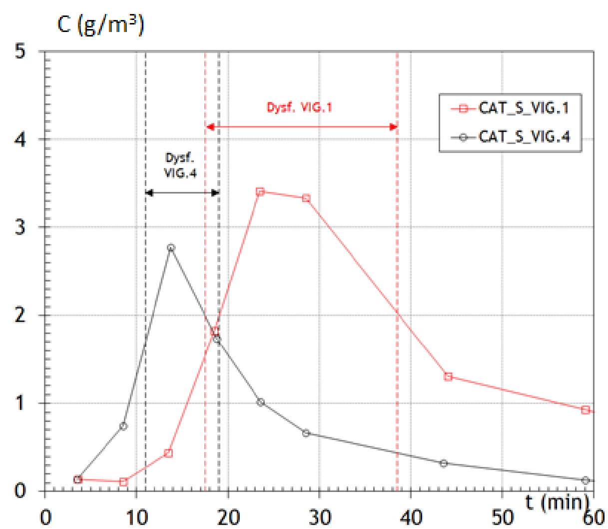
During the tests in the DIVA facility, the suspicion of soot contained in smokes was confirmed by the fact that no malfunction occurred during the eight-day period following the end of the tests (continuous monitoring of the electrical state of equipment). This well-functioning observed over several days, on equipment temporarily malfunctioned during the tests, excludes a corrosive origin of the failures observed during the fire tests (corrosion causing irreversible physicochemical damage on the components).

Analysis of Soot Concentrations

First, the time evolutions of the mass soot concentration (derived from concentrations measured close to the relay by sequential sampling on filters, averaged over the sampling time) have a similar shape for the four CATHODE SUIES tests (see Figure 12 (a)), reflecting a certain homogeneity of the soot concentrations for the different tests.



(a)



(b)

Figure 12 Mass soot concentrations near the VIGIRACK relay (CATHODE SUIES) - Time evolution for the 4 tests (a) - Occurrence time and malfunction duration projected on the soot concentration curves in CATS-VIG.1 and CATS-VIG.4 tests (b)

The graphical representation in Figure 12 (b) of the malfunction phases shows a coincidence between failure of relay and high values in soot concentrations. By linear interpolation, in terms of soot concentrations, the relay malfunction phase starts at 1.6 $g.m^{-3}$ and ends at 2 $g.m^{-3}$ for the CATS-VIG.1 test, and starts at 1.7 $g.m^{-3}$ and finishes at 1.7 $g.m^{-3}$ for CATS-VIG.4. These values are very similar and could indicate minimum values of soot concentrations that may induce a malfunction of the VIGIRACK relay.

Mapping of Normal and Malfunction States on a Diagram (T; Cs)

The previous experimental observations don't allow to determine a common failure criterion based on a single component (critical gas temperature and/or critical soot concentration), in a real fire environment. As a result, a relationship between the operating state of the VIGIRACK relay and a combined effect between ambient temperature T and soot concentration Cs is sought.

To do this, the coordinate points (T; Cs) around the relay are determined every minute on the first hour of the cabinet fire, and reporting on the diagram in Figure 13. The arrows indicate the direction of time during the tests. These points are coloured in blue if the relay operates correctly and red if it malfunctions at the record instant. To these points is added the single point corresponding to the critical temperature of VIGIRACK relay obtained by the analytical CATHODE tests carried out in the SIROCCO device, for which the concentration of soot was zero.

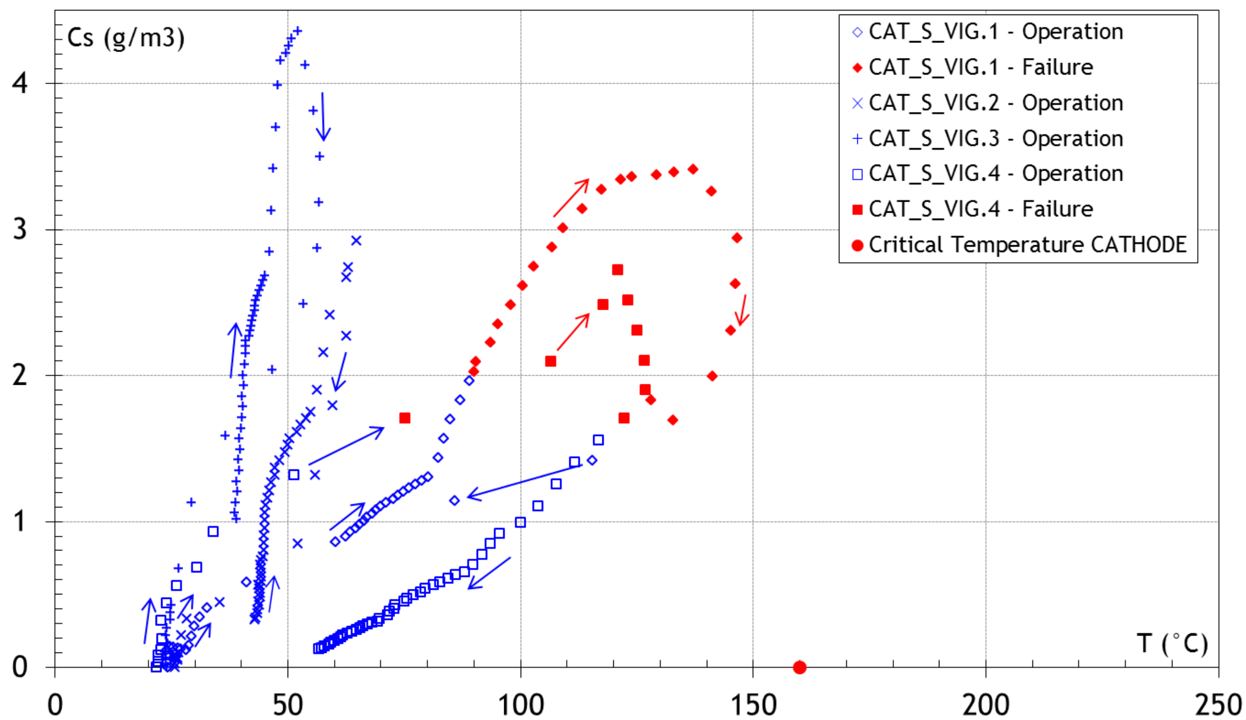


Figure 13 Electrical state of the VIGIRACK relay on a diagram (T: ambient temperature; Cs: soot concentration)

This mapping shows the combined effect of the soot concentration and the ambient temperature on the electrical state of the VIGIRACK relay. In Figure 14, it can be seen that the electrical state of the relay can either be into a domain of good operation (green range) or into a malfunctioning domain linked to a combined effect of temperature and soot (orange field), or in a thermal malfunction domain (in red). In the last case, the internal temperature of the equipment will exceed, at thermal equilibrium, the operating temperature limit of the internal components, with or without surrounding soot.

CATHODE SUIES tests have clearly shown that in a real fire environment, the VIGIRACK relay may malfunction beyond a certain level of soot concentration at temperature below the critical ambient temperature of 160°C determined in purely thermal mode in the CATHODE program.

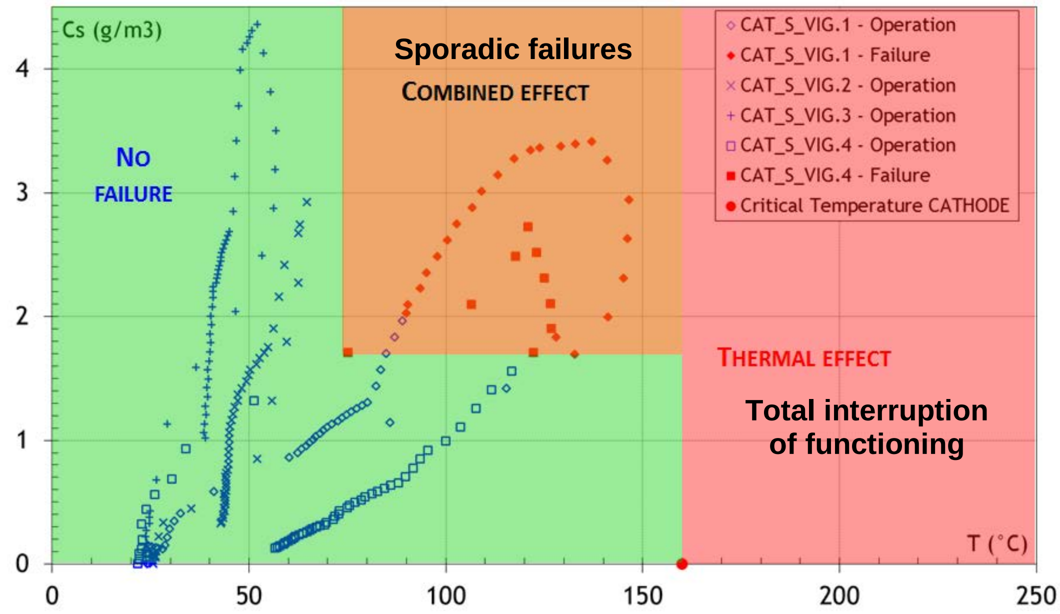


Figure 14 Electrical behaviour according to the temperatures and the soot concentrations of the environment: absence of failure, combined effect and thermal effect

CONCLUSION

The CATHODE and CATHODE SUIES experimental programs provide fundamental elements in the study of the malfunctions of real electrical equipment exposed to a fire environment. In the first place, the CATHODE thermal study, in steady state temperatures, allowed determining a critical malfunction temperature (160 °C) which far exceeds the recommended limits of the manufacturers. The malfunctions observed in CATHODE tests are linked to internal overheating and lead to an irreversible damage to the internal electronic components. This thermal destruction causes a definite interruption of the output relays, which no longer trigger after input solicitations and permanently lose their operability.

On the other hand, the subsequent CATHODE SUIES study showed that smokes generated by a real fire causes temporary electrical malfunctions for sub-critical temperatures compared the results obtained in the purely thermal mode (from 75 °C). Smokes and soot in particular, constitute clearly disturbing agents that promote the occurrence of an electrical malfunction. It is recalled that soot was suspected to be the malfunction agent, after the fact that no malfunction has been observed on the equipment during the eight-day monitoring period, following the fire tests (excluding corrosion as the origin of malfunctions observed during the fire tests).

But at this level of knowledge, CATHODE SUIES test results are not sufficient to understand finely the mechanisms explaining the occurrence of an electrical failure by the presence of smokes. One hypothesis, however, is to attribute to the conductivity properties of the soot particles the temporary character of the observed malfunctions.

In any case, the understanding of the mechanisms of malfunction of an electrical equipment requires to carry out other large-scale tests, but also analytical tests with a device able to expose an equipment to calibrated and regulated soot concentrations (in addition to the temperature, hence an evolution of SIROCCO). In order to do this, the DELTA experimental campaign, performed in the DANAIDES device of IRSN, is under development and should give interesting results on this subject, notably by characterizing more finely the coupling effect of the soot concentration and the temperature.

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FIRE-RETARDANT CABLE COATINGS – A FRESH LOOK INTO THEIR ROLE IN RISK-INFORMED PERFORMANCE-BASED APPLICATIONS

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ABSTRACT

Flame or fire-retardant electrical cable coatings have been used in commercial nuclear power plants to limit the spread of fire. A limited set of empirical data from the 1970s provides the basis for regulatory guidance. Over the past decade, nearly one-half of the U.S. nuclear fleet has voluntarily transitioned from prescriptive- to performance-based, risk-informed fire protection programs. Performance-based programs require quantification for the performance of these coatings. Difficulties were encountered using the prescribed guidance in a performance-based context, necessitating a fresh look into the performance of fire-resistive cable coatings.

In an effort to quantify the performance of flame-retardant cable coatings, the U.S. Nuclear Regulatory Commission (NRC) has sponsored a variety of experiments at Sandia National Laboratories (SNL) and the National Institute of Standards and Technology (NIST). A literature survey and regulatory review of the subject has been performed to provide a historical perspective on the use of cable coatings in nuclear facilities. An experimental series has evaluated the burning behaviour and temporal effects on circuit functionality for a variety of flame-retardant cable coatings. The experiments ranged from bench to full scale, using both standardized and non-standardized testing techniques.

Ignition temperatures have been measured using a well-controlled convection oven. Burning behaviour of coated cables has been measured using a cone calorimeter to determine burning rate, heat of combustion, and other properties. Full-scale horizontal and vertical flame spread experiments have been conducted to determine lateral and upward spread of fire. Finally, the impact of flame-retardant cable coatings on preserving circuit integrity during fire exposure has been evaluated. The results from this experimental series support updates to existing fire probabilistic safety assessment methods and fire modelling input parameters.

INTRODUCTION

The Browns Ferry Nuclear Plant Fire of 1975 prompted a new series of fire protection regulations and research including research in cable fires and flame-retardant cable coating materials [1]. The NRC Branch Technical Position (BTP) APCSB 9.5 1 "Guidelines for Fire Protection for Nuclear Power Plants" [2], provided the guidelines for protecting nuclear power plants from the adverse effects of fire. The BTP document directed licensees to have a fire protection program (FPP) and conduct a fire hazard analysis (FHA). As part of the FPP and FHA, the licensee performed bounding deterministic evaluations to estimate the area's fire fuel loads of combustible material. These fire loads included contributions from in-situ cables as well as transient combustibles. The fuel loads were used to establish the adequacy of passive fire barriers and fire protection systems in place at the time. During plant modifications, the fire fuel load and fire protection ratings also served as the basis to evaluate the possibility of adding transient combustibles.

In the first revision of the BTP ASB 9.5 1, the NRC required that electrical cable construction should, as a minimum, pass the flame test of the Institute of Electrical and Electronic Engineers (IEEE) standard IEEE 383-1974 [3] (typically referred to as qualified cables) and specified that even cables meeting the passing criteria could require other forms of fire protection. In this document, the NRC recommended that nuclear power plants (NPPs) add fire breaks along vertical and horizontal cable routings, and many plants applied fire-retardant cable coatings to satisfy the requirement.

In the late 1990s, the NRC staff revisited the strategy described in SECY-98-058 [4] and initiated work on an alternative risk-informed/performance-based fire protection rule. In the early 2000s, the NRC reviewed and accepted, with exceptions, NFPA 805 "Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants" as an alternative method for fire protection requirements of 10 *Code of Federal Regulations* (CFR) 50.48. In 2005, the Electric Power Research Institute (EPRI) and the NRC jointly published a fire probabilistic risk assessment (PRA) methodology for NPPs, EPRI-1011989 / NUREG/CR-6850, "Fire PRA Methodology for Nuclear Power Facilities" [5]. This Fire PRA methodology supported licensee use of risk tools to support NFPA 805 licensing applications to evaluate a fire's impact on reactor safety. Implementation of the fire PRA methodology necessitated the use of fire models, which require specific input parameters (e.g., heat release rate). Appendix Q of NUREG/CR-6850 addressed passive fire barriers including flame-retardant cable coatings. However, the data and criteria specified in this appendix were based on the limited data that was developed during previous research programs of the 1970s.

In the early 2010s, questions arose about the adequacy of the flame-retardant cable coating data of the 1970s and the implementation guidance provided in NUREG/CR-6850. A new research program was developed to obtain data of burning behaviour (e.g., ignition temperatures, flame spread, heat release rates, etc.) and electrical functionality response (i.e., circuit failure times) typically used in fire protection analysis, fire modelling, and fire risk assessment of NPPs. This paper will discuss preliminary results that were obtained under the testing performed at SNL and NIST under the auspices of the NRC.

RESEARCH PROGRAM DESCRIPTION

Under this research program, the properties of several cables and flame-retardant, cable-coating materials typically used at NPPs were evaluated. Two cable types were primarily tested; a thermoset cable with good fire resistive properties (i.e., passes flame spread test such as that in IEEE 383-1974 and/or IEEE 1202-1991) and thermoplastic cable with poor fire resistive properties (i.e., will not pass the flame spread test in IEEE-383/1202). Combinations of the cables and flame-retardant materials were tested. The cables and flame-retardant materials tested are listed in Table 1 and Table 2, respectively. The cables described in Table 1 are referred to as qualified if they have passed requirements of IEEE-1202 standard or as unqualified when not meeting the standard passing requirements.

Table 1 Primary test cable descriptions*

Test Cable No. ID	Insulation Material	Jacket Material	Year Manufactured	Description
802	XLPE	CSPE	2006	Qualified, Thermoset, 7-conductor cable
807	PE	PVC	2006	Unqualified, Thermoplastic, 7-conductor control cable
813	XLPE	CSPE	2006	Qualified, Thermoset, 12-conductor cable
900	PE	PVC	2015	Unqualified, Thermoplastic, 7-conductor control cable
902	PE	PVC	1975	Unqualified, Thermoplastic, 3-conductor cable
*Other cables have been evaluated under past NRC research programs.				

Table 2 Flame-retardant coating material used in testing

Flame-retardant material	Description
Carboline Intumastic 285	Product of the Carboline Company. The coating material is described as a water-based mastic that can be applied to impede fire propagation along the length of coated electrical cables.
Flamemastic F-77	Product of the Flamemaster Corporation. Manufacturer literature describes the coating material as consisting of water-based thermoplastic resins, flame-retardant chemicals, and inorganic, incombustible fibers. Moreover, literature describes It as a non-intumescent, thixotropic compound with no asbestos. Two product variations are available—one is appropriate for spraying and the other is mastic, the latter of which was used in the experiments.
Vimasco 3i	Product of the Vimasco Corporation. The manufacturer described the material as "a heavy-bodied, water-based intumescent coating that is designed to prevent flame spread along the jacketing of electrical (or other) cables and to provide a thermal barrier for protection against heat damage."
Fire Security Systems FS15	Product of Fire Security Systems. Water-based ablative coating made be Fire Security Systems. Its primary mode of protection is ablation as opposed to thermal insulation. This product is not used in U.S. NPPs.

To obtain data on the fire properties of these materials and their electrical response (i.e., circuit failure times) under fire conditions, several bench-scale and full-scale tests were performed. Bench-scale tests were performed to obtain data on properties of the materials while the purpose of full-scale tests was to have representative data on more representative configurations found at NPPs.

Thermogravimetric Analysis, Calorimetry, and Furnace Ignition Tests

The purpose of the bench-scale thermogravimetric analysis (TGA), micro-combustion calorimetry (MCC), cone calorimeter, and furnace ignition tests was to obtain data on the cable coating materials. This data includes density, heat capacity, thermal conductivity, mass loss as a function of temperature, heat of combustion, heat release rate, and ignition temperatures of the materials.

For the furnace ignition tests, coated and uncoated cable segments were placed within a convection oven and heated gradually until ignition was observed, and the temperature was measured with thermocouples at various depths within the cable. The objective of the experiments was to determine if the coatings increased the “effective” ignition temperature of the cable. The quotation marks are added to emphasize that ignition temperature is not a well-defined quantity in fire science. The temperature at which a solid object ignites is not only a function of the material properties but also the geometrical configuration of the solid. For example, bundled cables might ignite at a lower effective temperature than a single cable simply because the bundle produces fuel vapours at a high enough concentration to sustain flames whereas the single cable does not.

In general, uncoated thermoplastic cables ignited at temperatures in the neighbourhood of 300 °C (572 °F), whereas thermoset cable ignited in the neighbourhood of 400 °C (752 °F). However, some cables would exhibit periodic “flashing” at relatively low temperatures but would not experience sustained flaming conditions until higher temperatures were reached.

The results from this work indicate that the coatings did not systematically increase the effective ignition temperature of the cables. In fact, the bench-scale TGA and MCC and the cone calorimeter measurements indicate that the coatings pyrolyze in the neighbourhood of 350 °C (662 °F) and do contribute to the volatized fuel vapours, albeit weakly. The coatings are not designed to prevent pyrolysis and ignition but rather to delay it by slowing the heat penetration through the coating and into the cable.

These test methods have been used in past NRC tests to obtain this data on cable properties (e.g., NUREG/CR-7010 [6]) and have been used in the development of uncoated cable fire models such as the Flame Spread over Horizontal Cable Trays [6] and the Thermally-Induced Electrical Failure (THIEF) model [7].

Circuit Integrity Test

The circuit integrity test found in the International Electrotechnical Commission (IEC) Standard 60331-11 [8] was used with some variations to measure the effect of cable coating thickness on the electrical response of the cables to fire conditions. The experiments are similar to those described in the IEC international standard 60331-11 with the main deviation from the test standard being that the burner had a nominal face length of 25 cm (10 in) rather than 50 cm (20 in) as specified in the standard. The width of the burner was nominally 1 cm. The propane and air flow rates flowing into the pre-mixed burner were half of what is called for in the standard—2.5 l/min propane and 40 l/min air at 1 bar and 20 °C, producing a 3.6 kW flame. Another deviation included the use of the Surrogate Circuit Diagnostic Unit (SCDU) to characterize the electrical response rather than the “light bulb” test specified in the standard[1]. Figure 1 shows a typical experiment. In this experiment, a single cable, either coated or uncoated, was immersed in a pre-mixed propane-air flame generated by a line burner.

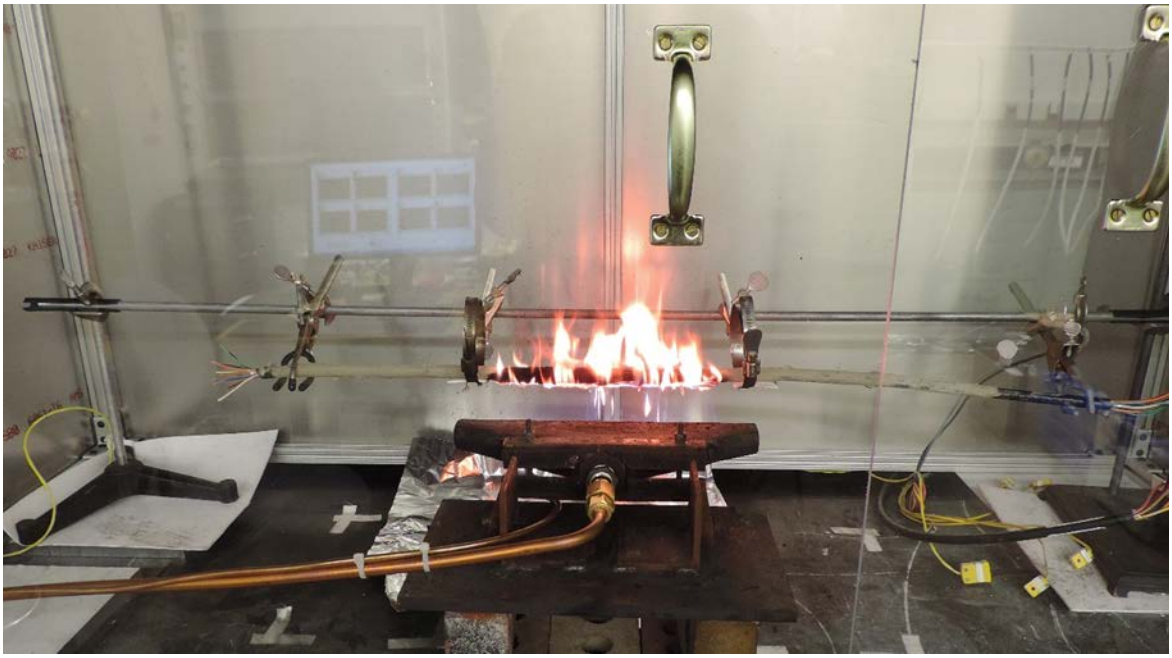

Figure 1 Photograph of a typical circuit integrity experiment

Per the standard, each test evaluated a single cable and as such, temperature and electrical integrity measurements could not be done within the same cable due to electrical “cross talk” between the instruments. Thus, for each test sample, separate experiments were conducted - one for circuit integrity and one for temperature measurement. Experiments involving coated cables were repeated three times (i.e., three circuit integrity experiments were performed and three temperature measurements were performed). For the circuit integrity experiments, three circuit pairs were energized with 120 V AC, and the cable was heated until a 3 A fast-acting fuse cleared, indicating circuit failure.

The average time to circuit failure of three replicate experiments and the corresponding cable interior temperature at the time of failure was obtained. The results exhibit variations among cable type and coating materials. Figure 2 shows the box plots for the results of circuit integrity tests for all unqualified thermoplastic cables uncoated and coated. Table 3 summarizes the results of the circuit integrity experiments.

[1] Previous NRC experience with “light bulb” functionality testing, also referred as circuit integrity monitory, indicated a weakness in test acceptance criteria where the fire could damage the cable insulation, but the electrical conductors did not come in contact with each other or short to ground. This would provide false acceptance of the test [11], [12].

Table 3 Summary of results of the circuit integrity experiment

Cable	Average Failure Time Uncoated cable	Delay in Failure Time	
		Coated to 1.6 mm (1/16 in or 62.5 mil)	Coated to 3.2 mm (1/8 in or 125 mil)
Unqualified cable 900	6.3 min	10.1 min	23.3 min
Qualified cable 913	4.1 min	3.4 min	12.8 min

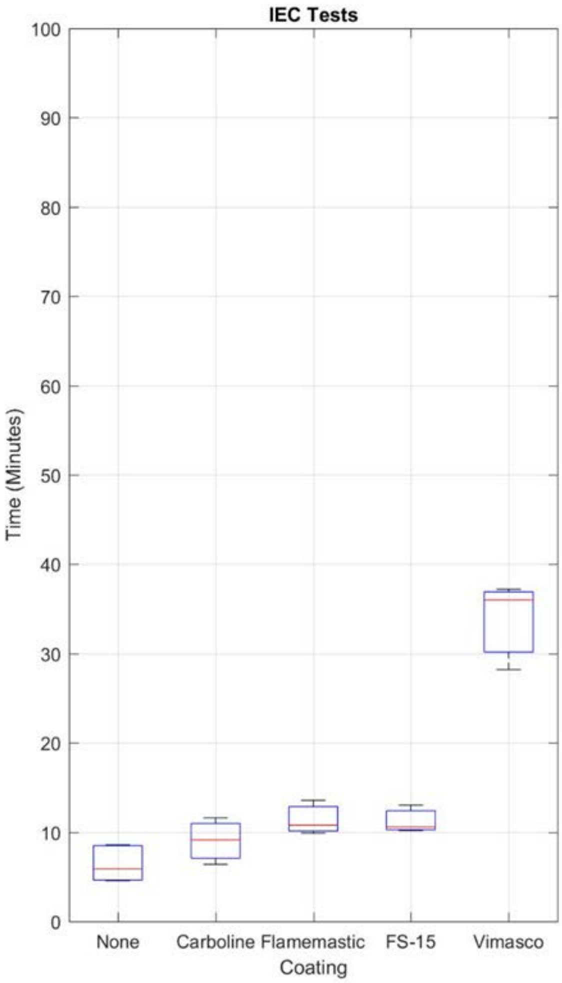

Figure 2 Time to failure box plots of circuit integrity (IEC) tests for all unqualified thermoplastic cables uncoated and coated

Full-scale Tests

The full-scale tests that were performed included radiant heat (described in section 3.2 of NUREG/CR-6931 [9]), IEEE standard 1202-1991 [10] (supersedes the flame spread requirements of standard IEEE 383-1974 [3] in nuclear industry requirements) vertical flame spread test, and multi-tray horizontal fire tests intended to represent typical tray configurations at NPPs.

For full-scale tests, cable electrical and temperature response were monitored. Two different electrical integrity measurement systems were used to monitor electrical response. The first system, the Insulation Resistance Measurement System (IRMS), measures actual insulation resistance between the conductors of a multi-conductor cable and between the conductors and ground. This system was only used during the SNL radiant experimental series. The second system, the SCDU, simulates a 120 V AC control circuit for a motor-operated valve (MOV). Both SNL and NIST experimental series used the SCDU system to monitor circuit integrity[2]. The cable's temperature response was measured beneath the cable's outer jacket (sub-jacket). This technique has been used in several prior test programs [6], [9]. Prior testing has shown that the cable insulation temperature is well correlated to electrical failure, and the sub-jacket thermocouples provide a reasonable measure of the cable insulation temperature.

Penlight Apparatus Radiant Heat Tests

The Penlight is a radiant heating apparatus shown in Figure 3 a., which uses computer-controlled, water-cooled quartz lamps to heat a thin, intermediate Inconel steel shroud. The shroud is painted flat black and acts as a grey-body radiant heating source, re-radiating heat to a test sample (cables for these experiments) located within the shroud. The exposure temperature is monitored and computer-controlled based on thermocouples mounted on the inner surface of the shroud. Penlight creates a radiant heating environment analogous to that seen by an object enveloped in a fire-induced, hot-gas layer or in a fire plume outside the flame zone. Test included cable trays loaded with a mirror image of two cables or bundles where one was monitored for temperature and the other for electrical response.

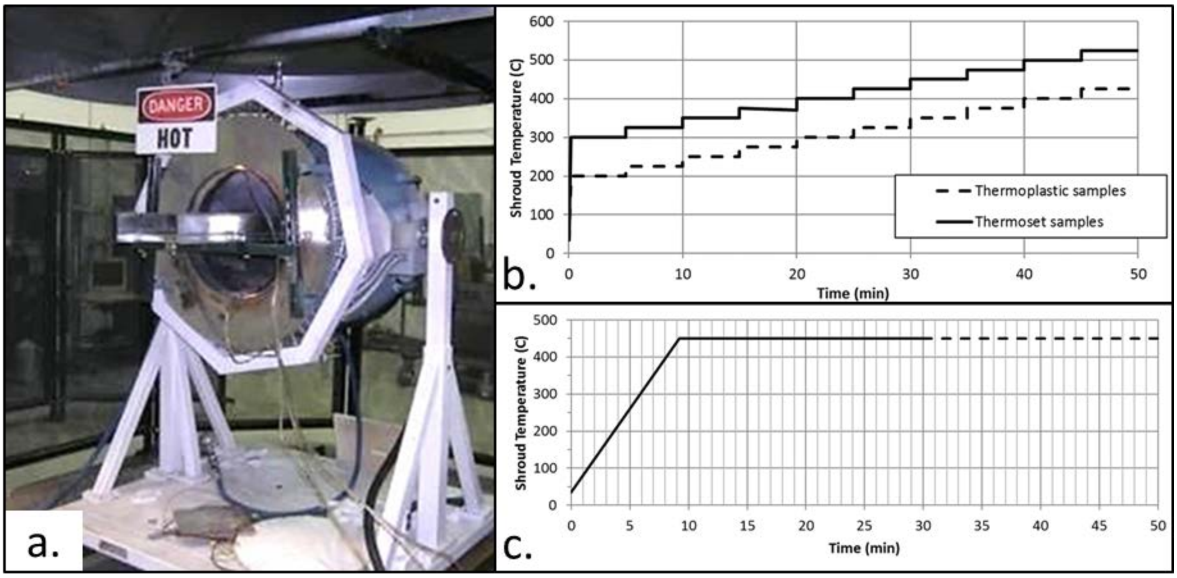

Figure 3 a. Penlight apparatus; b. Heating profiles using step-wise increases 25 °C (77 °C); c. Shroud temperature profile used in the final test set involving ten-cable bundles

All of the experiments performed in this series were conducted on a 30 cm wide (12 in), ladder-back style cable tray suspended through the centre of the Penlight shroud. Two temper-

[2] A detailed discussion of the IRM and SCDU instrument hardware can be found in Appendix B and C of NUREG/CR-6931 Volume 1 [9].

ature profiles were used for the tests shown in Figure 3 b. and Figure 3 c.. The step-wise profile was designed to nominally represent a transient fire development profile. For the larger 10-cable bundle tests, a ramp-and-hold profile was used to represent typical fire behaviour.

Cables 802 and 807 were used for this test. Samples tested were either in single cable, 7-cable bundle, or 10-cable bundle configurations and were tested uncoated or coated with one of the flame-retardant coatings (FS15 was not tested in this test as this coating was added later in the research program).

A total of 35 tests were performed. For single cable configurations, the test showed that coated samples (at the manufacturer recommended coating thickness of 1/16 inch (1.6 mm)) had little to no delay in electrical failure time when compared to the uncoated sample failure time. The bundle configurations showed at least five minutes of delay to electrical damage from that of the uncoated sample failure time.

Vertical Flame Spread Test

The vertical flame spread test was based on modified version of the flame spread test found in IEEE 1202-1991. Modifications included a removal of one of the walls to allow for video recording, increased burner times (i.e., test until electrical failure or 90 min, whichever came first), and use of the SCDU to monitor electrical response during the test. Two sets of tests were performed - one involving non-energized cables and the second with cables energized and thermally monitored. The objective of the experiments is to confirm that cable coatings prevent upward flame spread and to quantify the delay in electrical failure afforded by the flame-retardant coatings.

Cables 813, 900, and 902 were tested uncoated and coated with coatings identified in Table 2. A total of 41 tests were performed. Electrical response with the SCDU was monitored only in 20 of these tests. Flame spread beyond the test failure criteria (i.e., 1.5 meter above burner) and to the top of the tray in tests with uncoated cable 900 and 902. In one test of cable 900 coated with Flamemastic F-77, the flame spread 1 meter above the burner. In one test of cable 900 and Vimasco 3i, the test spread to 2 meters above the burner. In both these tests, the applied thickness was slightly less than the manufacturer-recommended value. All other coated samples (including repeats of cable 900 coated with Flamemastic F-77 and Vimasco 3i) as well as the uncoated cable 813 flame did not spread. Figure 4 shows a photo of the vertical flame spread test of uncoated Cable 900 and three of the coatings at nine minutes. The HRR for the uncoated test is about 220 kW while for the coated samples remained below 30 kW for each test.

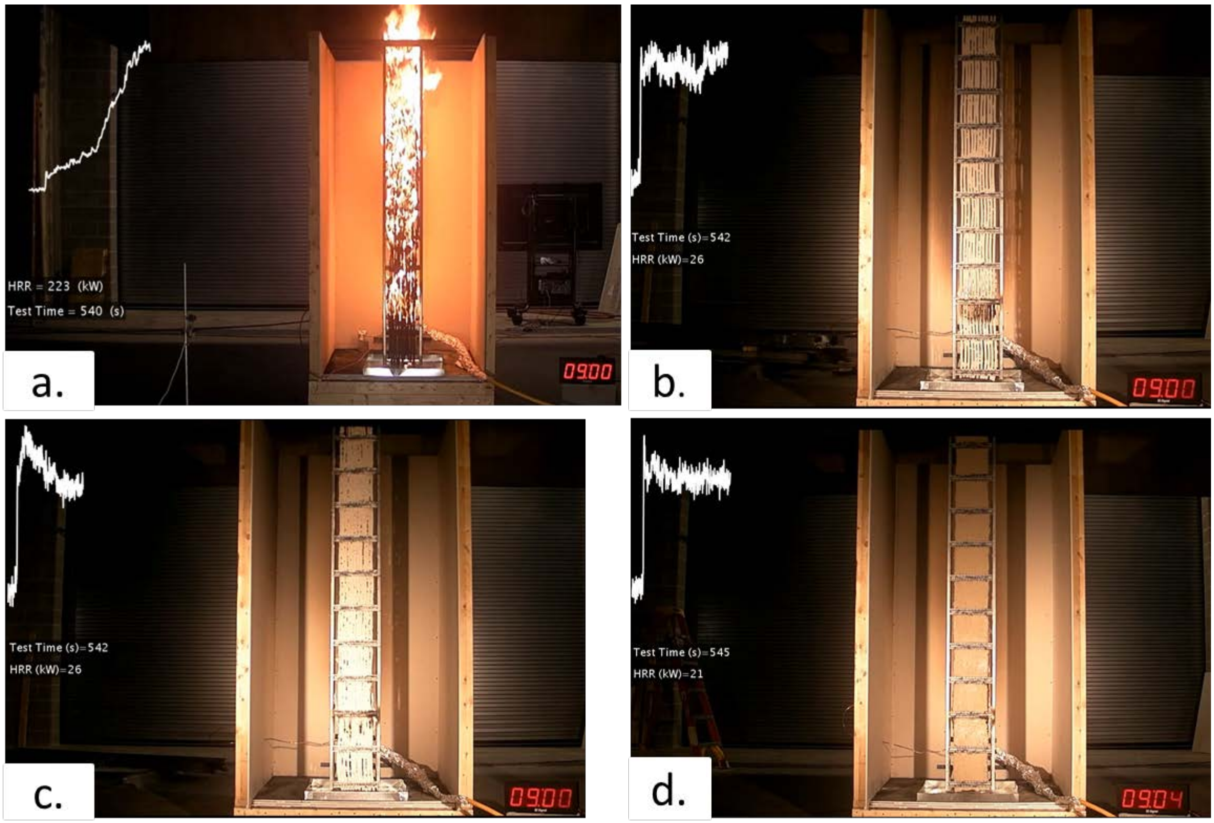

Figure 4 Vertical flame spread test with uncoated Cable 900 and the approximate HRR [kW] of the cable and burner at nine minutes: a. uncoated (approx. 223 kW); b. coated with Flamemastic F-77 (26 kW); c. coated with Vimasco 3i (26 kW); d. coated with Carboline Intumastic 285 (21 kW)

The electrical response of the cables was monitored on four cables located in the tray. The objective of the test was to determine the time when the electrical cable loses functionality and to compare the times of the uncoated sample to those of the coated samples to determine the delay in damage, if any. For thermoplastic cables, it was found that on average the application of cable coatings would delay the time to damage for at least several minutes. For thermoset cables, the application of cable coatings did not delay the time to damage. Figure 5 shows electrical time to failure box plots for IEEE 1202 test for cable 900 and cable 813 uncoated and coated. It is important to note that thermoset cables are typically not coated with flame-retardant cable coating materials unless they would share a tray with thermoplastics.

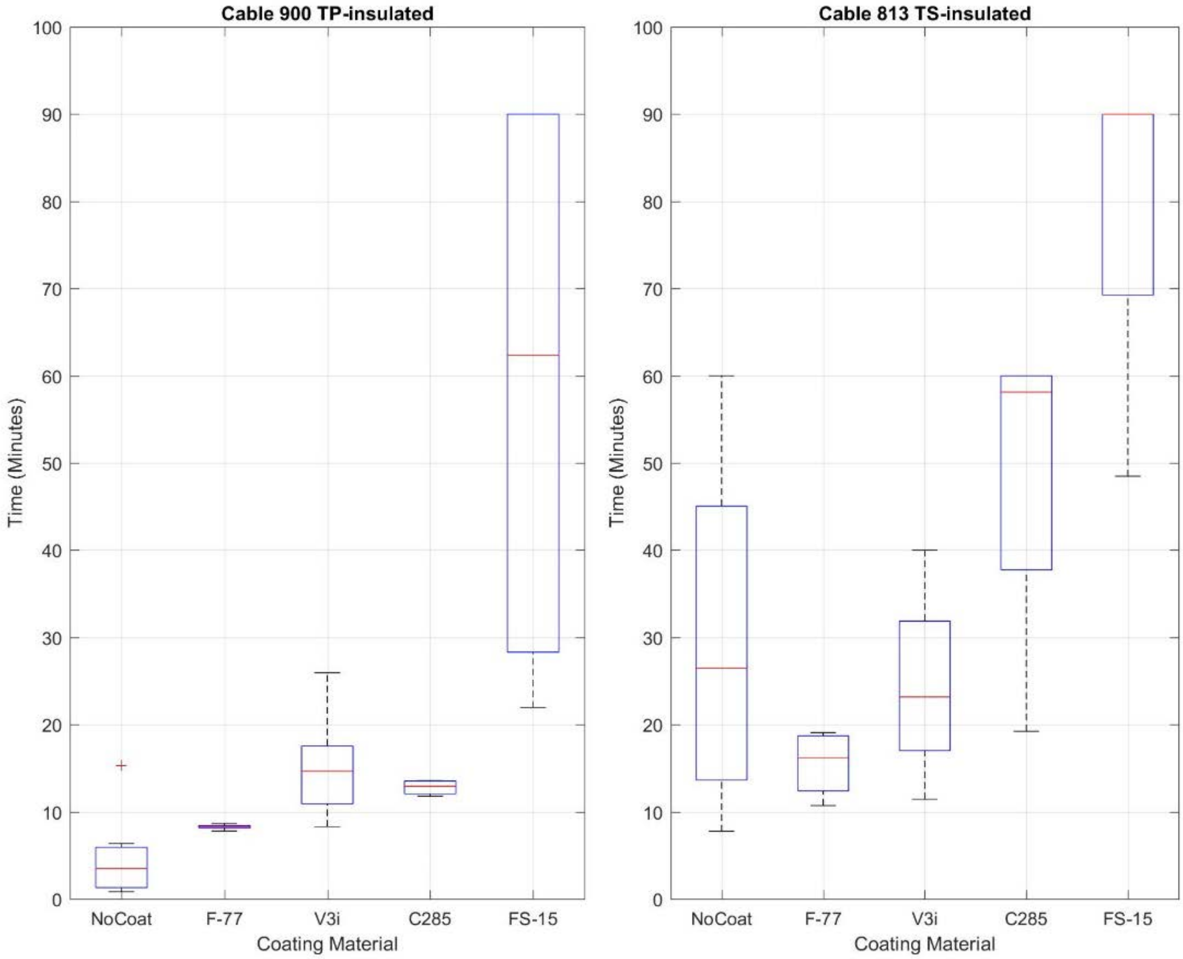

Figure 5 time to failure box plots of IEEE 1202 experiments for Cable 900 (left) and Cable 813 (right**)**

The test concluded that the four cable coatings tested in the vertical flame spread test prevented the flame spread of a fire from the 20 kW burner when applied according to the manufacturer recommendations. When flame-retardant coatings are applied, the HRR is substantially reduced as shown in Figure 6. The electrical response data shows that some delay to electrical failure could be assigned for unqualified thermoplastic cables coated with flame-retardant materials.

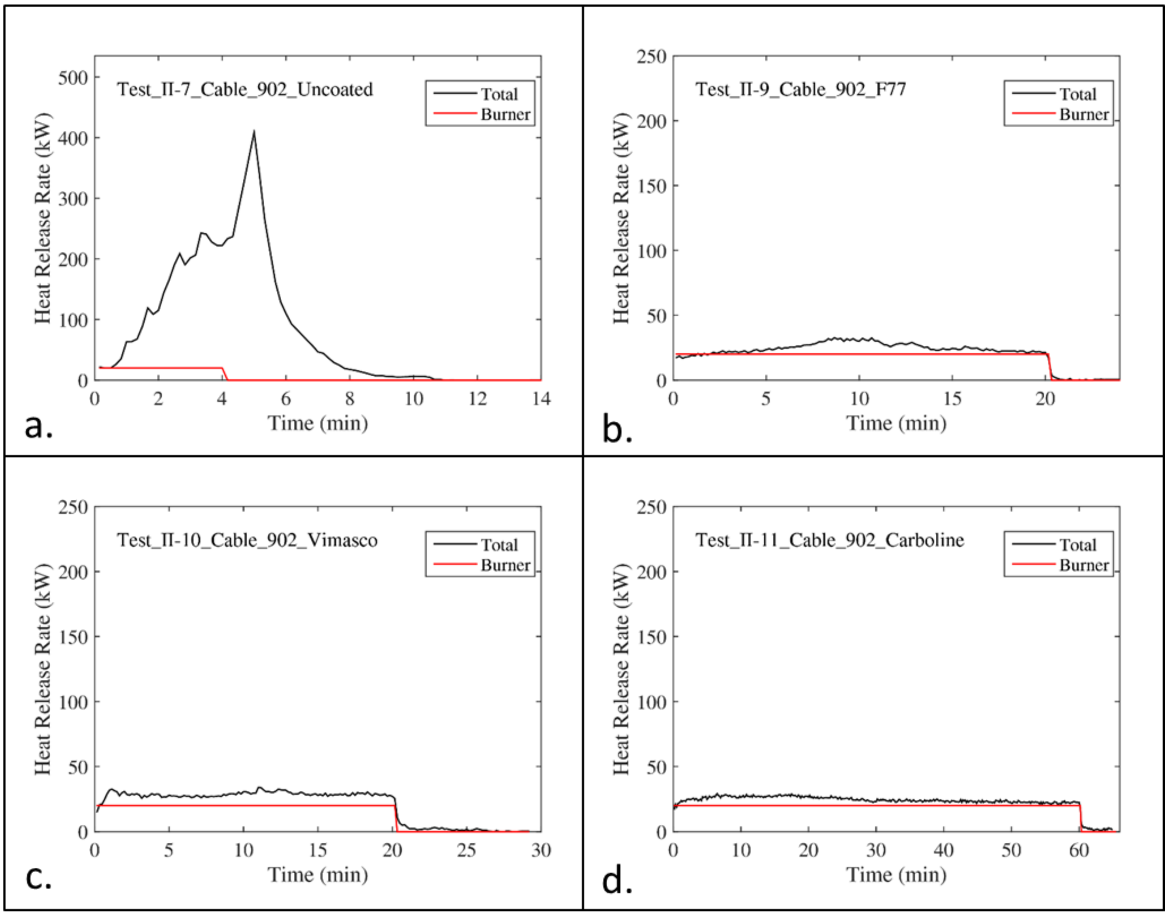

Figure 6 Cable 902 HRR a. uncoated; b. coated with Flamemastic F-77; c. coated with Vimasco 3i; d. coated with Carboline Intumastic 285

Multi-tray Horizontal Test

In this experimental series, horizontal cable trays containing coated and uncoated cables are exposed to a variety of thermal exposure conditions. The purpose of the experiments is two-fold. First, the circuit functionality will be evaluated using the SCDU unit to determine to what extent the various coatings delay electrical cable failure. Second, the experiments provide specific input parameters for performing fire model calculations including the HRR per unit area of tray, the lateral spread rate, and the vertical spread rate.

Figure 7 shows the test compartment, which is about 2.4 m (8 ft) long, 1.2 m (4 ft) wide, 2.4 m (8 ft) tall and is open all around the lower half. The upper half was lined with a layer of 1.6 cm (5/8 in) thick gypsum board covered with 0.6 cm (1/4 in) thick concrete board. The frame was constructed of steel studs. The compartment was positioned under an oxygen consumption calorimeter with a capacity of about 5 MW.

Four 30 cm (12 in) wide, 1.8 m (6 ft) long horizontal trays were positioned as shown in the figure, containing equal numbers of uncoated and coated cables. This arrangement allowed for direct flame impingement on the lowest tray, exposure to plume temperatures on the middle tray, and a gradual heating for the upper trays. All eight experiments used the un-qualified thermoplastic cable 900. Figure 8 shows the cables were arranged in the trays in two different configurations. For a given experiment, one coating and one cable arrangement was applied in all trays. The cables in the uppermost two trays dropped down from one tray to the other. In each tray, four cables were energized (yellow) and four cables were instrumented with thermocouples (red). Given that there were two cable configurations and four coatings, eight experiments were conducted.

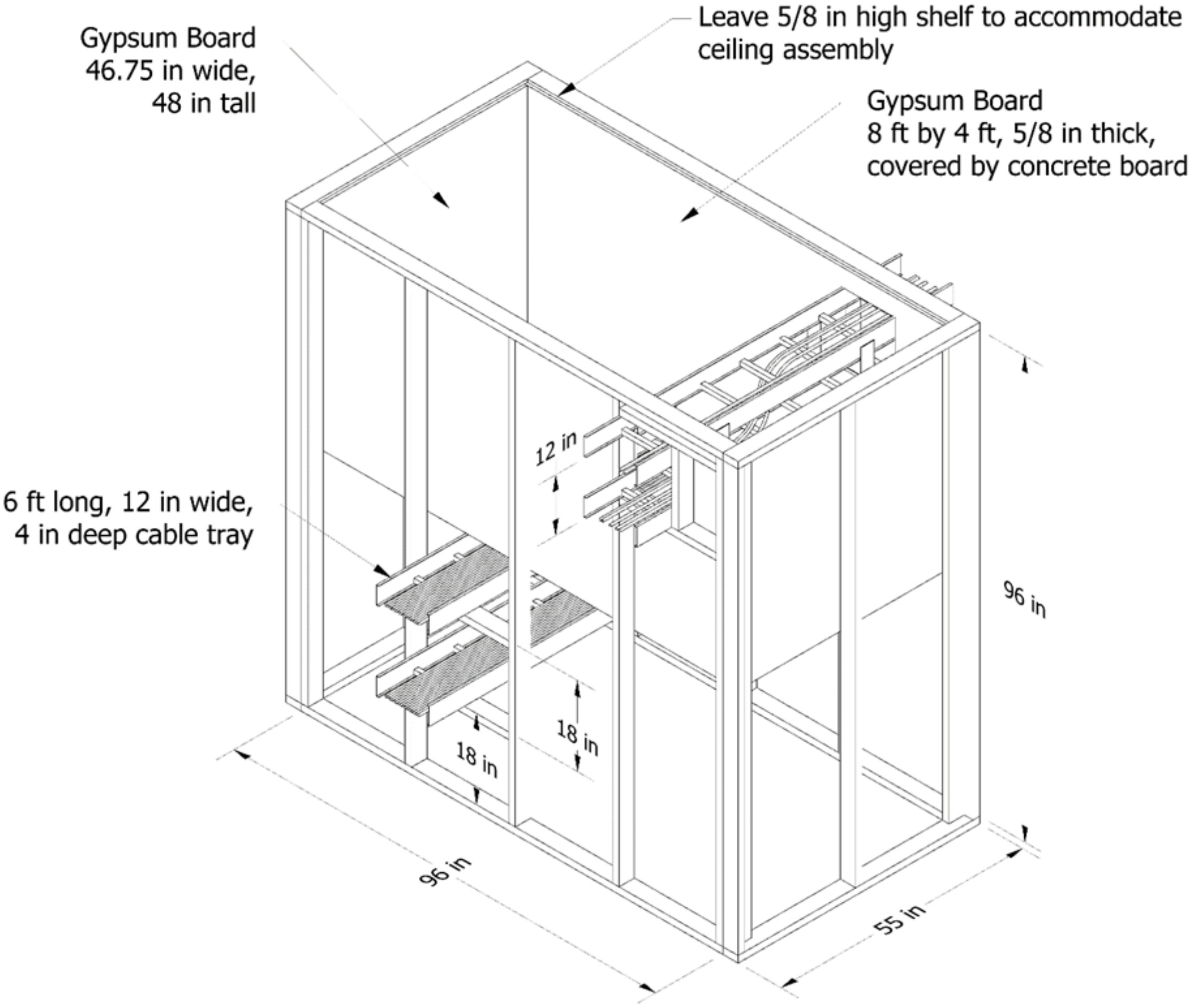

Figure 7 Compartment used on horizontal cable experiments

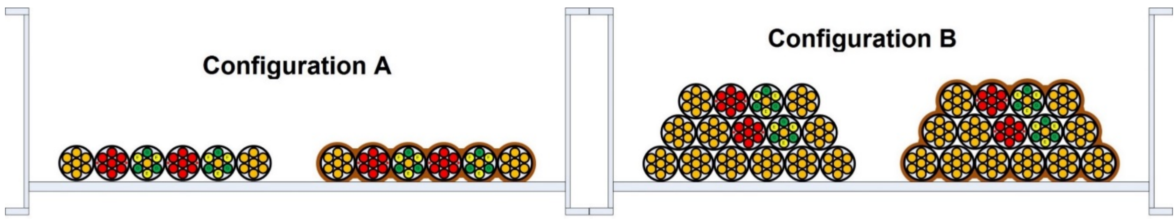

Figure 8 Schematic diagram of cable layouts. Configuration A is referred to as a “single row”, while B is referred to a “bundle”. Cables on the left of each configuration were uncoated, while the ones on the right were coated

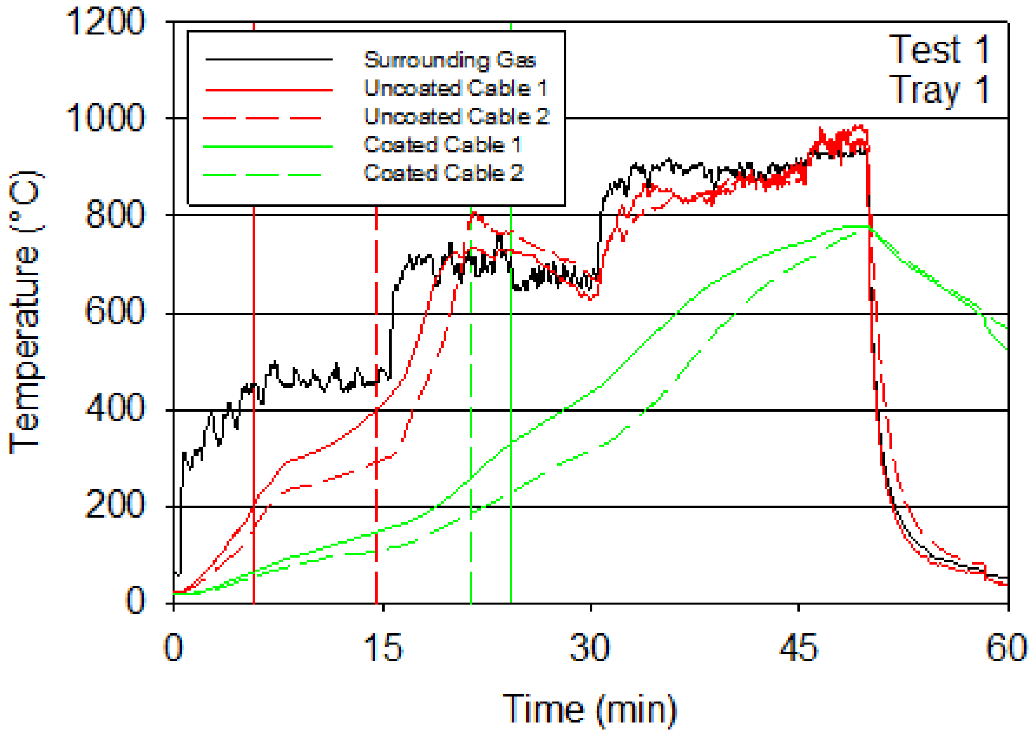

Figure 9 Horizontal Test 1, Carboline Intumastic 285 Coating, Tray 1 (i.e., lower tray) temperatures and electrical failure times

As shown in Figure 9, the temperatures and electrical response were monitored and plotted vs. time for each test tray. It was observed that the average time to failure for all uncoated cables in the single row configuration in Tray 1 was 7.8 min. The average delay time brought about by applying a protective coat for these same cables was 13.9 min. The average delay time for all cables in all trays was 13.3 min. The average interior cable temperature at the time of failure was about 300 °C (572 °F). The range of failure temperatures was considerable; from less than 200 °C to over 500 °C. The only clear trend for the failure temperature is that the cables in Tray 3, immersed in the hot gas layer, tended to fail at lower temperatures than the cables in Trays 1 and 2. Two possible explanations for this are that (1) these cables were subjected to a more gradual heating rate, and (2) these cables dropped from the upper tray to the lower tray, which were separated by 30 cm (12 in). This drop subjected the cables to a fairly tight bend radius (not exceeding the minimum bend radius) that would tend to draw the individual conductors closer together as the insulation underwent thermal and mechanical degradation.

In these experiments, the difference in performance among the four different coatings was not nearly as pronounced as in the bench-scale circuit integrity experiments discussed previously. Table 4 shows the average delay in time to failure for each cable coating and all trays and configurations.

Table 4 Average delay in time to failure for each cable coating

Flame-retardant cable coating	Average delay in time to failure
Carboline Intumastic 286	14.9 min
Vimasco 3i	11.6 min
Flamemastic F-77	10.4 min
FS-15	15.9min

CONCLUSIONS

The objective of this research program was to obtain thermal properties, ignition temperatures, burning rates, flame spread, and electrical response data of flame-retardant cable coating materials commonly used in U.S. NPPs. This data can be used to develop new models or to expand fire models that were developed to analyse uncoated cables. The data can also be used as input to fire risk assessments.

The furnace ignition tests did not demonstrate that the coatings increase the effective ignition temperature of the cables but rather delay the time to reach the ignition temperature. The burning rate of coated cables was measured at bench scale in the cone calorimeter. In general, the coatings delay the time to ignition, decrease the peak burning rate, and increase the total energy released because the coatings do add to the fuel load. The full-scale vertical and horizontal tray experiments indicate that even though the coatings might add to the overall combustible mass, they do effectively prevent the spread of fire and restrict it to the point of flame impingement. The amount of additional energy released due to the application of coatings is negligible.

The vertical flame spread tests showed that the coatings prevented the upward flame spread of fire from the 20 kW burner when applied according to the manufacturers' recommendations. In several experiments where the coatings were applied at a thickness just less than the recommended value, the fire did spread upwards to various extents, but this behaviour was not repeated when the coatings were applied as directed. This illustrates the importance of following the coating manufacturer installation requirements.

Application of flame-retardant coatings on non-qualified cables (i.e., that would not meet passing criteria of the vertical flame spread test) demonstrate a delay in time to damage of at least five minutes regardless of coating type when applied according to the manufacturers recommendations. Qualified electrical cables coated with a flame-retardant cable coating demonstrated mixed results. Bench-scale tests demonstrated a delay while full-scale vertical flame spread testing did not demonstrate a delay. Coating thickness beyond the manufacturer's specified minimum thickness appears to provide additional delay in time to electrical damage.

Figure 10 and Figure 11 present the results of the circuit integrity tests, vertical flame spread tests, and full-scale multi-tray horizontal tests for the unqualified thermoplastic cables 900 and 902, uncoated and coated. In general, it was concluded that use of flame-retardant cable coating materials delays the time to electrical damage by several minutes and limits the flame spread of a cable fire.

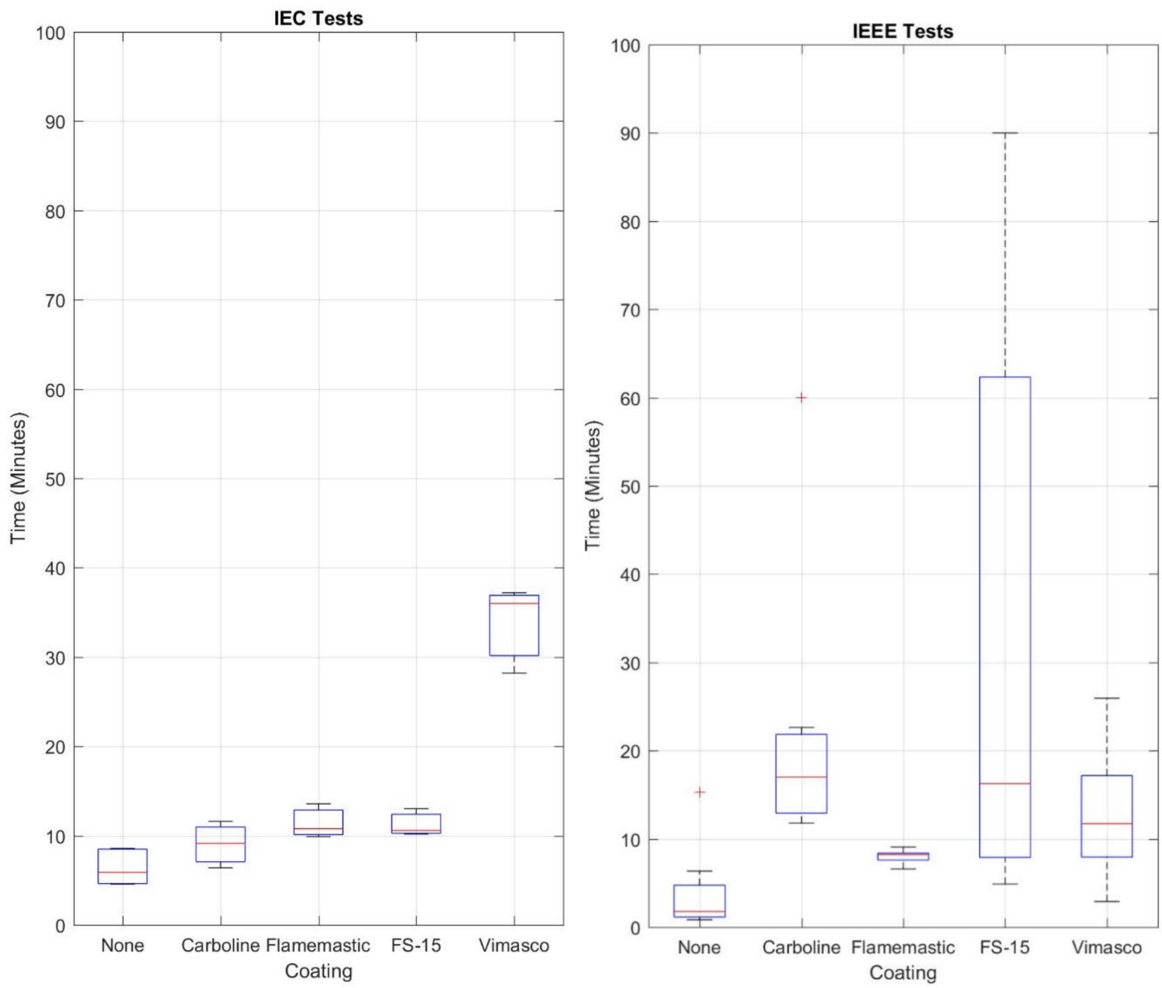

Figure 10 Time to failure box plots of circuit integrity, IEC tests (left) and vertical flame spread, IEEE-1202 tests (right) for all thermoplastic cables uncoated and coated

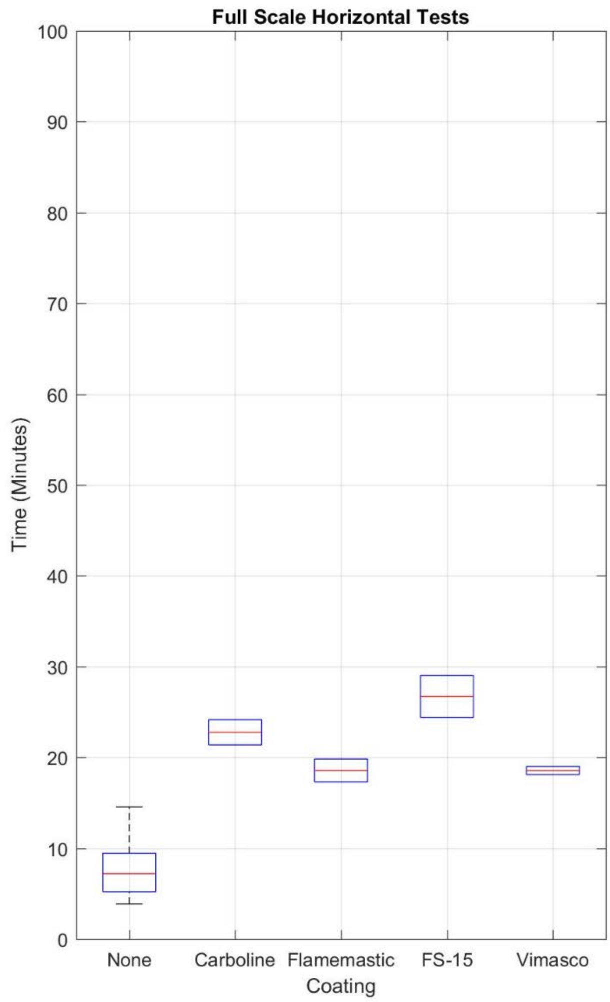

Figure 11 Time to failure box plots of full-scale multi-tray horizontal tests for all thermo-plastic cables uncoated and coated

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EXPERIMENTAL AND NUMERICAL INVESTIGATIONS OF THE INFLUENCE OF CABLE ARRANGEMENTS ON CABLE TRAYS CONCERNING MASS LOSS RATE AND FIRE PROPAGATION

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ABSTRACT

Cable trays influence the fire propagation within industrial buildings and power plants. Cables itself are a main fire source within these buildings, representing an ignition source due to technical malfunction. In this paper, the influence of different cable arrangements on the mass loss rate and fire propagation is investigated experimentally and numerically.

Overall two cable fire test series have been carried out, one within the CORE test campaign of the international OECD PRISME 2 Project and another one in the frame of a research project sponsored by the German Federal Ministry for Economics and Energy (BMWi). The second test series has been carried out by iBMB of Braunschweig University of Technology and consists of three single fire tests. In every fire test, the same number of cables per tray has been used as fire load but the arrangement of cables was different. The chosen cable type is a PVC power cable labelled NYM-J 5x25 RM representing a cable type typically installed in German nuclear power plants (NPPs).

The results show a large impact of the cable arrangement on fire development and propagation. A tight cable arrangement leads to different flow properties associated with a different burning behaviour as well as a decrease in the maximum mass loss rate, if neighbouring cables protect fractions of the cable sheath surface.

In the second step, simulations were performed using the international well-known fire simulation code Fire Dynamics Simulator to analyse the combustion sub-model. The fire spread data from experiments and the mass loss rate measured by Cone Calorimeter were used to model the heat release rate of the cables. The results show that the calculated course of the mass loss rate is in an acceptable agreement with the experimental values. The calculated surface and gas temperatures differ from the measured values due to the chosen model of a constant fire spreading velocity.

INTRODUCTION

Cable fires represent a potential hazard with safety relevance for industrial buildings and power plants. Because cables reach from one room to another to support every region of the building, an initial fire can spread from the ignition source to other regions of the building. Risk- and performance-based analyses are getting more and more important in fire protection engineering. Therefore, it is important to obtain models, which are able to predict the fire behaviour of cables and cable trays.

Previous research projects such as CHRISTIFIRE [1] and fire test series performed at iBMB during the 1990s [2] have shown that the burning behaviour of cable trays depends on the cable type as well as on the geometrical properties of the cable trays. The purpose of this work was on the one hand site to carry out fire test with different arrangements of the cables on the tray as well as number of cables and on the other hand to check the capabilities of the Fire Dynamics Simulator (FDS) to reproduce the effects observed in the fire tests.

The fire test campaigns were carried out within the international OECD/NEA PRISME 2 project as well as within a research project, short title pyrolysis model (FKZ 1501419), sponsored by the German Federal Ministry for Economics and Energy (BMWi). The fire test campaigns focused on a cable type with a nominal voltage < 1 kV representing a frequently used cable type in the low voltage area in German nuclear power plants. High Energy Arcing Faults (HEAF) can affect electrical components operating on voltage levels of 380 V and above. As defined by OECD/NEA, a HEAF is a short rapid release of electrical energy which may result fires involving the electrical device itself, as well as external exposed combustibles, such as cable trays. The effect of high energy arcing fault was not taking into account, so the cable trays were ignited using a propane fuelled gravel bed burner.

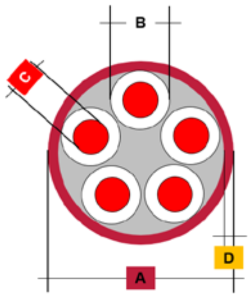
EXPERIMENTAL INVESTIGATIONS

As mentioned above, two different test campaigns were conducted. Both campaigns have in common, that the cable trays with a length of 3 m were built in front of an insulated wall. The number of trays, the amount of cables per tray and the cable type were also the same to enable the analyst to make comparisons between the test campaigns.

The cable applied and analysed in the experiments is a PVC sheath power cable labelled NYM-J 5x25 RM GRAU (GREY) according to the VDE 0250 standard [3] with a line weight of 1.82 kg/m (measured). The cable consists of a PVC sheath, five conductors, which are insulated with a PVC sheath and made of seven fold wires conductors. The space between sheath and insulation is filled with a filler material consisting of PVC and further organic and anorganic materials.

Additionally, mainly geometrical information regarding the cable type analysed is given in Table 1.

Table 1 Basic information of the cable type analysed

Basic information of the analysed cable type		
Cable type	PVC power cable Ø ≈ 28 mm	 
A	28.2 mm	
B	8.40 mm	
C	6.00 mm	
D	1.90 mm	
Label after VDE 0250		NYM-J 5 x 25 RM GRAU
Label information		N – VDE type Y – PVC insulation M – Sheathed cable J – With protective wire - wires: 5 wires - cross section; 25 mm²

Basic information of the analysed cable type	
Standards	IEC 60228/60332-1 VDE 0472-804-B DIN VDE 0295 class 1 or 2 DIN VDE 0293-308 DIN VDE 0250 part 204
Manufacturer / Delivery date	TKD Kabel GmbH / 07.01.2014

OECD PRISME 2 CORE-1 Experiment

The OECD PRISME 2 CORE-1 experiment was performed within in the SATURNE test facility (scheme see Figure 1. SATURNE is a large-scale calorimeter located at the research centre of Cadarache (France) by Institute de Radioprotection et de Sûreté Nucléaire (IRSN). The hood is 3 m in diameter and located within a 100 m² room with a height of 20 m. The hood is connected to an exhaust duct collecting all combustion products and connected to a ventilation network. Fresh air flow in is ensured by openings in the upper part. For the CORE-1 test, the initial flowrate at the outlet duct was set to 20,000 m³/h. The test aimed to investigate fire spreading over five horizontal trays. The trays were 3 m long, 0.45 m wide and their horizontal gap was 0.3 m. Each tray was loaded with 21 cables with a length of 2.4 m. The cables were ignited by a gas burner underneath the trays. The area of the gas burner was 0.3 m x 0.3 m and the gas burner was operated with an ignition power of 80 kW. The gas burner was stopped as soon as the heat release rate measured by the calorimeter exceeded 400 kW.

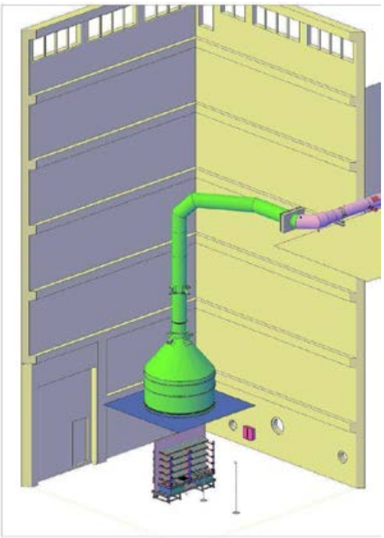


Figure 1 Scheme of SATURNE facility

Figure 2 Picture of the cable trays and loose cable arrangement of the PRISME 2 CORE-1 test before ignition

As shown in Figure 2 the cables were not arranged in a certain way. Although SATURNE is able to measure up to 350 devices, only the measured mass loss rate, the heat release rate and three thermocouple trees were taken into account. The results of mass loss rate measured by weight loss and heat release rate, measured by oxygen calorimeter, are presented in Figure 3.

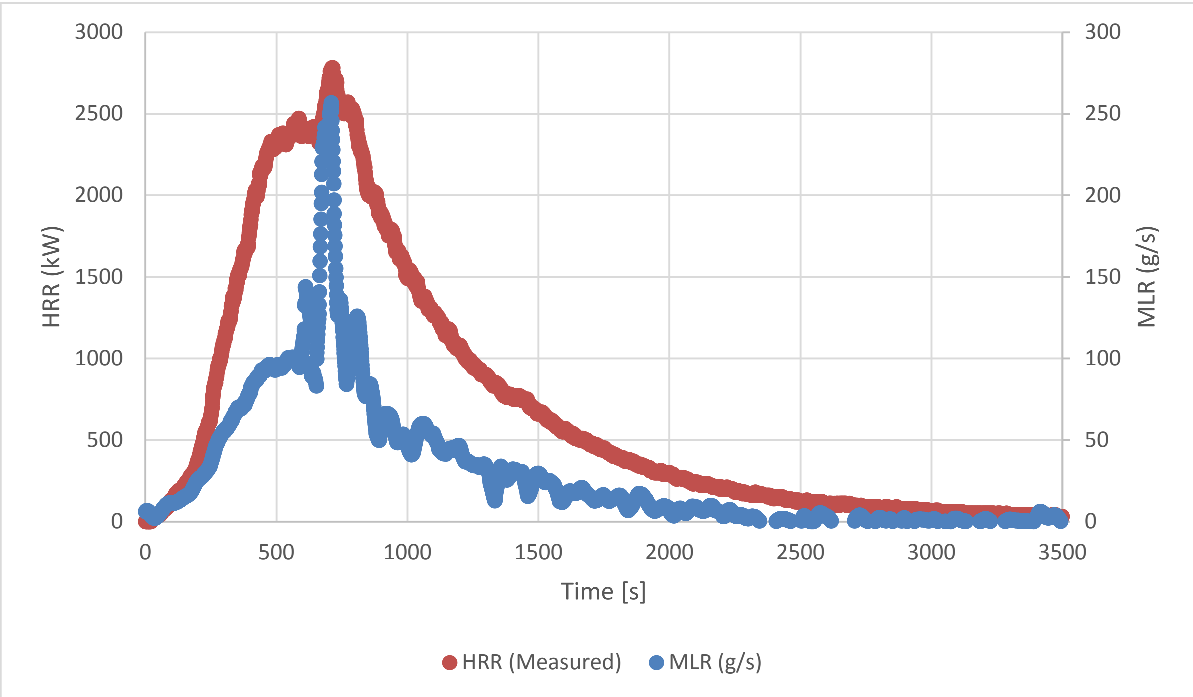


Figure 3 Mass loss rate and heat release rate measured in the CORE-1 test [4]

Cable Fire Experiments in the iBMB OSKAR Test Facility

To take a further look on the effect of cable arrangement on the burning behaviour of cable trays another test campaign was carried out at iBMB in Braunschweig (Germany). The test setup was based on CORE-1, so results are comparable.

The large-scale tray tests were carried out in a fire compartment of the iBMB, named OSKAR. This facility has a floor area of 3.6 m x 3.6 m and a height of 3.6 m. The inner surface walls and the ceiling are protected with light concrete, the floor is made of concrete. The ignition source is a gravel bed propane burner with a maximum power of 150 kW. The cable trays and the supporting structure were mounted on three weighing devices. Divergent to the CORE-1 test setup, the hood connected to the exhaust duct is not arranged directly above the cable tray. Air supply and exhaust is ensured using two openings. The first one is located on the side in direction of the hood with a width of 0.7 m and a height of 3.6 m. The door on the front has a width of 0.6 m and a height of 1.2 m. Both openings to the fire compartment were left open over the duration of all tests. The exhaust volume flow was set to a maximum of 10,800 m³/h. The gas burner used as ignition source was operated in the same way as in the PRISME 2 CORE-1 test.

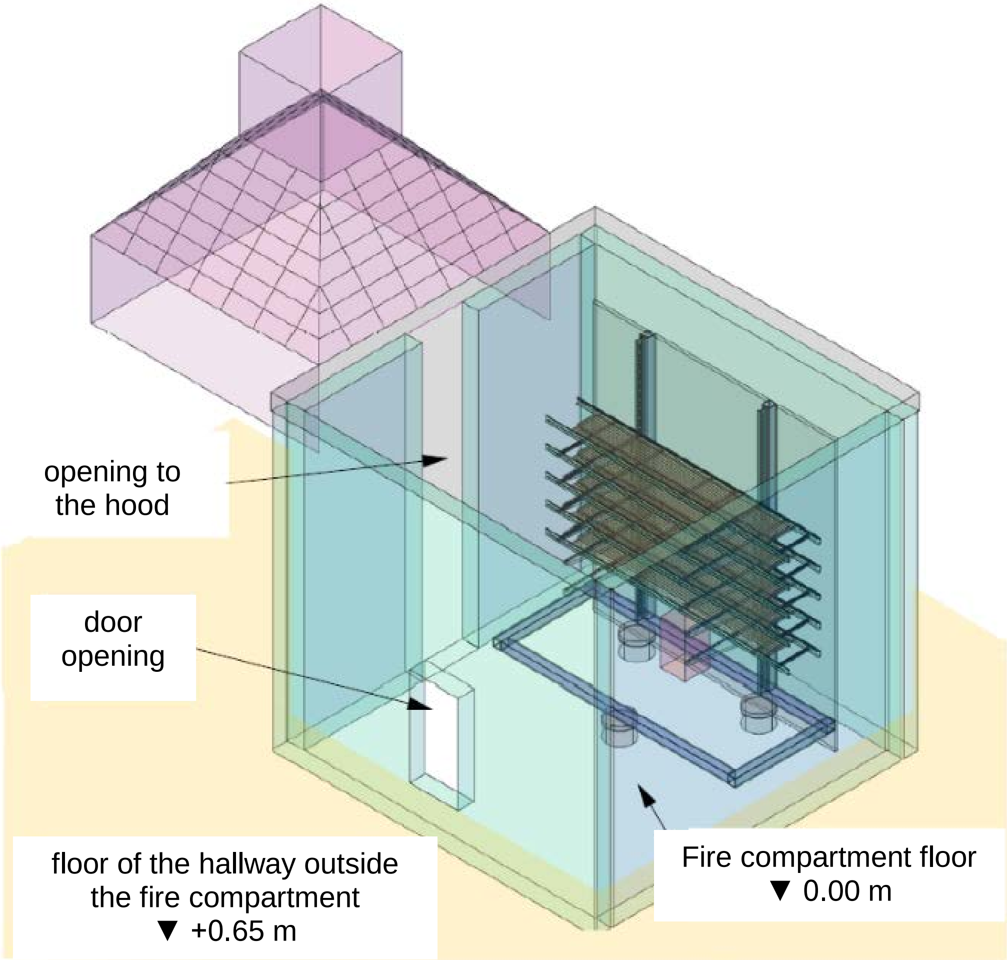


Figure 4 Scheme of the iBMB OSKAR test setup for tests T1 to T3

Three large-scale tray tests were carried out. The first test T1 was the reference scenario whereas the tray width was changed from 45 cm (T1) to 60 cm for the second test T2. The main idea for this parameter variation was the assumption that a larger tray width, resulting in a larger cable surface area exposed to fire, which leads to a different burning behaviour and fire spread. For the third test T3, the vertical tray distance was increased from 30 cm to 40 cm. Test specification and dates of the tests are given in Table 2.

Table 2 Large-scale cable tray tests carried out in the iBMB OSKAR facility

Name	Date	Difference compared to T1 (Reference)
T1 (Reference test)	25.06.2015	-
T2	30.06.2015	Tray width of 60 cm instead of 40 cm
T3	02.07.2015	Vertical tray distance of 40 cm instead of 30 cm

The cables were arranged on the trays in a way that the cables were routed close to each other. Because of the boundary condition to use 21 cables it was necessary to evolve two different layers for the tray width of 40 cm. The cable arrangement is presented in Figure 5.

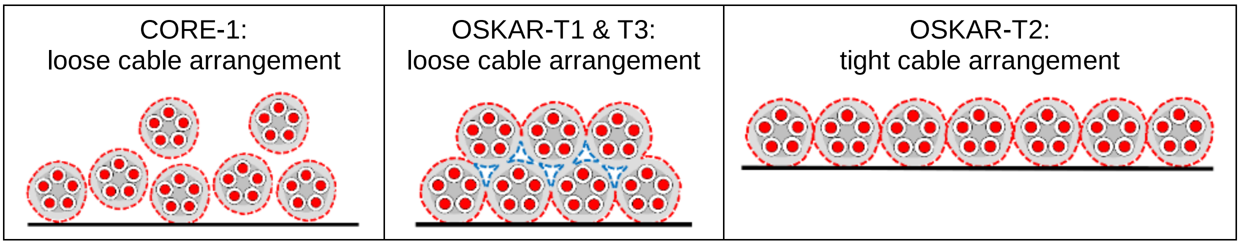


Figure 5 Sketch of the different cable arrangement

Due to technical problems the heat release rate could not be measured using the oxygen consumption method. The results of the mass loss rates determined by the weighting device data are shown in Figure 6.

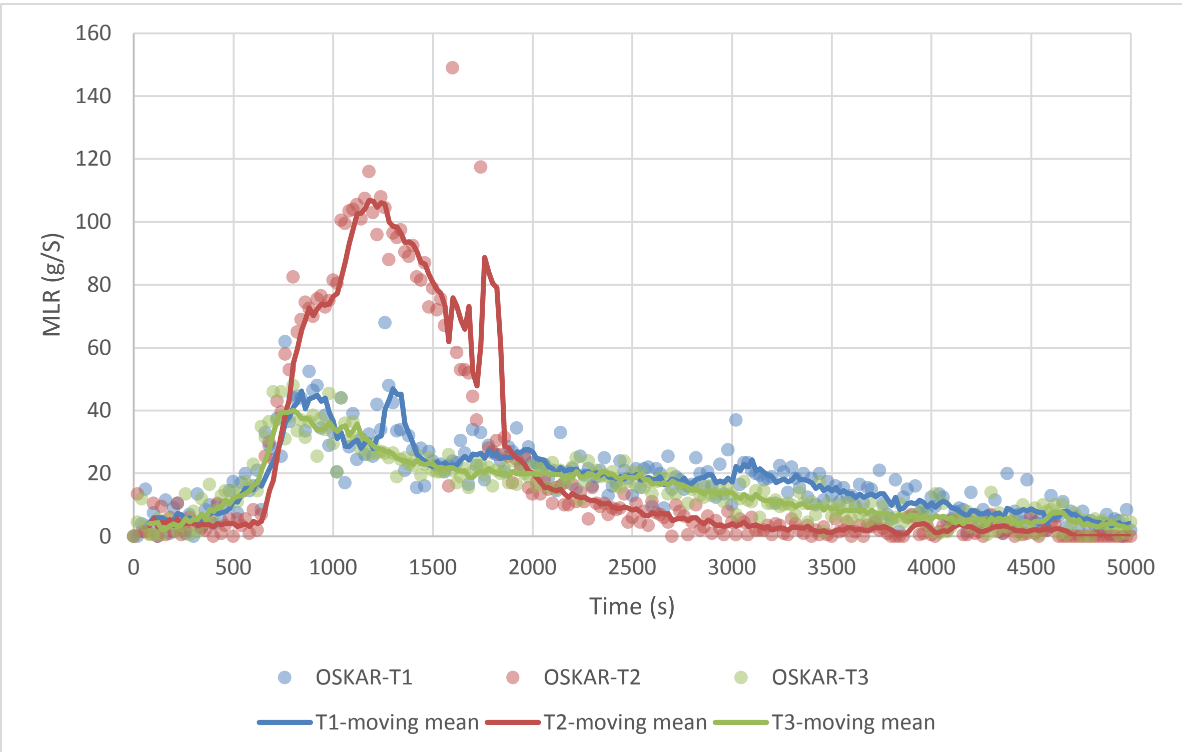


Figure 6 Mass loss rates measured in the OSKAR cable fire tests T1 to T3

Conclusion

Although all four tests in this project were based on the same cable type, cable age (the cables used for testing were produced and delivered to IRSN and iBMB at the same time) and number of cables (21 cables), the results show a clearly different burning behaviour depending on the packing density. The results thereby support findings from the CHRISTIFIRE [1] and BMU [2] projects, where a comparable behaviour was recorded.

Figure 7 shows the mass loss rates determined within the three OSKAR tests and the test CORE-1, starting with the power on of the propane burner (power of 80 kW in all four cases). It is obvious that the loose cable arrangement of the CORE-1 test, which allows the hot gases from the burner to flow through the cable trays, has a significant impact on the time until the fire propagation of the cable tray starts. Compared to the results of the T2 test, the fire development of CORE-1 starts 10 min earlier. This can be explained with the dense layer the cables form on the tray (cf. Figure 5). The hot gases of the propane gas burner flow around the lowest tray and cannot pass them. The qualitative flow directions of the hot gases for both, loose and tight cable arrangement, is shown in the following Figure 8.

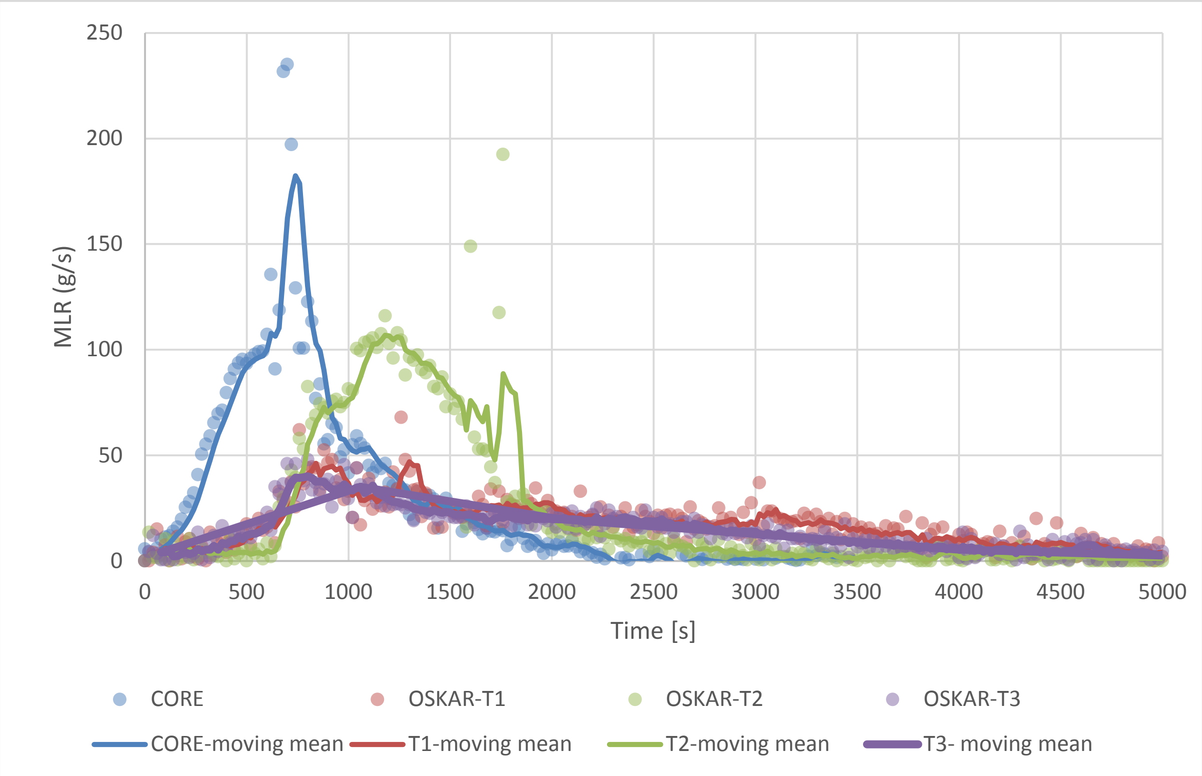


Figure 7 Mass loss rates measured in the tests T1 to T3 and PRISME 2 CORE-1, ignition propane burner at t = 0 s

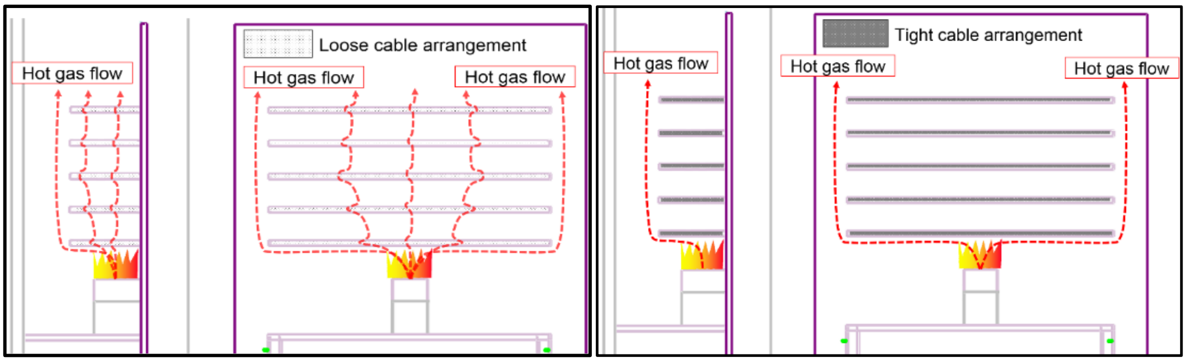


Figure 8 Qualitative flow direction of the hot gas layer during the ignition phase of the cable trays with a loose (left) and tight (right) cable arrangement

Comparing the results of the tests T1 and T3 to those of T2, the effect of the packing density and the resulting surface to volume ratio shows a high influence on the mean and maximum mass loss rates. Interestingly, the time when the fire propagates to the other trays, yielding in a growth of mass loss rate, is about 600 s (10 min) in all three OSKAR tests. Moreover, the increased vertical space between the trays (T1: 30 cm, T3: 40 cm) shows little impact on the mass loss rate in the beginning of the fire.

Another important factor is the potential surface which can be exposed during a fire. A larger value of the exposed surface in combination with a fixed cross-sectional area (number and type of cables are the same in all tests) leads to a significantly faster heating and therefore to the emission of a larger amount of pyrolysis gases.

The ratio between the surface exposed to fire can be calculated by considering the diameter of the cables and the number of cables. For this example, the complete circumference of the cable is considered as an exposed surface for the tests CORE-1 and OSKAR T2. In reality, for both loose and tight arrangements, overlapping areas and small gaps will reduce the real exposed surface.

Looking at the cable arrangement for the tests OSKAR T1 and T3, adjacent cables protect fractions of their circumferences (qualitatively shown in Figure 5, scheme in the middle). With the same cross-sectional area of the cables and combustible mass, the reduction of the surface exposed to fire to 69 % compared to a full exposure is responsible for the lower mass loss rate.

Using video analysis horizontal fire spreading velocities were determined. Table 3 shows fire spreading velocities in the CORE-1 and OSKAR T2 tests. Both tests have in common that the velocities on the lower trays are slower than those one the upper ones due to the fact, that the burning lower trays preheat the upper trays. It should be mentioned, that the fire spreading velocity in the OSKAR T2 test for the cable trays 3 to 5 was derived from the velocity for the trays 1 and 2. Fire spreading velocities for the cable trays 3 to 5 were hardly to derive from the OSKAR T2 test. In [5] a factor of 2 was determined for the velocity of the upper trays with reference to the analysis of further cable tray fire test campaigns on Finnish PVC cables.

Table 3 Horizontal fire spreading velocity

Fire Spreading Velocity v_f	CORE-1	Determined from T2
Tray 1-2	1.25 mm/s	1.07 mm/s
Tray 3-5	2.5 mm/s	2.14 mm/s

The fire spreading velocity in the OSKAR T2 test is less than 15 % of the one measured in the PRISME 2 CORE-1 test. With respect to Figure 7, where the slope of the mass loss rate can be interpreted as fire spreading velocity, it is demonstrated that the fire spreading velocity decreases, if the package density rises.

In conclusion, two major effects on the burning behaviour of cable tray installations have been identified.

- A loose cable arrangement led to an earlier fire growth and vertical fire propagation (CORE-1), when compared to the results of a tight cable arrangement with the same surface exposed to fire. The inclination of the mass loss rate is the same, but shifted by 10 min.
- The tight cable arrangement of the tests OSKAR T1 and T3 with partially protected cable sheath surfaces showed that the time where the maximum mass loss rate is reached is the same as determined in T2. In this case, the maximum mass loss rate is significantly lower compared to the tests PRISME 2 CORE-1 and OSKAR T2 with full circumference of the cables exposed to fire.

NUMERICAL INVESTIGATIONS

The test results of PRISME 2 CORE-1 and iBMB OSKAR T1 to T3 tests are suitable for validation of fire simulation codes. In a first step, blind calculations were performed for CORE-1 and, in a next step, the evaluated test results were used to determine appropriate input parameters for the simulation code.

In the frame of this activity the *Fire Dynamics Simulator (FDS) Version 6.3* [6] was used. FDS is a CFD (*c*omputational *f*luid *d*ynamics) fire simulation code mainly maintained and developed by National Institute of Standards and Technology (NIST).

FDS solves the Navier-Stokes equations considering an assumption of low Mach numbers ($Ma < 0.3$). The conservation of momentum can be formulated either in conservative form, using the DNS momentum equation, or as Large Eddy simulations (LES) momentum equation. Within this work LES were used and turbulent viscosity was modelled by a variation of Deardorff's model corresponding to the default settings of FDS. The ambient pressure was set to 101,325 Pa. A solver using the finite volume method (FVM) solves the radiative transfer equation for a grey gas model. For discretization, the number of radiation angels was set to 104 (by default). Further input parameters of the sub-models were set to default values. Details regarding the implementation, technical references, a user's guide and validation and verification of the code can be found in the corresponding documents [6].

Because of the good validation, FDS is used for a wide range of applications in the field of fire protection engineering. The applicability to specific fire scenarios typically occurring in nuclear power plants and installations, e.g., cable tray fires or electrical cabinet fires, was and is assessed in several Benchmark Exercises of the International Collaborative Fire Modelling Project (ICFMP) [7], and the research projects of the OECD NEA (*N*uclear *E*nergy *A*gency) PRISME [8] and PRISME 2.

Modelling of Combustion and Fire Spreading

The computational domain in FDS represents the solid phase and the gas phase of the experiment. Within the gas phase turbulent flows can occur, whereas the solid phase represents obstacles like walls. Combustion is modelled within the gas phase. The reaction itself can be modelled as mixing-controlled combustion or as finite rate combustion using the Arrhenius law. Due to the chosen formulation of the momentum equation, a single-step mixing-controlled reaction model simulates the reaction. This model requires the mixture of oxygen and fuel within the gas phase. Whereas the ambient mass fraction of oxygen is specified as an input variable (default: 0.232378), the mass fraction of the fuel is calculated using either a simple or a more complex pyrolysis model based on the definition of finite rate kinetics for each solid material component requiring calculation of heat conduction within the solid phase.

For the calculations presented in this paper the simple pyrolysis model was used. As area specific value, either the mass loss rate (MLR) or the heat release rate (HRR) of the fuel has to be transferred to the model as a function of time. In case the heat release rate is defined, FDS automatically calculates a mass loss rate by dividing with the effective heat of combustion (eHOC) given by the user.

As already mentioned above, the combustion is modelled in a single-step reaction. The reaction equation for burning PVC (Eq. 1) is shown below. Stoichiometric coefficients were based on a Carbon monoxide (CO) yield of Y_{Co} = 0.025 and a soot yield Y_{Soot} = 0.05 which are based on findings of [7].

$$C_2H_3Cl + 2.21O_2 + 8.30N_2 \rightarrow 1.00HCl + 1H_2O + 0.06CO + 1.68CO_2 + 0.26Soot + 8.30N_2 \quad (1)$$

The values on the left side of the reaction equation lead to a mixture fraction (ration between fuel mass and mixture mass) of 0.171 for ideal fuel consumption.

Horizontal fire propagation on the cable trays is modelled by using a simple fire spreading model implemented in FDS coupled to the computational mesh. To illustrate this model, Figure 9 shows a sketch of a burning surface, e.g., a cable tray. Starting from defined ignition point the first cell starts to emit fuel gases. Emission of fuel gases will spread radially with a predefined spread velocity v_f. It is important to mention that the spread velocity v_f is not a physical parameter but a time dependent switch starting emission of fuel gas in a mesh cell. Once switched on, the mesh cell will emit fuel gases following a predefined function MLR(t) or HRR(t). For the simulation shown, the heat release and burning time (t_{burn}) per cell were set to constant, so fire propagation depending only on spread velocity v_f.

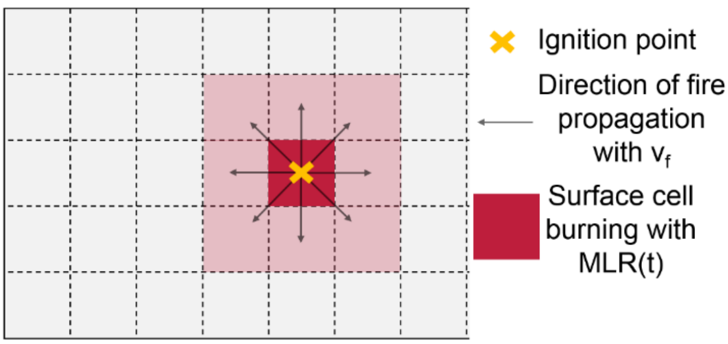


Figure 9 Fire propagation model used

In the simulation, neither the gravel bed burner as ignition source nor vertical fire propagation was considered. Instead of ignition by gas burner, the burning surface of tray 1 and tray 2 (starting from below) started with a width of 30 cm over the whole tray depth. The ignition of other three trays (trays 3 to 5) occurs at a location in the center of area of both the upper and lower tray surface.

Calculations for the PRISME2 CORE-1 and the iBMB OSKAR T1 Tests

Prior to the open simulation presented in this paper, blind calculations were carried out for the PRISME 2 CORE-1 test. The necessary input parameters mass loss rate and effective heat of combustion (eHOC = 18 MJ/kg) were derived from small-scale cone calorimeter tests based on the same type of cables. The resulting function of the heat release rate of the blind calculations is shown in Figure 10 as blue curve and the experimental results are outlined as orange curve. After 250 s, the fire heat release rate determined in the test is increasing faster, leading to an average maximum heat release rate of 2500 kW (local maximum 2750 kW at about 700 s), starting from 450 s. The decreasing phase starts at about 800 s and shows a nonlinear behaviour. The simulation led to a maximum heat release rate of 2000 kW, starting at about 650 s and a linear decrease after 1050 s.

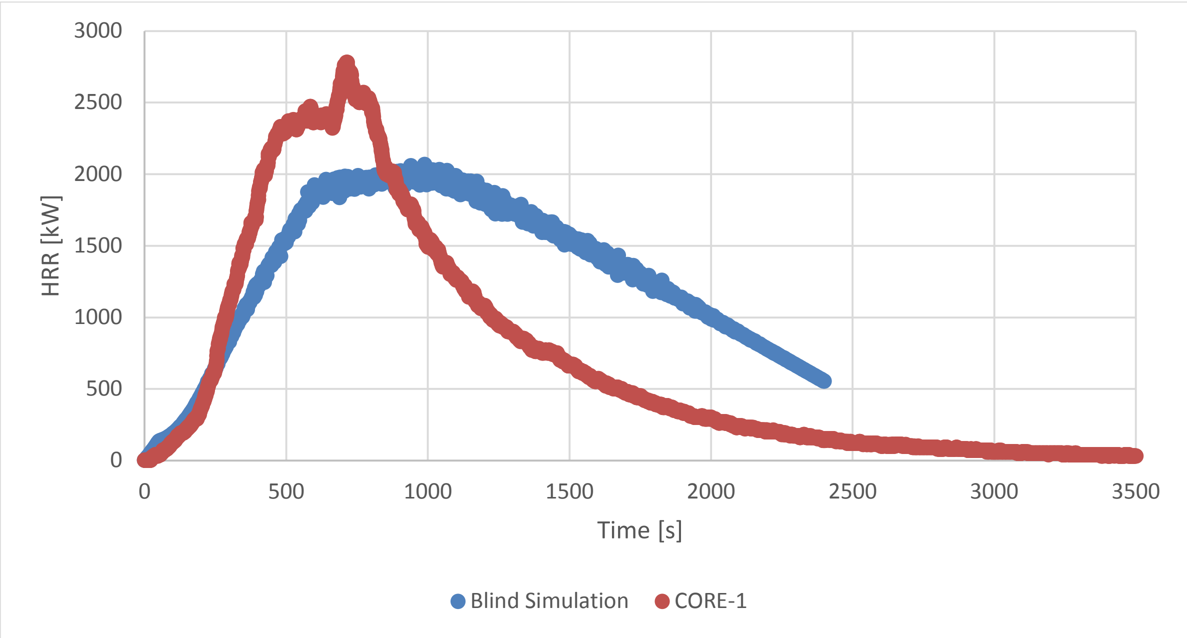


Figure 10 Heat release rate measured in the CORE-1 test and results of a blind FDS calculation based on cone calorimeter results

The results of the blind calculation applying FDS have shown that either the effective heat of combustion or the mass loss rate derived from cone calorimeter results were too low. To check this discrepancy the heat release measured in CORE-1 using oxygen consumption calorimetry test was compared to the measured mass lose rate multiplied with the effective heat of combustion of 18 MJ/kg. As shown in Figure 11, the estimated effective heat of combustion used in the blind calculation was too low for characterizing the heat release rate. For the open calculations the heat of combustion was set to 23 MJ/kg, which is in compliance with the mass loss rate and the heat release rate determined within CORE-1.

Regarding to the updated effective heat of combustion heat release rate per surface area (HRR'') is determined using the maximum mass loss rate determined in the CORE-1 test:

$$HRR'' = \frac{MLR}{A} \cdot eHOC$$
$$HRR'' = \frac{0.106\, kg/s}{2.4\, m \cdot 0.45\, m \cdot 2 \cdot 5} \cdot 23{,}000 \frac{kJ}{kg} = 225\ kW/m^2 \qquad (2)$$

Calculation of t_{burn} is done by dividing total heat release (THR) from the CORE-1 test report of 2479 MJ with the burning surface area and HRR'':

$$t_{burn} = \frac{THR/A}{HRR''} = \frac{2479000\ kJ/10.8\ m^2}{225\ kW/m^2} = 1020\ s \qquad (3)$$

Regarding to the test results the spread velocity was set to 2.14 mm/s. Mesh resolution was 5 cm in all directions, resulting in 80, 32 and 64 cells in x-, y- and z-direction, resulting in a total of 163,840 cells.

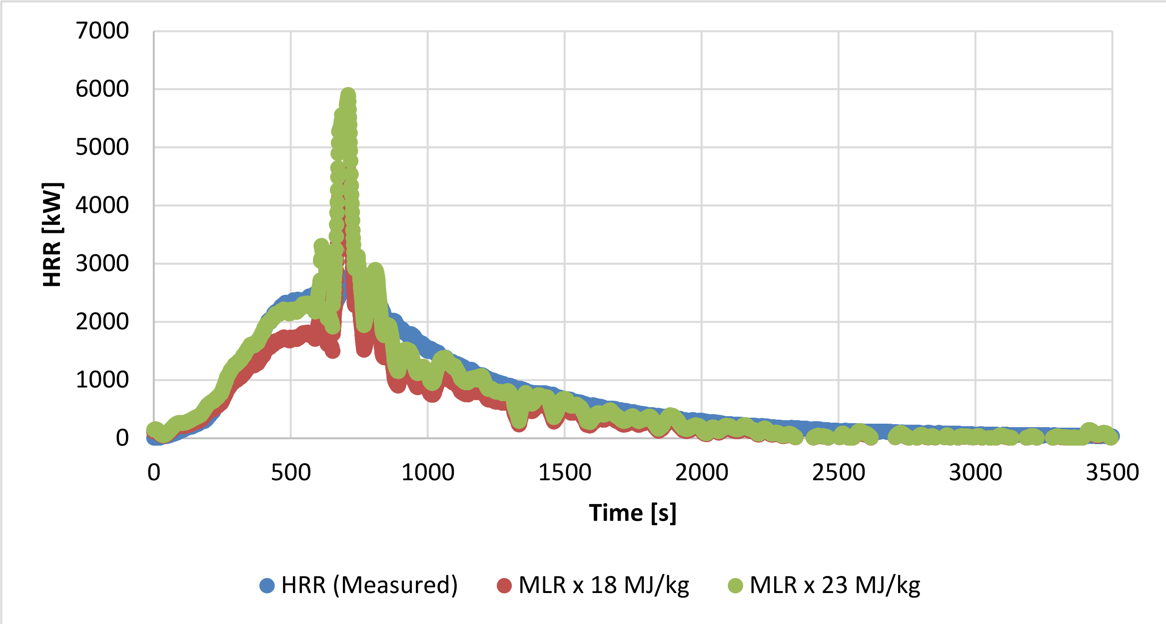


Figure 11 Heat release rate and mass loss rate multiplied with two different values for the eHOC

Figure 12 shows the main and important parts of the model used for this simulation.

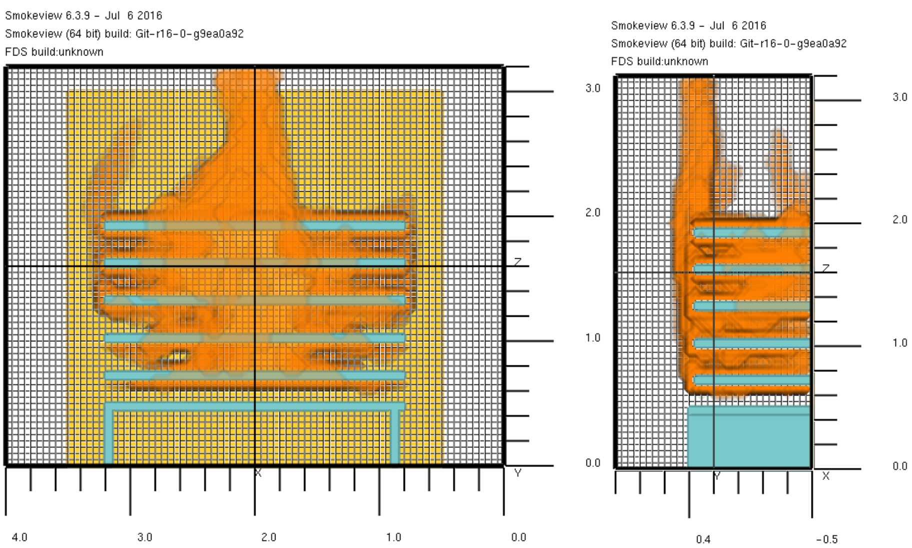


Figure 12 Front and side view of the FDS model showing grid and surface resolution, cable tray obstructions, the insulation plate behind the tray construction and the computational domain, exemplarily at a time step of 710 s

For the simulation of the cable fire test T2 performed in the iBMB OSKAR test facility an update of the effective heat of combustion was not required. eHOC and MLR'' were derived directly from a cone calorimeter test:

$$eHOC = 17.900 \frac{kJ}{kg}$$

$$MLR'' = 0.0083 \frac{kg}{m^2 s}$$

HRR'' is derived by:

$$HRR'' = 0.00833 \frac{kg}{m^2 s} \cdot 17{,}900 \frac{kJ}{kg} = 149 \frac{kW}{m^2} \qquad (4)$$

t_{burn} can be solved directly from MLR'' and the measured overall mass loss (ML) from test T2:

$$t_{burn} = \frac{ML''}{MLR''} = \frac{\left(\frac{103.5\,kg}{5 \cdot 2 \cdot 2.4\,m \cdot 0.6\,m}\right)}{0.00833\,kg/m^2 s} = 862\,s \qquad (5)$$

The same fire spreading velocities as in the calculations in CORE-1 test were used for the five cable trays. The computational domain of the model is divided into three meshes, which are depicted in the following Figure 13. Due to higher requirements concerning the resolution of the gas phase between the trays, the surrounding volume is discretized using a 5 cm mesh. The volume under the hood on the other hand is discretized using a 10 cm mesh. The front part of the burning chamber of the test facility is also meshed using a 10 cm grid to reduce the computational cost of the simulation.

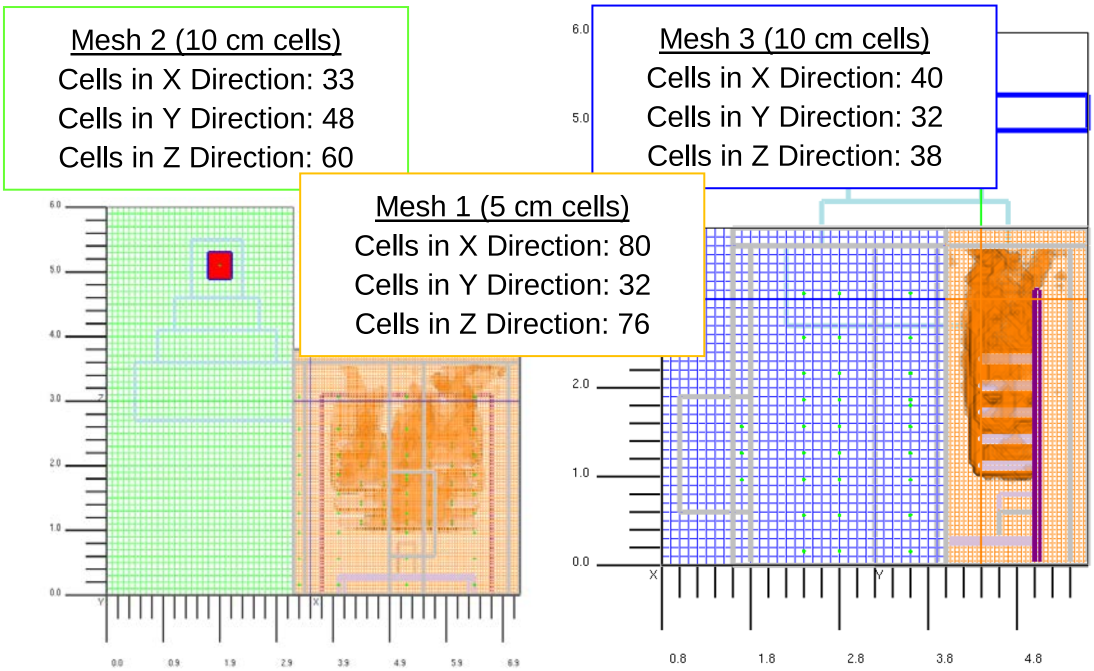


Figure 13 Front view (left) and side view (right) of the FDS model showing the grid and surface resolution, the cable tray obstructions, the insulation plate behind the tray construction, the hood with the exhaust opening (red surface) and the computational domain divided by three meshes (here two are visible), exemplarily at a time step of 510 s

Results

Figure 14 shows a comparison of the heat release rate measured in the OSKAR T2 test and the calculated one applying the fire simulation code, Figure 15 provides such a comparison of measured and calculated (with FDS) heat release rate for the CORE-1 test.. As mentioned above, the heat release rate could not be measured using oxygen consumption method in the OSKAR T2 test. Therefore, the heat release rate was derived by multiplying the mass loss rate (see Figure 6) with eHOC of 17,900 kJ/kg derived from cone calorimeter. The heat release in Figure 14 shows a peak at t = 1240 s. This peak is linked to the way of determining the heat loss rate. As weighting devices are sensitive to falling cables this measurement error leads to a peak of heat release rate.

Taking a look at the result, it can be shown that the simple fire propagation model using a constant fire propagation model, a constant heat release rate per surface area as input parameter is capable of describing the global curve of the heat release rate, both in the CORE-1 and OSKAR T2 test. The calculated HRR of OSKAR T2 is a little higher than the measured one except for the peak mentioned. The calculated HRR of CORE-1 is lower than the measured one. The decrease of the curve after the maximum heat release rate has been reached is not represented correctly as the measured HRR is decreasing more slowly to zero. Since the measured mass loss rate is used as input parameter in the calculation, it is necessary to compare the measured temperatures with the calculated temperatures. The results of the numerical simulation performed with FDS and the test are compared in Figure 16 and Figure 17.

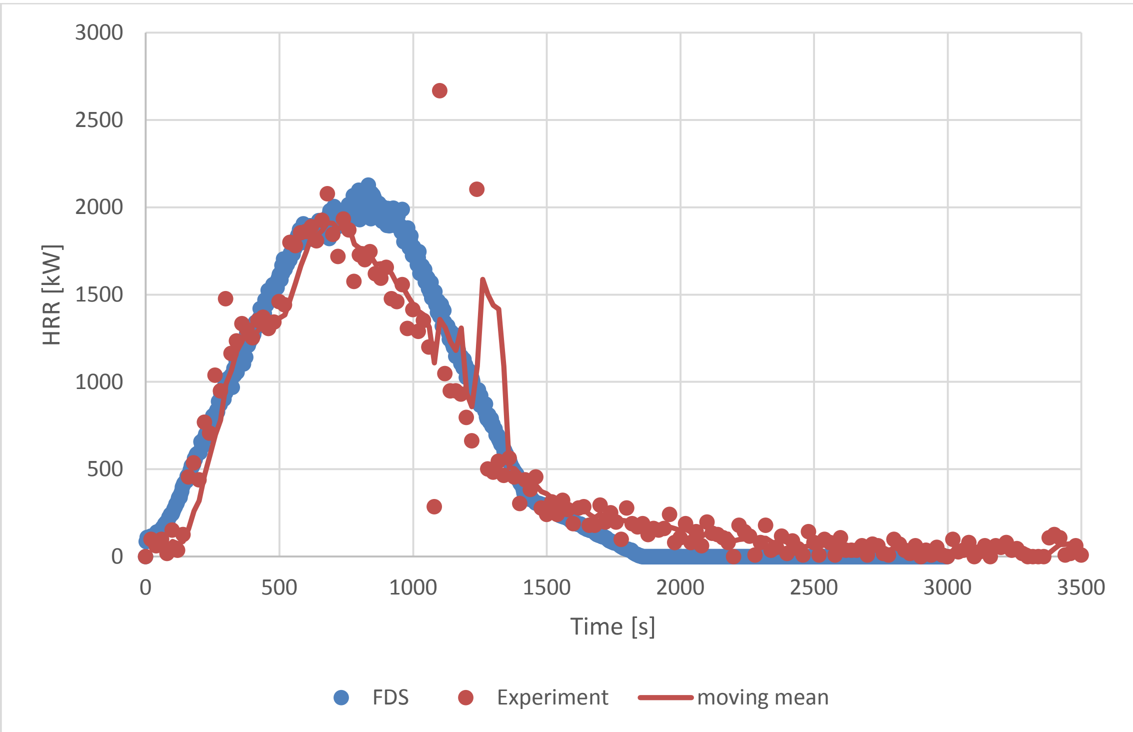


Figure 14 Comparison of the heat release rate experimentally determined in the OSKAR T2 test and the corresponding results of the FDS calculation

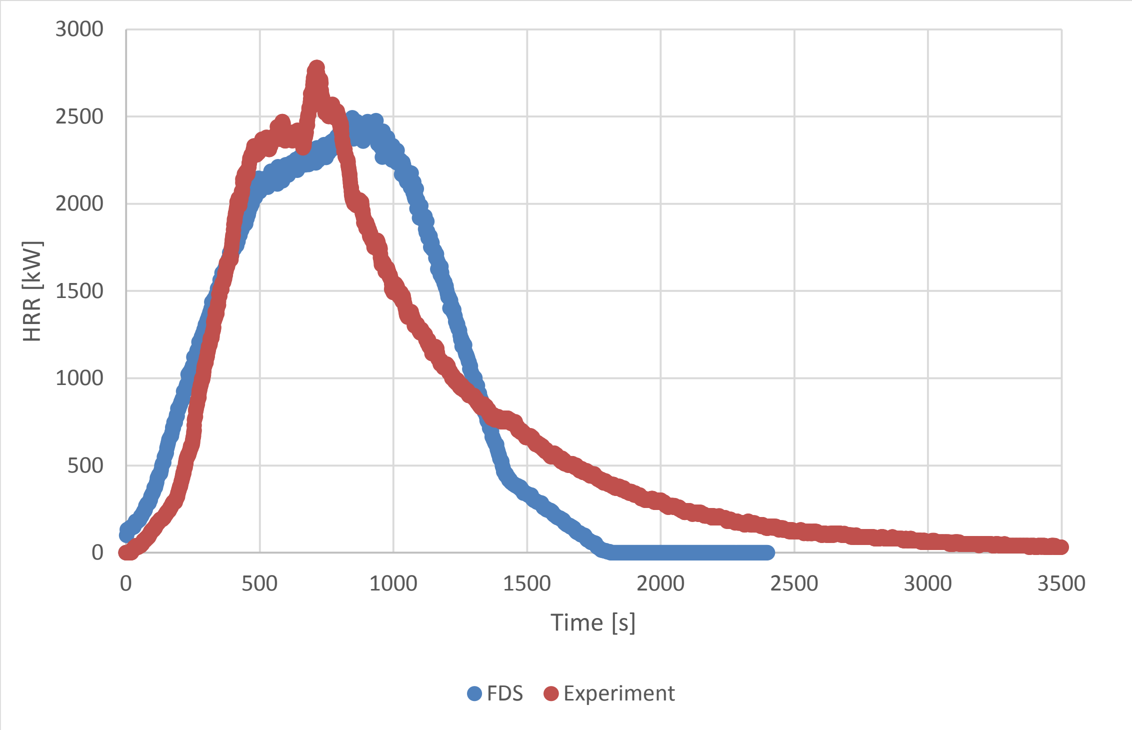


Figure 15 Comparison of the heat release rate experimentally determined in the PRISME 2 CORE-1 test and the corresponding results of the FDS

As shown in Figure 16, the calculated gas temperatures of the CORE-1 test overestimate the test results. Moreover, as the results in the two right rows (TG-CC5-500 and TG-CC5-1000) show, the effect of the exhaust hood mounted above the tray construction becomes visible by lower gas temperatures. Another interesting finding is the fact that the fire propagation from the midpoint to the ends is directly visible in the time shift of the increase of gas temperatures. The results confirm the idea of the qualitative gas flow shown in Figure 8, distinguishing between loose and tight cable arrangement.

In Figure 17, the test results are shown from 560 s after ignition of the propane burner. Due to this, the experimental data of TG_T1_UP_00 is starting at a temperature of about 180 °C. For the upper cable trays 3 to 5, the maximum temperatures were met with a better agreement. Looking at the results of the right column, showing the temperatures in ± 80 cm distance of the midpoint, the numerical results show a later increase in temperature. In this case, the approach chosen to model the fire propagation, starting from the center point of each tray with a constant spreading velocity, does not properly characterize the effects determined in the test. The test results indicate that the fire propagates vertically from the lowest to the highest tray, located at the midspan. The horizontal fire propagation starts afterwards in the fully developed fire phase.

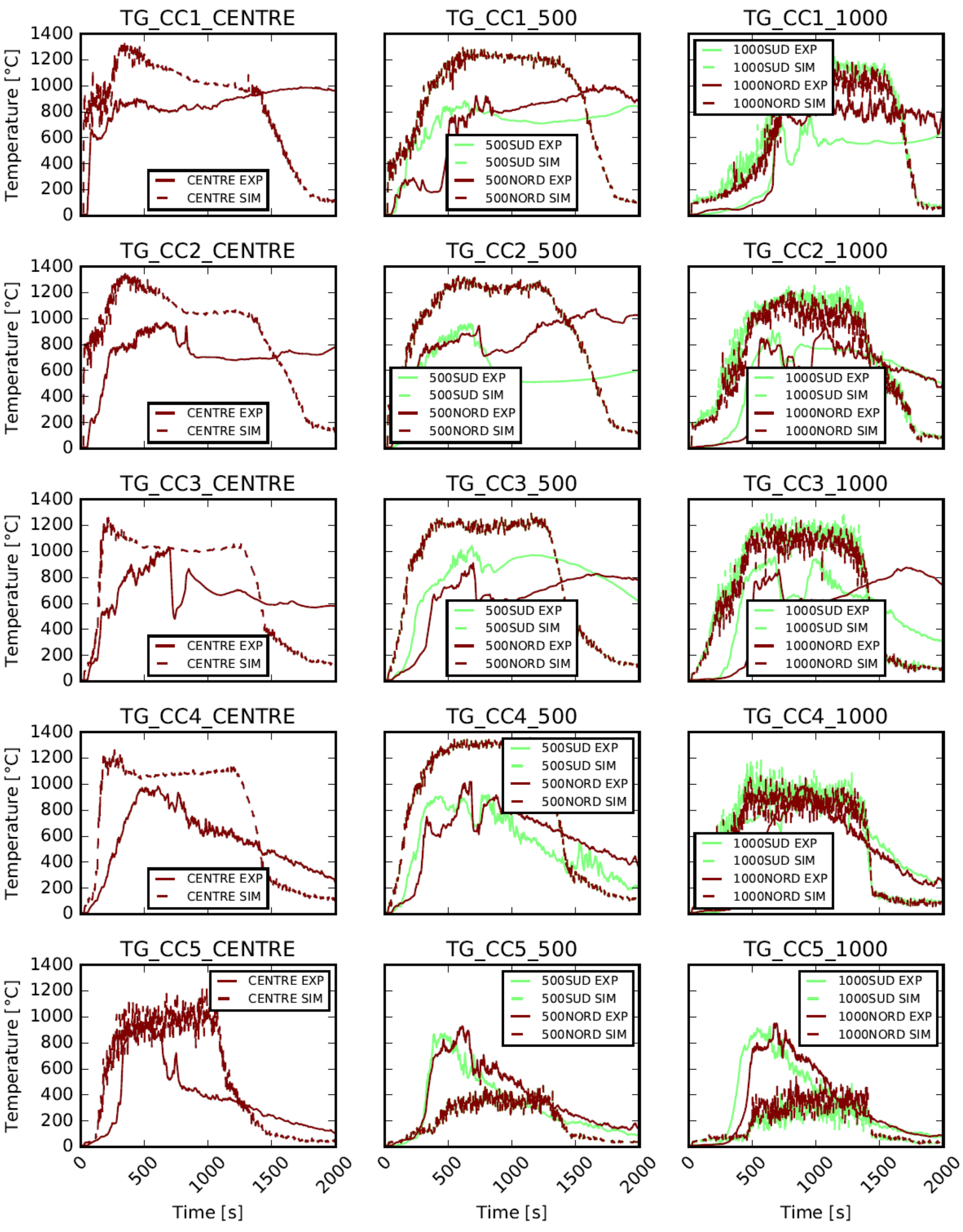


Figure 16 Comparison of gas temperatures measured in the CORE-1 test and the results of the FDS calculation

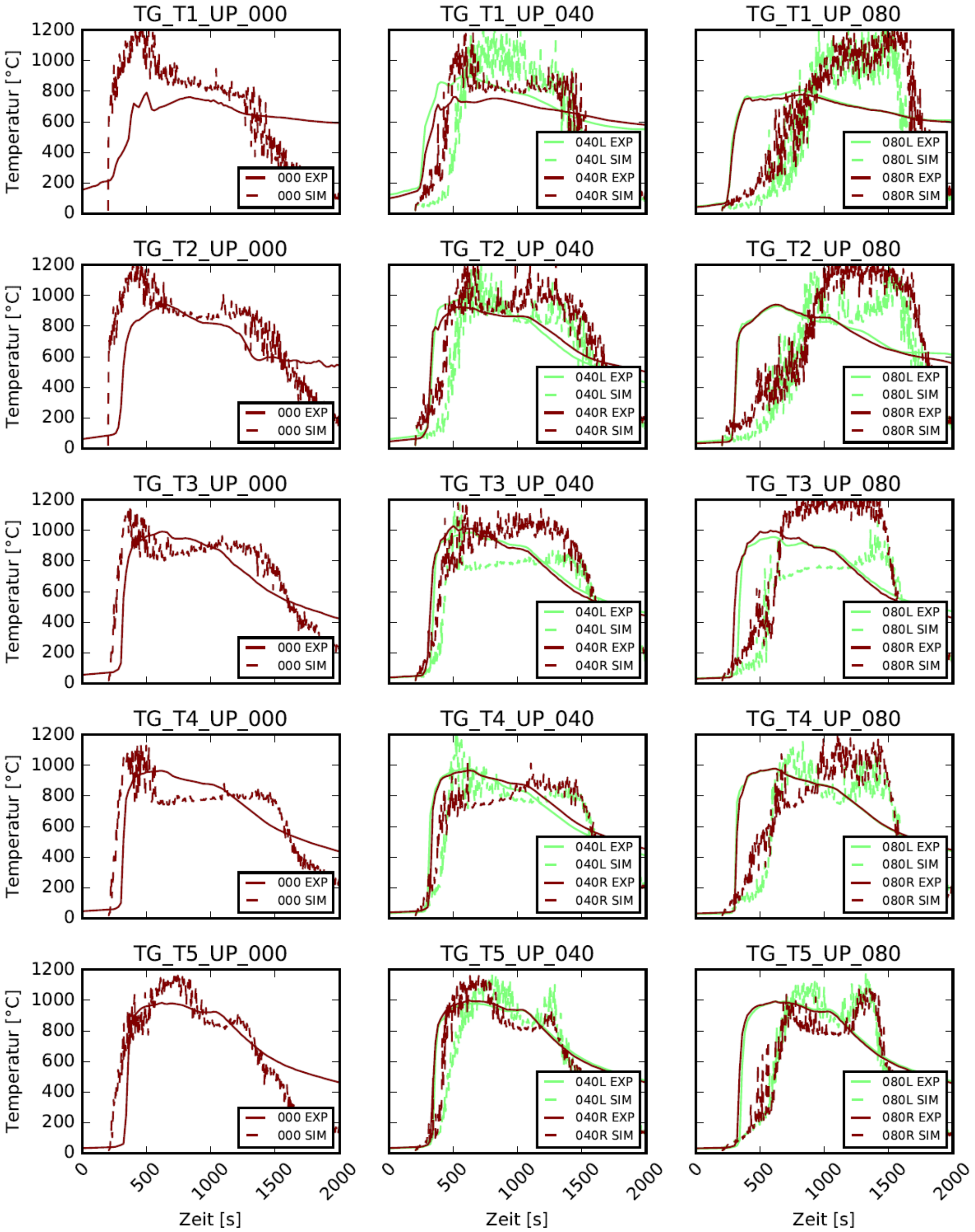


Figure 17 Comparison of the gas temperatures measured in the OSKAR T2 test and the results of the FDS calculation

CONCLUSIONS AND OUTLOOK

The experimental and numerical investigations conducted focussed on the effect of cable arrangement on the fire behaviour of cable trays. Furthermore the experimental data were used to validate combustion and pyrolysis model implemented in Fire Dynamics Simulator simulation code.

The experimental investigations show, that cable arrangement on cable trays have a great influence on the burning behaviour, although the test setup of the cable fire test by iBMB is not completely comparable to the CORE-1 test. Within the OSKAR test facility the effect of the surrounding walls was taken into account, whereas the CORE-1 test was performed in an open hall.

The main findings from cable experiments are:

- Loose cable arrangement allows the hot gases to flow through the cable package and to preheat the upper cable trays. This leads to an initial fire propagation over all five cable trays and to a higher mass loss rate.
- In contrast to this, the test OSKAR-T2 with a tight cable arrangement showed a delay of about 10 minutes until the fire propagates from the lower surface of the lowest tray onto the trays above. If the mass loss rate, determined in both experiments, is shifted about 10 minutes, both curves show a comparable progression.
- The maximum mass loss rate decreases for cable arrangements with a partially protected cable circumference due to adjacent cables. This was determined in the tests T1 and T3.
- The increase of the vertical tray distance from 30 cm (T1) to 40 cm (T3) showed a less significant effect on the mass loss rate.

The numerical investigations show:

- The input parameters determined in small-scale cone calorimetry test transferred to large-scale experiments do not necessarily lead to the observed mass loss rate and heat release rate. For the loose cable arrangement, the mass loss rate had to be raised by 27 %, whereas for tight cable arrangement an update of mass loss rate was not necessary. These results are in line with other cable tray experiments using PVC cables, like CFS(S)-1, where an effective heat of combustion of 17.7 MJ/kg was determined in small-scale cone calorimetry tests [9], where the large-scale tray experiments revealed a value of 22.5 MJ/kg.
- For the T2 test, a combination of small-scale cone calorimeter results with the total mass loss and a fire propagation velocity from the video analysis was capable to describe the global mass loss rate obtained in the test. This might be connected to the steady state test setup of the cone calorimeter test, shown in Figure 18. As well as in the iBMB OSKAR test campaign cables are arranged tight not allowing hot gases to flow through the cables.

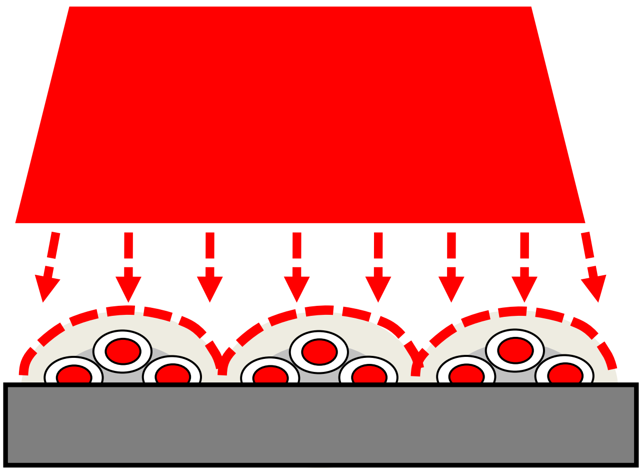


Figure 18 Cone calorimeter test setup

The FDS simulations utilized an approach of a determined fire propagation velocity and specific mass loss rate to describe the fire source term. Besides the direct use of the experimentally determined mass loss rate respectively heat release rate, this is a typical approach used in engineering practice. The advantage of its simplicity involves a highly significant influence of the input parameters chosen. Considering the different hot gas flows the detailed analysis of the gas temperatures determined near the tray surfaces show a different behaviour. While the utilization of a constant fire propagation velocity seems more practical for a loose cable arrangement, it cannot describe the fire propagation mechanisms recorded in T2.

In a practical situation, no large-scale test results dealing with the burning behaviour of the cable type are available. The results obtained in the four tests deliver an impression of the effects of cable arrangement on the mass loss rate and fire propagation. With a view to the forecast capability of the simulation code Fire Dynamics Simulator, the simple approach of modelling fire propagation is reasonable to present global effects, e.g. mass loss rate. Local effects and local temperatures were partly predicted with low accuracy. It is assumed that the accuracy at some distance from the fire source will become better, because increasing the distance will lead to less influence of the local effects. In this case, temperatures are mainly dominated by the global heat release rate. For fire risk assessment in small scale fires not leading to complete cable tray fires, the experimental database on cable fires needs to be further extended.

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NUMERICAL STUDY OF THE OSCILLATORY COMBUSTION PHENOMENON IN A SMALL-SCALE AND MECHANICALLY VENTILATED COMPARTMENT FIRE

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ABSTRACT

In this paper, oscillatory combustion in a confined and mechanically ventilated small-scale compartment (1.5 m in length, 1.25 m in width and 1 m in height) is studied. A circular 18-cm-diameter heptane pool fire is located in the centre of the room at the floor level. An oscillatory signal is observed for the recorded Mass Loss Rate (MLR), pressure and ventilation volume flow rates after 260 s of combustion. This scenario is simulated using the Computational Fluid Dynamics (CFD) Code ISIS developed by the Institut de Radioprotection et de Sûreté Nucléaire (IRSN). First, simulations are performed without fire to study the influence of the cell size on the numerical results. The outcome indicates that a 2 cm cell size is a suitable compromise between accuracy and simulation time for the test at hand. Second, simulations prescribing the experimental MLR are completed. In general, a good level of agreement is achieved between the experimental and numerical profiles of pressure, ventilation volume flow rates (inlet and outlet), temperature, and species concentrations. In addition, the studied transport of oxygen from the inlet branch to the pool fire shows a preferential path when a low MLR is observed. The present study lays the groundwork for forthcoming predictive simulations of the oscillatory behaviour.

INTRODUCTION

A low frequency oscillatory combustion phenomenon has been observed for pool fires in a large-scale (5 m x 6 m x 4 m), well-confined and mechanically ventilated compartment [1]. The analysis of the experimental data, obtained in the framework of the PRISME 2 Project [2], shows that such a phenomenon is induced by an interplay between the mass loss rate (MLR [kg/s]) of the liquid pool, the room pressure and the volume flow rates of the ventilation.

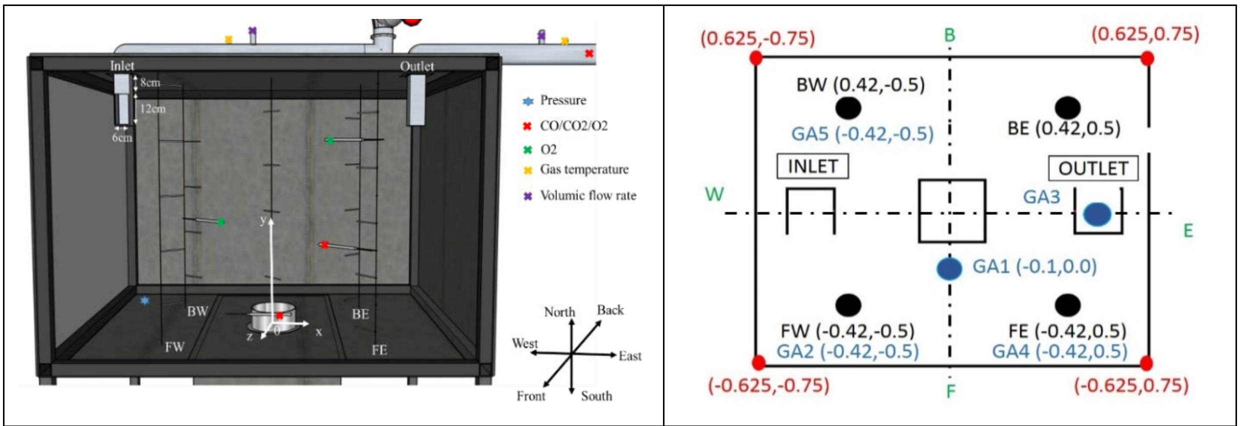
The work presented in this paper is undertaken in the context of a research program that aims at studying oscillatory combustion in a reduced-scale model (1:4), as a support to the PRISME 2 experiments. The reduced-scale model constructed at the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) offers the possibility to perform more tests (at a reduced cost) with the objective of characterizing combustion instabilities in terms of (1) likelihood of occurrence with respect to the ventilation conditions, (2) amplitude and (3) frequency of oscillations. More specifically, in the present paper, the experimental results of one small-scale test are shown. The fire source is an 18 cm diameter heptane pool fire located in the centre of the room. The ventilation system is characterized by a Renewal Rate (R_h [h^{-1}]), calculated as the volumetric flow rate divided by the volume of the room, of 15 h^{-1}. In this test the mentioned oscillatory behaviour is observed.

Later, this scenario is simulated with the Computational Fluid Dynamics (CFD) code ISIS[1], a dedicated solver to simulate fire in confined and mechanically ventilated enclosures. Preliminary simulations are performed first without a fire source in order to validate the boundary condition of the ventilation, to visualize the flow field in the compartment prior to ignition and to study the influence of the cell size. Then, fire simulations are undertaken by prescribing the MLR. The predicted pressure (P (Pa)), volume flow rates in the inlet and outlet (VFR_{in} and VFR_{out} [m^3/s]), temperatures (T [°C]) and species concentrations in the compartment are compared with the experimental data. Besides, the transport of O_2 from the inlet to the pool fire is studied.

EXPERIMENTAL CONFIGURATION

Experimental Set-up

The experimental set-up called NYX (see Figure 1 a) is a 1:4 scale reproduction of the DIVA facility of IRSN [2]. This scale ratio was deduced from the Froude number similarity of the inlet air flow. The small-scale model is a 1.5 m × 1.25 m × 1 m rectangle parallelepiped, with interchangeable side panel components. This last feature allows modifying the thermal properties of the walls and thus the interaction with fire.



a)	b)

Figure 1 a) Sketch of the set-up NYX and b) location of BW, FW, FE and BE (top view)

In the present case, the side walls, namely E, F and B, and the ceiling and floor, S and N respectively (see Figure 1), are composed of a 2 mm thick steel plate internally covered with a 4.5 cm thick calcium silicate plate. The side wall W (see Figure 1) is made of heat-tempered glass in order to visualize the movement of the flame in the compartment. The inlet air flow is free whereas the outlet flow is mechanical. Ventilation ducts have a diameter of 4 cm. The openings of the inlet and exhaust branches are 6 cm × 12 cm, situated vertically in the upper part of the room at 0.2 m from the ceiling. A variable opening valve is used to adjust the specific outflow rate in the compartment.

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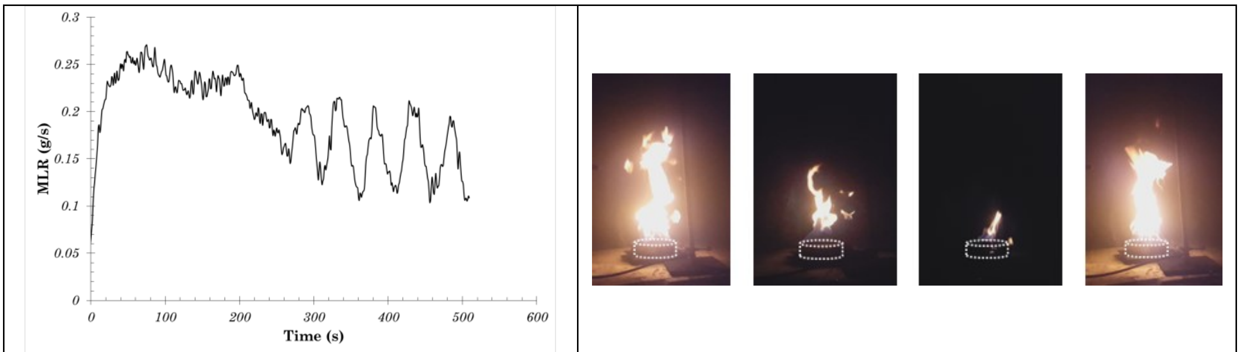
[1] The CFD code ISIS can be freely downloaded from the following website: https://gforge.irsn.fr/gf/project/isis/.

The MLR is deduced from the loss of fuel mass as measured over time using a SARTORIUS® electronic scale. The electronic scale is placed under the room floor in order to protect it from the fire-induced thermal loads. The range of applicability of the scale is from 0 to 7 kg and the experimental uncertainty is 0.1 g. For the measurement of gas temperature, vertical trees of five K-type 0.5 mm diameter thermocouples are positioned in each of the four corners of the room at FE, FW, BW and BE (see Figure 1 b). These devices can measure temperatures from 0 to 1300 °C with an uncertainty of 0.016 %. The O_2, CO_2 and CO molar fractions (X_{O_2}, X_{CO_2} and X_{CO} respectively) are simultaneously measured inside the room by means of three commercial gas analysers (XSTREAM and SIEMENS ULTRAMAT apparatus) (see Figure 1 b): one near the fuel pan (GA1), one in the corner FE (GA2) at 0.42m from the floor and one in the exhaust branch (GA3). Two additional measurements of X_{O_2} are made: one in the corner BW (GA5) at 0.42 m from the floor and the other in the corner FE (GA4) at 0.83 m from the floor. The range of applicability for the measurement of X_{O_2}, X_{CO_2} and X_{CO} is 0 - 25 %, 0 – 20 % and 0 – 1 % respectively with an experimental uncertainty approximately of 0.1 %. Two McCaffrey probes [3], previously calibrated, are positioned in the ventilation ducts and connected to membrane pressure transducers in order to determine VFR_{in} and VFR_{out}. The range of this apparatus is between – 80 m^3/h and 80 m^3/h and the experimental uncertainty is 0.5 %. A thermocouple is placed in each branch to monitor the variations in gas density due to temperature changes. The range and uncertainty of this device are similar to the 0.5 mm diameter thermocouple. One Emerson ROSEMOUNT pressure transmitter measures the difference between the *P* inside the compartment and the exterior in a range between - 1000 Pa and 1000 Pa. The uncertainty of the measurement is 0.038 %. Finally, to visualize the displacement of the flame through the glass wall, a video camera is set-up outside the compartment. During the fire, all measurements are displayed on a monitoring screen and recorded at a rate of 1 Hz. Note that the mentioned uncertainties do not take into account the expanded factor related to the physics around the sensor. This expanded factor is difficult to assess.

The fire source is a heptane pool fire located in the centre of the room. The fuel pan is circular, 0.18 m in diameter and 5 cm of height. The distance between the surface of the fuel and the lip of the pan is 7 mm prior to ignition. In the present case, the ventilation outlet flow rate before ignition is maintained at $7.78 \times 10^{-3} \pm 1.0 \times 10^{-4}$ m^3/s, finally leading to a renewal rate of 15 h^{-1}. Ignition is performed using a remote-controlled propane gas burner.



a) b)

Figure 2 a) Development of the MLR over time and b) flame snapshots after 307, 328, 358, and 380 s of fire

Results

As shown in Figure 2 a), the MLR exhibits a low frequency oscillatory behaviour, with a frequency of 0.0218 Hz, which corresponds to a period of oscillations of 46 s. In the first 200 s, the MLR grows and stabilizes. Subsequently, it decreases to 0.15 g/s before it starts oscillating after 260 s of fire. The MLR is maximum when the flame is above the pan and minimum when the flame is outside the pan (see Figure 2 b)). This phenomenon results from the coupling between the MLR due to the heat feedback from the flame to the fuel surface, the pressure inside the compartment, the ventilation flow rates, and the oxygen concentration.

NUMERICAL SET-UP

Governing Equations

The conservation equations of mass, momentum and state are solved in a conservative form based on the low-Mach number approach [4].

Turbulence

Turbulence is treated by means of Large Eddy Simulation (LES). The sub-grid scale (SGS) viscosity (μ_s (kg/m/s)) is modelled using the Wall Adapting Local Eddy (WALE) [5] method. The expression of μ_s reads:

$$\mu_s = \rho (C_w \Delta)^2 \frac{\left(\sum_{i,j} \bar{\gamma}_{ij}\bar{\gamma}_{ij}\right)^{3/2}}{\left(\sum_{i,j} \bar{S}_{ij}\bar{S}_{ij}\right)^{5/2} + \left(\sum_{i,j} \bar{\gamma}_{ij}\bar{\gamma}_{ij}\right)^{5/4}} \tag{1}$$

where C_w is a parameter of the model (0.325 in the present paper [6]), Δ is the characteristic cell size (m) ($\Delta = (Cell\ Volume)^{1/3}$), $\bar{S}$ is the mean stress tensor of the resolved scale and $\bar{\gamma}$ is an operator described in [5].

Combustion

The combustion of heptane is modelled by a one-step irreversible reaction. The fuel burning rate ($\overline{\dot{w}_F}$, kg/m^3/s) is predicted in the simulations using the Eddy Dissipation Model:

$$\overline{\dot{w}_F} = -\bar{\rho} \frac{D_{LES}}{C\,\Delta^2} min\left(\widetilde{Y}_F, \frac{\widetilde{Y}_O}{s}\right) \tag{2}$$

where C is a dimensionless constant taken as 0.1 [7], s is the stoichiometric ratio of the reaction, $\widetilde{Y}_F$ and $\widetilde{Y}_O$ are respectively the resolved fuel and oxygen mass fractions and D_{LES} is the diffusivity coefficient in the SGS level.

Discretization of the Domain

The volume of the small-scale compartment described previously is taken as the numerical domain in the present simulations. The mesh consists of uniform cubic cells. Three cell sizes are used, more specifically 1 cm (fine), 2 cm (medium) and 3 cm (coarse) in order to determine how sensitive the results are to changes in the cell size in the non-fire conditions for 100 s. The shape of the pan used during the experiments is circular. However, to accommodate the pan shape to the cubic cells the contour of this element is modified to a square in the simulations. The relative deviation (ε [%], see Equation 3) between the experimental and modelled fuel surface is 0.6 %. The impact of this deviation on the numerical results can be neglected because the MLR is imposed in the fire simulations. Thus, the MLR does not depend on the area of surface of the fuel.

$$\varepsilon = \frac{x - x_{ref}}{x_{ref}} * 100 \quad (3)$$

The time steps imposed for the coarse, medium and fine meshes are respectively 1.3875×10^{-2} s, 9.25×10^{-3} s and 4.625×10^{-3} s. These values are estimated based on the cell size and the maximum expected velocity provided by the ventilation system during the experiment (2.29 m/s). The imposed values ensure a maximum Courant-Friedrichs-Lewy (CFL) number of approximately 1.0.

Boundary Conditions

Heat Transfer to the Walls

The ceiling, floor, side walls, ventilation branches and pan are modelled as walls. The pan and ventilation branches are modelled as adiabatic surfaces. The heat transfer through the ceiling, floor and side walls is calculated using the 1D Fourier's equation for conduction.

The thermal characteristics of the materials (glass, steel and calcium silicate) imposed in the simulations are shown in Table 1.

Table 1 Conductivity, density and specific heat of the materials used in the walls

Material	λ [kW/m/K]	ρ [kg/m^3]	C_p [kJ/kg/K]
Glass	0.96×10^{-3}	2600	0.840
Steel	50×10^{-3}	7850	0.490
Calcium Silicate	0.21×10^{-3}	870	0.920

Fuel Surface Boundary Condition

The experimentally measured MLR of the fuel is imposed (see Figure 2 a)) in the fire simulations. The surface temperature of the pan is fixed as the boiling temperature of heptane (98.42 °C).

Pipe-junction Boundary Condition

The interplay between the compartment and the ventilation system (outlet) and the outside (inlet) is modelled using the pipe-junction boundary condition. The mass flow rate ($\dot{m}_v$ [kg/s]) in each branch is predicted using a simplified Bernoulli equation.

$$\dot{m}_v = \sqrt{\frac{\rho f}{sign(\dot{m}_v)Res}} \quad (4)$$

where Res is the aeraulic resistance [m^{-4}] and f is the pressure difference [Pa], calculated as:

$$f = P(t) - P(ext) \quad (5)$$

where $P(ext)$ is the pressure at the end of the ventilation branch [Pa].

The Res in the inlet and the outlet (Res_{inlet} and Res_{outlet}) are calculated using the experimental $\dot{m}_v$ prior to the ignition. The expression used to calculate Res reads:

$$Res = \frac{\rho f}{sign(\dot{m}_v)\dot{m}_v{}^2} \quad (6)$$

The density used to calculate Res_{inlet} (1.18 kg/m^3) is the one expected for air at the ambient temperature (24.5 °C). However, to determine Res_{outlet} the density of the combustion products must be known beforehand. Because of this limitation, the density used in the calculations of Res_{oulet} is the same than that used for Res_{inlet} (1.18 kg/m^3). Therefore, the ventilation parameters used in the present simulations are those given in Table 2.

Table 2 Parameters of the ventilation system

Branch	P_{ext} [Pa]	Res [m^{-4}]
Inlet	101325	1000886
Outlet	98980	33599196

RESULTS AND DISCUSSION

Simulations without a Fire Source

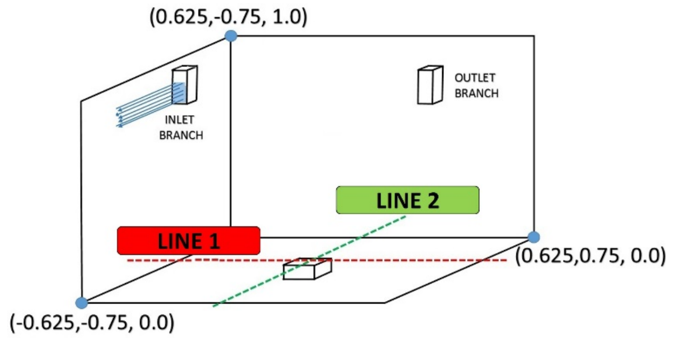
Mesh Convergence Analysis

To analyse the deviation between the different grids used the instantaneous velocities are averaged over a period of 10 s after the VFR and the pressure have reached a steady state condition. These average velocities are compared along two lines (see Figure 3 a)). Lines 1 and 2 (red and green lines respectively in Figure 3 a)) are located at a height of 0.065 m above the floor level. These lines are placed in order to assess the influence of the cell size on the fire source. The average vector and velocities at 0.065 m (see Figure 3 b)) and at 0.5 m (see Figure 3 c)) from the floor show that the air is transported from the inlet towards the bottom of the enclosure and then to the pan zone. In addition, the sharpest gradients in the velocity field are observed in the lower part of the compartment. Subsequently, the most significant impact of the cell size on the flow behaviour and velocity field must be observed at the height where the velocities are compared. Note that the flow behaviour is studied in fire conditions later in this paper.

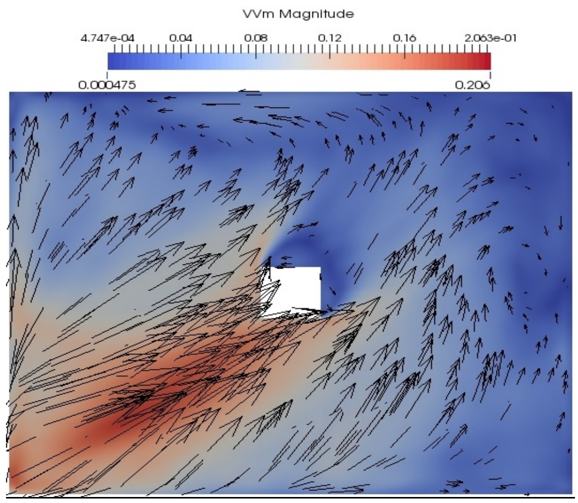
The numerical results show that the velocities are in the same order of magnitude using the fine, medium and coarse meshes. However, a clear numerical convergence is not reached. These deviations are more significant in the vicinity of the inlet branch. For instance, in line 1 (see Figure 3 d)) the velocity profile between - 0.75 m and - 0.1 m is significantly different using the fine mesh that those observed with the other cell sizes. A similar deviation is observed in line 2 (see Figure 3 e)) between - 0.625 m and - 0.2 m. These phenomena are expected based on the described flow behaviour. Besides, the ventilation boundary condition is the same in the three tests. It indicates that the cell size has an impact on the transport of the injected air inside the compartment and consequently on the local velocities in the zone where the largest deviations between grids are observed. However, the velocity profiles are converged for the three grids in the pan area (around 0 m) where the flame is expected. Besides, the times of calculation of the shown test are 1.25 h, 5.85 h and 90 h for the coarse, medium and fine grids respectively. Thus, because the similarity of the results in the pan area and the large impact of the cell size on the simulation time fire simulations are performed using the 2 cm cell size. Note that in future steps a mesh convergence analysis must be performed considering the influence of fire on the results.

Validation of the pipe-junction Boundary Condition

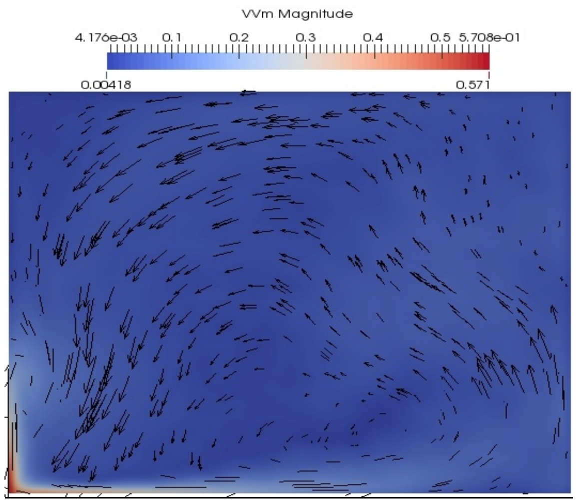
During the experiment and prior to the ignition of the fire source the pressure in the compartment decreases until a steady volume flow rates in the inlet (7.8 × 10^{-3} m^3/s) and outlet (7.7 × 10^{-3} m^3/s) and relative *P* (- 72 Pa) are reached. A similar procedure is followed in the simulations. The steady state pressure and VFR_{in} and VFR_{outlet} are the same using the three grids. It is – 69 Pa and 7.5 ×10 $^{-3}$ m^3/s for the inlet and outlet VFR. The relative deviations between the numerical and experimental data are 4.3 % for the *P* and - 3.8 % for the VFR_{in} and - 2.6 % for the VFR_{out}. These results are shown in Table 3. The observed deviations are not significant and the pipe-junction boundary condition and the used set-up are validated in this scenario.



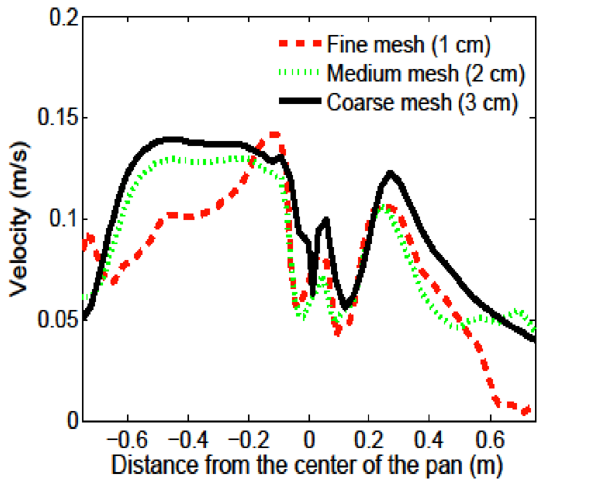
a) Isometric sketch of the compartment. Lines 1 (red) and 2 (green) are shown



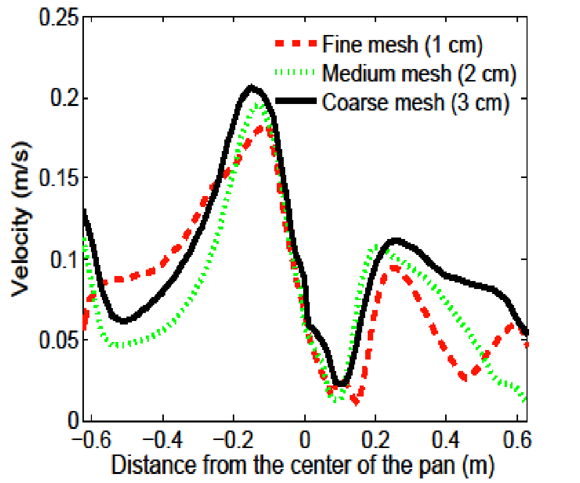
b) Iso-contour of the average velocity and velocity vector in the horizontal plane at 0.065 m from the floor



b) Iso-contour of the average velocity and velocity vector in the horizontal plane at 0.5 m from the floor



d) Average velocity using the fine, medium and coarse grids along line1

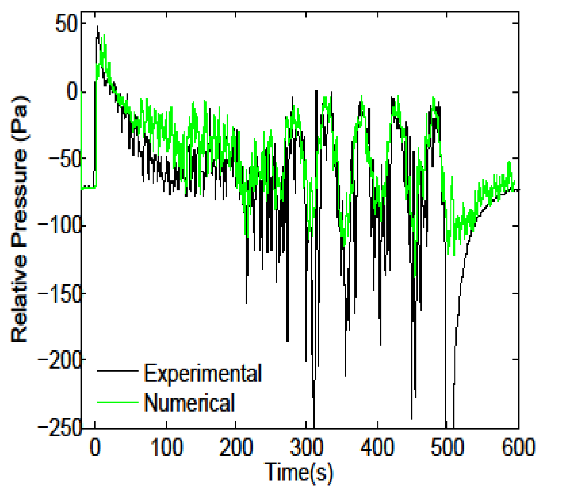


e) Average velocity using the fine, medium and coarse grids along e) line 2

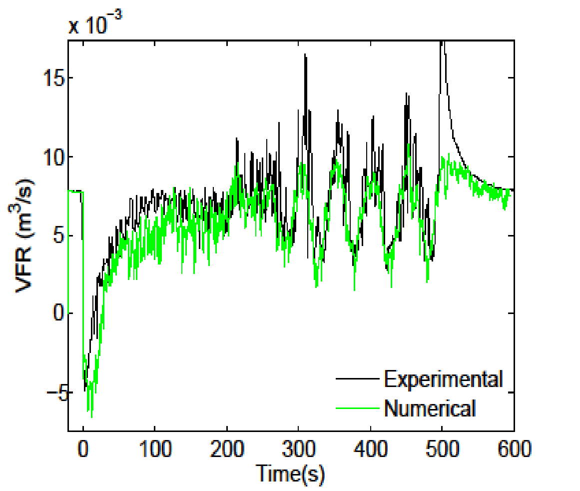
Figure 3 Numerical study of the influence of the cell size on the velocity fields

Table 3 Numerical and experimental steady *P*, VFR_{in} and VFR_{out} in the period prior to ignition and relative deviations between the results

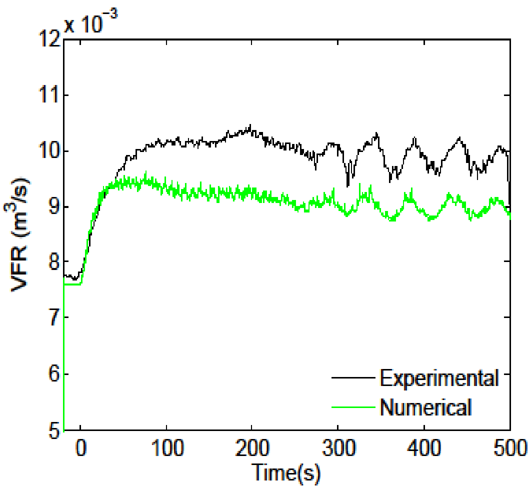
	Steady rel. P [Pa]	**ε-Steady rel. P [%]**	**Steady VFR_{in} [m^3/s]**	**ε-Steady VFR_{in} [%]**	**Steady VFR_{out} [m^3/s]**	**ε-Steady VFR_{out} [%]**
Experimental	- 69	-	7.8×10^{-3}	-	7.7×10^{-3}	-
Numerical	- 72	4.3	7.5×10^{-3}	- 3.8	7.5×10^{-3}	- 2.6



a) relative P



b) VFR_{in}



c) VFR_{out}

Figure 4 Comparison between the numerical and experimental values of the pressure (a)) in the compartment and the VFR in the inlet (b)) and outlet (c))

Simulations Imposing the Mass Loss Rate

Prediction of Pressure and Volume Flow Rates

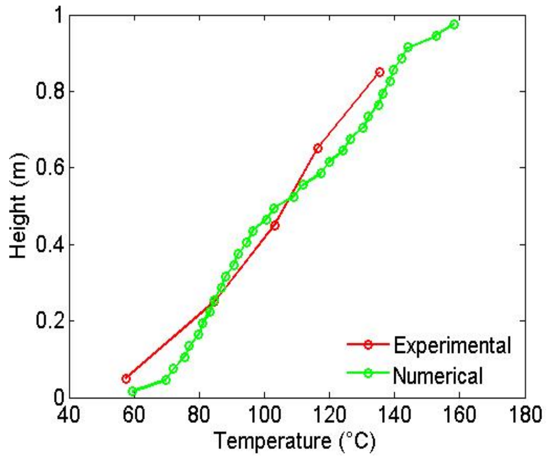
As mentioned before, the oscillatory period extends from 260 s. Besides, the oscillations are very clear in the period between 300 s and 450 s. Thus, the calculation of the averages (referred with the superscript ‾) as shown in the following are performed using the data between these times. The average experimental and predicted relative pressures during the period of interest (300 s to 450 s) are - 74.6 Pa and - 52.4 Pa respectively (see Table 4). The relative deviation between these values is - 29.4 % but the trend of the oscillation of the pressure is well captured by the numerical simulation (see Figure 4 a)). However, low pressure peaks with a value around – 200 Pa observed in the experiments are not captured by the simulation. This can be explained because the recorded MLR in the experiment is an average value per second and the sharp decreases in the MLR can occur in periods shorter than 1 s, for instance due to local extinction, which could not be measured. This average MLR per second is later imposed in the simulation. On the contrary, the gauged pressures are instantaneous values and the effect of the decreasing of the MLR could be detected. The lack of this phenomenon in the simulation can explain partially the over prediction of the relative pressure. The numerical and experimental $\overline{VFR}_{in}$ are respectively 6.3×10^{-3} m^3/s and 7.4×10^{-3} m^3/s. In the outlet the predicted and measured $\overline{VFR}_{out}$ are 9.0×10^{-3} m^3/s and 9.9×10^{-3} m^3/s respectively. Thus, the ε between the experimental and numerical VFR are - 14.9 % and - 9 % for the inlet and the outlet (see Table 4). This deviation is produced partially because the mentioned low pressure peaks are not captured by the code. However, in the period without oscillations both VFR are under predicted indicating the parameter used to set up the ventilation boundary condition (see Table 2) must be improved. For instance, Res (see Equation 6) could be calculated each time step using the predicted ρ and f.

Table 4 Numerical and experimental relative pressure, volume flow rates, temperatures in the lower and upper zones and CO_2 and O_2 molar fractions in GA1 during the period of interest and relative deviations between the results

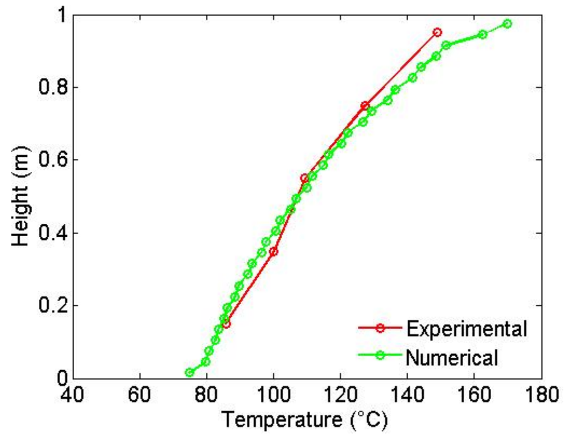
	Experimental	Numerical	ε [%]
$\overline{rel.P}\ [Pa]$	- 74.6	- 52.4	- 29.8
$\overline{VFR}_{in}\ [m^3/s]$	7.4 × 10^{-3}	6.3 × 10^{-3}	- 14.9
$\overline{VFR}_{out}\ [\frac{m^3}{s}]$	9.9 × 10^{-3}	9.0 × 10^{-3}	- 9
$\bar{T}_{lower}\ [°C]$	61	68	11.5
$\bar{T}_{upper}\ [°C]$	149	171	12.8
$\bar{X}_{O_2-GA1}$	15.4	15.2	- 1.3
$\bar{X}_{CO_2-GA1}$	3.6	3.4	- 5.5

Prediction of Temperature and Species Concentrations

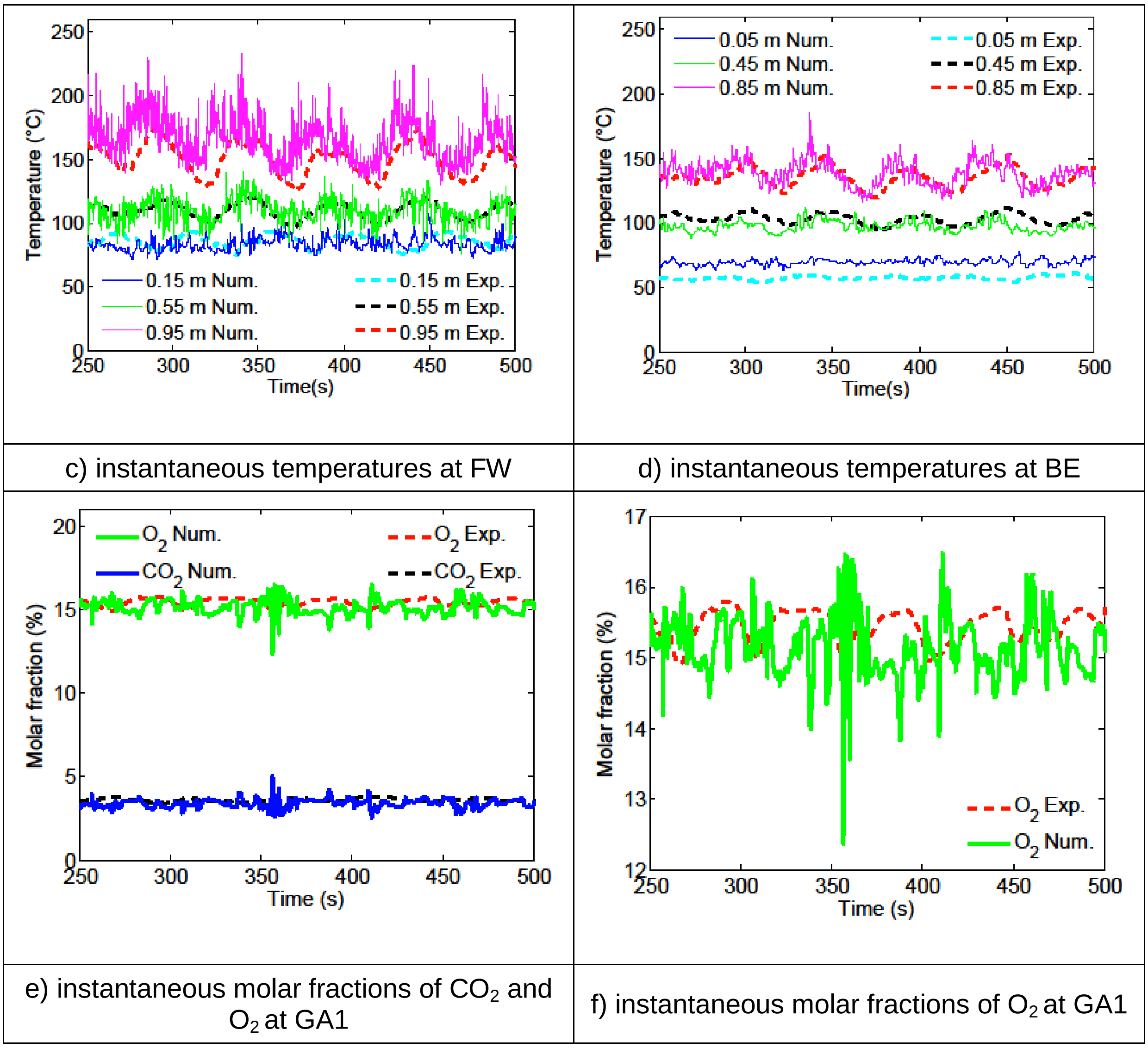
The predictions of temperature are shown in the locations FW and BE (see Figure 1 b)). The FW position is located in the blowing area of the inlet and the BE is in the aspiration zone of the outlet. In addition, the level of agreement between the numerical and experimental results observed in FE and BW is similar to FW and BE. The numerical and experimental average temperatures in the period of interest at different heights are shown in Figure 5 a) and Figure 5 b), respectively. The agreement between the experimental data and the calculations is excellent in both locations. The instantaneous temperature profiles in the same locations (FW in Figure 5 c) and BE in Figure 5 d)) at different heights show that the oscillatory behaviour of the temperature is more clearly observed in the upper part of the compartment because this zone is directly affected by the plume of the pool fire and the oscillations of the MLR. This behaviour is well captured by the numerical code.



a) average temperature at FW



b) average temperature at BE



c) instantaneous temperatures at FW

d) instantaneous temperatures at BE

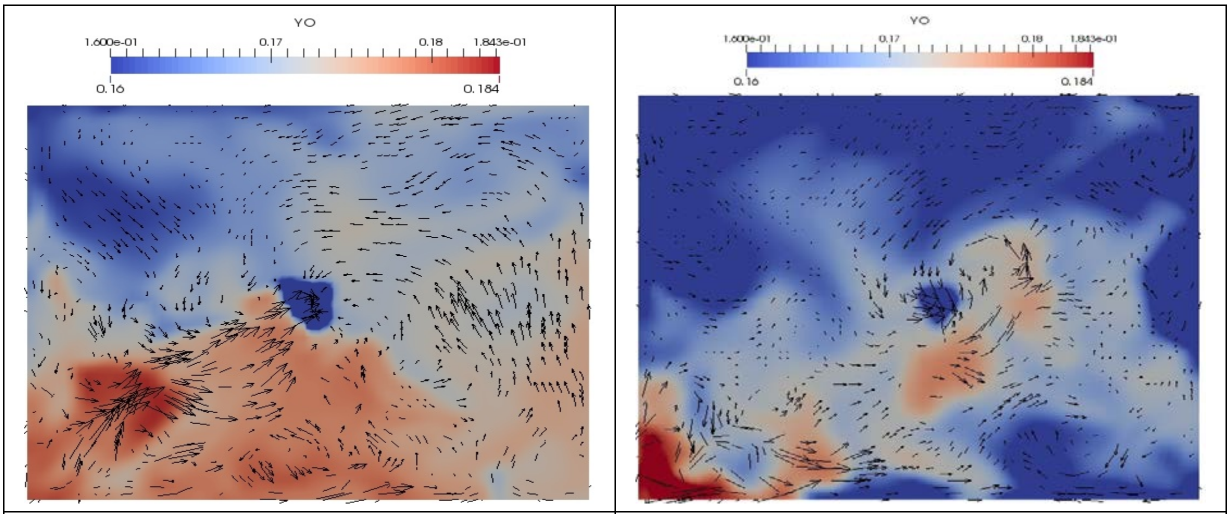
e) instantaneous molar fractions of CO_2 and O_2 at GA1

f) instantaneous molar fractions of O_2 at GA1

Figure 5 Numerical and experimental average (a) and b)) and instantaneous (c) and d)) temperatures in the period of interest and molar fractions at GA1 (e) and f))

The largest temperature deviations between the results are observed at 0.05 m ($\overline{T}_{lower}$) and 0.95 m ($\overline{T}_{upper}$) from the floor in BE and FW respectively. The average measured temperatures are 61 °C and 149 °C at 0.05 m and 0.95 m respectively. The predicted temperatures in these locations are 68 °C and 171 °C. Thus, the relative deviations in the lower and upper part of the compartment are 10.29 % and 12.88 %, respectively (see Table 4). These deviations can be explained because the complexity to model the flow-wall interaction.

In Figure 5 e) the numerical CO_2 and O_2 molar fractions at location GA1 are shown. Besides, the O_2 concentration is shown in detail in Figure 5 f). The observed O_2 concentration at GA1 is approximately the amount of O_2 available for the combustion. The experimental average molar fractions of O_2 and CO_2 are respectively 15.4 % and 3.6 %, and the numerical averaged results are 15.2 % and 3.4 % for the O_2 and CO_2. The relative deviations between the experimental and numerical results are - 1.3 % and - 5.5 % for the O_2 and CO_2 molar fractions, which is an excellent agreement (see Table 4). Besides, the oscillation is captured by the numerical code. Note that a time delay is observed between the experimental and numerical concentrations due to the transport of the combustion products from the enclosure to the detector. The gas analysers are located outside the compartment to avoid the thermal loads.



a) at 0.1 m from the floor | b) at 0.5 m from the floor

Figure 6 Instantaneous iso-contours of the O_2 mass fraction and velocity vector field

Analysis of the Transport of Oxygen from the Inlet to the Pool Fire

The amount of injected air that reached the vicinity of the pool fire has a direct impact on the MLR. This transport phenomenon has not been extensively analysed using CFD. Thus, the instantaneous oxygen mass fraction and velocity vector fields in two horizontal planes (0.1 m and 0.5 m from the floor in Figure 6 a) and Figure 6 b) respectively) are shown. These variables are examined at 400 s when a low MLR and high VFR are recorded. It is observed that two areas with different oxygen concentrations can be delimited. Besides, in the down left corner of the figures an area with a high concentration of O_2 is found. It indicates that the injected air is not well-mixed at this time for both heights. In addition, the velocity vector field at 0.1 m shows that O_2 is transported from the lower part of the compartment towards the pool fire. A similar behaviour is exhibited by the flow in the simulations without a fire source (see Figure 3 b)). On the contrary, this behaviour is not observed at a height of 0.5 m as in the simulation without fire (see Figure 3 c)). A similar analysis has been repeated for a time when the VFR is high. However, in that case, the conditions inside the compartment are more well-mixed and the flow pattern described was not observed. It indicates that the flow dynamics depends on the VFR.

CONCLUSIONS

In this paper, the oscillatory behaviour in the small-scale model NYX is studied numerically. First, simulations without fire are performed. The results indicate that a cell size of 2 cm is a suitable compromise between accuracy and simulation time. Secondly, simulations are completed imposing the experimental Mass Loss Rate. The numerical results prove that, using the 2 cm cell size, Large Eddy Simulation and Eddy Dissipation Model, ISIS can capture the ventilation conditions, the temperature and the concentration of species inside the enclosure. However, the level of relative deviation between the experimental and numerical tests observed for the pressure (approx. - 30 %) is larger than the discrepancy for the volume flow rate (VFR) (- 10 % approx.), temperature (approx. 10 %) and species concentrations (approx. 5 %). Understanding the relation between the mentioned variables still requires a deeper analysis. For instance, the renewal rate could be modified and the impact of the conditions in the compartment assessed.

Besides, the study of the oxygen and velocity distribution inside the compartment during a low MLR period proves that:

1) Two clearly different zones can be observed in terms of oxygen concentration and
2) The air is transported from the inlet branch to the bottom of the compartment, and thus, to the pool fire zone.

It indicates the existence of a clear direct link between the inlet branch and the fire source in the form of a preferential path for the injected air. Analysing the transport of air using different VFR or geometries could enhance the prediction of the flow behaviour in compartments.

The present paper is an initial step before carrying out predictive simulations of the oscillatory behaviour in compartments by using an evaporation model.

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NUMERICAL METHOD FOR DETERMINING DROPLET SIZE DISTRIBUTIONS OF SPRAY NOZZLES USING A TWO-ZONE MODEL

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ABSTRACT

Water spray systems are widely used as protection means for fire suppression and are a well-established technique for providing safety and protection of nuclear installations and industrial facilities. One major challenge is to be able to properly determine the technical features of the water spray system required for predictive simulations. For that purpose, a Phase Doppler Interferometer (PDI) for measuring the droplet size distributions and the droplet velocities is used. However, usual water spray models require as input data the overall droplet size distribution and initial droplet velocity. Some statistical methods are needed to determine these parameters from local accurate measurements given by the PDI. A new calibration approach for assessing the input parameters of this modelling by using large-scale and well-controlled fire tests has been addressed in this paper. Then, by introducing some correlations to take into account different operating conditions of the pressure at the spray nozzle head, this technique is validated on other large-scale fire tests. After discussing thoroughly the results, this new method shows that it can be a valuable and efficient tool for determining the overall features of water spray systems linked with the modelling of the water spray system used in this study.

INTRODUCTION

Water spray systems used as protection means for fire suppression is a well-established technique for providing safety and protection of industrial and nuclear installations. The research in the domain of water spray systems remains important due to the complexity involved in predicting the interaction between water sprays and fire environment. Indeed, a continuous research activity is underway to improve the capability of modelling and predicting tools [1] to [6], to measure accurately the characteristics of water spray systems [7] to [10], and to investigate the efficiency of such systems [11] to [13] depending on the technique of water spraying of interest and on the sought objectives (for instance, fire extinguishing by flame cooling and oxygen concentration reduction through an increase of water vapour content, reduction of aggressive hot smoke particles by gas cooling and soot removal by water droplets or protection of structural elements by direct or indirect cooling).

The main advantages of sprinkler or spray water deluge systems are the broad availability, the relatively low costs, the low level of operating pressure (< 5 bar except for water mist systems) and a high efficiency in fire suppression, if amounts of water being large enough are supplied to a relevant location and in early time. An accurate experimental characterization of the spray nozzle in terms of droplet size distribution at injection and initial droplet velocity is required as input data for predicting tools since droplet evaporation kinetics is highly dependent on droplets size and droplets fall time. Nevertheless, determining the water spray characteristics could be very challenging due to the design of spray nozzles (i.e. the geometric features of sprinkler heads) mainly made for practical engineering goals involving often the complexity of water spray behaviour (particularly the breakup process of water jet inducing large variations of droplet size and velocity close to the nozzle, and various spray diameters). In order to determine the main technical features of water spray systems, a Phase

Doppler Interferometer (PDI) device is generally used for measuring droplet size distributions and droplet velocities allowing to perform accurate local measurements. Nevertheless, some usual water spray models [1], [6] require as input parameters an overall droplet size distribution and an initial droplet velocity. Thus, it is needed to apply some statistical methods over these experimental data to determine them. A second difficulty is linked to the high sensibility of droplet size distribution and initial droplet velocity due to the pressure effect at nozzle head. Indeed, an initial characterization of a water spray system is performed at a given pressure for the nozzle head before using in fire scenario. However, a slight change of the water flow rate (i.e. pressure head) can lead to significant variations of droplet size distribution and initial droplet velocity. Thus, an adjustment on both droplet size distribution and initial droplet velocity must be performed in predictive simulations in case of change of spray water flow rate compared to the one used during the initial characterization of the water spray system. A third difficulty lies on the experimental measurement of initial droplet velocity used as input data in spray modelling. Water droplets from sprinkler or spray water deluge systems are produced by impingement of the water jet on the deflector of the nozzle. Droplet velocity measurements are consequently performed several tens of centimetres below the spray nozzle (see e.g. [8]). At this elevation, the droplets are under-relaxed and therefore the velocity measurements do not correspond strictly to the initial velocity of droplets.

As an alternative way for defining the features of spray nozzles, a numerical method for determining droplet size distributions and initial droplet velocity is developed using both the two-zone model SYLVIA [17] and experimental data [11]. Indeed, this approach proposes to perform a calibration of spray modelling by means of full-scale fire tests in an enclosure, for which the fire power and the ventilation system are perfectly controlled.

After a description of the water spray model implemented in the SYLVIA software, this work addresses a new calibration approach for assessing the input parameters of this modelling by using large-scale fire tests in the DIVA facility [11]. Then, this technique is validated on other fire tests having different pressure heads for the water spray nozzles. The results of this study are discussed thoroughly and show that this new approach can be a valuable and efficient tool for determining the overall features of water spray systems based on the spray modelling used in this work.

BRIEF DESCRIPTION OF THE SYLVIA SOFTWARE

The SYLVIA software [17] has been developed at the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) to simulate a full ventilation network, fire scenarios in confined and ventilated facilities, and airborne contamination transfers inside nuclear installations. This software is based on a zone approach which consists in calculating mass and energy balances in each of two zones, separated by an interface, which constitute the enclosure: the lower zone simulating the fresh gas and the upper zone simulating the combustion products and the gas entrained by the plume. In a zone approach, a plume feeds the upper zone of the fire compartment, whose volume increases lowering the interface, if the gas flow in the exhaust duct or at the level of openings of the fire compartment is not sufficient to remove all gases supplied by the plume.

SPRAY MODELLING

Droplet Size Distribution

The spray model implemented in the SYLVIA software is based on mass and heat transfers between droplets and surrounding gas during their fall [1]. No direct interaction between spray droplets and the fire source is modelled. The rates of mass and heat transfers between surrounding gas and falling droplets are strongly dependent on the droplet size. To characterise statistically the droplet size in a control volume, a concept of distribution function $f(d_w)$ is introduced. This function is such that the number of droplets per unit of volume for droplet diameters from d_w to $d_w + dd_w$ are:

$$dn = n_0 f(d_w) dd_w \tag{1}$$

In practice, the droplet size distributions produced by most of the spray nozzles are well represented by a log-normal distribution function as:

$$f(d_w) = \frac{1}{\sqrt{2\pi}\, d_w \ln\sigma_g} exp\left[-\frac{\left(ln \frac{d_w}{CMD} \right)^2}{2(ln\sigma_g)^2} \right] \tag{2}$$

The log-normal distribution function requires the knowledge of two parameters for its determination: the geometric standard deviation σ_g and the count median diameter (CMD) or the mass median diameter (MMD). For a log-normal distribution function, the MMD is directly related to CMD by the following equation:

$$MMD = CMD\, exp\left[3 \cdot ln(\sigma_g)^2\right] \tag{3}$$

Dynamics of Droplets

Droplets are assumed to fall down vertically from their injection area (no interaction with compartment walls is considered). Gas environment is assumed to be steady during a droplet fall (i.e. it is assumed that the characteristic time for a droplet fall is less than the characteristic time for changing the mean gas conditions in the enclosure). Coalescence of droplets is also neglected according to low droplet fall heights in fire applications (several meters). The development over height of mass, velocity and temperature of a droplet during its fall is obtained by solving a set of coupled equations for the mass, momentum and energy balance [1]:

$$\frac{dm_w}{dz} = \pi\, d_w\, Sh_g\, \overline{D}_s\, \overline{c}_g\, M_w\, B_M / v_w \tag{4}$$

$$m_w \frac{d}{dz} v_w = m_w\, g / v_w - \frac{\pi d_w^2}{8} C_D\, \rho_g\, v_w \tag{5}$$

$$\frac{d}{dz}(m_w H_w) = (\pi\, d_w\, \lambda_g\, Nu_g\, (T_g - T_w))/v_w + \varepsilon\sigma\pi d_w^2 \left(T_g^4 - T_w^4\right)/v_w + \frac{dm_w}{dz} H_s \tag{6}$$

Knowing both, gas conditions and injection conditions of droplets (velocity, diameter and temperature), the dynamics of droplets is defined by the expression of the three dimensionless numbers Sh_g, Nu_g and C_D. The Nusselt number Nu_g and Sherwood number Sh_g are deduced from steady evaporation in dry air of droplets having diameters in the range from 600 to 1100 µm by Ranz and Marshall [2]:

$$Sh_g = 2 + 0.6\, Re_w^{1/2}\, Sc_g^{1/3} \tag{7}$$

$$Nu_g = 2 + 0.6\, Re_w^{1/2}\, Pr_g^{1/3} \tag{8}$$

The drag coefficient C_D is obtained from the Oseen formulation [14] for hard spheres:

$$Re_w < 3 \quad C_D = 24 / Re_w \text{ (Stokes flow)} \tag{9}$$

$$3 < Re_w < 905 \ C_D = \frac{24}{Re_w}\left(1 + \frac{Re_w^{2/3}}{6}\right) \text{ (intermediate flow)} \quad (10)$$

$$Re_w > 905 \ C_D = 0.44 \text{ (potential flow)} \quad (11)$$

Equations are solved on a fixed meshing by using a Forward Euler method.

Mass and Energy Balance

Gas composition and temperature are assumed to be homogeneous inside a given zone. The development over time of the thermal dynamics conditions in the compartment (pressure, temperature and relative humidity) due to the spray is determined from a mass and energy balance. This balance corresponds to the mass and enthalpy removed by the water droplets during their fall. This one is determined from the results of the dynamics of droplets and the development over height of the droplet size distribution function between the top and the bottom of each zone crossed by droplets:

$$\frac{d\rho_s}{dt} = -\frac{d}{dz}\left(\int f(r,z) \cdot m_w(r,z) \cdot v_w(r,z) \cdot dr\right) \quad (12)$$

$$\frac{d\rho_s}{dt} = -\frac{d}{dz}\left(\int f(r,z) \cdot m_w(r,z) \cdot v_w(r,z) \cdot dr\right) \quad (13)$$

Validation of the Model against the CARAIDAS Experiments

An experimental device named CARAIDAS [16] was designed and built at IRSN in order to determine the collection efficiency of aerosols and iodine absorption by droplets spray with representative conditions of nuclear post-accident atmosphere. CARAIDAS allows measuring experimental droplet diameter development over height as a function of different experimental conditions. The experimental vessel is a 5 m high cylinder with an inner diameter of 0.6 m as shown in Figure 1. The vessel is heated up by circulating a thermo-fluid through the double-walled stainless steel casing. Homogeneous thermodynamic conditions are obtained during the experiments by using an air-steam circulation. As soon as operating conditions (pressure, temperature, relative humidity) are reached, the air handling system is stopped and the vessel is thermally insulated. The droplet generator is located at the top of the experimental vessel. In order to release droplets monodispersed in size, the generator is designed on the basis of a break-up process of a water jet to droplets by applying a periodic disturbance. This specific device can produce water droplets monodispersed in size with a diameter ranging from 200 to 700 µm. Droplets are injected at very low mass flow rate in an ambient atmosphere with steady and homogeneous conditions. Optical measurements of the droplet diameter are performed at three elevations: one at the upper part of the vessel where the droplets are released (z = 0 m), a second one at about mid-height (z = 2.51 m) and the last one at the lower part of the device (z = 4.39 m).

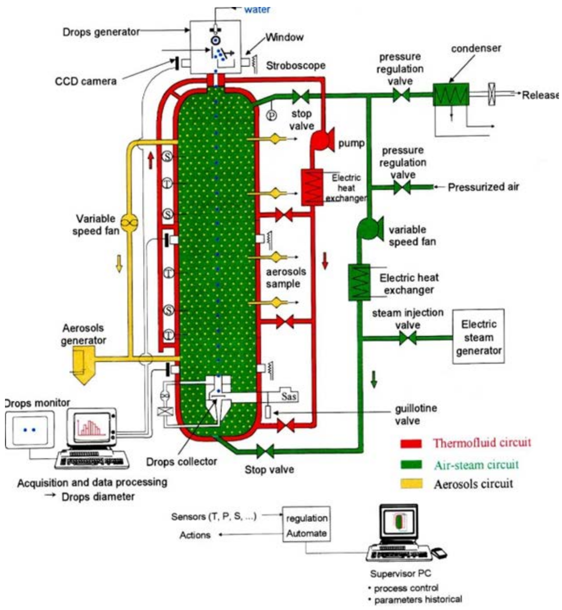


Figure 1 Experimental device of CARAIDAS

Results and Discussion

The experimental results obtained from the CARAIDAS device allow validating the modelling of dynamics of water droplets. During these tests, a wide range of experimental conditions was performed: pressure from 1 bar to 7 bar, ambient temperature from 20 °C to 160°C, and relative humidity from few percent to 95 %. For each test, measurements of the mean droplet diameter and geometric standard deviation of droplets are determined at the three measurement levels. Only experiments performed at atmospheric pressure and low relative humidity (summarized in Table 1) are used for the validation of the model, corresponding to gas conditions that could be met in the fire compartment prior the actuation of a spray system. Comparison between experimental data and SYLVIA simulations of droplet diameter development over height is reported in Table 2. With the formulation of the mass, momentum and heat transfer described in the previous section, a very good prediction of the droplet dynamics is obtained on the CARAIDAS tests. Indeed, the difference between experimental data and SYLVIA simulations is typically less than 4 %. An equilibrium between the heat flow rate transferred to the droplet and the heat flow rate lost by evaporation is quickly reached in the first meters of the droplet fall. Thus, the temperature inside the droplets can be considered thermally as homogeneous and steady (evaporation period) while its diameter decreases during its fall.

Table 1 Test conditions of three EVAP tests of the CARAIDAS program

	Gas conditions			**Spray droplets at injection**		
	P_g [Pa]	T_g [°C]	RH [%]	T_w [°C]	d_w [µm]	v_w [m.s^{-1}]
EVAP4	10^5	47	12	25	387 ± 5	1.44
EVAP8	10^5	106	< 1	25	414 ± 7	1.55
EVAP11	10^5	147	< 1	28	423 ± 4	1.59

Table 2 Comparison between CARAIDAS and SYLVIA for the droplet diameter development over height

	d_w [µm] at z = 2.51 m			d_w [µm] at z = 4.39 m		
	Test	SYLVIA	Diff.	Test	SYLVIA	Diff.
EVAP4	375 ± 4	375	0 %	363 ± 6	365	+ 0.5 %
EVAP8	393 ± 6	381	- 3 %	363 ± 5	352	- 3 %
EVAP11	393 ± 4	377	- 4 %	342 ± 7	333	- 2 %

CALIBRATION OF SPRAY MODELLING BASED ON FULL-SCALE FIRE TESTS IN THE DIVA FACILITY

Methodology for the Calibration Process

A numerical method for determining droplet size distribution and initial droplet velocity of a water spray system using the two-zone model SYLVIA is developed. This method is based on a calibration of spray modelling using full-scale fire tests carried out in the DIVA facility of IRSN. More precisely, a parametric study is firstly performed with the SYLVIA software to adjust the droplet size distribution at injection and initial droplet velocity on a given fire test. Indeed, the numerical technique [15] consists to keep the best inputs for minimizing the difference between some appropriate outputs (or responses) from experiments and simulations. The validation of the method is then performed on other fire tests of the campaign with different operating conditions (water flow rate, heat release rate for the fire source, ventilation flow rate) using the same water spray system.

However, several prerequisites in using this method must be considered. First, the heat release rate of the fire source must be well controlled and known to reduce the uncertainties on the prediction of the droplet size distribution and initial droplet velocity. Secondly, the spray model used in the method must be relevant with respect to the water spray system of interest. Thirdly, the aeraulic resistivity of the ventilation network must be well simulated by the predicting tool. Indeed, the aeraulic resistivity of the ventilation network plays a major part on the thermal hydraulic behaviour in the fire compartment. Fourth, a minimum of two relevant outputs from the numerical results is required in the parametric study, because a single output can lead to a good fit even if the spray model is weakly satisfactory. This is no more the case with several responses.

Propane Gas Fire Tests

The propane gas fire tests [11] used for the calibration of spray modelling have been conducted in the large-scale DIVA facility of IRSN. The scenario of this tests campaign consists of a fire in one compartment of the facility. This compartment is a 3.90 m high parallelepiped with a ground surface area of 42.3 m^2 (4.88 m × 8.67 m). Walls are made of re-enforced concrete and the top of the compartment is covered with a false ceiling made of 100 mm of air, 10 mm of insulated fibre wool panels (Thermals ceramics, Board 607) and 12.7 mm of calcium silicate panels (Monalite M1-A). The ventilation configuration consists of one admission line and one exhaust line in the upper part of the compartment, at about 0.80 m from the ceiling. The ventilation lines are connected to an industrial ventilation network equipped with blowing and exhaust fans. For all tests, the ventilation is set to the same operating conditions, with a volumetric flow rate of 2550 m^3/h which corresponds to a renewal rate of 15.4 h^{-1}. This level of ventilation maintains the fire source under well ventilated conditions. As shown in Figure 2, the fire source is located in a corner of the compartment in order to minimize water projection directly towards the fire source, fire suppression being not required in these tests. This fire source is a propane gas burner apparatus that simulates the behaviour of a pool fire. Water spray system is made of two nozzles located at 2.97 m from the ground. The nozzles are connected to a piping system equipped with valves, pressure transducer and water flow rate device. The nozzles are activated manually by opening (or closing) valves on the water pipe. Nozzles are of the spray water deluge type, Protectospray® D3, HV with a coefficient k of 26 l/min/bar$^{0.5}$ (see Figure 2).

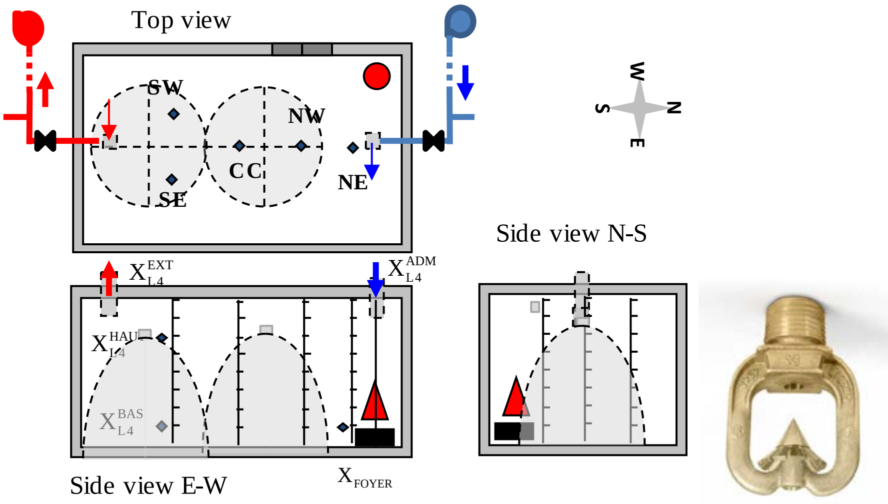


Figure 2 Description of the facility for Propane gas fire test campaign and picture of the spray water deluge nozzle

Four fire tests are considered in this study as reported in Table 3. The varying parameters are the heat release rate (HRR) of the fire source (140, 210 and 290 kW) and the total water flow rate of the water spray system (80 and 110 l/min, which corresponds to an operating pressure head of 236 and 447 kPa). The HRR is computed as the propane volumetric flow rate measurement multiplied by the gas density and the effective combustion enthalpy of propane (43 MJ/kg). For the four tests, the spray system is activated 8 min after fire ignition, for a 5 min period. The time period for the water spray system to reach the targeted water flow rate or to drop down to zero has a significant influence on the pressure variation inside the fire compartment. For all tests, the water flow rate increases from zero to the targeted value in about 5 s. Water spray is injected at 20 °C.

Table 3 Test conditions of propane gas fire tests campaign performed in the DIVA facility

Test	Gas burner	Spray water deluge nozzle	
	Flow rate [l/min]	Flow rate [l/min]	Droplet size distribution
A2	210 (290 kW)	110	fitted
B2	150 (210 kW)	110	evaluated
C2	100 (140 kW)	110	evaluated
C5	100 (140 kW)	80	evaluated

SYLVIA Modelling of the Ventilation Network

A fully dataset of the ventilation network of the DIVA facility was used to simulate properly the experimental aeraulic resistivity of the ventilation network for the propane gas fire tests. Indeed, the various nodes and branches of the modelled ventilation network correspond to aeraulic elements for which one or more experimental measurements were performed.

Description of the Calibration Technique

The goal is to measure the effects of some input parameter variations on some output responses of interest. More precisely, since the uncertainty associated with each considered parameter is summarized by a range of variation, a uniform probability distribution is chosen to represent this information. The propagation through SYLVIA modelling is then achieved by Monte Carlo simulations: each uncertain parameter is randomly sampled according to the chosen probability distribution and then the output of interest is evaluated for each set of values of input parameters provided by the sampling matrix.

The uncertain input parameters of the study are the two parameters characterizing the log-normal droplet size distribution function and initial droplet velocity:

- Mass median diameter (MMD) of the droplet size distribution, ranging between 700 and 1200 µm;
- Geometric standard deviation of the droplet size distribution (σ_g), ranging from 1.4 and 1.6;
- Initial velocity of droplets (v), ranging between 5 and 10 m.s^{-1}.

The droplet size distribution was discretized into 15 classes, according to a logarithmic scale.

The outputs of the study focus on two major parameters considered as the most influenced by the spray:

- Minimum value of the pressure in the fire compartment over the spray period;
- Minimum value of the mean gas temperature in the fire compartment over the spray period.

A first series of about one thousand runs was performed to determine the area of uncertain parameters satisfying in the best the expected responses. A second series was carried out to improve the accuracy of final values for the three input parameters (i.e. MMD, σ_g, v).

Pressure Effect on Initial Droplet Velocity

A change in the pressure of the nozzle head leads to a change in the initial droplet velocity. The sprinkler orifice is designed to provide a known water flow rate at a design water pressure. Sprinkler orifices verify the Bernoulli's orifice equation, which states that the velocity of the water through the orifice is proportional to the square root of the water pressure [7]. Since the volumetric flow rate is more suitable than the velocity for applications, the Bernoulli's orifice equation is rewritten as:

$$Q_w = k\sqrt{P} \tag{14}$$

The orifice flow coefficient, k, is nearly constant for the range of operating pressures used in sprinkler applications. This relationship will be used hereafter to take into account some changes in the pressure head compared to the initial characterization of the spray nozzle.

Pressure Effect on Droplets Size

A change in the pressure of the nozzle head also leads to a change in the droplet size. The relationship proposed by Dundas [3] links the sprinkler orifice size to the characteristic droplet size. He shows that the ratio of the characteristic droplet size to the sprinkler orifice size is connected to the Weber number by the relationship:

$$\frac{d_w}{D_A} = \frac{\alpha}{W_e^{1/3}} \tag{15}$$

which can be written as:

$$d_w = \alpha \left(\frac{16\rho_w}{\pi^2 \sigma_w} \right)^{-1/3} D_A^{\ 2} \ Q_w^{\ -2/3} \tag{16}$$

Eq. 16 leads to the same variation of the droplet diameters and therefore, the droplet size distribution remains log-normal if the water flow is modified. Using this relationship, a reduction by half of the sprinkler flow rate contributes to a 60 % increase in the droplet size. This relationship is widely used in sprinkler spray analysis because it allows the characteristic droplet size in the spray to be calculated using initial known parameters about the sprinkler. As previously for the water flow rate, this relationship will be used hereafter to take into account some changes in the pressure head compared to the initial characterization of the spray.

RESULTS AND DISCUSSION

Determination of Droplet Size Distribution and Initial Droplet Velocity on Test A2 by Means of the Calibration Technique

The droplet size distribution and initial droplet velocity of the deluge spray nozzle were fitted on test A2 (see Table 3 for the detailed description of test conditions). For this test, Figure 3 shows the development over time of pressure and mean gas temperature in the fire compartment. As a first comment, it can be observed that compartment atmosphere is strongly modified by the triggering of the water spray system during the fire. The kinetics of decrease of pressure and gas temperature at the start of the spray period is very sharp. Indeed, the temperature slope appears to be as high as 0.5 °C per second despite the heat release rate from the fire source and an under-pressure peak of - 11 hPa is achieved. This phase is followed by a stationary phase of the fire. At the end of the spray period, the gas temperature increases significantly and a pressure peak is observed, the fire extinction not being reached during the spray period. Thanks to the calibration technique, the predicted droplet size distribution produced by the spray water deluge nozzle for a volume flow rate of 55 l/min per nozzle is assessed by a mass median diameter of 920 µm and a geometric standard deviation of 1.5 (cf. Figure 4). The predicted initial droplet velocity is 7.0 m/s. The predicted development over time of pressure and mean gas temperature obtained with the fitted droplet size distribution is reported in Figure 3. It can be seen that droplet size distribution of the spray water deluge nozzle appears to be well fitted by a log-normal distribution function. The under-pressure peak at the start of the spray period is correctly reproduced by SYLVIA and the difference of mean gas temperature between experimental data and prediction during the stationary phase of the fire is less than 10 °C, this result being considered as satisfactory.

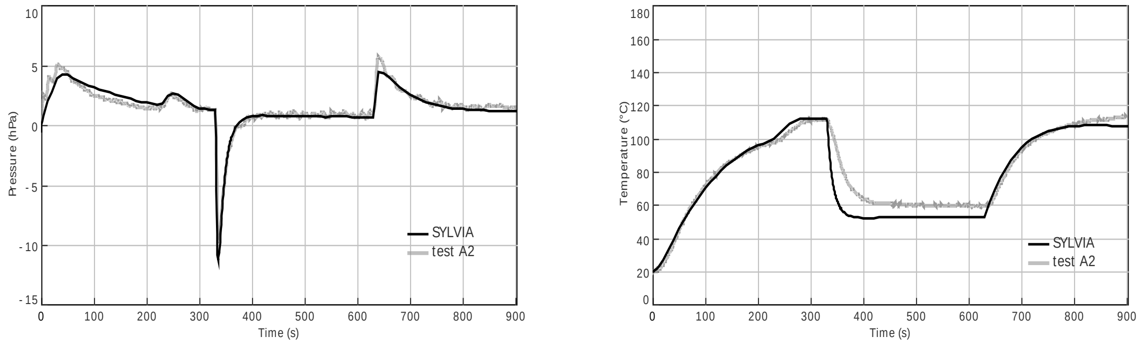


Figure 3 Development over time of pressure and mean gas temperature in the fire compartment for test A2

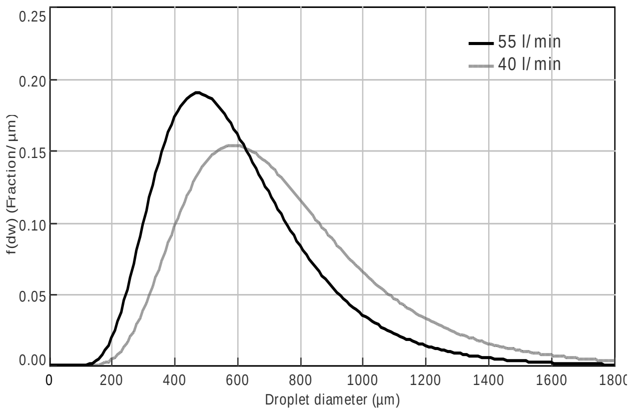
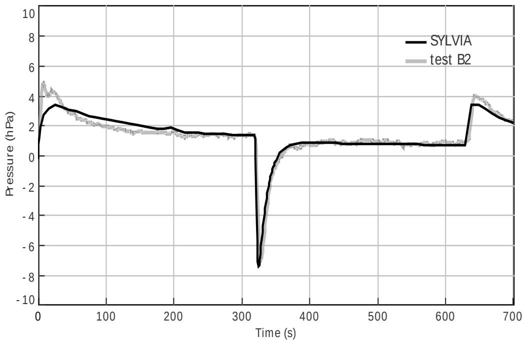


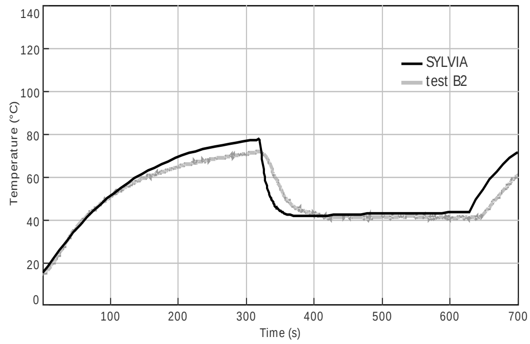
Figure 4 Droplet size distribution function obtained from the calibration technique

Validation of the New Technique on Tests B2, C2 and C5

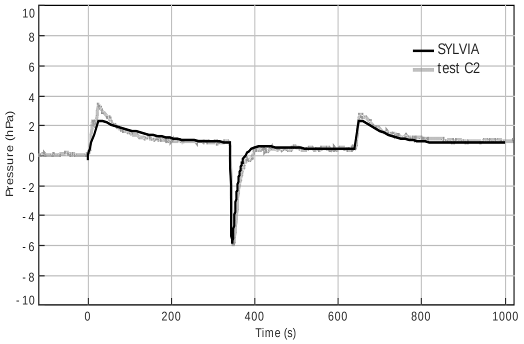
The validation of the droplet size distribution and initial droplet velocity fitted on test A2 is performed on tests B2, C2 and C5 with other operating conditions (see Table 3). Tests B2 and C2 were performed with the same spray volume flow rate as the one used in test A2 but with a lower HRR. This decrease of HRR leads to a reduction of the under-pressure peak at the start of the spray period and to a lower gas temperature in the fire compartment during the stationary phase of the fire, as seen in Figure 5 a and Figure 5 b for test B2 and in Figure 5 c and Figure 5 d for test C2.



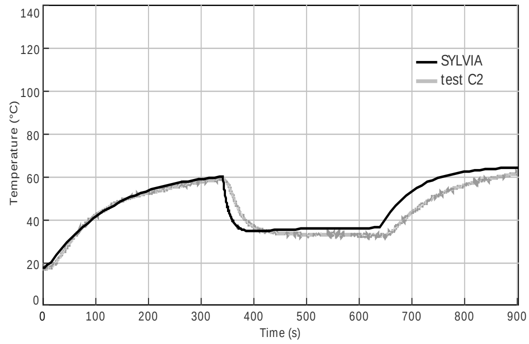
a) pressure in the fire compartment



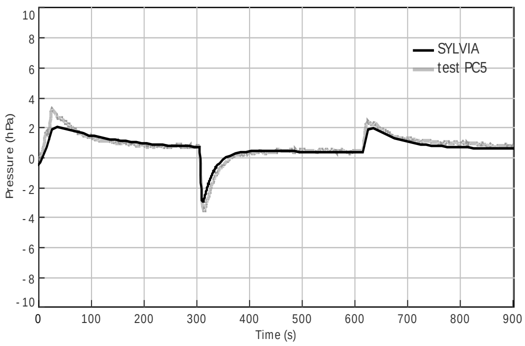
b) mean temperature in the fire compartment



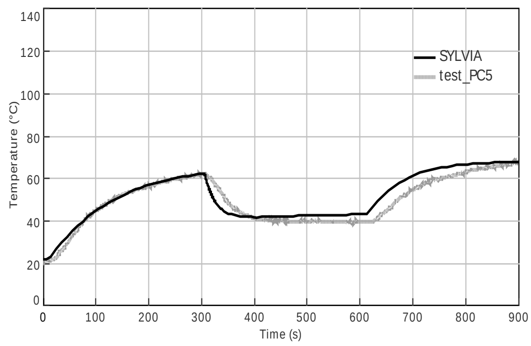
c) pressure in the fire compartment



d) mean temperature in the fire compartment



e) pressure in the fire compartment



f) mean temperature in the fire compartment

Figure 5 Pressure and mean temperature in the fire compartment for tests B2, C2 and C5

Predicted development over time of pressure and mean gas temperature in the fire compartment obtained with the droplet size distribution and initial droplets velocity fitted on test A2 are in good accordance with experimental data for both tests, as seen in Figure 5 a through Figure 5 d. The under-pressure peak at the start of the spray period is correctly simulated by the SYLVIA software and the difference of mean gas temperature between experimental data and prediction during the stationary phase of the fire is kept less than 4 °C for both tests.

With the reduction of the spray volume flow rate in test C5, the adjustments discussed previously in this paper have been performed on droplet size distribution and initial droplet velocity. According to Eq. 14 and Eq. 16, the predicted droplet size distribution produced by the spray water deluge nozzle for a volume flow rate of 40 l/min per nozzle is characterized by a mass median diameter of 1140 µm and a geometric standard deviation of 1.5 (see Figure 4). The initial droplet velocity is estimated at 5.1 m/s. Using these spray characteristics in the simulation of test C5, development over time of pressure and mean gas temperature in the fire compartment are well predicted by the SYLVIA software as seen in Figure 5 e and Figure 5 f. This good result shows that the adjustments on input parameters based on the previous correlations applied on size and velocity of droplets is a valuable and efficient approach.

CONCLUSIONS

A numerical method for determining droplet size distributions and initial droplet velocity of spray nozzles using a two-zone model has been developed. This method is based on a calibration of spray modelling on full-scale fire tests carried out in the DIVA facility of IRSN for which the fire was perfectly controlled. A parametric study was performed with the SYLVIA software to fit the droplet size distribution at injection and the initial droplet velocity on a given test of the propane gas fire test campaign. The validation of the method was then performed on other tests of the propane gas fire test campaign, with other operating conditions. For all tests, a good agreement between experimental data and predictions was obtained on development over time of pressure and mean gas temperature in the fire compartment, even with the adjustments performed on droplet size and initial droplet velocity to take into account the change of operating conditions for the spray water flow rate.

This alternative new technique is able to overcome some difficulties encountered in the experimental characterization of droplet size distributions and initial droplet velocity of large size sprays such as sprinkler or spray water deluge systems, as discussed previously. Finally, experimental characterization of droplet size distributions and droplet velocities is performed at a given pressure head. An adjustment of the droplet size distribution and initial droplet velocity is required in predictive simulations to take into account the change of droplet size distribution and initial velocity due to different operating conditions of water flow rate.

The method that has been developed appears to be valuable and efficient in the frame of this work, and can be likely more widely applied to other water spray system for which some difficulties in the experimental characterization of such spray equipment are encountered.

NOMENCLATURE

Symbols

$\bar{c}$	average molar concentration [mol m^{-3}]
C_D	drag coefficient [-]
CMD	count median diameter [m]
d	diameter [m]
D_A	nozzle orifice size [m]
$\overline{D}$	average diffusion coefficient [m^2 s^{-1}]
f	distribution function of droplets [m^{-1}]
g	gravity acceleration [m s^{-2}]
H	specific enthalpy [J kg^{-1}]
HRR	heat release rate [W]

k	orifice flow coefficient [m^3 s^{-1} $Pa^{-0.5}$]
m	mass [kg]
MMD	mass median diameter [m]
M	molar mass [kg mol]
n_0	number concentration of droplets [m^{-3}]
RH	relative humidity [%]
T	temperature [K]
t	time [s]
U	internal energy per unit volume [J m^{-3}]
v	velocity [m s^{-1}]
z	height [m]

Greek letters

α	nozzle coefficient [-]
ε	emissivity [-]
λ	thermal conductivity [W m^{-1} K^{-1}]
ρ	density [kg m^{-3}]
σ	Stephan-Boltzmann constant [W m^{-2} K^{-4}]
σ_w	surface tension of droplet [N m^{-1}]
σ_g	geometric standard deviation [-]

Subscripts

g	gas
s	water vapour
w	water droplet

Dimensionless numbers

B_M	spalding number for the mass
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
We	Weber number

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BLIND AND OPEN COCOSYS CALCULATIONS OF THE OECD PRISME 2 FIRE EXTINCTION EXPERIMENT 1 (FES-1)

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ABSTRACT

Fire safety analysis is a major issue for nuclear power plants (NPP). Oil reservoirs and cables represent major fire loads in NPP. Firefighting by water-based fire extinguishing systems such as spray water deluge or sprinkler systems represent well-established fire suppression means in nuclear installations worldwide.

The 'lumped parameter' code COCOSYS developed by GRS for the comprehensive simulation of design basis accidents (DBA) as well as severe accidents in light water reactor (LWR) configurations contains models for water spray systems. Those are typically applied to consider spray systems installed in NPP containments. The applicability of these models to fire extinguishing systems has been analysed by blind and open calculation of the *F*ire *E*xtinction **S**ystems experiment FES-1 as part of the international PRISME 2 (French: *P*ropagation d'un *i*ncendie pour des *s*cénarios *m*ulti-locaux *é*lémentaires) Project launched by the OECD Nuclear Energy Agency (NEA).

COCOSYS is capable to calculate the impact of a water-based extinguishing system on the room temperature and pressure ratios. Particularly, the calculation of temperature stratification in the fire room shows high level of agreement to the experimental results. Moreover, the effects of the spray system on the ventilation of the fire room could be simulated with a high level of consistency to the experimental data. Effects caused by turbulences in the atmosphere generated by the spray droplets could not be reproduced, because momentum exchange between the droplets and the atmosphere is so far not considered in the spray model of COCOSYS.

INTRODUCTION

Fires can compromise the entire safety of a nuclear power plant. Hence, much effort is used for the further development of fire simulation tools.

Besides appropriate combustion models the codes need validated models for water-based extinguishing systems to be able to assess fire safety measures by simulation, as these systems are well-established fire suppression means in nuclear installations worldwide.

As a part of the OECD PRISME 2 experimental program a test campaign called "Fire Extinction System (FES)" has been carried out by IRSN (*I*nstitut de *R*adioprotection et de *S*ûreté *N*ucléaire) in the DIVA facility in Cadarache for this validation scope. In the fire tests the extinguishing system implemented was not supposed to extinguish the fire. Therefore, the water was not sprayed on the fire source. The objectives of these experiments were to investigate the effects of the spray system on the combustion in general, the gas temperatures, the oxygen distribution and the effects on the ventilation.

This paper presents the results of a blind calculation of the FES-1 test performed with the GRS code COCOSYS in order to investigate the applicability of the spray model implemented in COCOSYS to simulate containment spray systems to fire scenarios. Additionally, open calculations were performed to clarify the limitations of COCOSYS, hence momentum transfer between spray droplets and the atmosphere is not considered in the spray model, and the consequences for the applicability need to be known.

IMPLEMENTATION OF PYROLYSIS AND COMBUSTION MODEL IN COCOSYS

The pyrolysis and combustion model for oil fire simulation is implemented in the thermal hydraulic module of COCOSYS [1]. Burning is simulated in two steps [2]. In a first step, a calculated percentage of fuel is pyrolysed from the fuel surface to the atmosphere. In a second step, these gases may participate in the combustion. In case of a liquid pool fire, usually the open fire pyrolysis rate is taken from experimental data or estimated by the Babrauskas correlation [3] for the steady state phase:

$$\dot{m}_{PYR,o} = \dot{m}_{MAX} \cdot (1 - e^{-k\beta D}) \quad (1)$$

It only requires the maximum burning rate $\dot{m}_{MAX} \left[\frac{kg}{m^2 s}\right]$ in an open atmosphere, the absorption-extinction coefficient k [m^{-2}] and a mean beam length corrector β representing known material properties of the fuel. The effect of the oxygen depletion on the pyrolysis rate in a confined compartment $\dot{m}_{PYR}$ is described by the correlation of Peatross and Beyler [4]:

$$\dot{m}_{PYR} = \dot{m}_{PYR,o} \cdot \left[(1+\alpha) \cdot \frac{c_{O2}}{c_{O2,o}} - \alpha\right] \quad (2)$$

with c_{O2} being the oxygen concentration [vol %] in the lower layer and $c_{O2,o}$ = 21 vol % the oxygen concentration in open atmosphere. It was confirmed in the PRISME SOURCE [5] and DOOR experiments [6] for α = 1.1. Details related to the radiative feedback can be found in [1].

The pyrolysed combustible gases react (burn) in the control volume bearing the fuel structure, if the oxygen concentration and the concentration of the pyrolysed combustible gases as well as the gas temperature exceed certain user-defined thresholds. Oxygen and combustible gases are converted into combustion products instantaneously. The completeness of the combustion can be affected by user defined factors. Combustible gases that are not burned in the control volume with the fuel can flow in neighbouring control volumes and can be burned there, if separate user-specified thresholds for the concentrations of reactants and temperature are met.

SPRAY SYSTEM MODELLING IN COCOSYS

The simulation of water-based fire extinguishing systems such as spraywater deluge systems with COCOSYS can be conducted by using the spray system model of COCOSYS. The concept of the spray system interface is illustrated in Figure 1 on the left side and the interaction between spray droplets and zones is presented in Figure 1 on the right side. For each spray system, a spray nozzle type and spray droplet paths, composed of several path sections must be defined. User defined droplet paths characterise the way the water droplets fall through several zones or onto structure surfaces [7]. Spray droplets injected into a zone (mass flow rate G_{in}, temperature T_{in}, energy flow E_{in}, average droplet diameter d_{in}, falling velocity v_{in}) interact with the zone atmosphere resulting in an evaporation of the droplet or a condensation of steam on the droplet surface. This affects the zone atmosphere and the droplets themselves leaving the zone atmosphere under the condition G_{out}, T_{out}, E_{out}, d_{out} and v_{out} and entering the next zone below. In case of a sufficient long spray height the droplets will reach the stationary falling velocity. There is no direct influence of the spray jet on the atmosphere. Gas entrainment from the atmosphere induced by the spray droplets is not considered. The change of droplet behaviour along the falling distance is iteratively solved by a local time step size Δt for each path section, depending on the inlet velocity and section length. Droplet temperature is calculated considering convection and condensation/evaporation [7]

$$dT_{\text{drop}} = \frac{6\Delta t}{\rho_{\text{drop}} \cdot c_{\text{v, drop}} \cdot d_{\text{drop}}} \left[(\alpha_{\text{convection}} + \alpha_{\text{condensation}})(T_{\text{zone}} - T_{\text{interface}}) \right] \quad (3)$$

with $\alpha_{\text{convectiv}}$ and $\alpha_{\text{condesation}}$ representing the heat transfer coefficients for convective heat transfer and the heat transfer via condensation/evaporation.

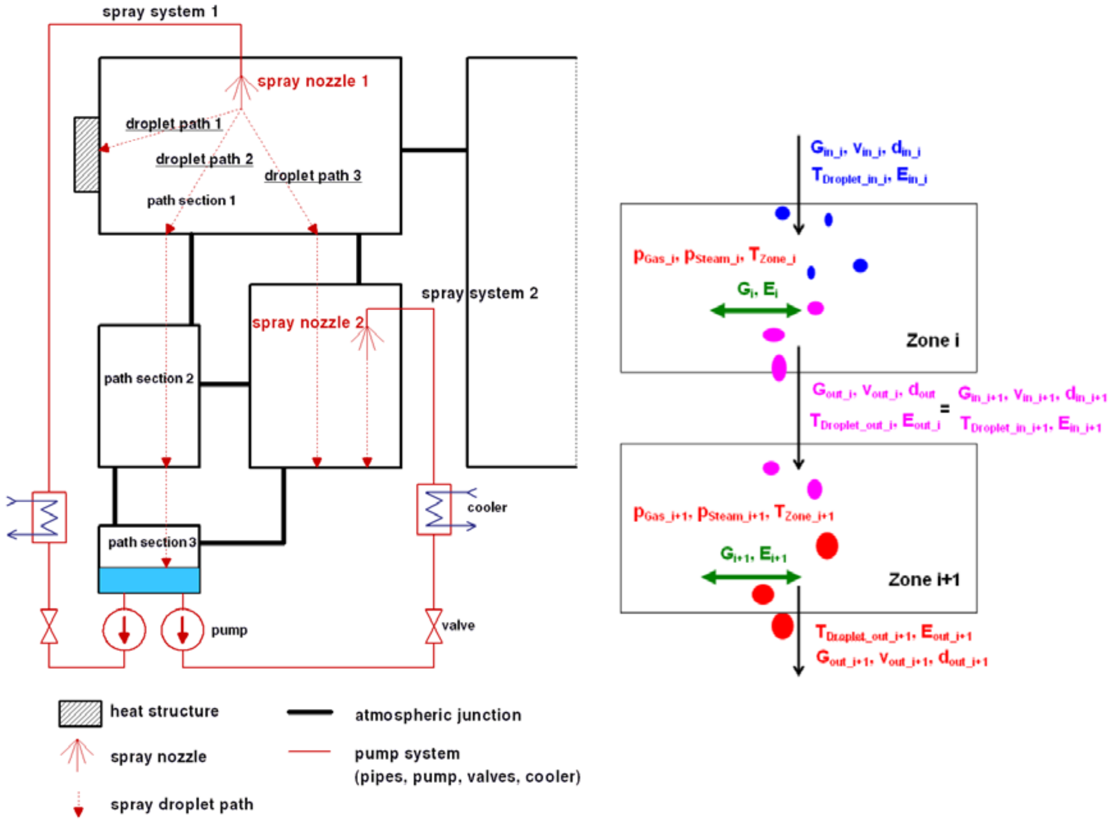

Figure 1 Left: Principle structure of a spray system in COCOSYS [7]; Right: Interactions between spray droplets and zones [8]

OECD PRISME 2 EXPERIMENT FES-1

The OECD PRISME 2 experiment FES-1 has been carried out by IRSN in the multi-compartment DIVA facility in Cadarache, France (Figure 2 left). The facility has been built in the JUPITER compartment with a volume of 3600 m³ (20 m x 15 m x 12 m). The objective of the FES test campaign was to investigate the efficiency of a water spray system for the control of the fire and the cooling of smoke.

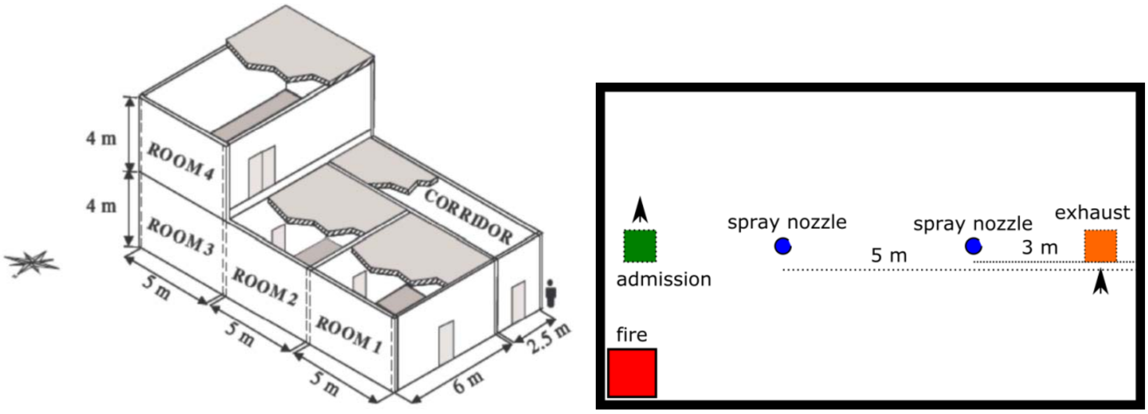

Figure 2 Left: Scheme of the DIVA facility [9]; Right: Scheme of the experimental setup in room 4

The test campaign was carried out in room 4 of the DIVA facility. The experimental setup is presented in Figure 2 on the right. The fire pan had a surface of 0.7 m² and was filled with 25 kg of pre-heated lubricant oil ($C_{31}H_{64}$). The spray system consisted of two deluge nozzles. The position of the nozzles was chosen in order to ensure that water did not reach the fire pan and no water was sprayed at the side walls in order to achieve interaction between the spray droplets and the atmosphere only. The nozzles were installed in about 3 m height. The spray system was actuated 15 min after ignition of the oil and operated for 11 min. The total flow rate was 110 l/min. The fire room was mechanically ventilated. The ventilation rate was 2550 m³/h corresponding to a renewal rate of 15 h^{-1}.

BLIND COCOSYS CALCULATION

In a first step, a blind calculation is presented to investigate the applicability of the spray system model of COCOSYS and its influence on the combustion, room temperature, O_2 concentrations and the ventilation. In order to be able to calculate temperature stratification the nodalisation needs to have horizontal layers. The used nodalisation had eleven layers (Figure 3, right). As COCOSYS does not use an empirical plume model and the air entrainment into the fire plume is calculated as a volume flow through the respective junctions, frustum shaped control volumes are needed above the fire pan (Figure 3, left).

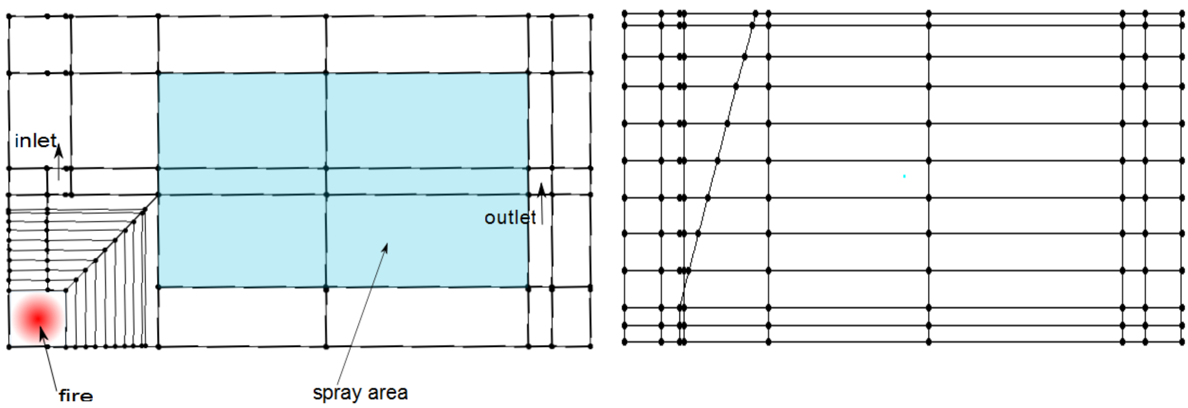

Figure 3 COCOSYS nodalisation of experimental setup in room 4; Left: top view, Right: side view

For calculating the mass loss rate of the fire under confined conditions the Peatross-Beyler correlation [1] is used. Therefore, COCOSYS requires mass loss rate of an open atmosphere fire as an input. From the COCOSYS input of the PRISME INTEGRAL D4 fire test [1] and the given total fuel mass of 25 kg the open atmosphere mass loss rate was deduced (see Figure 4). The comparison of the resulting calculated mass loss rate of the indoor fire and the experimental data shows some surprises. In the calculation the mass loss rate decreases when the spray system is activated a t = 900 s, while it increased in the experiment. The decrease in the calculation is due to steam replacing oxygen. Additionally, the rapid reduction of the gas temperatures and therefore the changes in the gas densities in the horizontal layers create a turbulence that reduces the oxygen concentration in the vicinity of the fire. After the deactivation of the spray system the mass loss rate increases but does not reach the level of the stable combustion before the activation of the spray system. In contrary, the experimental data show a significant increase of the mass loss rate after the activation of the spray system. This was not expected because even in the experiment the O_2 concentration in the lower part of the room decreased after the activation (Figure 6). This seems to be contradictory, but it was discussed if the spray may create atmospheric turbulences that enhance the O_2 supply of the combustion even if the O_2 concentration is reduced.

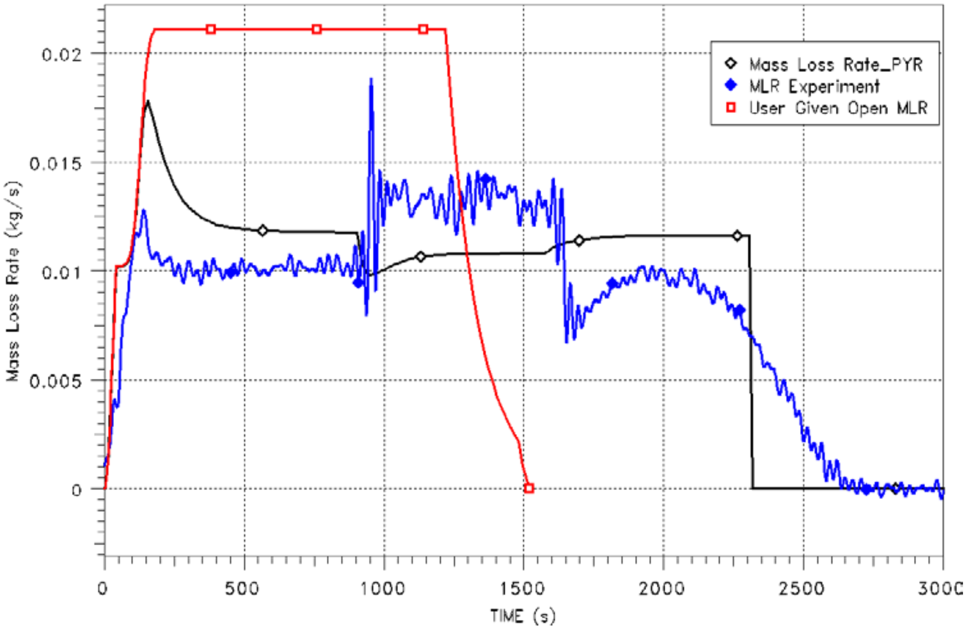

Figure 4 Measured and calculated ass loss rates

A comparison of the calculated and measured gas temperatures (Figure 5) demonstrates that COCOSYS calculates a temperature stratification that is observed in the experiment. Still before the spraying, the temperatures are overestimated by COCOSYS. This corresponds to the overestimation of the mass loss rate during that period (see Figure 4).

During the spraying the simulated cooling effect is much stronger than in the experiment. The temperature stratification below the spray nozzles is destroyed in the simulation (Figure 5). The higher room temperatures in the experiment can be ascribed to the increase of the mass loss rate. On the other hand, simulated cooling could be overestimated by overestimating the droplet surface.

The calculated and observed O_2 concentrations show clear deviations (Figure 6). In the beginning, there is a clear overestimation of the O_2 consumption. After the spray system activation the stratification of the O_2 concentration is destroyed mainly due to atmospheric turbulences created by momentum transfer between droplets and gas. After the deactivation the stratification re-establishes. As momentum transfer between droplets and atmosphere is not simulated by COCOSYS, the activation of the spray system creates gas mixing for a short period of time due to a rapid gas cooling and change in the gas density in the horizontal layers.

During the spraying, a new equilibrium is reached that is not destroyed after deactivation of the spraying as the gas temperature change is not that rapid after deactivation. This can be deduced form the ventilation air flow (Figure 7). The rapid atmosphere cooling and density change create a rapid pressure reduction causing the high peak in the simulated air flow rate. The deactivation has a much lower impact on the air flow rate, because the corresponding changes in temperature and gas density are much more moderate.

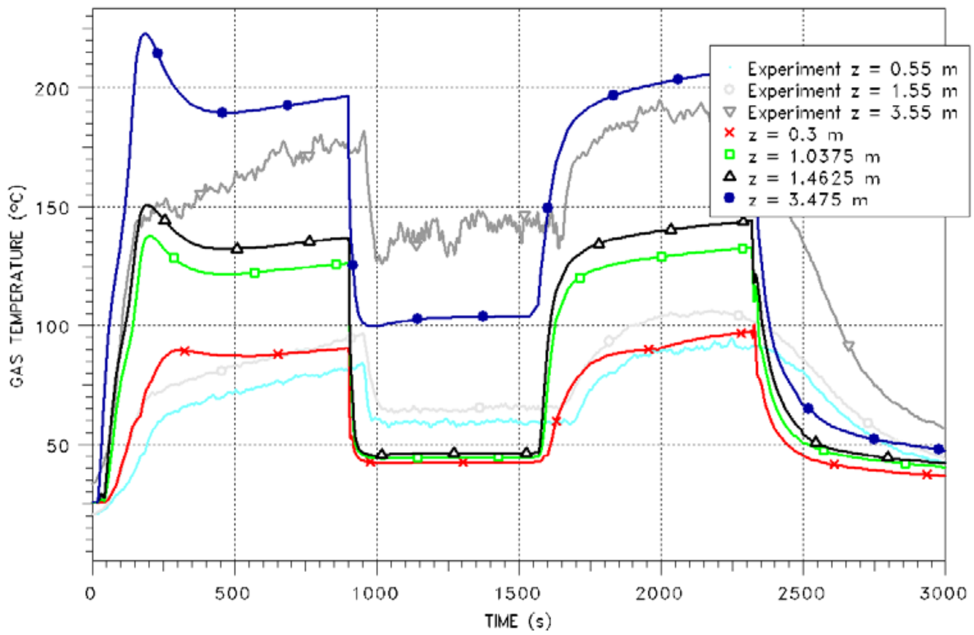

Figure 5 Measured and calculated room temperatures

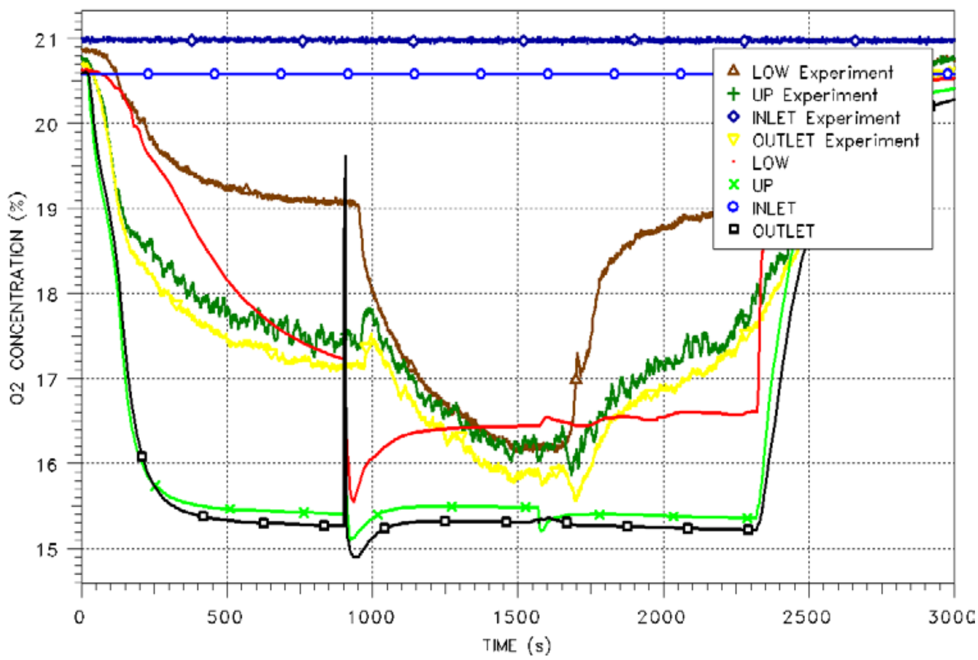

Figure 6 Measured and calculated O_2 concentrations

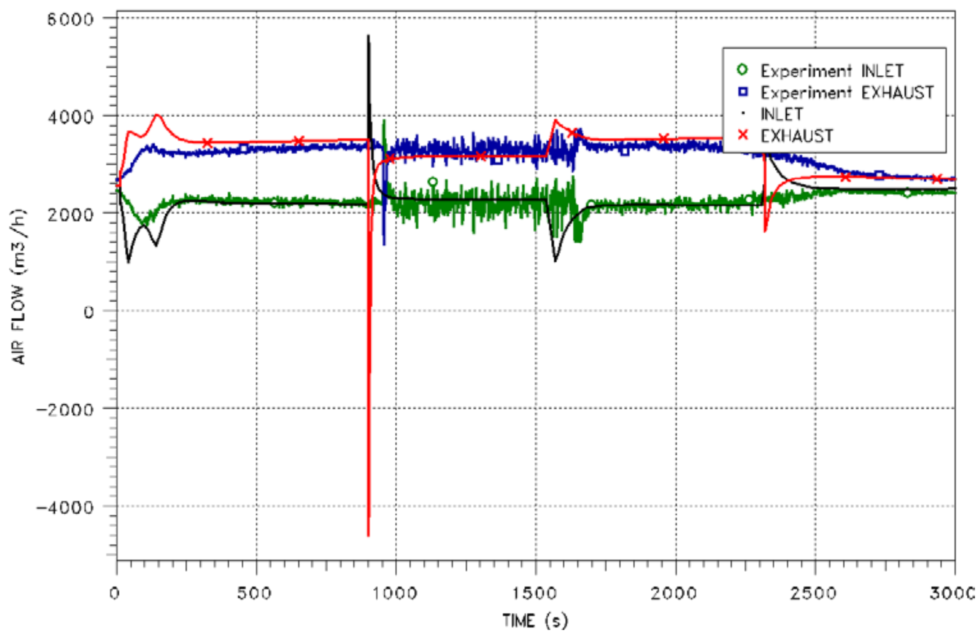

Figure 7 Measured and calculated ventilation flow rates

OPEN COCOSYS CALCULATION INCLUDING PARAMETER STUDY

In order to investigate the relevance of the mass loss rate and the droplet surface for the measured variables discussed in the previous chapter, three additional calculations were performed. In all calculations the mass loss rate measured in the experiment was used and the surface of the spray droplets was varied. COCOSYS calculates the droplet surface from the droplet diameter that has to be given by the user. The diameter used in the blind calculation was deduced from support tests [10]. For the calculation with small droplets the droplet diameter was divided in half, and for the calculation with large droplets the diameter was doubled.

Figure 8 presents the resulting gas temperatures. Before the of the spray system the temperatures at 3.65 m and 0.4 m are consistent to the experimental data. For the period with activated spray system the temperature underestimation of the temperature gets worse for reduced droplet size, because the diameter reduction results in an enlargement of the total droplet surface and therefore in a more effective cooling. By enlarging the droplets the experimental temperatures can be reproduced very well for the spray period. When the spray system is deactivated the temperatures on medium height are overestimated.

In Figure 9 it can be seen that during the period before the activation of the spray system the calculated O_2 concentrations are underestimated. The temperatures on medium height could be an indicator for an overestimation of the combustion effectiveness which would cause a higher O_2 consumption. The activation of the spray system again causes a sharp peak in the calculated O_2 concentration due to the cooling of the atmosphere and the enhancement of this cooling effect for reduced droplet size can be seen clearly. While the calculated mass loss rate did not change considerably after deactivation of the spray system in the blind calculation, the given mass loss rate in the open calculation is significantly reduced, hence the O_2 concentration rises after spray system deactivation. While the mass loss rate and the O_2 distribution are affected by the spray system due to entrainment that is not considered by COCOSYS, the ventilation air flow is mainly driven by the pressure difference between the ventilation system and the fire room. Figure 10 shows the ventilation flow rates for the three open calculations. The calculation with large droplets is in very good agreement with the experimental data. It can be deduced that the pressure reduction in the fire room due to spraying is reproduced by COCOSYS very well.

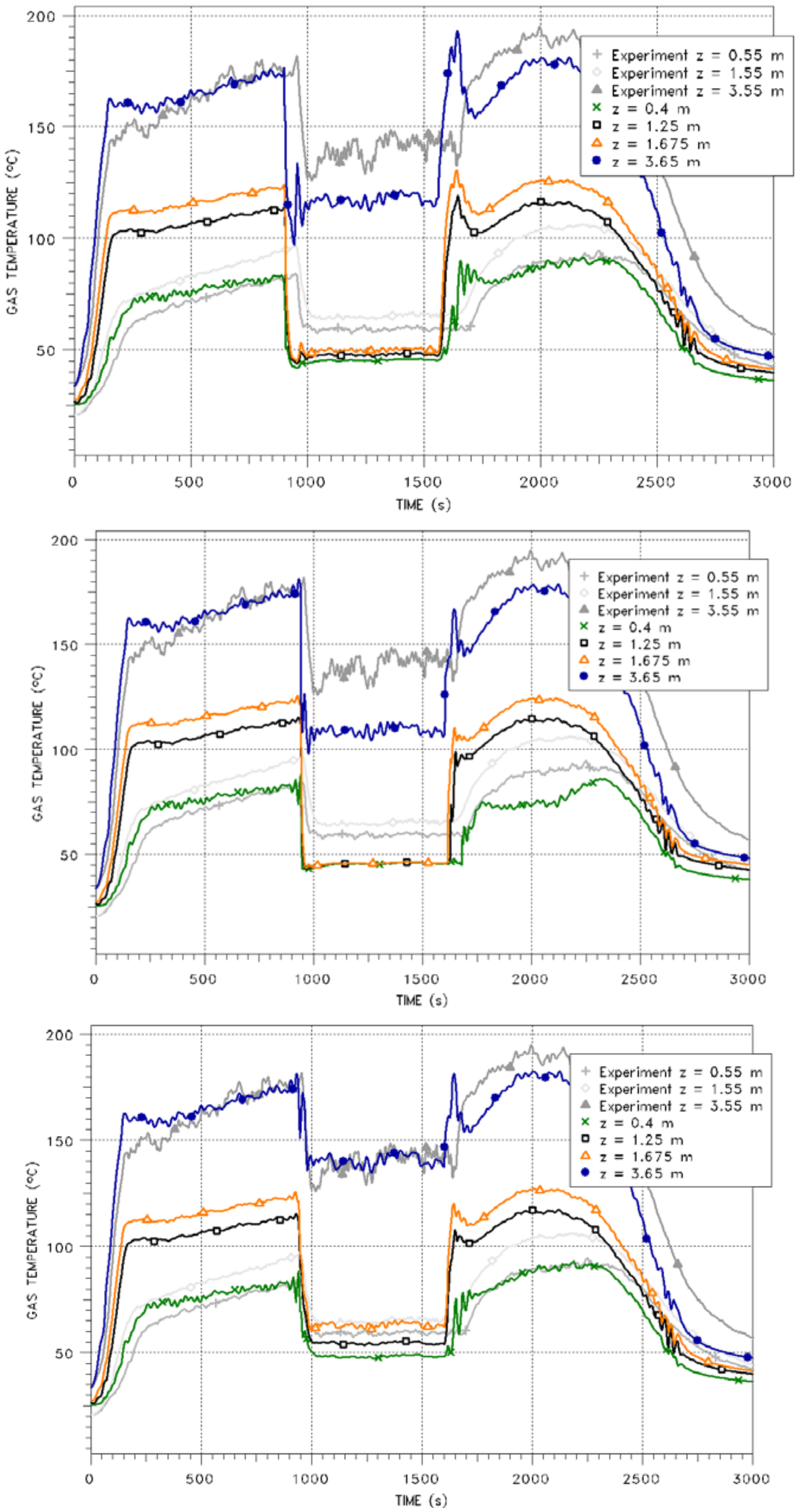

Figure 8 Gas temperatures for open calculation with original droplet size (top), small droplets (middle) and large droplets (bottom)

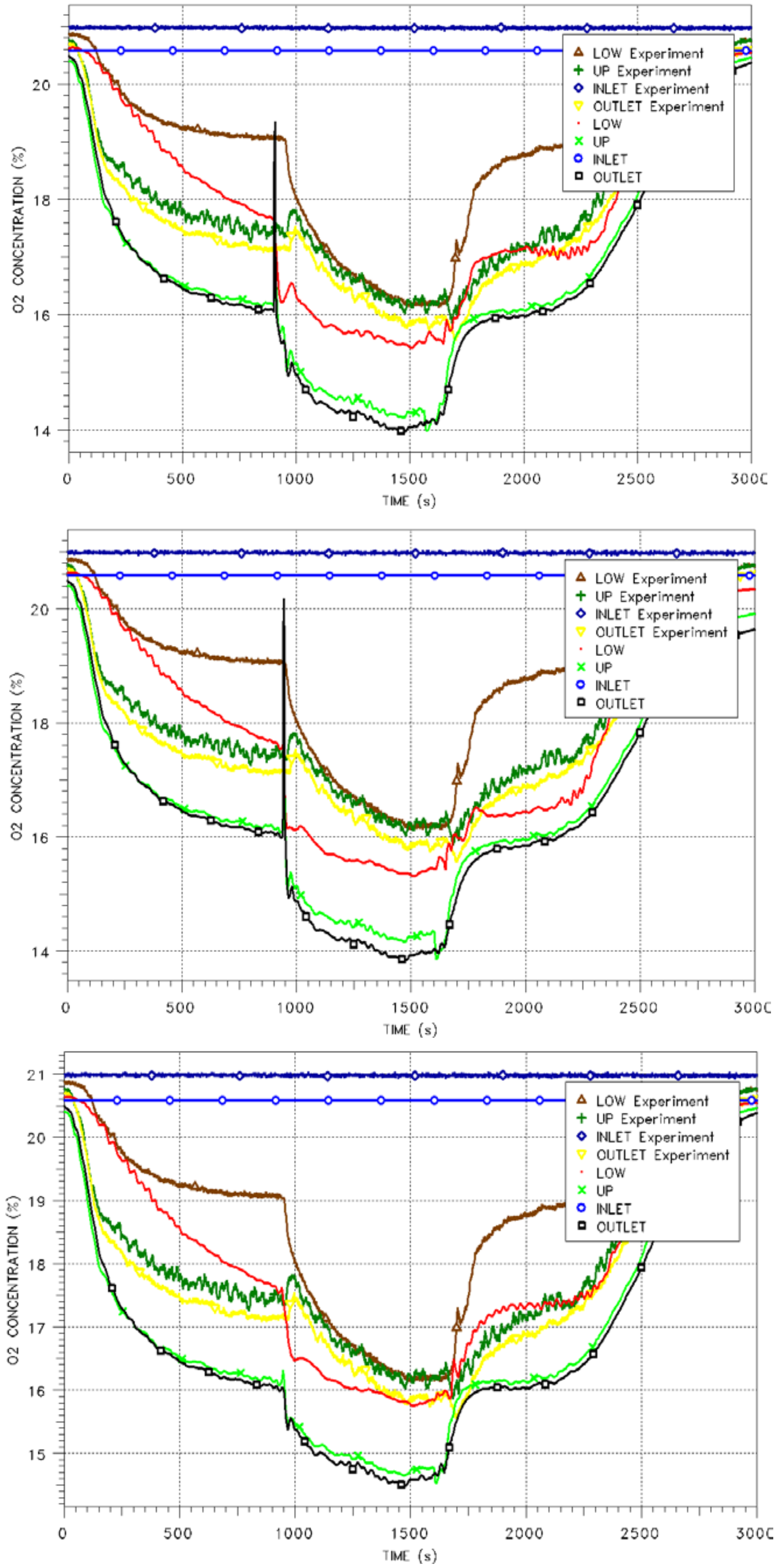

Figure 9 O_2 concentration for open calculation with original droplet size (top), small droplets (middle) and large droplets (bottom)

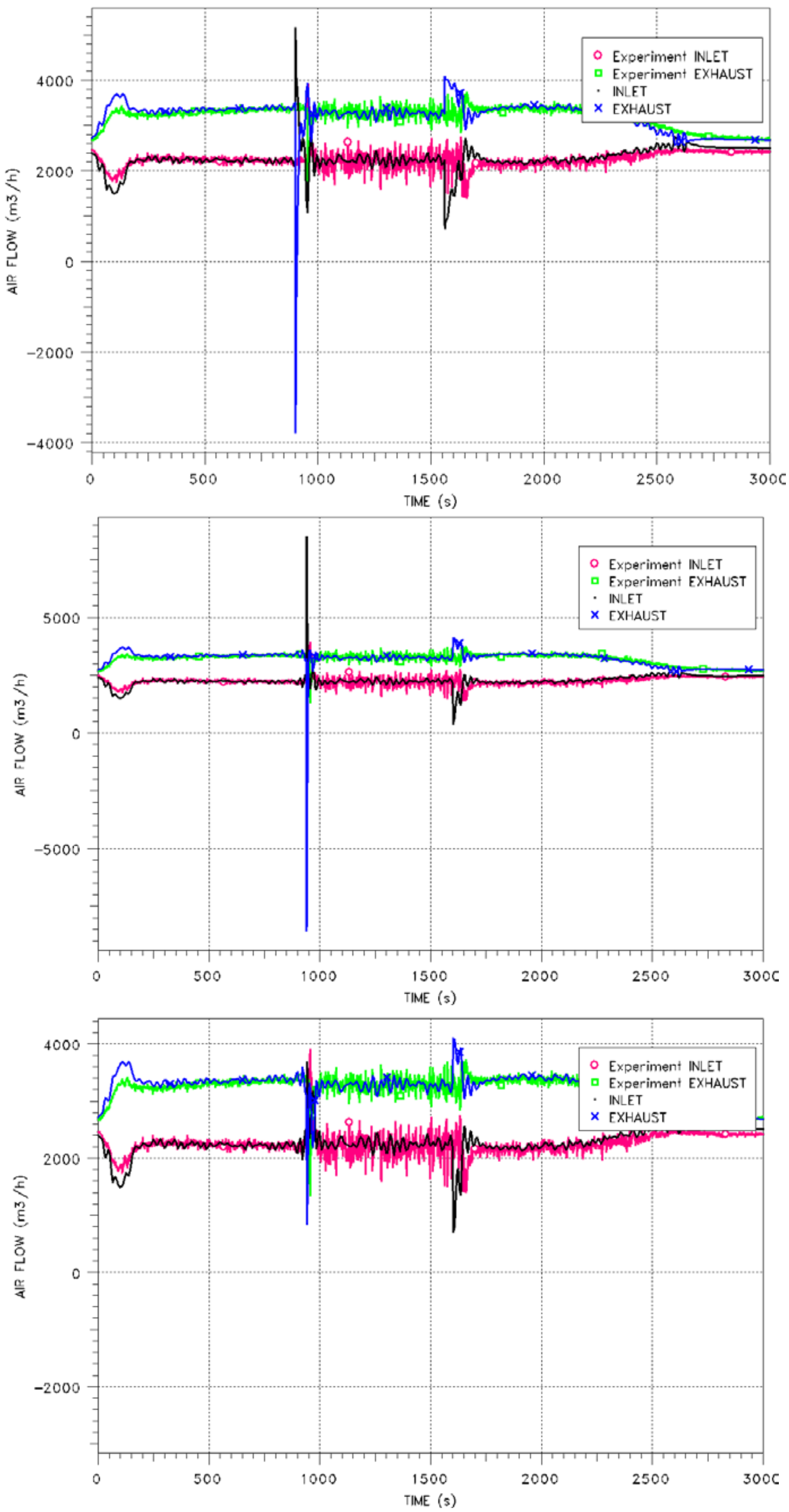

Figure 10 Ventilation flow rate for open calculation with original droplet size (top), small droplets (middle) and large droplets (bottom)

CONCLUSIONS

COCOSYS provides a spray system model that can be used in principle for simulations of water-based fire extinguishing systems as well. Nevertheless, the applicability is limited, as it can be seen from the blind calculation. The effect of the spray droplets on the mass loss rate is not met by the simulation due to the fact that momentum transfer between the droplets and the atmosphere (entrainment) is not simulated and therefore continuing turbulences in the fire room atmosphere by the spray droplets are not considered. This also causes deviations between the calculated and measured oxygen distribution. The calculation of the room temperature is in good agreement with the experimental results; nevertheless, the cooling effect of the spray system is slightly overestimated. Satisfying results could also be achieved for the influence of the spraying on the ventilation rate.

The open calculations verify the shortcoming of COCOSYS concerning the atmosphere entrainment, as the O_2 stratification is not destroyed by the spray droplets. By variation of the droplet size the importance of the knowledge of the spray nozzle characteristics is demonstrated as the droplet size significantly affects the room temperature, pressure and ventilation. The calculation with large droplets is in very good agreement with the experimental data. It can be deduced that the pressure reduction in the fire compartment due to spraying is reproduced by COCOSYS very well.

The latest version of COCOSYS contains a spray model which can consider gas entrainment. However, this model requires an adaption of the nodalisation. The spray path needs to have an inverted plume nodalisation [11]. Within the PRISME 2 project the new spray model could not be tested but it seems to be worth to repeat the analysis considering the entrainment model.

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NUMERICAL SIMULATIONS OF MECHANICALLY-VENTILATED MULTI-COMPARTMENT FIRES

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ABSTRACT

Computational Fluid Dynamics (CFD) is increasingly being used in the nuclear industry for fire consequence modelling. Of key importance is the ability of models to adequately capture fire behaviour in confined, mechanically-ventilated environments typical of nuclear installations. This paper assesses the capabilities of the widely-used Fire Dynamics Simulator (FDS) for modelling scenarios of practical interest for the nuclear industry. FDS simulation results are compared to experimental data obtained from the PRISME Integral experimental series of tests conducted by the Institut de Radioprotection et de Sûreté Nucléaire (IRSN). Here the 'PRISME INTEGRAL-4' test, conducted in the DIVA facility, a well-sealed mechanically-ventilated multi-compartment configuration at IRSN, is simulated. The scenario comprises a hydrogenated tetra-propylene (HTP) pool fire. This paper serves as an evaluation of FDS and its HVAC (*H*eating, *V*entilation and *A*ir *C*onditioning) network model focussing on model sensitivity to the choice of combustion modelling approach. The CFD results show that FDS is capable of capturing the main fire-induced effects on the mechanical ventilation system and the fire behaviour in under-ventilated conditions for a well-prescribed fire source. However, the ability of the model to accurately capture species concentrations in under-ventilated compartment conditions is poor. The choice of combustion modelling approach can have a substantial influence on model predictions of the concentration of combustion products.

INTRODUCTION

The PRISME (*P*ropagation d'un *I*ncendie pour des *S*cénarios *M*ultilocaux *E*lémentaires) project, coordinated by the OECD Nuclear Energy Agency (NEA), is a joint international research project focussing on fires in nuclear power plants. The main objectives of the project are to address knowledge gaps in modelling fire growth and propagation, fire extinction phenomena, and the prediction of damage to and the impact of smoke on safety-critical systems. The project addressed these objectives by performing experiments in a large-scale, well-sealed, mechanically-ventilated multi-compartment enclosure. In addition to the experimental work the members of a working group conducted benchmark simulations of a number of the experiments. Audouin et al. [1] give an overview of the PRISME project and the main experimental findings from each of the PRISME test campaigns. The initial campaigns in the PRISME project characterised single effects related to fires in enclosures. PRISME SOURCE characterised well defined pool fires as sources, PRISME DOOR looked at the transport of smoke and hot gases between compartments through open doors, and PRISME LEAK considered the transport of smoke and hot gases between compartments through leaks and ventilation ducting. The final campaign, PRISME INTEGRAL, consisted of experiments that included combinations of these different effects.

The effects of fire on mechanical ventilation systems are of critical importance for many fire safety applications. The fire-induced pressure rise in connected multi-compartment facilities, common in both nuclear and offshore oil and gas facilities, can overwhelm a mechanical ventilation system. This can lead to a loss of containment of the fire and propagation of smoke and other gaseous combustion products through an HVAC network. Conversely, a mechanical ventilation network can be used as a means of fire control, for example, through the use of dampers to reduce oxygen supply leading to fire extinction.

FDS, a CFD model designed to simulate fire-induced flow and heat transfer [2], has been used to simulate experiments from the PRISME project to predict the effects of fire on mechanical ventilation systems. Previous studies have been reported using both FDS 5 and 6 for studying the interaction of fires with mechanical ventilation. A major update in FDS 6 was the addition of an HVAC network solver, although a simple HVAC fan model was included in FDS 5.5 onwards [3]. Beji et al. [4] conducted a parametric analysis using FDS 5.5 to assess the influence of a number of key parameters on the pressure and temperature within a confined, mechanically-ventilated compartment. The scenario considered was similar to that used in the PRISME Source tests, with a pool fire source located at the centre of a single compartment. Their results showed that the specified ventilation operating conditions substantially influenced compartment pressure profiles and highlighted the need for accurate HVAC boundary conditions in the model. Wahlqvist and van Hees [5] presented validation of a pre-release version of FDS 6 against a number of the PRISME experiments from the Source, Door and Leak test campaigns. This work was primarily focussed on the evaluation of the HVAC network solver. Their results showed that the model was capable of capturing the pressure-induced effects on the mechanical ventilation system and complex combustion phenomena, such as ghosting flames, were predicted as a result of fluctuating flow rates at the ventilation inlet. Beji et al. [6] used FDS 5 to simulate the PRISME INTEGRAL-4 test, which involved a connected, multi-compartment configuration with a pool fire source. This modelling incorporated a simplified representation of the HVAC network, using isolated ducts with imposed fan curves for each of the HVAC inlets and the exhaust. Their results showed that the model correctly captured qualitative trends in compartment pressure, temperature and ventilation flow rates, but under-predicted the measurements by up to 22 %.

This paper seeks to extend the work reviewed above to use FDS 6, including its HVAC network solver, to investigate a complex fire scenario taken from the PRISME Integral experimental series of tests. The scenario, PRISME INTEGRAL-4, involves a hydrogenated tetrapropylene (HTP) pool fire source located in a multi-compartment facility ventilated entirely through a mechanical ventilation network.

DETAILS OF THE PRISME EXPERIMENTS

Description of the Experimental Facility

The PRISME fire tests were conducted inside the DIVA facility at the IRSN laboratories. The facility is located inside the JUPITER compartment. The DIVA facility is confined, mechanically-ventilated and constructed of 30 cm thick reinforced concrete walls. It comprises four interconnected rooms and a corridor (see Figure 1). Each of the rooms on the lower floor has dimensions of 5 m x 6 m x 4 m and the corridor, which runs alongside all three of these rooms, is 15.6 m x 2.5 m x 4 m in size. The rooms can be connected through openings and doors, or these can be closed. For the Integral tests simulated here, the upper room (Room 4 in Figure 1) was not connected and was not used in the experiments. Each room in the DIVA facility can also be connected to the inlet and outlet ducts of the mechanical ventilation system.

The combination of rooms and mechanical ventilation allow fire experiments to be performed in configurations representing nuclear power plant. The data acquisition system in the DIVA facility allows measurements of these experiments to be made on up to 800 channels [7].

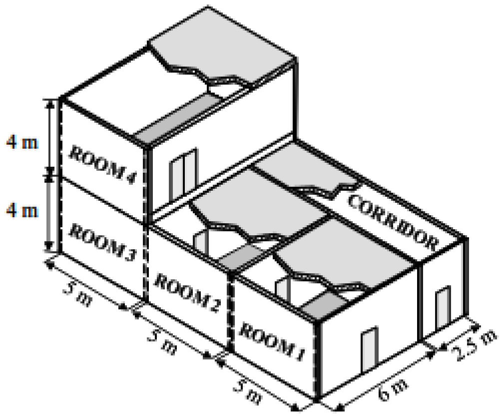

Figure 1 Perspective view of the DIVA facility inside the JUPITER compartment (Figure courtesy of IRSN [7])

Overview of the PRISME INTEGRAL Test Series

The Integral test series was the final experimental campaign conducted under the PRISME project. The previous campaigns had investigated single effects. The Integral experiments were designed to investigate more complex scenarios by combining these effects and were aimed at studying fire behaviour of different fire sources in mechanically-ventilated, multi-compartment configurations. Six experiments were performed to investigate: the influence of room configuration on smoke propagation through doorways in confined and mechanically-ventilated conditions; the behaviour of cable and electrical cabinet fires in under-ventilated conditions; the influence of damper closure and sprinkler activation on fire behaviour.

Details of the PRISME INTEGRAL-4 Test

The fire experiment used in the numerical study presented here is the PRISME INTEGRAL-4 test [7]. The test involved the lower three compartments and the corridor of the DIVA facility, shown schematically in Figure 2.

For the Integral test simulated here, the ceilings of all three rooms and the corridor were lined with 50 mm thick rock-wool insulation. The walls of the fire room were lined with 30 mm and 60 mm thick rock-wool panels in the lower and upper portions of the room, respectively. The walls of room L3 were also lined with 30 mm thick rock-wool insulation. The walls of room L1 and the floor in all of the rooms and the corridor were not insulated.

For the INTEGRAL-4 test the fire source was a 1 m diameter pool of HTP with an initial mass of 52 kg located at the centre of room L2 (see Figure 2). The fuel was contained in a steel pan of diameter 1.129 m, shielded with 50 mm thick rock-wool insulation, at an elevation of 0.4 m above the compartment floor. A propane burner was used as the ignition source.

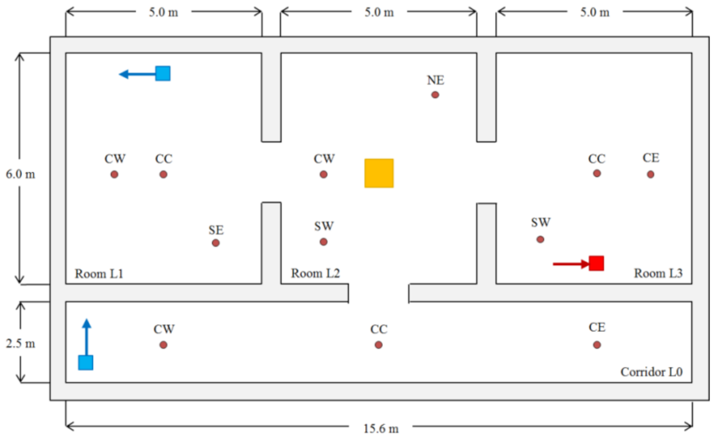

Figure 2 Schematic of the DIVA facility as used for the PRISME INTEGRAL-4 test– HVAC supply vents (blue) in L0 and L1, HVAC exhaust (red) in L3, fire (orange) at centre of room L2 and thermocouple tree locations (red dots)

The multi-compartment configuration was mechanically ventilated through supply vents located in room L1 and the corridor L0, and an exhaust vent located in room L3. All of the vents had a cross-sectional area of 0.18 m^2 (0.3 m x 0.6 m). Initial flow rates of approximately 500 m^3/h and 2600 m^3/h were supplied through the vents in L0 and L1, respectively, and an exhaust flow rate of 3100 m^3/h through vent L3 was used. The mechanical ventilation was used to ensure negative pressure confinement inside the DIVA compartments at the start of the fire tests.

The DIVA facility was heavily instrumented during the PRISME tests with measurements of room pressure, ventilation flow rates, doorway velocities, room temperature and concentrations of O_2, CO and CO_2 obtained during the INTEGRAL-4 test. In addition, the fire heat release rate (HRR) was estimated based on a carbon dioxide generation (CDG) chemical method as described in [8], and the mass loss rate (MLR) of the source was also measured.

CFD MODELLING

CFD Model Setup

The modelling work described in this paper has been performed using FDS version 6.4.0 [2]. This version of the model incorporates a full HVAC network solver coupled to the hydrodynamic solver used to model the fluid flow. These two aspects of the model are coupled such that changes in compartment pressure affect the mechanical ventilation, which in turn influences compartment conditions. An HVAC model was first included in FDS version 5.5 [3] to meet the need for more advanced ventilation boundary conditions. In earlier versions of the model it was only possible to use simple, fixed-flow or fixed-pressure boundary conditions to represent sources of ventilation and openings. The new functionality of the HVAC network solver expands the capabilities of FDS so that fire-induced pressure effects can more readily be accounted for within ventilation boundary conditions.

Grid sensitivity tests were performed using mesh resolutions based on the characteristic fire diameter D^* [2], where

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{\frac{2}{5}} \quad (1)$$

Here $\dot{Q}$ is the fire power [kW], ρ_∞ is the ambient air density [kg/m^3], c_p is the ambient air specific heat capacity [kJ//kg/K], T_∞ is the ambient temperature [K) and g is the acceleration due to gravity [m/s^2]. Coarse, medium and fine grid resolutions, corresponding to values of $D^*/4$, $D^*/10$ and $D^*/16$ respectively, were used following the approach used in the extensive validation of FDS performed by the U.S. NRC [9]. This resulted in mesh cell spacing of approximately 36 cm, 14.5 cm and 9 cm.

Turbulence was modelled using the default FDS formulation of the LES model with Deardorff turbulent eddy viscosity. The gray-gas radiation model, solved using the finite volume method, was also used [10].

The thermal properties of the rock-wool insulation and the concrete used in the DIVA facility were specified in the model in accordance with values determined by IRSN. For the rock-wool insulation, the following material properties were used: thermal conductivity 0.102 W/m/K, specific heat capacity 840 J/kg/K, emissivity 0.95 and density 140 kg/m^3. The thermal properties used for the concrete were: thermal conductivity 1.5 W/m/K, specific heat capacity 736 J/kg/K, emissivity 0.7 and density 2430 kg/m^3 [1].

Fire Source and Combustion Modelling

Thermal boundary conditions for the simulations of the INTEGRAL-4 test were specified following experimentally-determined fire characteristics. The measured fuel mass loss rate was used in FDS with the fire boundary condition imposed as a time-varying mass flux of fuel. The heat of combustion was specified as 42 MJ/kg in the model, following the value given in Audouin et al. [11].

The pool fire source used in the INTEGRAL-4 test was modelled as a horizontal 1 m x 1 m surface in FDS. Three approaches to modelling the pool fire combustion were used. Sensitivity of the model predictions to the specified combustion process was assessed. The first approach comprised a single-step, infinitely-fast combustion reaction with fixed soot and carbon monoxide yields of 0.042 kg/kg and 0.012 kg/kg, respectively. This is the default combustion model used in FDS, and widely used in other fire models. The resulting reaction mechanism is described by Eq. (2).

$$C_{12}H_{26} + 17.86857\ O_2 \rightarrow 13.0\ H_2O + 0.07286\ CO + 11.33214\ CO_2 + 0.595\ soot \tag{2}$$

The second approach was an extension of the single-step reaction mechanism to incorporate a carbon monoxide oxidation step. The same soot yield as for the single-step reaction was used. This approach aims to allow additional CO formation if compartment conditions allow, thereby capturing effects of under-ventilation on species formation. The resulting combustion process is described by the following two-step reaction:

$$\begin{gathered} C_{12}H_{26} + 12.2025\ O_2 \rightarrow 13.0\ H_2O + 11.405\ CO + 0.595\ soot \\ CO + 0.5\ O_2 \rightarrow CO_2 \end{gathered} \tag{3}$$

The third approach uses a modelling approximation which aims to independently capture CO production in the well-ventilated and under-ventilated regimes. For this approach the total CO produced through combustion is defined to consist of two separate species, CO_a and CO_b, both of which are produced during a fuel oxidation step. The CO contribution from the well-ventilated regime, CO_a, is produced with a fixed yield and does not undergo any further reaction step. The CO contribution due to effects of under-ventilation, CO_b, may oxidise to CO_2, provided sufficient oxygen is present. The total CO is then defined by the sum of the two constituent species, CO_a and CO_b, using the same soot and total CO yields as specified in the single-step reaction case. This modified two-step combustion process is described by Eq. (4) and follows the approach introduced by Floyd and McGrattan [12].

$$C_{12}H_{26} + 12.2025\, O_2 \;\rightarrow 13.0\, H_2O + 0.07286\, CO_a + 11.33214\, CO_b + 0.595\, soot$$
$$CO_b + 0.5\, O_2 \;\rightarrow CO_2 \qquad (4)$$
$$CO = CO_a + \; CO_b$$

Modelling the mechanical ventilation

One of the principle aims of the PRISME tests was to investigate the interaction between fire-induced compartment conditions and the mechanical ventilation system. Compartment pressure significantly influences ventilation conditions, which can lead to loss of containment and spread of gaseous combustion products and smoke.

An advantage of FDS 6 over previous versions of the model is the inclusion of an HVAC network solver to couple the CFD model with complex mechanical ventilation boundary conditions. The solver computes the flow through a network described by a collection of nodes and interconnected ducts. Each node must be a connection between one of the following: multiple ducts; the HVAC network and the CFD domain; or the network and ambient atmosphere. Ventilation components, such as fans and dampers, can also be incorporated in the HVAC network model.

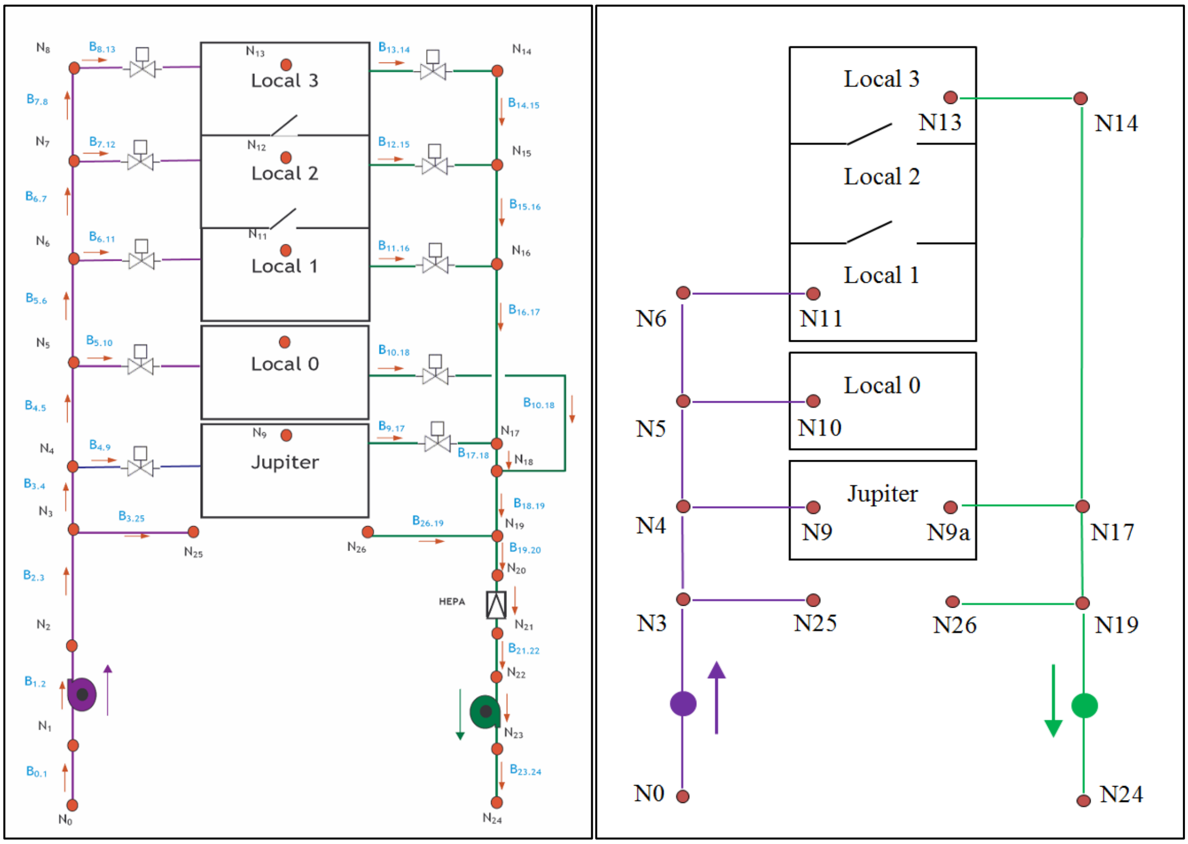

Figure 3 Schematic of the HVAC network: IRSN (left); FDS model setup (right)

In the FDS setup for the PRISME Integral fire scenario modelled here, the HVAC network has been defined as a simplification of the network at the IRSN experimental facility with ducts combined where possible to minimise the number required. Figure 3 shows a comparison of the complete network (left) and the simplified version incorporated into the modelling (right). In the model it has been assumed that the nodes inside the JUPITER compartment can be considered ambient, since it is not feasible to model the DIVA facility within the JUPITER enclosure.

Nodal pressure and duct flow rate measurements, taken prior to ignition, have been used to calculate total loss coefficients for each of the modelled ducts using the following formula [3]:

$$k = \frac{2\Delta p}{\rho_\infty u^2} \tag{5}$$

Here k is the total loss coefficient for the duct, Δp (Pa) is the pressure drop across the duct, ρ_∞ (m^3/s) is the ambient air density and u (m/s) is the velocity inside the duct (calculated from the volumetric flow rate and duct cross-sectional area). Where ducts were combined in the model, the average cross-sectional area of the combined ducts was used.

Where there are discrepancies in the measured flow rates, for example where the inflow and outflow through a duct do not match, the 'lost' mass has been directed to an ambient node, since the FDS HVAC model does not allow mass storage inside the ducts. Furthermore, fixed flow rate fans have been used at the inlet and outlet branches of the ventilation network as the fans are considered to be sufficiently far along the network so as to be unaffected by the pressure inside DIVA. This is aided by the two significant bypasses in the system through the JUPITER compartment (N9 and N9a) and to open atmosphere (N25 and N26).

Sensitivity Analyses

To assess the sensitivity of the model to the choice of mesh resolution, model predictions of key quantities of interest have been compared for the coarse, medium and fine grids as defined previously. Figure 4 to Figure 6 compare model predictions of the HRR, temperature and oxygen concentration in the fire room for the single-step (left) and two-step (right) reaction mechanisms with the experimental data. Comparison of the medium and fine mesh results from these figures shows that reasonable grid independence is achieved for both of the combustion models.

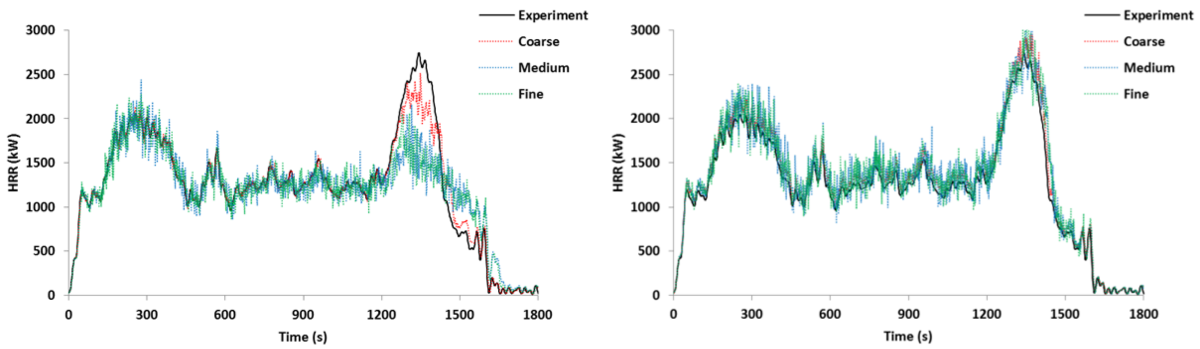

Figure 4 INTEGRAL-4 grid sensitivity results in comparison to the experimental HRR for the single-step (left) and two-step (right) combustion modelling approaches

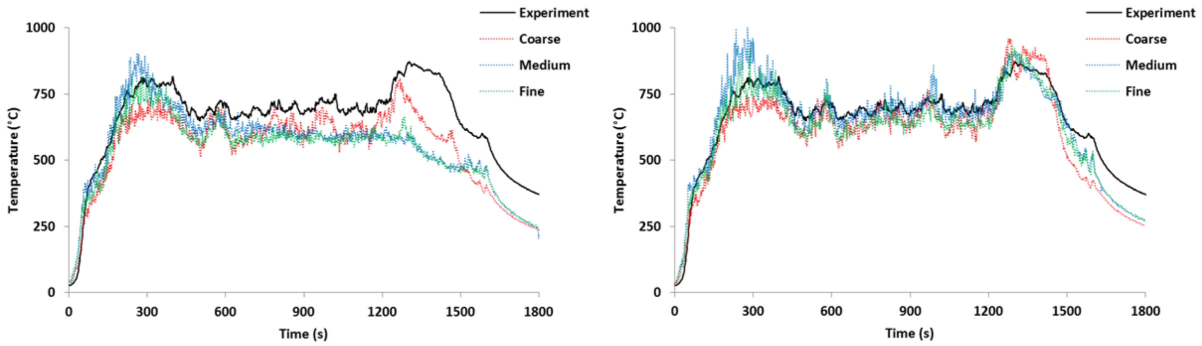

Figure 5 INTEGRAL-4 grid sensitivity results in comparison to the experimental temperature profile at a height of 3.9 m at the NE corner of the fire room (L2)

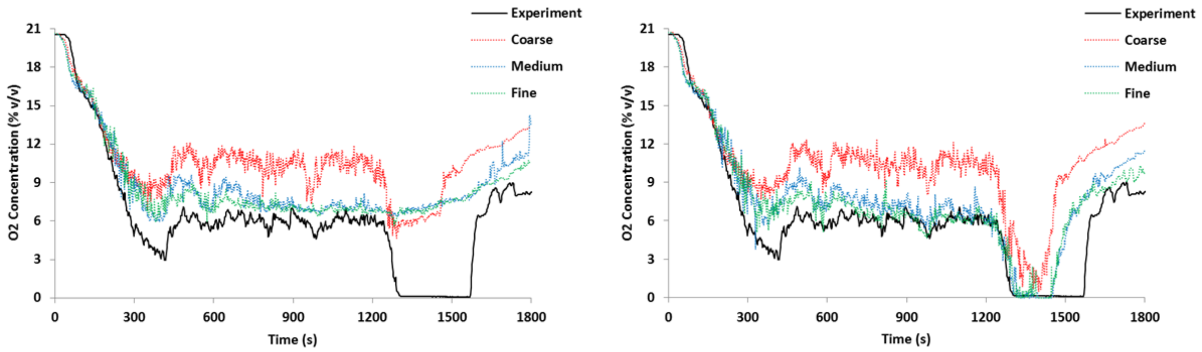

Figure 6 INTEGRAL-4 grid sensitivity results in comparison to the experimental O_2 concentration profile at the upper sensor in the fire room (L2)

Sensitivity of the model predictions to the combustion model used in the simulations was also examined. Figure 4 to Figure 6 clearly illustrate the difference in behaviour of one- and two-step combustion modelling approaches. The differences are most evident in the latter stage of the fire where the single-step reaction mechanism gives poorer agreement with the experimental data than the two-step model. It is clear that the second measured HRR peak at 1200 s to 1500 s is not captured when a single-step combustion reaction is used. However, with a two-step reaction mechanism, the model captures this second HRR peak well. Figure 5 and Figure 6 show that there is a second peak in fire room temperature and a large drop in O_2 concentration, which correspond to the second HRR peak. The figures illustrate that the two-step combustion model captures these features more accurately than the single-step approach.

Whilst the two-step combustion modelling approach has been shown to outperform the single-step model in terms of capturing the measured HRR, fire room temperature and O_2 concentration, the two-step model does not accurately reproduce the CO concentrations measured during the INTEGRAL-4 test. As such, a modified two-step combustion model [12], as described previously, has been used in an attempt to capture the influence of under-ventilated compartment conditions on CO production. This model combines features of the single-step and two-step combustion models to improve predictions of the CO concentration. For the quantities presented in Figure 4 to Figure 6, this model gives results which are negligibly different to those for the two-step approach, thus figures showing these results have not been included here. This hybrid combination of combustion models has been used to produce the INTEGRAL-4 simulation results presented throughout the remainder of this paper.

RESULTS

In this section, FDS 6.4.0 results are presented in comparison to measured data taken from the PRISME INTEGRAL-4 experiment. The ability of the model to predict compartment pressure, ventilation flow rates, compartment temperature profiles and concentrations of combustion products is assessed.

HVAC Network

Compartment pressure and ventilation conditions in the HVAC network govern compartment fire behaviour to a large extent. As such it is important that the initial conditions are closely matched to the experimental data. For the simulations of the INTEGRAL-4 test the predicted initial static pressures at the HVAC network nodes were within 5.5 % of the measured values at all of the measurement locations. As such, it is clear that the initial HVAC network pressure conditions are generally well captured by the model.

INTEGRAL-4 HTP Pool Fire

The following simulation results presented for the INTEGRAL-4 scenario are based on a model setup using the modified two-step combustion approach [12], as previously described, with a mesh resolution of approximately 14.5 cm, corresponding to the medium mesh used during the grid sensitivity analysis.

Comparisons of model predictions with the experimental data are shown in the subsequent figures for each of the three compartments and the corridor of the DIVA facility as used for the INTEGRAL-4 test.

Figure 7 to Figure 17 show that FDS version 6.4.0 can be used to reproduce transient compartment conditions for a confined, mechanically-ventilated multi-compartment fire scenario. These figures show that profiles of temperature, species concentration, doorway velocity, pressure and HVAC flow rate are, in general, qualitatively captured by the model for the INTEGRAL-4 scenario.

Figure 9 shows that FDS version 6.4.0 captures the variation in fire compartment pressure and the ventilation flow rates well. This is in part due to the inclusion of the HVAC network model resulting in more accurate ventilation boundary conditions, and in part due to the fact that the modified two-step combustion model better predicts the fire behaviour with regards to the HRR. As a result, the FDS version 6.4.0 results obtained here show better agreement with the experimental data than the results presented by Beji et al. [6] in which a simpler representation of the mechanical ventilation and a standard single-step combustion model were used.

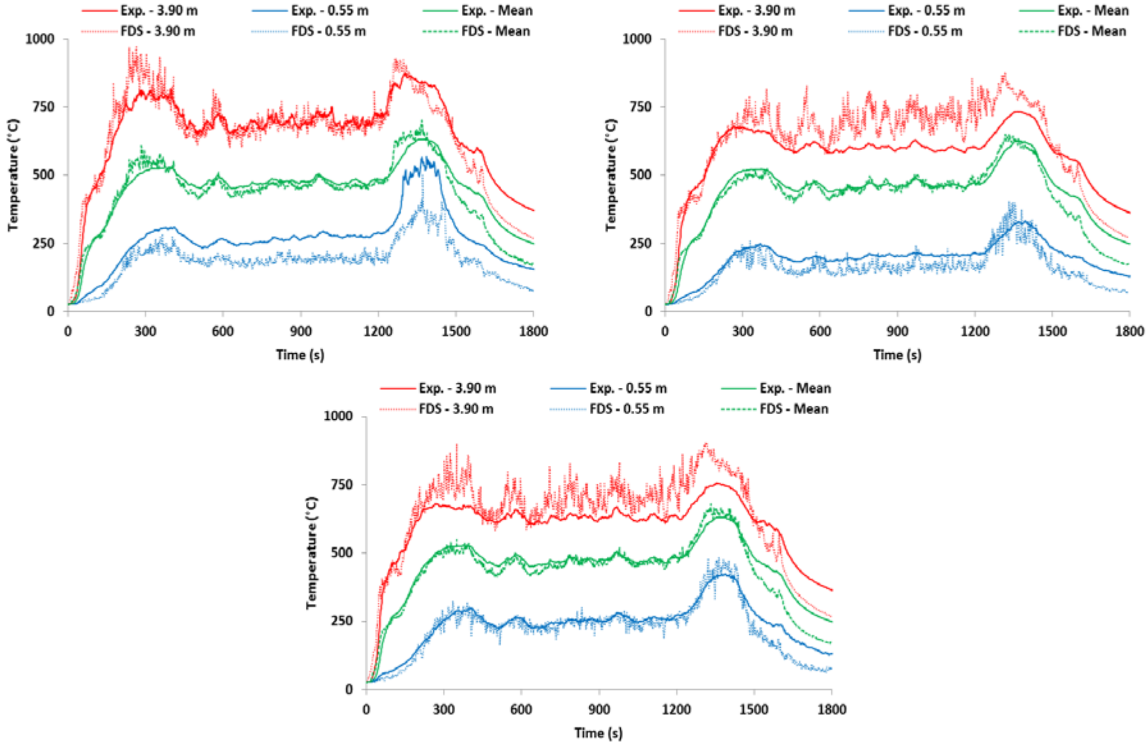

Figure 7 Comparison of measured and predicted temperature in the fire compartment (L2) on the NE (top left), SW (top right), CW (bottom) thermocouple trees

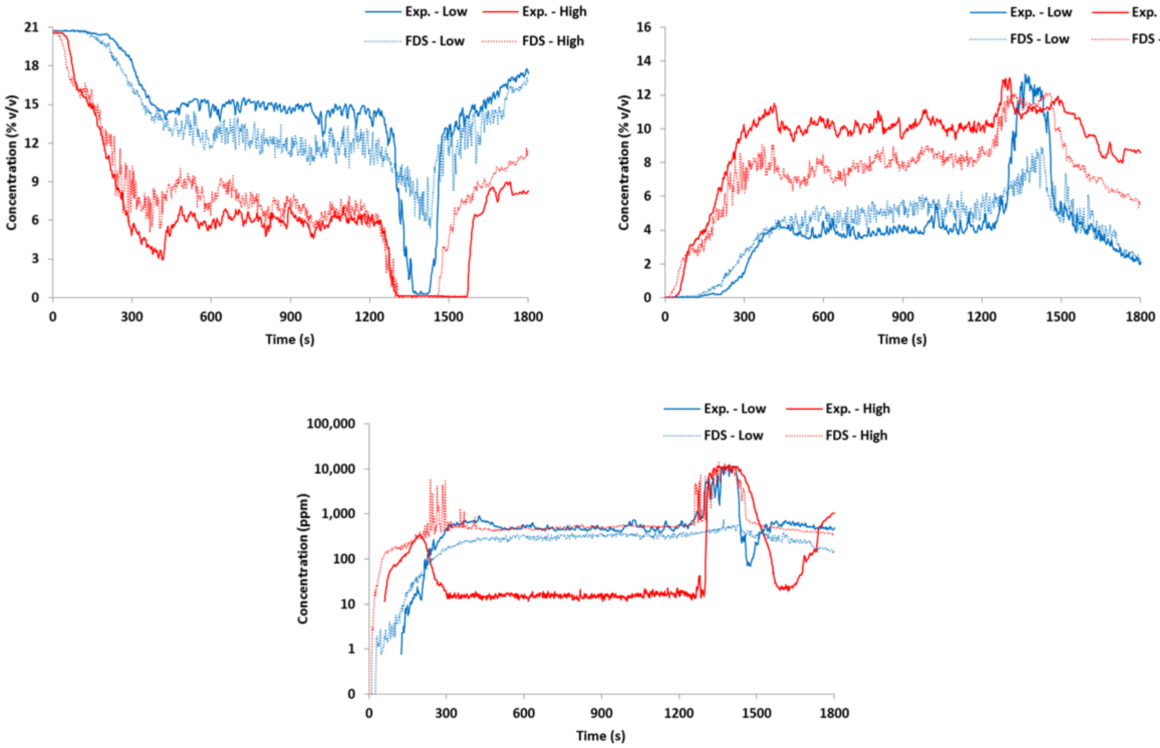

Figure 8 Comparison of measured and predicted species concentrations in the fire compartment (L2): O_2 (top left), CO_2 (top right) and CO (bottom)

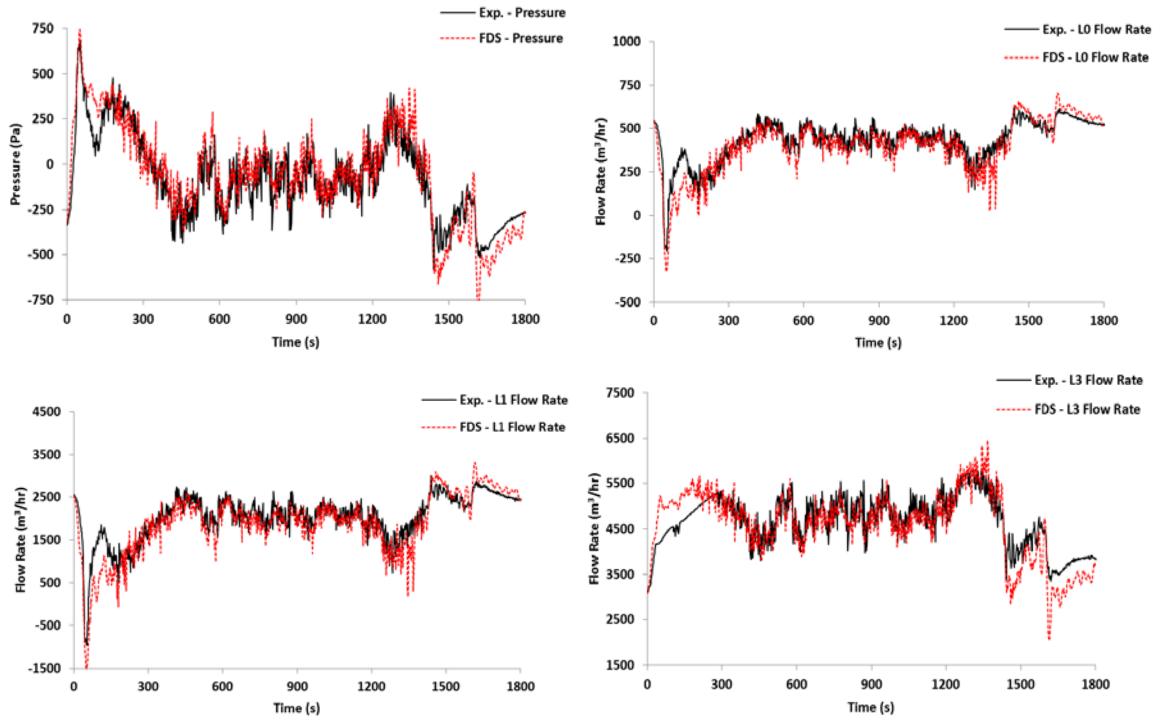

Figure 9 Comparison of measured and predicted ventilation conditions: fire room (L2) pressure (top left), L0 inlet flow rate (top right), L1 inlet flow rate (bottom left), compartment L3 exhaust flow rate (bottom right)

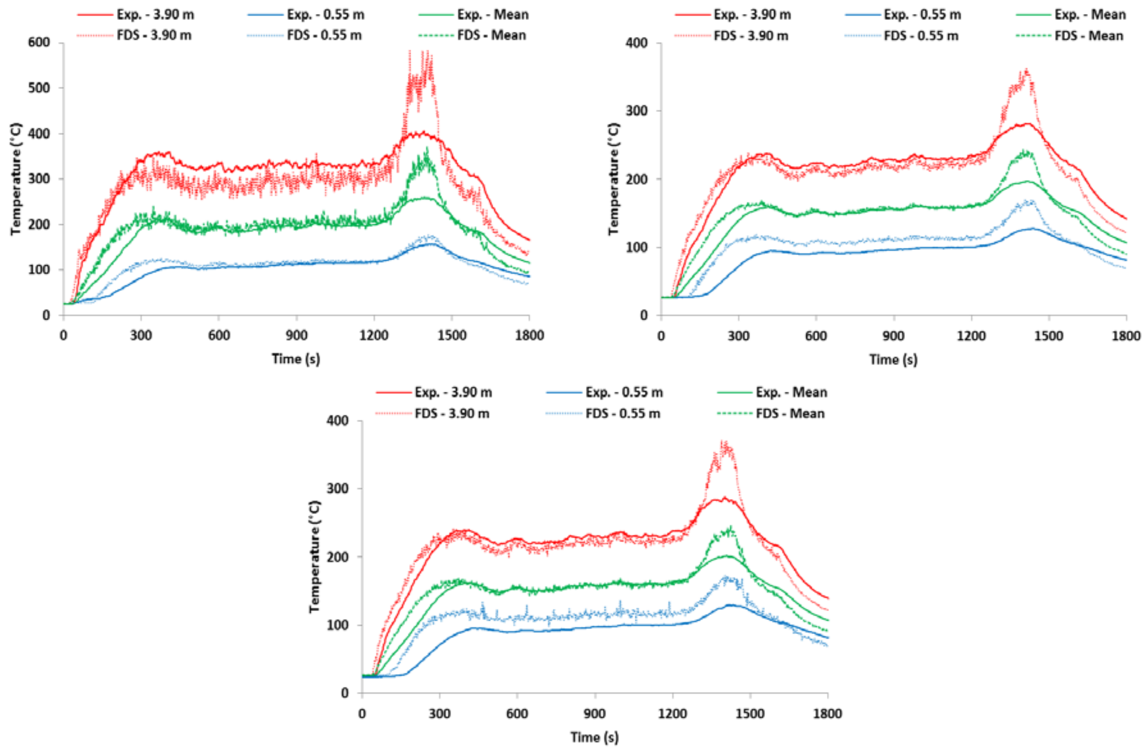

Figure 10 Comparison of measured and predicted temperatures in the corridor (L0) at the CC (top left), CE (top right) and CW (bottom) thermocouple trees

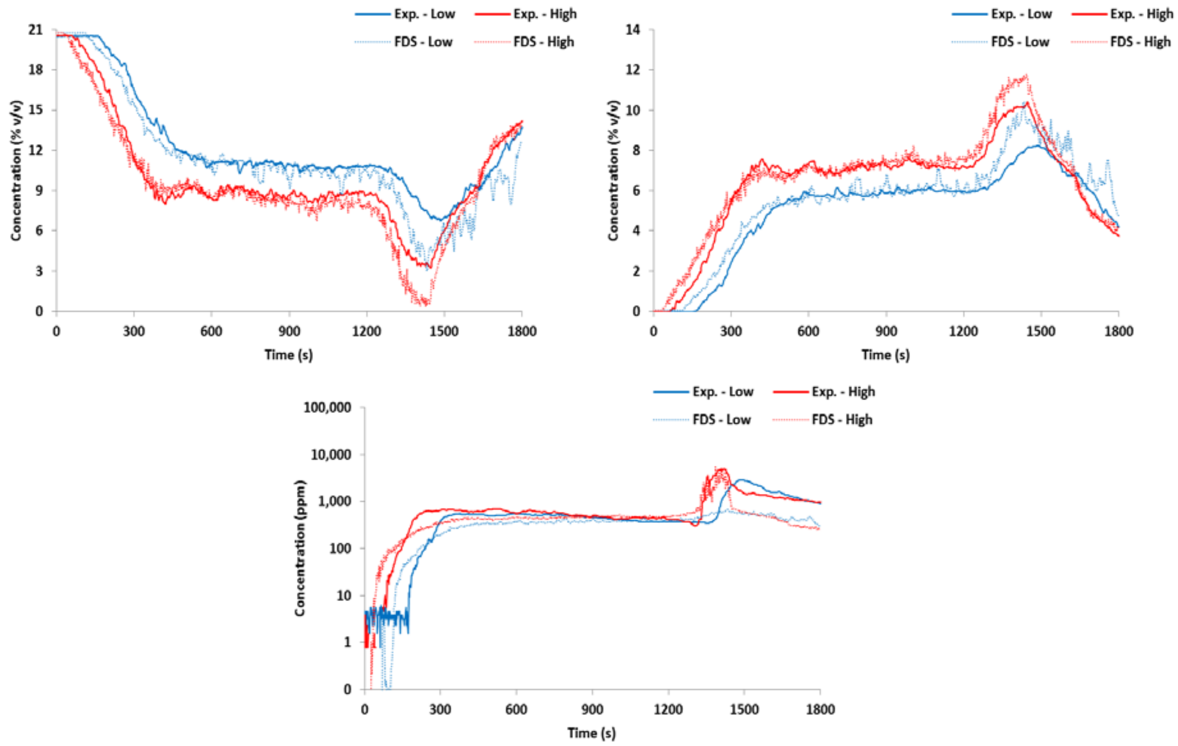

Figure 11 Comparison of measured and predicted species concentrations in the corridor (L0): O_2 (top left), CO_2 (top right) and CO (bottom)

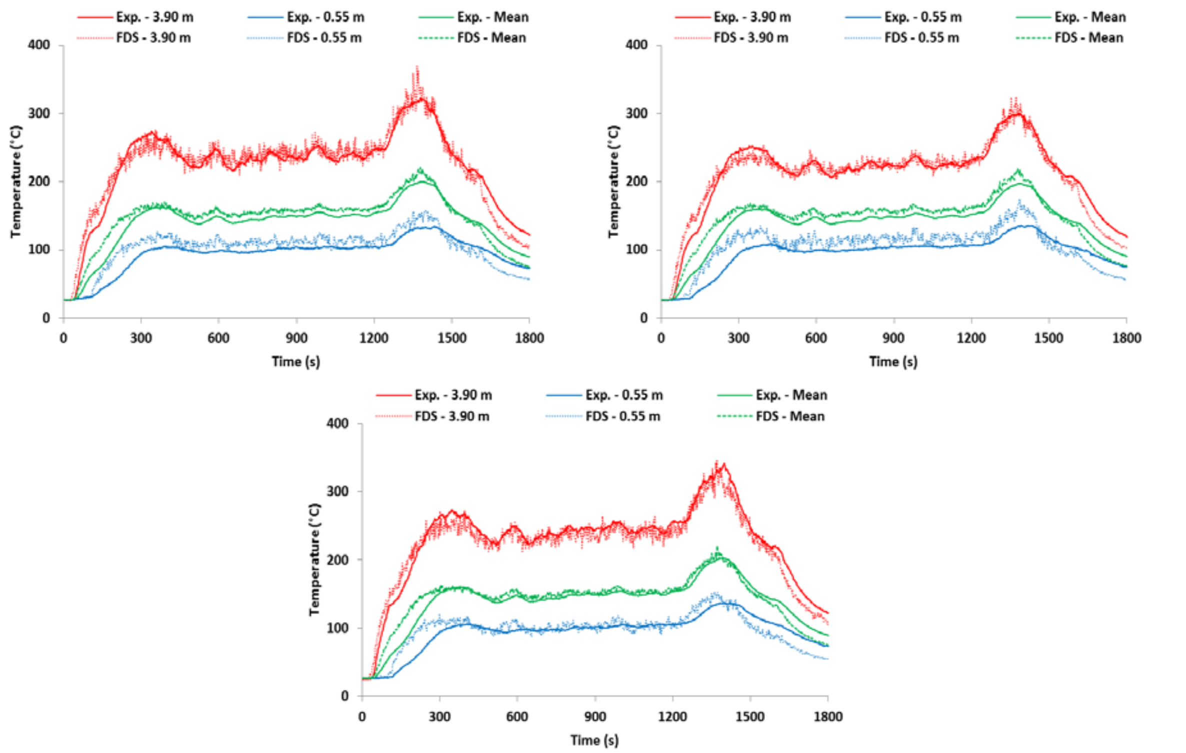

Figure 12 Comparison of measured and predicted temperatures in compartment L1 at the CC (top left), CW (top right) and SE (bottom) thermocouple trees

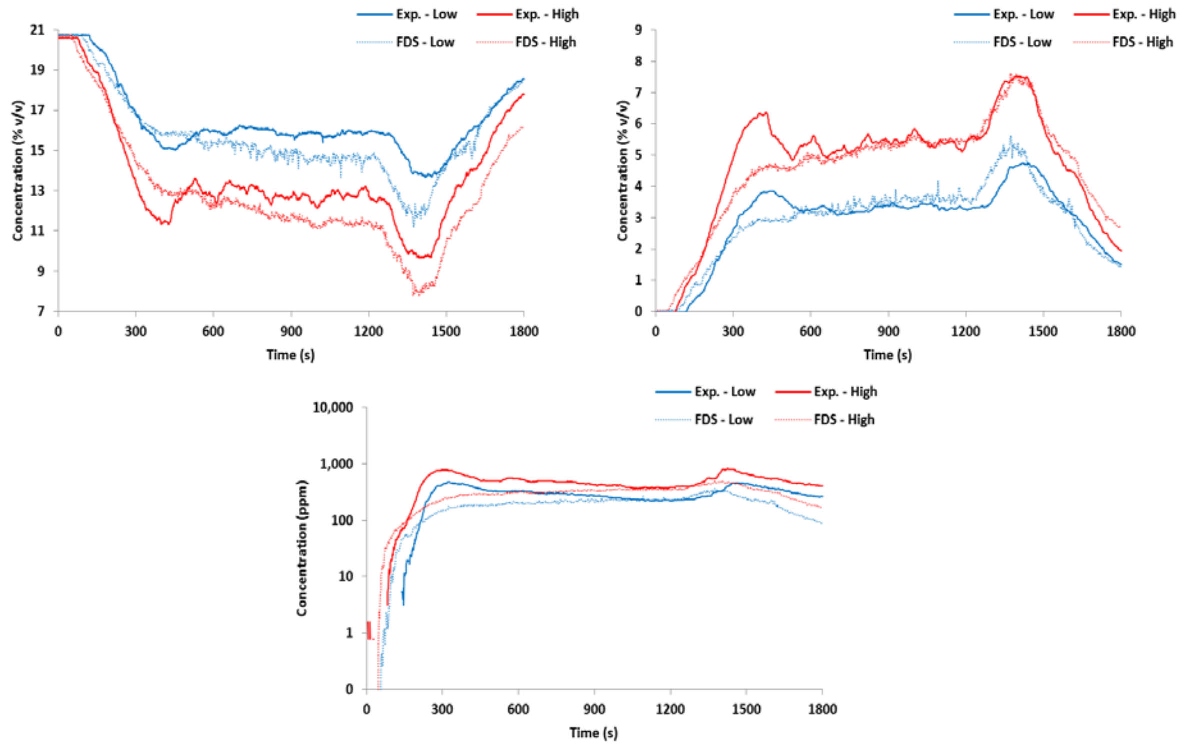

Figure 13 Comparison of measured and predicted species concentrations in compartment L1: O_2 (top left), CO_2 (top right) and CO (bottom)

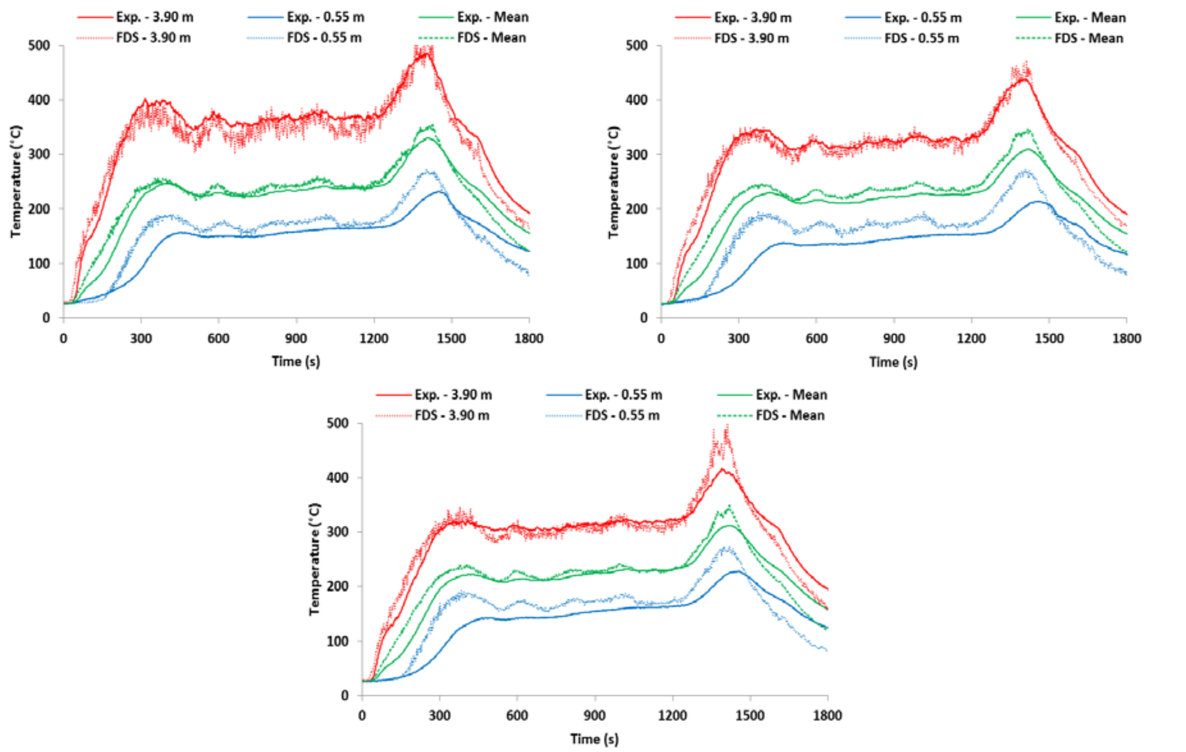

Figure 14 Comparison of measured and predicted temperatures in compartment L3 at the CC (top left), CE (top right) and SW (bottom) thermocouple trees

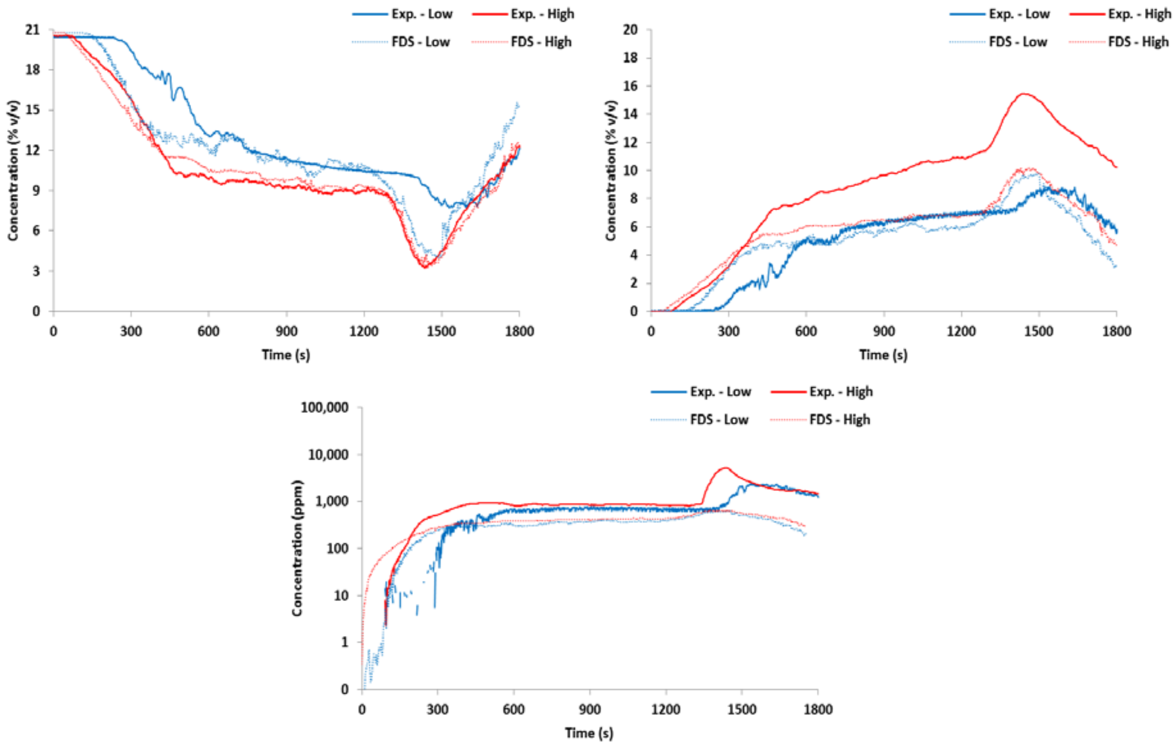

Figure 15 Comparison of measured and predicted species concentrations in compartment L3: O_2 (top left), CO_2 (top right) and CO (bottom)

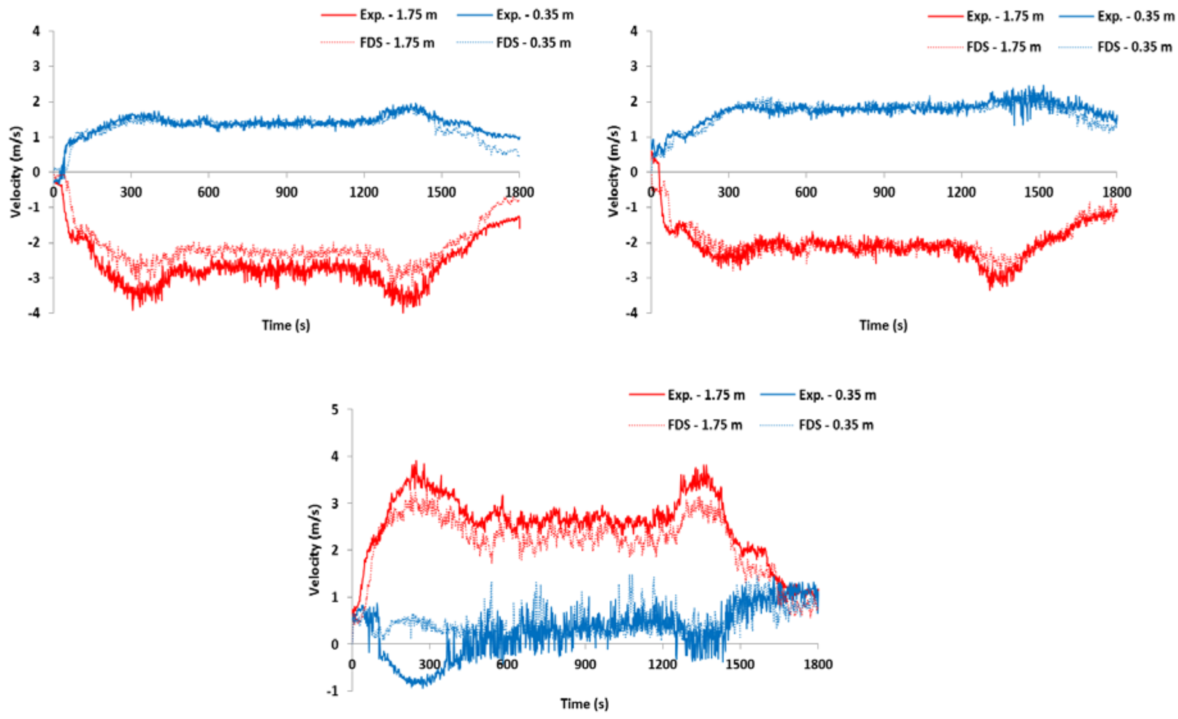

Figure 16 Comparison of measured and predicted doorway velocity profiles: L0 – L2 doorway (top left), L1 – L2 doorway (top right) and L2 – L3 doorway (bottom)

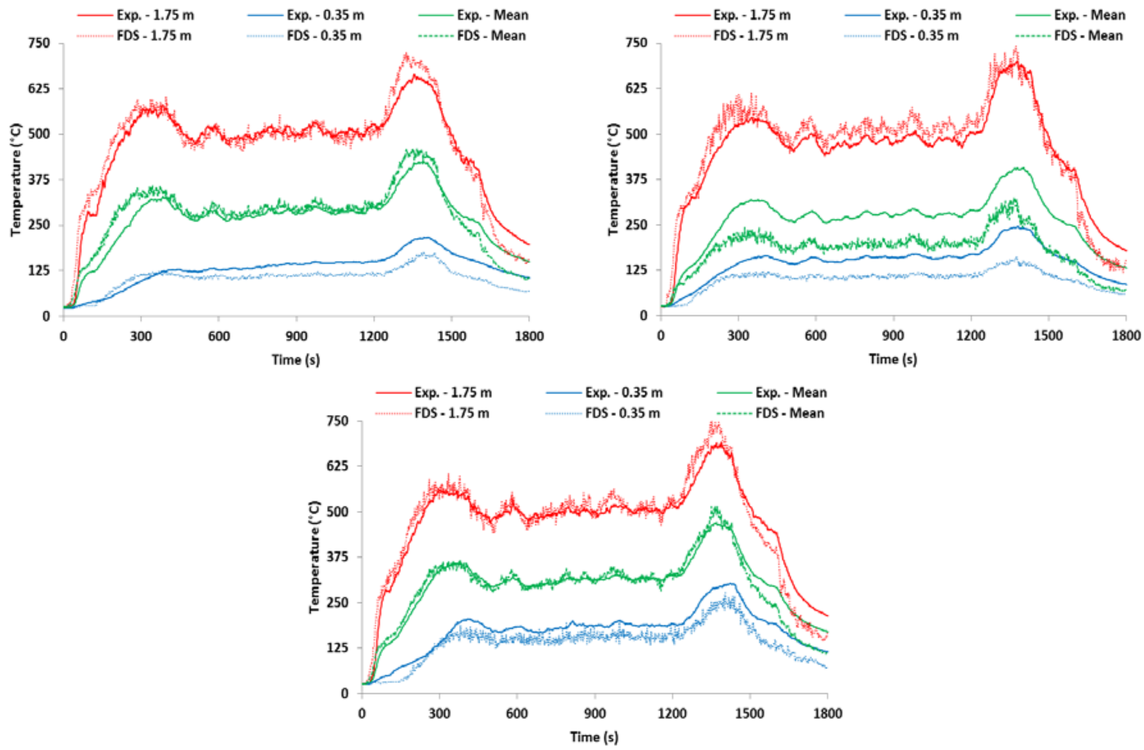

Figure 17 Comparison of measured and predicted doorway temperature profiles: L0 – L2 doorway (top left), L1 – L2 doorway (top right) and L2 – L3 doorway (bottom)

To quantify differences between the model predictions and the experimental results a functional analysis approach, as proposed by Peacock et al. [13], is used. The following metrics [13, 14] are used here to compare temporally-varying quantities:

- Cosine: taken as the inner product cosine between two datasets,
- Relative difference: taken as the normalised Euclidean distance between two datasets.

This approach also formed the basis of model comparison to experimental data for the first PRISME benchmark exercise [11], which looked at tests involving single effects, rather than the more complex Integral tests.

The functional analysis *cosine* values [11] and [13] further illustrate that the profiles predicted by the model capture the observed behaviour. For each compared variable these show how closely the functional form of the model prediction is to that of the measured data. Values approaching unity indicate that the shape of the two curves differ by a constant multiplier [13]. The *cosine* values for the FDS predictions of the INTEGRAL-4 test are summarised in Table 1.

The cosine values listed in Table 1 illustrate that the model predictions for CO concentrations show the largest deviation from the experimental data in terms of the shape of the predicted profiles. This is particularly evident in the fire room, L2. Figures 8, 11, 13 and 15 show comparisons of the measured and predicted CO profiles in the fire room (L2), corridor (L0), room L1 and room L3, respectively. The model predictions for the fire room show the largest deviation from the measured CO concentrations. In this room there is a significant difference in CO concentration in the upper and lower portions of the compartment. In the other compartments, where the upper and lower CO concentrations are similar, the model performs well. This result highlights a limitation of the FDS combustion model, and the modelling approximation used here to account for the effects of under-ventilation. It is clear that FDS is not yet capable of reliably capturing the effects of under-ventilation on rates of CO production.

Table 1 Cosine values [13] for FDS version 6.4.0 predictions of the PRISME INTEGRAL-4 test

Measured Quantity	Range *
Temperature	0.98 – 1.0
O_2 concentration	0.97 – 1.0
CO_2 concentration	0.95 – 1.0
CO concentration	0.57 – 0.96
Pressure	0.91
HVAC flow rates	0.99 – 1.0
* No *cosine* range for pressure as measurements were only taken in one of the compartments	

Figure 18 shows the *relative difference* [13] between the predicted and measured compartment temperature profiles. The figure compares *relative difference* values for the upper and lower measurement locations for each of the compartments and doorways. From this figure it is clear that the quantitative performance of FDS is significantly better for predictions of upper layer temperatures than those in the lower gas layer.

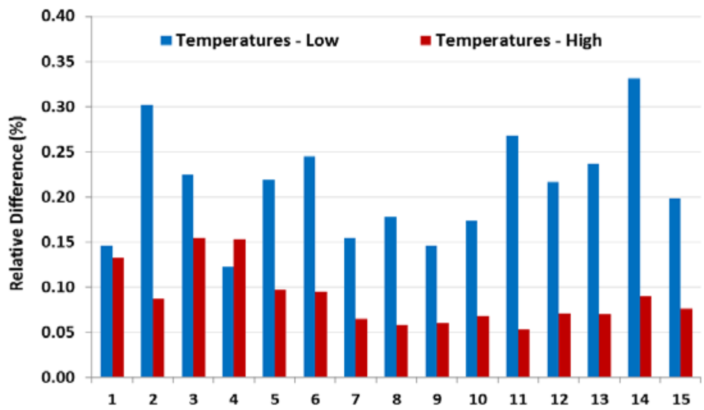

Figure 18 Comparison of the *relative difference* between predicted and measured temperature profiles for the upper and lower gas layers in the fire room L2 (bars 1-3); corridor L0 (bars 4-6); inlet room L1 (bars 7-9); exhaust room L3 (bars 10-12) and the three doorways (bars 13-15).

CONCLUSIONS

FDS 6.4.0 has been used to conduct numerical simulations of the PRISME INTEGRAL-4 fire test. The test considered a confined, mechanically-ventilated, multi-compartment scenario with an HTP pool fire as the source. The ability of the model to capture the fire-induced compartment conditions and the interaction between the fire and the mechanical ventilation system has been assessed through comparison of model predictions with the experimental results.

The INTEGRAL-4 simulation results show that FDS 6 is capable of capturing the fire-induced compartment conditions and the interaction between the fire and the mechanical ventilation system with reasonable accuracy for the majority of the parameters of interest. However, it has been shown that there are limitations in the available combustion modelling approaches. This inhibits the model's ability to predict concentrations of gaseous combustion products, most notably CO, accurately in the under-ventilated compartment conditions observed during the experiment.

It is clear from the sensitivity analysis simulations conducted for the INTEGRAL-4 test that the choice of combustion modelling approach can have a large impact on the ability of the model to accurately reproduce qualitative fire behaviour. The results presented here indicate that model sensitivity to the choice of combustion model should be assessed for scenarios for which under-ventilated conditions are anticipated.

Comparison of the results presented in this paper with the work of Beji et al. [6], in which an earlier version of FDS was used, shows that the inclusion of coupled HVAC network and CFD solvers in FDS v6 results in improved model predictions for the scenario considered. The updated version of FDS gives model predictions which more closely match the measured compartment pressure and ventilation flow rates.

The results presented here show that for well-defined fire sources FDS can provide reasonable predictions of fire consequences. For scenarios involving complex fire sources there will be significant uncertainty in both the specification of the source and representation of the source in the model. For such scenarios, carefully-chosen simplified fire sources could be used, such as standard design fire curves.

Additional work is required to develop combustion modelling approaches which can adequately capture the influence of under-ventilated conditions on fire behaviour and combustion product yields.

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AN EXPERT SYSTEM APPROACH BASED ON A SYLVIA DATABASE

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ABSTRACT

The SYLVIA software system is developed by IRSN to simulate the consequences of a fire in an industrial facility featuring a ventilation network. SYLVIA is the two-zone model used (at IRSN) for the evaluation of the fire safety in nuclear facilities. In order to take into account the different sources of uncertainty coming from initial and boundary conditions as well as from models parameters, SYLVIA is associated with the SUNSET statistical software. The SUNSET/SYLVIA coupling allows deriving, through Monte-Carlo studies, the variation range of any results which is of prime importance if these results are to be used for safety matters. Moreover, the statistical analysis of Monte-Carlo simulations is also a way to determine among the uncertainty sources, which ones have the most contribution. However, such a use of SYLVIA has a major drawback; it requires a large number of SYLVIA runs and a significant statistical analysis that is not always compatible with the requirements of an expertise. To overcome this difficulty, IRSN is currently developing an expert system based on a SYLVIA runs database. This approach allows to derive in a negligible time prognostic and diagnostic like inference, but also to derive a more complex form of reasoning intertwining prognostic and diagnostic inferences. To achieve these results, a large SYLVIA result data base has to be built. In this study, the SYLVIA expert system, built from a data base regrouping a set of 1,600,000 runs of the SYLVIA software, is presented in order to show how it can be used as an aid-tool for expertise.

INTRODUCTION

The SYLVIA software system [1] was developed by the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) to simulate a full ventilation network, fire scenarios in a highly confined and ventilated facility, and airborne contamination transfers inside nuclear installations. This software is based on a two-zone approach which consists in calculating mass and energy balances in both zones, these two zones are separated by an interface, which constitutes the enclosure (fire compartment or not): the lower zone simulating the fresh gas and the upper zone simulating the combustion products and the gas entrained by the plume (see Figure 1). In a two-zone approach, a plume feeds the upper zone of the fire compartment, whose volume increases, which has the effect of lowering the interface if the gas flow in the exhaust duct or at the level of openings of the fire compartment is not sufficient to remove all gases supplied by the plume.

The SYLVIA software is used by IRSN as a support tool for fire safety studies. For example, SYLVIA simulations can be used to identify fire sectors for which the overpressure generated by a fire would be likely to damage fire barrier devices, either by mechanical breakdown of the fire barrier elements, or by transfer of smoke. In such cases, the SYLVIA simulations must take into account the specificities of the installation (e.g., the number of compartments, their volumes, etc.) and also the uncertainties related to other input data (e.g., leakage rates, fire growth factor, etc.).

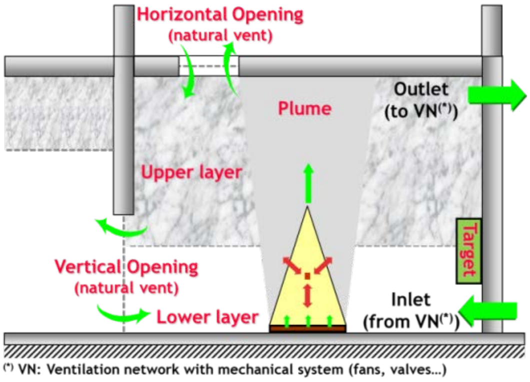

Figure 1 Two-zone approach of fire compartments

To evaluate the impact of uncertainties, the SYLVIA software is coupled to the SUNSET IRSN statistical tool [2]. This coupling makes it possible to directly carry out a set of parametric studies as well as measuring the impact on the selected responses. A typical use of the SYLVIA/SUNSET coupling is to perform a Monte Carlo simulation in which a set of variables, known as study parameters, is modelled by random variables. The results obtained from a Monte Carlo simulation constitute a database linking parametric configurations (determined by the set of values assigned to the study parameters) and uncertainties to the corresponding results. However, the direct use of this database in the context of an expertise encounters two difficulties:

- The database is necessarily very limited considering the possible configurations. The SYLVIA simulations constituting the database represent a small percentage of the possible parametric configurations. This is due to the combinatorial explosion of the configurations as a function of the possible values taken for each parameter and the number of parameters considered. For example, if we consider 16 parameters and each of them can take only three values, the number of combinations of values is 3^{16}, i.e. approximately 43 million configurations;
- The database is not specific to the characteristics of an expertise. It is necessary to extract from the database the information compatible with the specificities of the expertise to be carried out. For example, an expertise can focus more specifically on large volumes, high heat release rates ... and seek to discriminate configurations compatible with safety issues, such as maximum temperature, pressure, etc. in a compartment.

To meet this dual challenge, it is necessary to be able to correctly update the information contained in the database by integrating the characteristics of each expertise. One solution is to develop an expert system. This approach allows to derive in a negligible time prognostic and diagnostic like inferences, but also to derive a more complex form of reasoning intertwining prognostic and diagnostic inferences. To achieve these results, a large SYLVIA results data base has to be built.

In the following section, a description of the methodology used to set up the SYLVIA expert system is presented, and in a third section, some examples of results are presented to illustrate the contribution of this approach as an aid-tool for expertise.

THE SYLVIA EXPERT SYSTEM

An expert system in artificial intelligence is defined as a computer program that has the ability to represent and reason on knowledge. It can be divided into three components:

- The observation base: it gathers together all the contingent or specific information;
- The knowledge base: it contents all the generic information;
- The inference engine: it is the set of algorithms used to make inferences.

For an expertise, it is useful to be able to quickly discern the configurations at risk of an installation. The idea behind the expert system approach is to take advantage of the SYLVIA software to build a database covering a wide range of configurations, and then to use the expert system reasoning abilities to discern configurations of this database useful to the specific expertise. Thus, the three components of the SYLVIA system expert are (see Figure 2):

- The observation base that defines the specific values of parameters (upstream contingent information) or responses (downstream contingent information), such as, and for example, the volume of a compartment or a level of overpressure that is considered in the expertise;
- The knowledge base that gathers all the generic information in which the expert system will operate. In the SYLVIA case, the generic information comes from a large SYLVIA data base which allows the association of the set of values used for the study parameters with the corresponding results for variables of interest. This information is encoded by means of conditional probability tables (cf. the green rectangle in the Figure 2 and constitutes the stable part of knowledge;
- The inference engine that is the algorithmic part of the expert system. It is the set of algorithms (the yellow arrows in the Figure 2) that pushes the information coming from the observation database through the knowledge base in order to answer queries such as what configurations can lead to exceed 60 hPa.

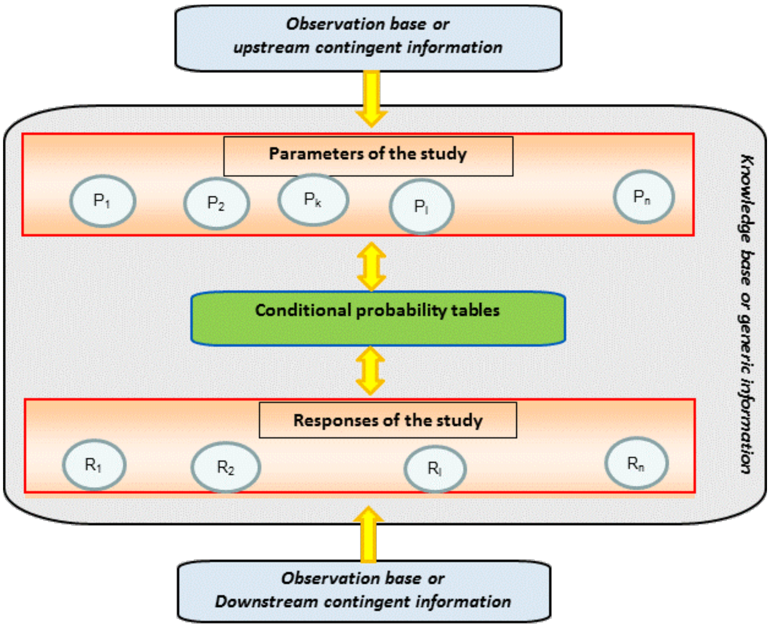

Figure 2 Flow chart of the SYLVIA expert system

Before looking concretely at how the knowledge base is built, it is useful to detail the theoretical principle and the assumptions on which it is based.

Theoretical Model of the SYLVIA Knowledge Base

In a schematic way, the SYLVIA software can be seen as a transfer function associating response values to a set of parameter values.

Indeed from a formal viewpoint, any SYLVIA results can be written:

$$R_i = S(P_1, \ldots, P_N) \qquad (1)$$

where R_i is the response of interest, P_j the parameters and S, the SYLVIA software acting as a transfer function.

The principle of the SYLVIA knowledge base consists in transcribing the transfer function S into numerical tables (one for each response) called conditional probability tables.

To carry out this transcription of SYLVIA into numerical tables, two simplifications are necessary. The first one consists in discretizing the parameters and responses of the study. This discretization leads to a numerical mesh of the space of variation of the parameters and the responses, and, like a physical mesh, the appropriate mesh size depends on the problem considered and on the desired resolution accuracy. The second simplification concerns the combinatorial aspect of the u-plets of parameters associated with a response by relation (1). Thus, if P_1, ..., P_N are discretized respectively in n_1, ..., n_N, the number of parametric configurations is $n = n_1 * .... * n_N$. Therefore, to limit this combinatorial explosion, the relation (1) is only discretized for its influential parameters.

More precisely, for each response R_i, one determines the most influential n_i, and equations (1) becomes:

$$R_i = S(P_1, ...,P_{ni}, U_i) \qquad (1')$$

where U_i is a random variable modelling the loss of information induced by neglecting the less influential variables and the discretization. It is worth noting that equation (1') has become stochastic since U_i is a random variable.

In summary, the SYLVIA model is written formally:

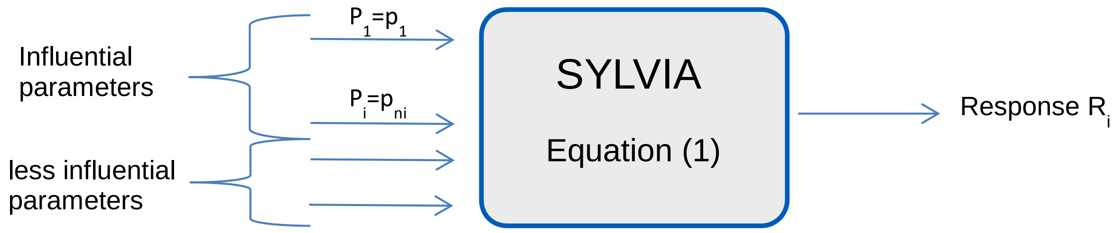

Figure 3 The formal model of SYLVIA

And its transcription into a structural model defined by numerical tables:

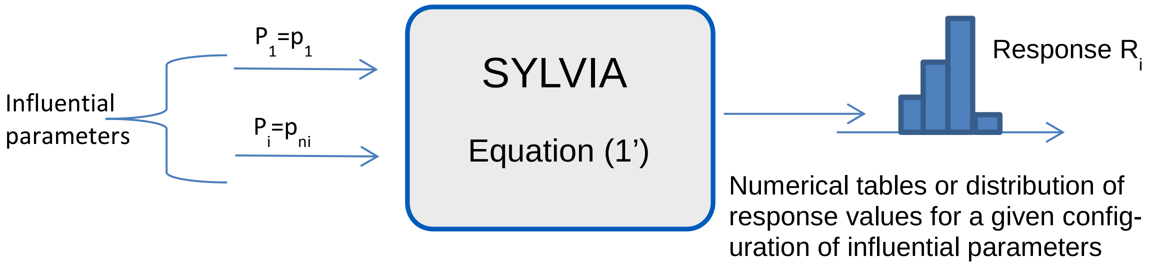

Figure 4 The structural model of "SYLVIA"

The Building of the Knowledge Base

The knowledge base collects all the generic information from which the expert system will perform inferences, therefore it determines the application domain of the expert system. Thus, a first step consists in delimiting the general framework of the study: the responses of interest, the variables of the study and their variation ranges.

Delimitation of the Framework

Our expert system is applied to the study of the pressure effect resulting from a fire in a well-confined enclosure. The need expressed by fire experts on this topic is to be able to identify the fire sectors for which overpressures generated by a fire would be likely affect the fire barriers, either by mechanical breakdown of fire barrier elements, or by smoke transfer. Thus, the general framework of the study consists in two fire sectors, represented by two compartments, connected by a fire break door, as shown in Figure 5.

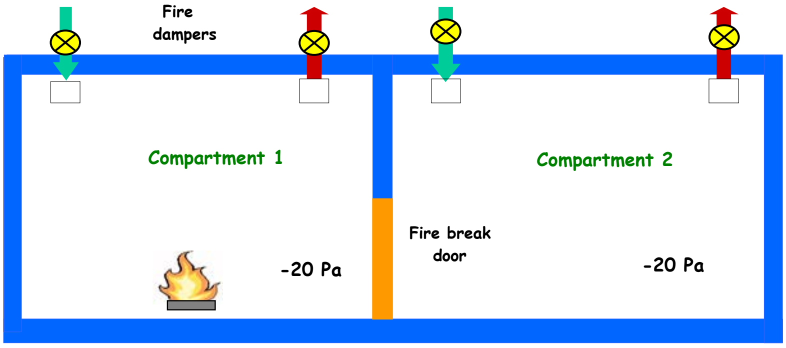

Figure 5 General framework of the study

Compartments height is set to 4 m, whatever the considered volume. Each compartment is equipped with fire dampers located at the inlet and exhaust air vents. The ventilation management of the two fire sectors is independent. The fire source is centered in compartment 1 and is modelled by a design fire, characterized by its maximum heat release rate in open atmosphere and by its fire growth factor. In nominal conditions, the fire break door is closed and no pressure difference between the two fire sectors is considered (- 20 Pa relative to the atmospheric pressure is set in each compartment).

Responses of the Study

According to the issue addressed in this study, the responses are the following:

- Maximum value of the differential pressure at the fire break door;
- Maximum pressure, in each compartment;
- Maximum gas temperature in the hot gas layer, in each compartment;
- Maximum soot concentration in the hot gas layer, in each compartment.

Selected Parameters

Sixteen variables were chosen for the parametric study, grouped in four categories as reported in Table 1. Also specified in this table are the ranges of values of the variables. Those will be used in the Monte Carlo simulation from which the different conditional probability tables linking a response to its influential variables will be established.

Table 1 Variables of the study and their ranges of values (C: continue, D: discrete, black colour, parameters related to compartments, blue colour, related to the ventilation, red colour, related to the fire source and green colour, related to fire barrier elements)

Parameters	Type	Range of values
Volume of the compartment (m^3) *2	C/D	[100 ; 7000] +{∞ for adjacent compart.}
Closing time of fire dampers (s) * 2	D	{0 ; 150 ; 1200 ; ∞}
Free volume of the compartment (%) *2	C	[80 ; 100]
Leakage rate of the compartment ($vol.h^{-1}$) * 2	C/D	{0} + [0.1 ; 1]
Air renewal rate of the compartment (h^{-1}) * 2	C	[1 ; 40]
Resistivity of the ventilation network (hPa)	C	[1 ; 10]
Fire growth factor ($kW.s^{-2}$)	D	{2 10^{-4} ; 3 10^{-3} ; 0.012 ; 0.047 ; 0.19}
Maximum HRR in open atmosphere (kW)	C	[200 ; 5000]
Oxygen limiting law and fire extinction (-)	D	{no limit ; 0 %} {no limit ; 8 %} {no limit ; 12 %} {Peatross ;12 %}
Production rate of soot (%)	C	[0 ; 20]
Aeraulic resistivity of the fire break door (m^{-4})	C	[1000 ; 9000]

The SYLVIA Database

To study a set of configurations, the SYLVIA software is coupled to the SUNSET IRSN statistical tool. This coupling allows to directly perform a Monte Carlo simulation in which a set of variables, known as study parameters, is modelled by random variables. Thus, each study parameter is associated with a variation domain and the Monte Carlo simulation provides a means of exploring the whole range of variation of the parameters and to know the impact of these variations on the responses.

The results obtained from a Monte Carlo simulation constitute a database linking parametric configurations (determined by the variation domain assigned to the parameters) to the corresponding results. To have a sufficient statistics for each combination of classes, 1,600,000 runs were performed. For information, this number of runs required 9 days of CPU time on 60 processors.

Identification of the Influential Parameters

The identification of the influential parameters of a response is based on its correlations with the parameters determined from the Monte-Carlo simulation. The results are reported in Table 2. In this table, it can be seen that free volume of compartments, air renewal rate of the adjacent compartment and the resistivity of the ventilation network do not constitute influential parameters according to the selected responses. As a consequence, they will not appear explicitly in the knowledge base. Nevertheless, the variability induced by the less influential parameters is taken into account in the conditional probability tables.

Table 2 Correlations (in percent) of the responses with respect to the parameters (influential variables are highlighted in colours)

	P_{max} C1	P_{max} C2	ΔP_{max} FBD	T_{max} C1	T_{max} C2	$C_{s,max}$ C1	$C_{s,max}$ C2
Vol C1	-3%	0%	-4%	-52%	-14%	-13%	4%
Vol C2	-3%	-8%	2%	0%	-20%	0%	-12%
Air renewal C1	4%	2%	4%	3%	1%	-6%	-2%
Air renewal C2	0%	-1%	1%	0%	-3%	0%	-3%
Res fire door	7%	0%	10%	0%	-3%	0%	-1%
tc dampers C1	-18%	-9%	-17%	11%	-10%	-29%	-7%
tc dampers C2	-5%	-10%	3%	0%	-1%	0%	-5%
Fire kinetics	17%	4%	21%	12%	5%	-1%	-1%
HRR max	20%	9%	21%	55%	28%	5%	11%
Res vent network	2%	1%	1%	0%	2%	0%	1%
Free volume C1	2%	1%	2%	3%	3%	-1%	1%
Free volume C2	0%	0%	0%	0%	-1%	0%	-1%
Leakage C1	-34%	-19%	-32%	0%	-25%	1%	-18%
Leakage C2	-7%	-18%	4%	0%	9%	0%	7%
O_2 limitation	-4%	-3%	-3%	-25%	-13%	-22%	-15%
Soot production	-2%	-1%	-2%	-4%	-1%	78%	22%

Computation of the Conditional Probability Tables

As seen previously, in order to compute the conditional probability tables of each response R_i, it is necessary to discretize the influential parameters and the response. For this application, the following discretization has been considered:

Table 3 Discretization of the parameters (D: discrete value; C: continue)

Parameters	Type	Discretization
Volume of compartments (m^3)	C/D	[100 ; 300] [300 ; 500] [500 ; 700] [700 ; 1000] [1000 ; 3000] [3000 ; 7000] {inf}
Closing time of fire dampers (s)	D	{0 ; 150 ; 1200 ; inf}
Free volume of compartments (%)	C	[80 ; 90] [90 ; 100]
Leakage rate of compartments ($vol.h^{-1}$)	C/D	{0} [0.1 ; 0.4] [0.4 ; 0.7] [0.7 ; 1]
Air renewal rate of compartments (h^{-1})	C	[1 ; 5] [5 ; 10] [10 ; 20] [20 ; 40]
Resistivity of the ventilation network (hPa)	C	[1 ; 4] [4 ; 7] [7 ; 10]
Fire growth factor ($kW.s^{-2}$)	D	{2 10^{-4} ; 3 10^{-3} ; 0.012 ; 0.047 ; 0.19}
Maximum HRR in open atmosphere (kW)	C	[200 ; 800] [800 ; 1500] [1500 ; 3000] [3000 ; 5000]
Oxygen limiting law and fire extinction (-)	D	{no limit ; 0 %} {no limit ; 8 %} {no limit ; 12 %} {Peatross ; 12 %}
Production rate of soot (%)	C	[0 ; 2] [2 ; 5] [5 ; 10] [10 ; 15] [15 ; 20]
Aeraulic resistance of the fire break door (m^{-4})	C	[1000 ; 3000] [3000 ; 6000] [6000 ; 9000]

Table 4 Discretization of the responses

Reponses	Discretization
Maximum pressure difference at fire break door (hPa)	< 20 [20 ; 40] [40 ; 60] > 60
Maximum pressure in each compartment (hPa)	< 20 [20 ; 40] [40 ; 60] > 60
Maximum gas temperature in the hot gas layer for the two compartments (°C)	< 65 [65 ; 100] [100 ; 140] [140 ; 180] [180 ; 210] [210 ; 300] [300 ; 350] [350 ; 400] [400 ; 500] > 500
Maximum soot concentration in the hot gas layer for the two compartments ($g.m^{-3}$)	< 1 [1 ; 2] [2 ; 3] [3 ; 5] [5 ; 10] > 10

From this discretization, the formal model of SYLVIA is transcribed into a structural model. More precisely, for each response, the Monte-Carlo simulations are reordered according to the configurations defined by its influential parameters, and then for each configuration the values of the conditional probability table are given by the empirical distribution.

For example, let us consider the response “maximum pressure in the fire compartment”. For this response, seven influential parameters are determined and according to their discretization, the total number of its parametric configurations is: 3*4*4*5*4*4*4=15360 and therefore the conditional probability table for this response has 15360 rows and 4 columns. The first row of this table is obtained by extracting among the data base all the calculations that have for the seven influential variables, values in their minimal class. In the data base, there were 105 SYLVIA runs for this parametric configuration, with the following distribution 72 (< 20 hPa), 23 (20 – 40 hPa), 10 (40 – 60 hPa) and 0 (> 60 hPa). So, the first line of the conditional probability table is: 0.69 (< 20 hPa), 0.22 (20 – 40 hPa), 0.09 (40 – 60 hPa) and 0 (> 60 hPa),

By repeating this procedure for each one of the 15360 parametric configurations, we obtain the conditional probability table associated to the response “maximum pressure in the fire compartment”.

By proceeding in the same way for each response, we obtain seven conditional probability tables that are the numerical transcription of the SYLVIA model into a structural model.

The Inference Engine

The technique used to propagate the information specific to the current expertise through the knowledge base was proposed by J. Pearl [5] and called message passing. Its principle is to first separate the information relative to a variable (parameter or response) into upstream information and downstream information.

For a parameter P_i, its upstream information is given by the value entered for P_i in the observation base and its downstream information is given by the set of data entered for the responses and the other parameters. Indeed, the information relating to a parameter can be transmitted to another parameter only by the knowledge of a response. For example, knowing the heat release rate informs about the volume value of the compartment only if the pressure reached in the compartment is known. Conversely, the downstream information of a response is the one entered in the observation base and its upstream information is made up of all the other information given in the observation base.

The "message passing" technique consists in transferring the upstream information by weighting the lines of the conditional probability tables and the downstream information by weighting the columns. This way, the information contained in the data base is updated by integrating the characteristics of each expertise.

To sum up, the inference engine makes it possible to dynamically use the knowledge base constituted from the data of a very large number of SYLVIA simulations. The calculations relevant to the current expertise are automatically selected in the knowledge base and possibly weighted if some values of parameters are deemed more likely than others. It should be noted that a strong benefit of expert systems using Bayesian network is to be able to reverse this weighting mechanism when the available information concerns responses.

RESULTS

To illustrate the potential interest of our expert system's approach as an aid tool for expertise, we consider the following issue: how to identify the configurations that could lead to a pressure difference at fire break door beyond 60 hPa (ΔP_{FBD} > 60 hPa) in the specific case of a medium kinetics fire growth in a compartment with leaks?

First, if the expert system is used as a prognostic tool or in a forward chaining (see Figure 6), only the knowledge relative to the parameters can be used. In this case, the result of the expert system is rather like a direct exploitation of the data base. There are 239 967 runs out of the 1 600 000 computations in the data base that meet this parametric configuration and their distribution is 238 170 (< 20 hPa), 1602 (20 – 40 hPa), 163 (40 – 60 hPa) and 32 (> 60 hPa), or respectively 99.26 %, 0.66 %, 0.07 % and 0.01 %.

If the expert system is used as a diagnostic tool or in backward chaining (see Figure 7), only the knowledge relative to the responses is used, in our case ΔP_{FBD} > 60 hPa. If our interest is on parameters, for example how are distributed the leakage rates out of ΔP_{FBD} > 60 hPa cases (45,700 runs out of the 1,600,000 runs), the expert system informs us that 96 % (0 % vol.h^{-1}), 4 % (0.1 - 0.4 vol.h^{-1}), 0 % (0.4 - 0.7 vol.h^{-1}) and 0 % (0.7 - 1 vol.h^{-1}). The expert system also indicates that the distribution for the maximum heat release rate in open atmosphere is 0 % (< 800 kW), 8 % (500 – 1500 kW), 36 % (1500 – 3000 kW) and 56 % (3000 - 5000 kW): a ΔP_{FBD} > 60 hPa is not possible for a maximum heat release rate in open atmosphere lower than 800 kW.

To fully answer the following question - what are the configurations that could lead to a ΔP_{FBD} > 60 hPa in the specific case of a medium kinetics fire growth in a compartment with leaks?, it appears necessary to combine the forward and the backward reasoning (see Figure 8). The crossing of the upstream information (a medium kinetics fire growth in a compartment with leaks) and downstream information (ΔP_{FBD} > 60 hPa) indicates that the distribution for the maximum heat release rate in open atmosphere is 0 % (< 800 kW), 0 % (500 - 1500 kW), 8 % (1500 -3000 kW) and 92 % (3000 – 5000 kW) and the distribution for the leakage rate is 0 % (0 vol.h^{-1}), 100 % (0.1 - 0.4 vol.h^{-1}), 0 % (0.4 - 0.7 vol.h^{-1}) and 0 % (0.7 - 1 vol.h^{-1}). Some other interesting information: according to compatible values for maximum HRR and volumes of the fire compartment (in the range (500 – 3000 m^3)), the expert system indicates that cases leading to a ΔP_{FBD} > 60 hPa are given for a late closing time of the fire dampers of the fire compartment (100 % of the cases).

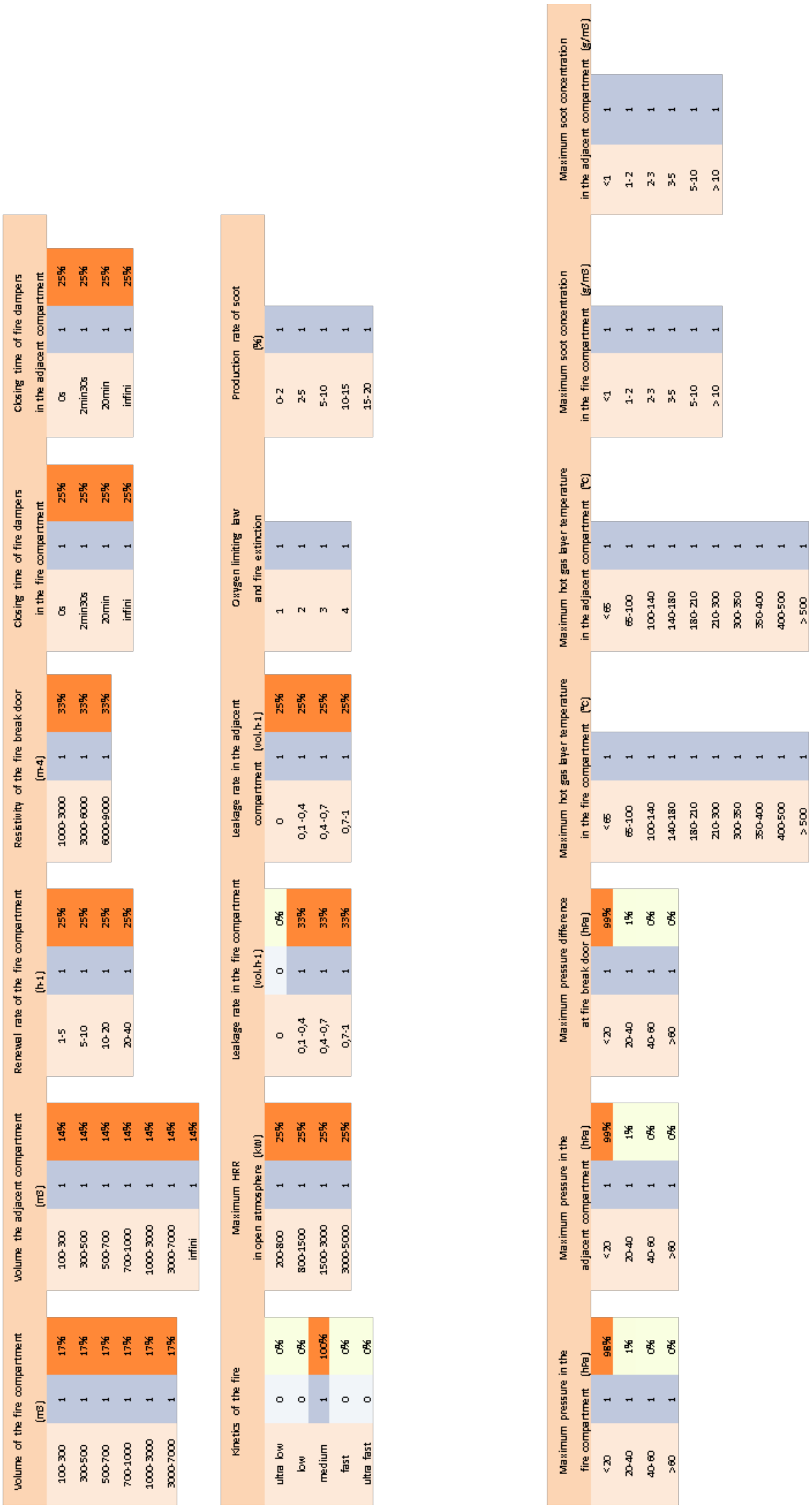

Figure 6 Example of a query in a forward chaining

Volume of the fire compartment (m3)		
100-300	1	6%
300-500	1	14%
500-700	1	19%
700-1000	1	22%
1000-3000	1	22%
3000-7000	1	17%

Volume the adjacent compartment (m3)		
100-300	1	14%
300-500	1	14%
500-700	1	14%
700-1000	1	14%
1000-3000	1	14%
3000-7000	1	14%
infini	1	14%

Renewal rate of the fire compartment (h-1)		
1-5	1	21%
5-10	1	21%
10-20	1	24%
20-40	1	34%

Resistivity of the fire break door (m-4)		
1000-3000	1	16%
3000-6000	1	34%
6000-9000	1	49%

Closing time of fire dampers in the fire compartment		
0s	1	51%
2min30s	1	35%
20min	1	13%
infini	1	0%

Closing time of fire dampers in the adjacent compartment		
0s	1	25%
2min30s	1	25%
20min	1	25%
infini	1	25%

Kinetics of the fire		
ultra low	1	0%
low	1	5%
medium	1	14%
fast	1	37%
ultra fast	1	44%

Maximum HRR in open atmosphere (kW)		
200-800	1	0%
800-1500	1	8%
1500-3000	1	36%
3000-5000	1	56%

Leakage rate in the fire compartment (vol.h-1)		
0	1	96%
0,1-0,4	1	4%
0,4-0,7	1	0%
0,7-1	1	0%

Leakage rate in the adjacent compartment (vol.h-1)		
0	1	21%
0,1-0,4	1	25%
0,4-0,7	1	27%
0,7-1	1	27%

Oxygen limiting law and fire extinction	
1	1
2	1
3	1
4	1

Production rate of soot (%)	
0-2	1
2-5	1
5-10	1
10-15	1
15-20	1

Maximum pressure in the fire compartment (hPa)		
<20	1	0%
20-40	1	0%
40-60	1	17%
>60	1	83%

Maximum pressure in the adjacent compartment (hPa)		
<20	1	79%
20-40	1	7%
40-60	1	3%
>60	1	10%

Maximum pressure difference at fire break door (hPa)		
<20	0	0%
20-40	0	0%
40-60	0	0%
>60	1	100%

Maximum hot gas layer temperature in the fire compartment (°C)	
<65	1
65-100	1
100-140	1
140-180	1
180-210	1
210-300	1
300-350	1
350-400	1
400-500	1
> 500	1

Maximum hot gas layer temperature in the adjacent compartment (°C)	
<65	1
65-100	1
100-140	1
140-180	1
180-210	1
210-300	1
300-350	1
350-400	1
400-500	1
> 500	1

Maximum soot concentration in the fire compartment (g/m3)	
<1	1
1-2	1
2-3	1
3-5	1
5-10	1
> 10	1

Maximum soot concentration in the adjacent compartment (g/m3)	
<1	1
1-2	1
2-3	1
3-5	1
5-10	1
> 10	1

Figure 7 Example of a query in a backward chaining

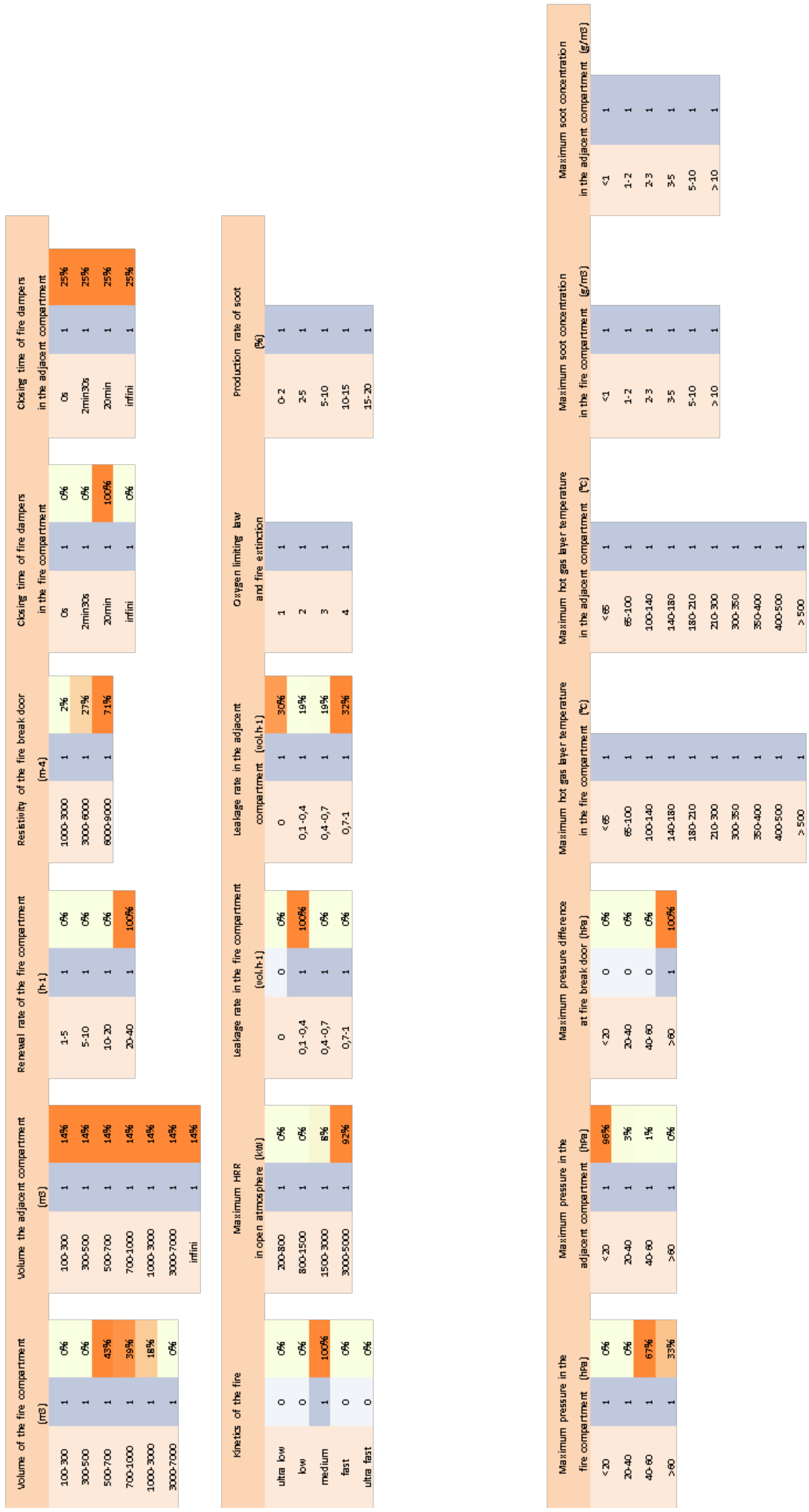

Figure 8 Example of a query in a mixed chaining

CONCLUSION AND PERSPECTIVES

An expert system approach based on a SYLVIA database for the study of pressure effects resulting from a fire has been developed. The first results seem to confirm the interest of an expert system approach in order to dynamically use large databases as part of an expertise. This new computer tool is thus to be understood as a complementary tool of SYLVIA allowing an analyst to quickly target the configurations of interest for his expertise.

It is useful to remind that the perimeter of the knowledge base determines the scope of the expert system. This one is determined by the general framework of the study. If the framework were to change, it would then be necessary to integrate the new generic knowledge.

For other expertise needs, another SYLVIA study may be required. The algorithmic part is unchanged but may need to be adapted so as to take into account the specific characteristics of the expertise question.

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OPEPPI: TOOL FOR ASSESSMENT OF PASSIVE FIRE PROTECTION

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ABSTRACT

The need for assessment of the necessity of passive fire protection appears during all phases of the life of a nuclear power plant – design, construction, operation and decommissioning. The main difficulty comes from deviation between the original design and the real-life situation, which may come from many reasons: modifications of the environment during construction, addition of new material within the room, upgrade of the fire protection, etc. The main solution for solving such problem up to now was to recalculate fire scenario with help of software such as MAGIC. The processing is very powerful, however it needs a quite complex process of on-site measurement leading to remote calculation by specialized engineer.

The particularity of the OPEPPI tool is that it can to meet the needs of customers in terms of time (because it can be used on the site), ease of use (it is not necessary to model nor entering all) and Budget (because it is a tool that gives fast and reliable results for a decision), these three qualities (time, budget, ease of use) make this tool allow us to answer the problems encountered on nuclear power plants and installations.

INTRODUCTION

Whenever passive fire protection is implemented, several questions can be asked by its characteristics. Do we need to install a screen or do we need to have a fire compartment surrounded by fire barriers? And if so, what should its characteristics be? A screen is generally good enough if the air temperature of the room during a fire does not exceed the failure temperature of the equipment to be protected, if we disregard the plume effect. In this situation, only the radiation is considered. The rated fire barrier is necessary if the air temperature is higher than the failure temperature of the equipment or if the equipment is located within the ceiling jet or the plume area.

The particularity of the OPEPPI tool is that it can meet the needs of customers in terms of time (because it can be used on the site), to simplify the use (it is not necessary to have a complete model) and budget (because it is a tool that gives fast and reliable results), These three qualities (time, budget, simplification) allow the tool to solve the problems encountered on the nuclear power plants and installations.

GUIDELINES

Pre-project

Engineering: Knowledge of the local temperature requires a software modelling under different environmental constraints (size, HRR, etc.). It is the same for the related characteristics (flux, rate, flow, etc.).

In order to optimize the computing time, we propose to achieve prior calculations that will almost immediately provide a reliable estimation of characteristics of the situation to be analysed, on which we can justify the adequacy of constructive solutions to be implemented, the final software modelling would then be restricted to specific studies.

Development after Engineering: The tool to be used determines the characteristics of the equipment to be protected in local fire areas, it is a tool to consolidate data and recover the data recorded prior for use in the fire modelling software 'MAGIC', the mesh resulting in hundreds of previous simulated studies, allowing us to determine the most forthcoming solutions compared to the situation studied, and to frame and calculate the various request characteristics (gas temperature , flux ,higher layer temperature, etc.).

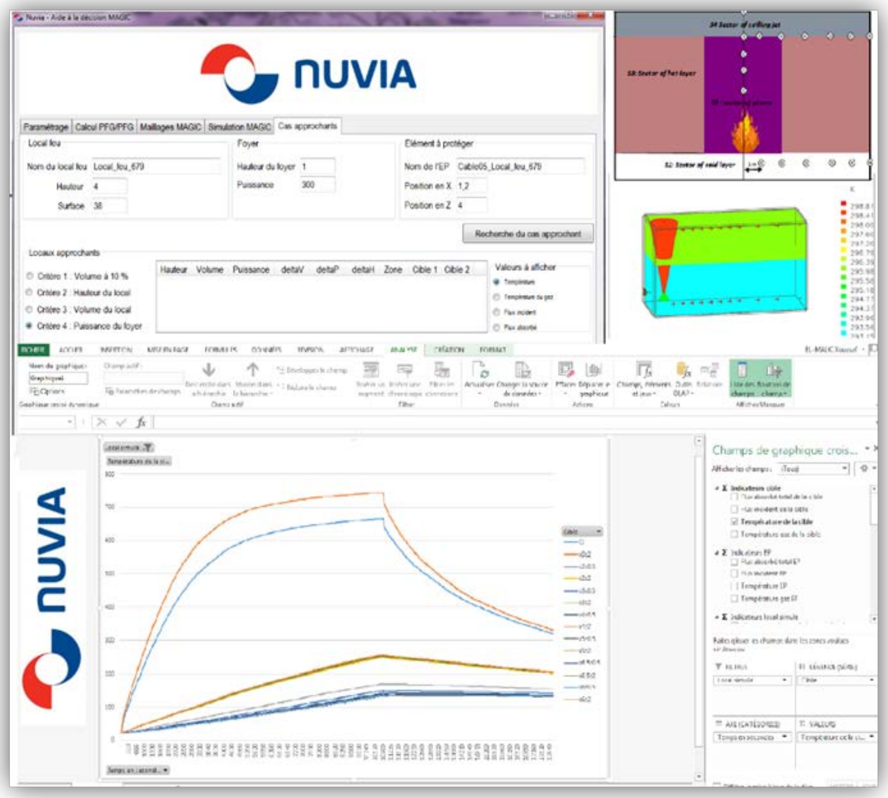

Figure 1 View of the modules used for the tool

Development

Hypotheses and Tool Validation Limits

The goal is to take the results from the calculations that are performed on the MAGIC software, to integrate them into the tool OPEPPI, several, simulations were made (more than 1,500 simulations), and the results were included in a database for later use.

General Assumptions

In all calculations from MAGIC, we use only one room with a fire, an air opening, and targets for the determination of different results at different times and in several positions.

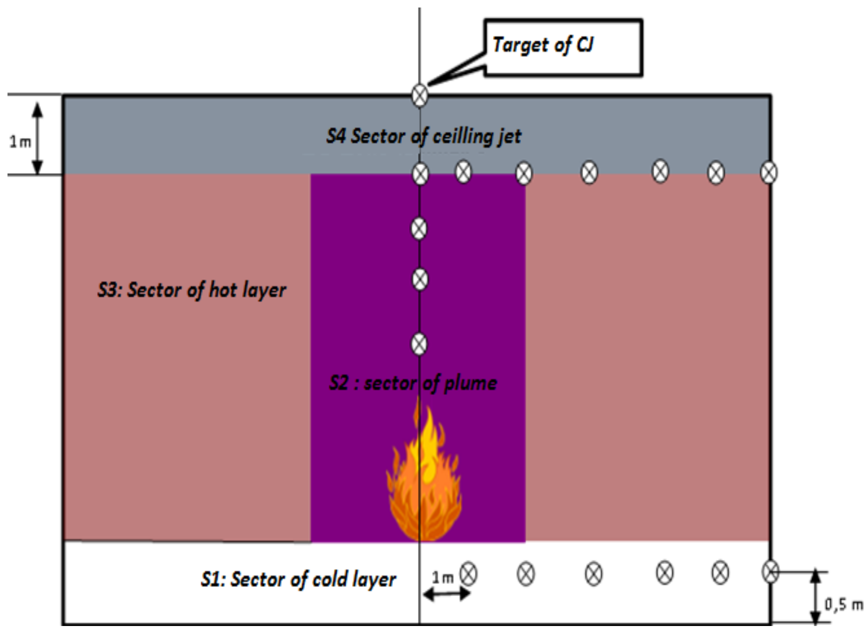

Figure 2 Critical parts in a fire room

For a system covering all the possibilities for a limited power of fire, the input data was changed and combined in each case to have a large number of fire scenarios.

The key inputs data are: Room volume, room height, section and the open position, position the fire and type of fire.

To reduce the large number of simulations, we have optimized the input data thus:

A. Room Volume and Fire Power

Fire modelling has been defined under the curve (PLF-Part of Localized Fire / PFO-Part of Flash-Over), In the case of flashover, An IN-CLOSED protection is mandatory.

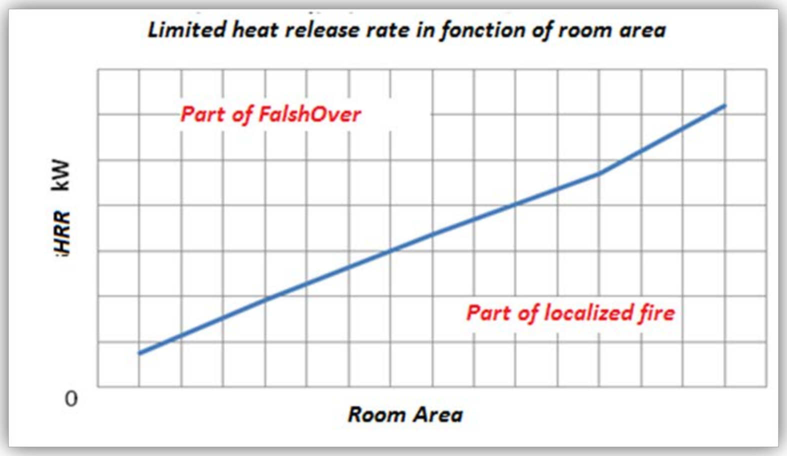

Figure 3 HRR curve [kW] between the two parts of fire according to room area.

The mesh of the volume determined from this curve guided us to optimize other data input thus.

B. Room Height and Air Opening

We made several calculations to determine the critical height, combining several parameters; we reduced a critical height of 6 m.

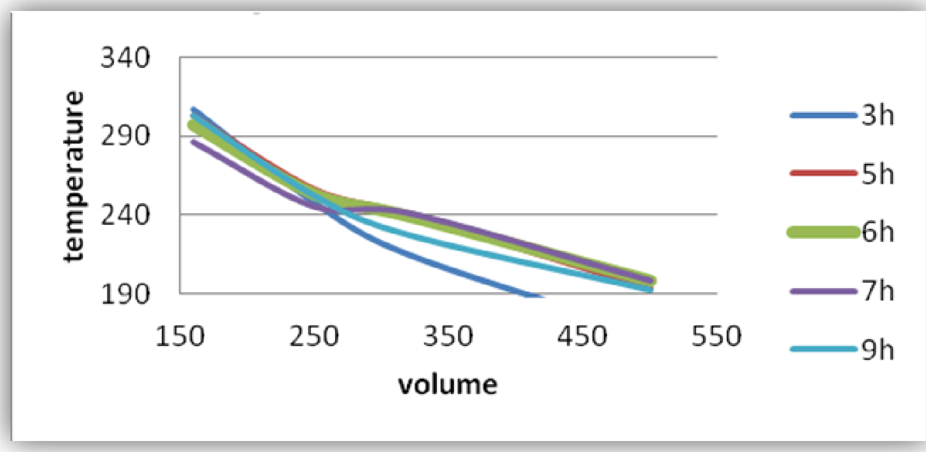

Figure 4 Temperature [°C] for different volumes and room heights versus time t [s]

The openings depend on the HRR of the fire and the calorific power:

- ✓ O (Opening) = A * HRR + B (1)
- ✓ B = a * CP² + b * CP + c (2)

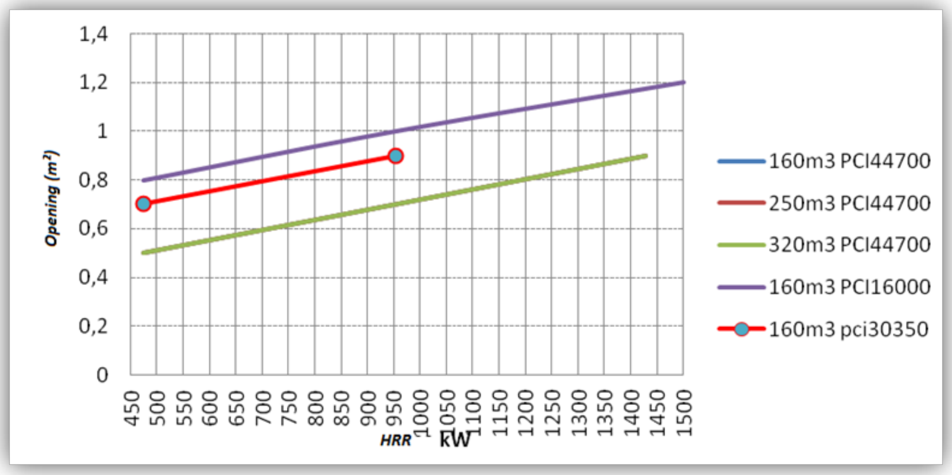

Figure 5 Opening size [m²] for different HRR and calorific power according to the time t [s]

C. Position and Fire Type

We considered a fire located above the ground to avoid the smothering of the fire source (the fire stop) due to lack of oxygen.

For the type of fire, we considered several materials to review the most critical cases.

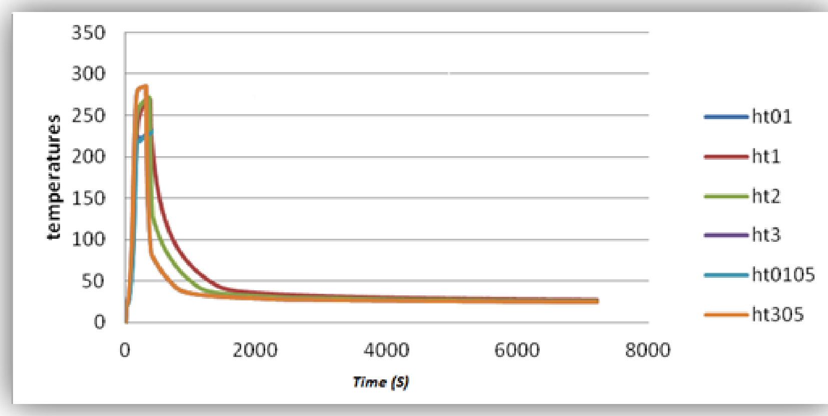

Figure 6 Temperature T [°C] for different position of fire according to the time t [s]

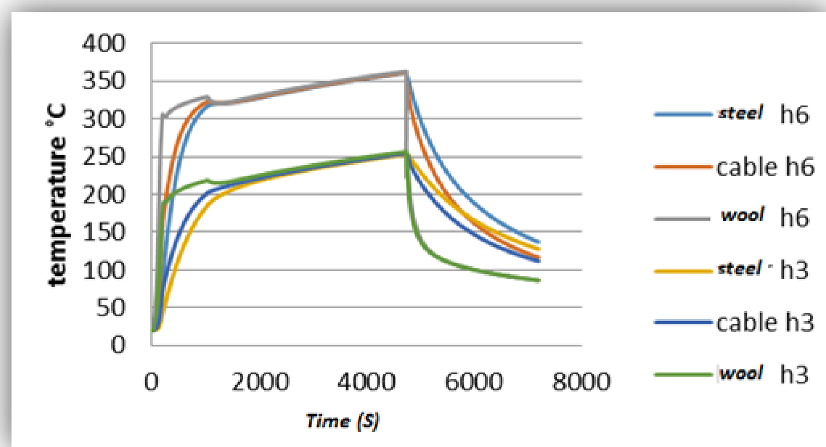

Figure 7 Temperature T [°C] for different types of target materials according to the time t [s]

Heat release rate calculations are integrated in the tool, for example:

$$Dp\text{max}=Dpsurf*(\pi*D24)*(1-(-k\beta*D))$$

Results and Their Integration in OPEPPI

All the results obtained are integrated on the tool:

- Temperature (gas, targets, etc.),
- Flux (total, absorbed),
- Temperature (In different parts of room).

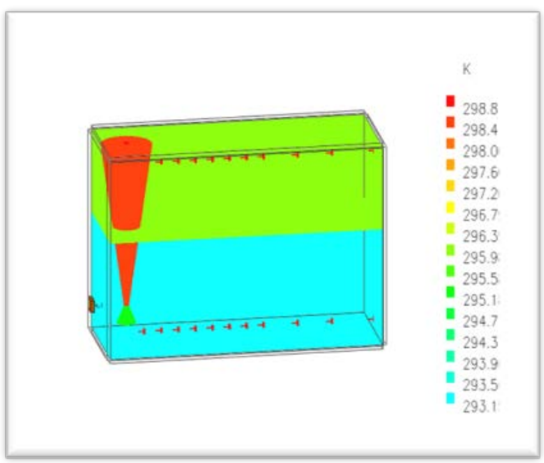

Figure 8 View results on MAGIC according to the time t [s]

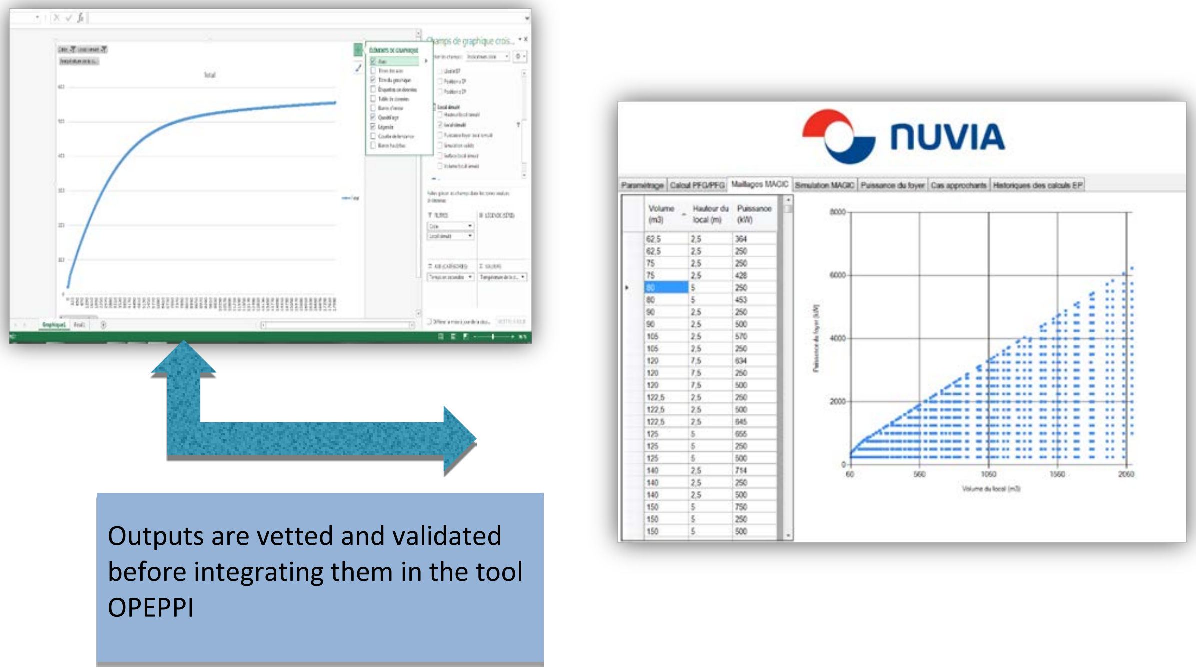

Figure 9 Conversion results and their integration in the OPPEPI tool

OPEPPI TOOL

OPEPPI is an easy tool to use, instant and practical on site. Two versions are available, one version for the users and a version for administrator.

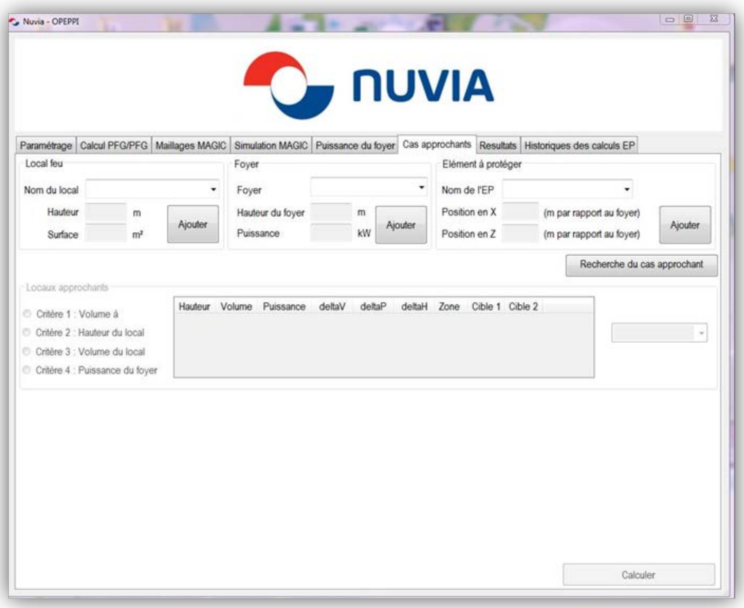

Figure 10 OPPEPI tool user interface

Use of OPEPPI: There is neither a need for modelling nor for entering all data and physical parameters. OPEPPI is easy to use through its three modules characterized in the following.

1_Pre-processor:

The following data must be entered: Room size, location of the equipment to be protected and the heat release rate of the fire (which can also be calculated with this tool if you do not know the exact value of the HRR is).

Figure 11 Interface for the input data indicated by the user

If you do not know the power (HRR), OPEPPI proposes power values from the items that are in the room, e.g., (cables, wood, electrical cabinets, oil, etc.). For example, if we have cables that will burn, we must enter the number cables trays, mass of cables (measured or estimated), number of cables and the distance between cables trays and the ceiling.

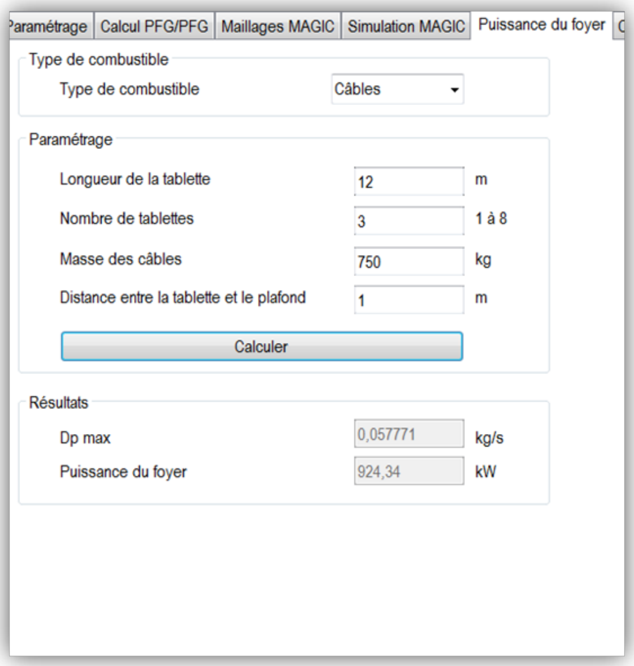

Figure 12 Interface for the HHR data

2_Calculation/Algorithm:

As soon as the input data of the room is entered for exploring, the tool uses an algorithm which searches at least two matching cases within thousands of pre-calculated cases with the MAGIC software. This allows for protecting the location of the equipment which needs to be protected, through matching cases, to be calculated and linearization from the results previously calculated.

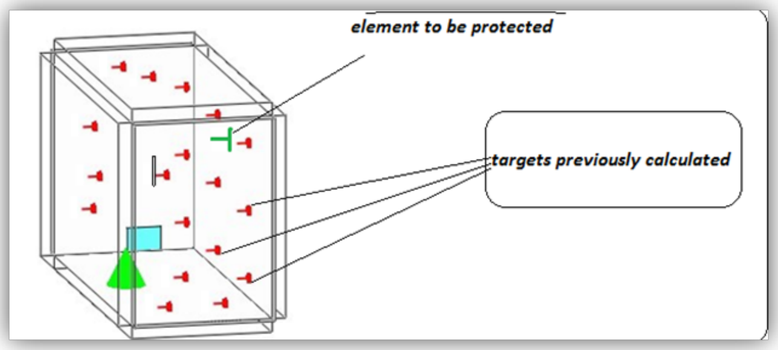

Figure 13 Example of an equipment to be protected

When dealing with an equipment to be protected which is not the same terms as that of the calculated target, the tool allows interpolation formulas to be stored (in the tool), an example of some interpolation formulas is given in the following:

$$T°Gaz = -x * ((TVCIB(t) - Tzc(t))/2) + TV\_CIB(t) \quad (3)$$

$$T°Gaz = (0.0014 * P + 0.2444) * x2 - (0.0231 * P + 5.2162) * x + TV\_(t) \quad (4)$$

3_Post-processor:

As soon as the calculations are completed, OPEPPI, displays all the graphical results such as time dependent temperatures, flows, etc. A detailed report of the assessment study is generated, demonstrating the fire resistance rating of the equipment per its location in the room or the HRR of the fire.

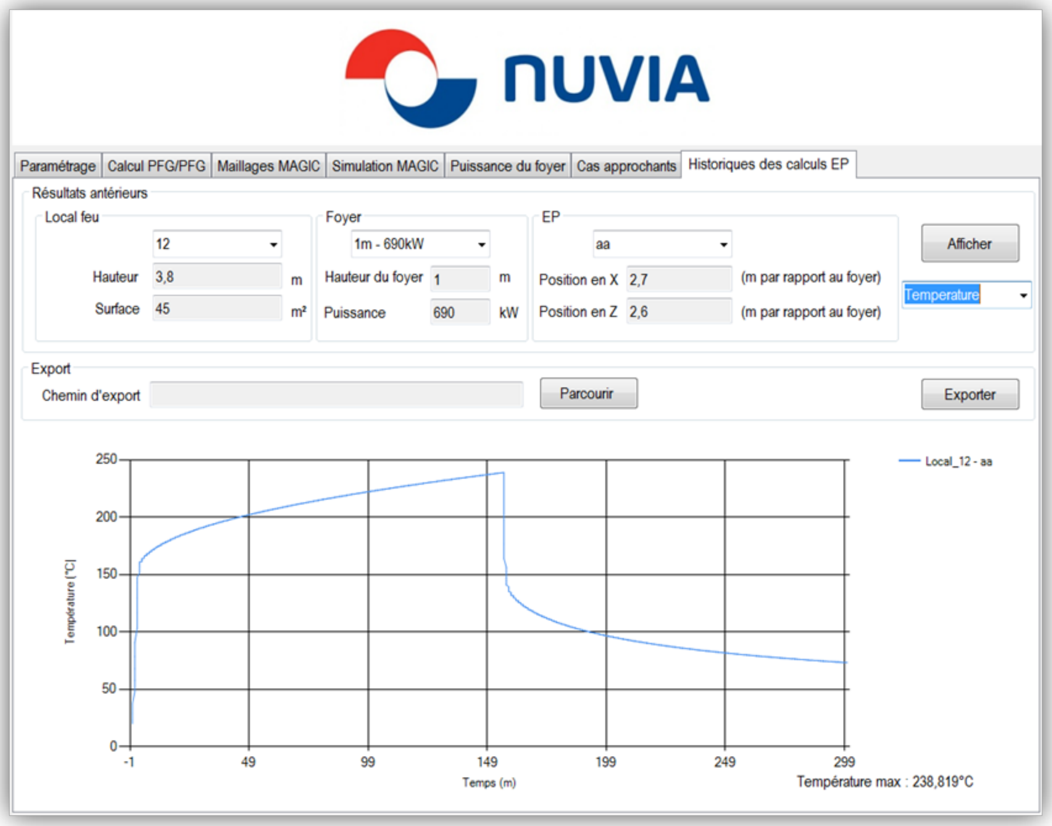

Figure 14 Example of the temperature in a case study

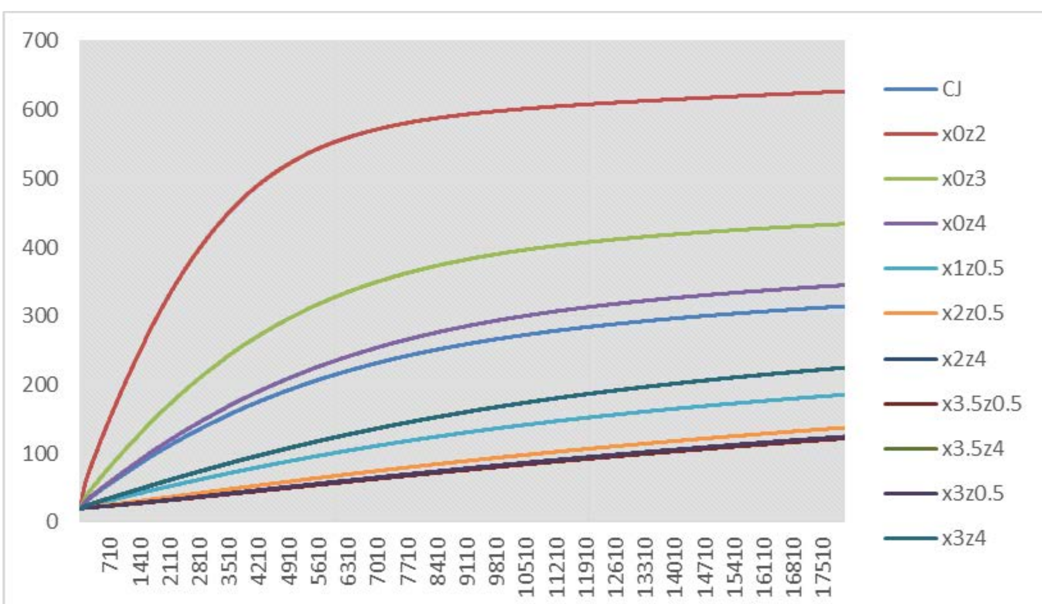

Figure 15 Example of the temperature T [°C] of targets versus time t [s]

We can calculate temperatures for several items (equipment) located in the same room; this allows us to calculate the risk of equipment malfunction.

When the temperature of an equipment is beyond its malfunction temperature, the tool warns the need to protect this equipment.

Table 1 Example of malfunctioning temperature of some type of material

Type of material	Malfunctioning temperature
fittings	160 °C
valves	160 °C
tubing	100 °C
…	…

Table 2 Example of max permissible flow of some type of material

Equipment to be protected	Max permissible flow [Kw/m²]
Electronic	0.8
Electromechanical	1.5
Mechanical	1.8

Generally, for using this tool, you must know the input data (room size, position of the equipment to be assessed, the Heat Rate Release of fire HRR (if possible)). OPEPPI is a tool that provides major results compared to the MAGIC software, and in case of uncertainty for the results at the critical operating temperature, a more precise calculation by MAGIC software will be requested.

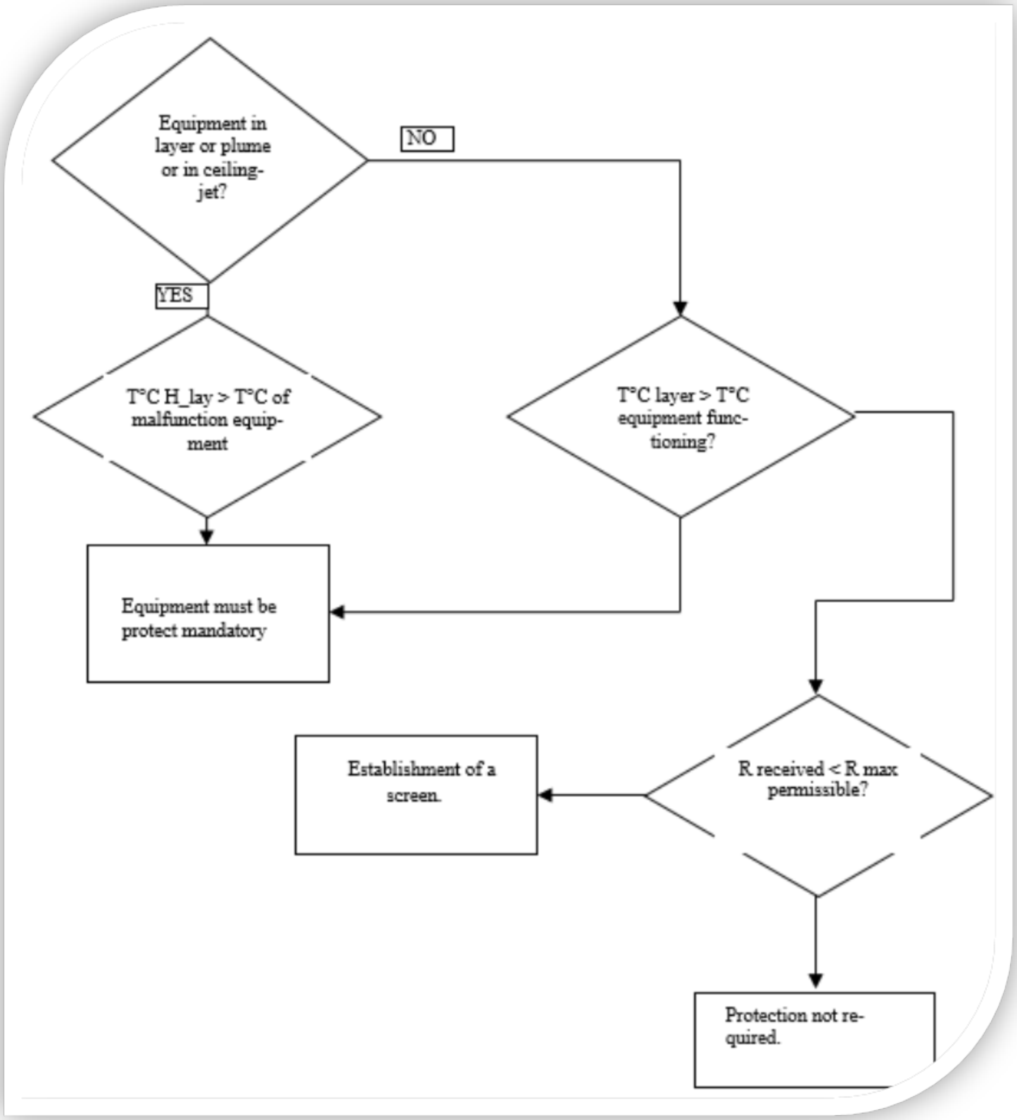

Figure 16 Thermal reasoning process

CONCLUSIONS

Quick and easy, the OPEPPI tool can be downloaded on a tablet computer and used on site to justify the resistance rating of barrier elements needed to protect the equipment and to ensure that the equipment remains functional in case of fire hazards.

REFERENCES

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FOCUS ON THE STUDES IN SUPPORT OF FIRE SAFETY ANALYSIS: IRSN FIRE MODELLING APPROACH FOR NUCLEAR POWER PLANTS

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ABSTRACT

For a fire safety analysis, in order to comply with nuclear safety goals, a nuclear power plant licensee has to define the safety functions and its linked equipment to be maintained, even in case of fire (safety targets). One of the key issues of this fire analysis is the assessment of fire scenarios in the plant. This paper presents the IRSN method applied to a case study to assess fire scenarios which lead to the most harmful effects on safety targets. The layout consists in a fire compartment divided into 2 rooms containing electrical equipment of two distinct safety trains. A fire scenario was studied with fire ignition occurring in an electrical cabinet. The fire compartment integrity as well as common failure modes were assessed to fulfil safety goals. This case study was conducted with the SYLVIA [1] IRSN code based on two-zone modelling. Safety goals were associated with key parameters and performance criteria. Modelling assumptions were also defined in order to maximize physical effects of the fire regarding the safety issues. In order to consolidate the use of these results for drawing safety conclusions, sensitivity studies were conducted on key parameters. A critical analysis of the models used is also carried out to assess their relevancy in the studied case.

INTRODUCTION

Over several years now, the French nuclear fire safety regulation (cf. [2] and [3]) has turned from prescriptive to performance based requirements. Consequently, the Fire Safety Analysis (FSA) focuses now on the compliance of fire effects with performance criteria for fire protection measures. These performance criteria are mainly related to the vulnerability of targets (for instance, containment equipment) within nuclear power plants (NPP) or research reactors (RR) in order to avoid accidental sequences potentially compromising facility safety functions and leading to a core melt accident. To assess this demonstration in its FSA, the licensee has to ensure that nuclear safety objectives are met in case of accidental fires. A key step in this analysis process is the identification of the targets associated to the elements important for safety to be maintained. These targets may include structural elements, all types of nuclear systems and various components important to nuclear safety. Furthermore, the protection of employees, who have to ensure safety operations for nuclear facilities, must also be considered.

The analysis of specific issues (for example common mode failure) in the frame of safety evaluation conducted both by IRSN and licensee can consist in the evaluation of the effects of a fire on targets, performed with numerical simulations.

To illustrate this method, an analytical case-study of a sample fire compartment of a NPP is presented below. For this case-study, the fire safety analysis highlights a scenario in which fire starts in an open-door electrical cabinet in one of the rooms inside a fire compartment. In order to assess the fire consequences for this scenario, a series of fire simulations was carried out with the SYLVIA fire code developed by IRSN. This fire code is based on a two-zone modelling to calculate smoke and heat transfers from fire source to other compartments or ventilation network and the impact on targets. To properly perform these fire simulations and predict the relevant target damages, IRSN needs to establish fire properties and failure criteria of safety equipment by means of both experimental tests and literature data:

- fire source characteristics (heat release rate, fire growth, mass loss rate, combustion products, etc.) based on open fire tests representative of fire scenarios in power plants;
- rupture criteria of fire compartment equipment and malfunction criteria of electrical components due to fire effects (pressure, smoke, heat, etc.);
- fire spreading criteria for potential fire sources.

This work presents a time effective application of this method in order to verify potential fire issue. An important point to note is that inherent limitations to the zone modelling assumptions apply to this work. The results hence focus on the operational results of potential failure of equipment and the consequences relative to common mode failure. As the purpose of this paper is the illustration of the method on a sample case study, the design improvements proposed after the result description are not to be taken as general guidelines from IRSN.

After this introduction, a complete description of the case study is given in detail. Then, some experimental tests performed at IRSN are presented concerning the determination of characteristics of electrical cabinet fire, cable trays vulnerability, fire and rupture criteria of fire compartment equipment. From these experimental outcomes and a dataset (geometry, ventilation network, etc.) describing the case study, the criteria related to the safety issues, the fire modelling and the key assumptions needed for the computations by means of SYLVIA fire code are detailed. A discussion is proposed about the computations results before concluding this paper, including a summary sensitivity study of some key parameters.

CASE-STUDY DESCRIPTION

The case-study represents a fictive fire compartment in a NPP electrical building or a RR. In the frame of his FSA, the licensee concludes that, in case of fire, the integrity of the fire compartment has to be restored. A full description is presented in Figure 1. This fire compartment contains electrical equipment relative to two safety trains. It is divided in two rooms (1 and 2) separated by a double-door and connected to a corridor room representing the link with the rest of the building. The fire resistance according to the ISO-834 [4] standard nominal fire curve is 90 min. Whereas the door between room 2 and the corridor is required to be kept closed for safety, there is no such safety requirement for the double-door between rooms 1 and 2.

The compartment encompasses two safety trains:

- Safety train A regroups cabinet rows no. 1 to 4 in room 1 and both cable trays.
- Safety train B regroups cabinet rows no. 5 to 8 in room 2.

The cable trays have a cross section of 0.45 m x 0.15 m and are loaded with 11 kg of cables per metre. The cables are assumed to be mainly composed of polyvinyl chloride (PVC) for a fire load of 66 MJ per metre of cable tray. The electrical cabinets have a footprint of 0.6 m x 1.2 m and are 2.2 m high. The proposed load is 170 kg of electrical components, for a fire load of 1200 MJ per cabinet.

Each room is equipped with a mechanical ventilation system. The ventilation rate of rooms and corridor is 5 h^{-1}. Inlet and exhaust ducts are located near the ceiling. All the ducts are equipped with a fire damper, which automatically close at a temperature threshold of 70 °C (passive local fuse).

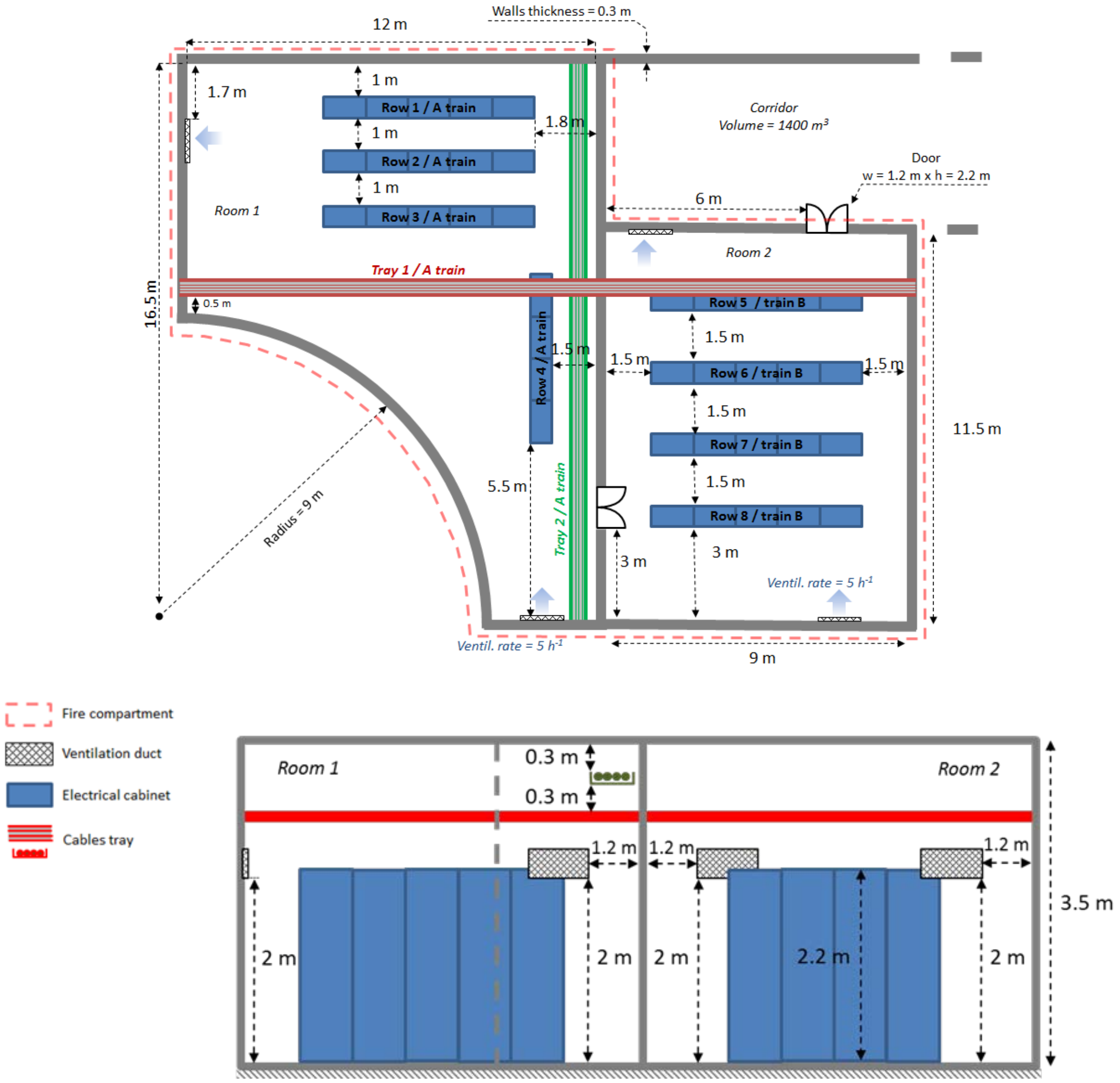

Figure 1 Top and front view of the fire **compartment**

PRIOR EXPERIMENTAL STUDIES FOR ASSESSING FIRE CHARACTERISTICS AND FAILURE CRITERIA

In order to properly simulate a fire scenario with a fire code, the first stage consists in the determination of the fuel source fire properties and the relevant failure or ignition criteria.

Failure Criteria

Because of a lack of data on the behaviour of fire compartment equipment under pressure stresses representative of a fire scenario in a facility, IRSN built an experimental aeraulic facility, called STARMANIA. The main objective of this facility is to determine the mechanical strength which is the differential pressure value corresponding to the equipment failure but also to determine the aeraulic resistance. Experimental studies on fire dampers and on fire doors were conducted. The results obtained during these tests have permitted to determine the aeraulic behaviour and the rupture pressure of such equipment. More technical details and main outcomes about these tests are available in [5].

Regarding the malfunction criteria of electrical equipment (relays, electronic boards, switchgears, etc.), previous tests conducted in the IRSN DIVA facility showed that both gas temperature higher than 65 °C and soot concentration higher than 1.5 g m^{-3} led to the malfunction of a relay board. These values come from CATHODE experimental program where electronic devices were tested in real fire conditions during a series of large-scale fire experiments (electrical cabinet fires) performed in mechanically ventilated rooms. Electrical malfunctions were observed well below the purely thermal malfunction criterion previously measured in a furnace (i.e. 165 °C). These results led IRSN to set up a dedicated experimental facility (DANAIDES) to assess the behaviour of electronic device under both thermal and concentration of soot stress. More technical information and main outcomes of these tests are available in [6].

The malfunction criterion for electrical cables is based on analytical tests conducted by IRSN [7]. These tests involved several cable types placed in an analytical furnace. The cables were electrically monitored during the application of the thermal stress to determine the malfunction temperature threshold. The results showed that the first failure mode was a short circuit and occurred when the gas temperature around the cable reached about 220 °C.

Fire Characteristics

Concerning the characteristics of an electrical cabinet fire, open atmosphere fire tests concerning real electrical cabinets were performed under a large-scale calorimeter [8]. Heat release rate, incident radiant heat fluxes in front of the cabinet and combustion products were measured. Two configurations were mainly investigated in open atmosphere:

- Open door cabinets allowing the fire to freely growth along wires and components inside cabinet;
- Closed door cabinets with two square openings on each door (one on the upper part and the other one on the bottom part of the door) limiting the oxygen availability.

For real electrical open door cabinets, a significant quantity of smoke appeared just after ignition and the flame spread slowly from the bottom to the top, all along the electrical components. A few minutes later, the fire was fully developed leading to a powerful fire. In this configuration, all the combustibles burnt. Just after ignition, for real closed-door cabinets, smoke was observed exiting from the upper ventilation openings. Moreover, flames could also appear through these openings [9]. Sometimes, puffs of smoke could exit through the lower ventilation openings [8]. Depending on material nature, combustible load and opening sizes, the fire could quickly extinguish by lack of oxygen [8], [10] leading to a less material pyrolysis in comparison with real open-door cabinet. More technical details and main outcomes about these fire tests are available in [8], [9] and [10].

Concerning the characteristics of a cable tray fire, IRSN also conducted fire tests involving horizontal cable trays burning either under a calorimetric hood in open atmosphere (CFSS tests campaign) or inside a mechanically ventilated facility (CFS test campaign) to investigate this topic. These tests were conducted within the framework of the PRISME 2 international program, under the auspices of OECD Nuclear Energy Agency (NEA). The purpose of these tests was to characterize such fires in open atmosphere as well as investigate the effects of confined and under-ventilated conditions on the fire behaviour and on its consequences. The tests were conducted with several configurations of cable trays, involving various cable types in different ventilation conditions. More technical details and outcomes of these fire tests are available in [11], [12] and [13].

SCENARIO

Assuming maintenance work, the middle cabinet of row 5 has its door left opened. The other electrical cabinets of the fire compartment are assumed to be in normal state (doors closed).

The fire ignites in the open-door cabinet, and fire compartment dampers closure is triggered by a thermal fuse on the device. The ventilation of the corridor is maintained. The fire spreading from a cabinet to the adjacent one is modelled with the approach recommended by NUREG/CR-6850 [8], i.e. assuming a fire propagation delayed by 15 min. As there is no safety requirement, the door between rooms 1 and 2 is left open.

SAFETY ISSUES EXAMINED

The computations related to this scenario shall address the following issues:

Issue a. Does fire cause fire damper closure?

Fire damper closure is assumed if ambient temperature near the duct reaches 70 °C. This is labelled **[Vx]** in the result tables (x referring to the room the damper is connected with).

Issue b. Does fire cause the malfunction of the electrical cabinets?

Electrical cabinet malfunction is defined with a combined criterion based on both gas temperature higher than 65 °C and soot concentration higher than 1.5 g m^{-3} around the electrical component. This is labelled **[T+S-Rx]** in the result tables (x referring to the room where the cabinet is located).

Issue c. Does the fire spread to other cabinet rows?

Fire spread to other cabinet rows is based on the main plastic material contained in the experimental cabinet. An ignition flux of 15 kW m^{-2} (corresponding to a PE equipment), a material ignition temperature of 380 °C or an ambient gas temperature of 500 °C (corresponding to flashover conditions) are assumed. Note that, due to lack of experimental data, the casing of the cabinet is not taken into account, which is a conservative assumption. This criteria are respectively labelled **[R-y]** and **[F]** in the result tables (y referring to the row number of the target cabinet row).

Issue d. Does the fire cause a malfunction of the electrical cables?

A cable malfunction criterion is assumed, based on gas temperature of 300 °C or internal temperature of the cable insulation material of 220 °C. This is labelled **[CM-y]** in the results tables (y referring to the tray number).

Issue e. Does the fire spread to the cables trays?

An ignition flux of 13 kW/m² (PVC cable), a material ignition temperature of 318 °C (PVC flexible) for insulation material [7]or an ambient gas temperature of 500 °C (corresponding to flashover conditions) are assumed. This criterion is labelled **[CI-y]** in the results tables (y referring to the tray number).

Issue f. Does fire duration cause a failure of fire compartment?

The thermal failure of the fire compartment is examined via two criteria: either the fire lasts longer than 90 min, or the gas temperature inside the fire compartment exceeds the standard nominal fire curve at any instant. This set of criteria is labelled **[FC]** in the results tables. Another failure mode is also taken into account: the overpressure due to the fire is also monitored to see if it can lead to fire door opening. This is considered to happen if the double-door pressure gap exceeds 18 hPa. This criterion is labelled **[D]** in the results tables.

Concerning these criteria, a major assumption is made: an event (e.g., malfunction, ignition, rupture, …) immediately occurs when one of its relative criteria is reached. In the frame of a safety analysis, this assumption ensures conservative results.

FIRE SIMULATIONS

Numerical Tool

The SYLVIA software system [1], developed by IRSN, is designed to simulate the fire growth and its consequences in an industrial facility featuring a ventilation network. Especially, SYLVIA calculates the development of the fire, the transportation of hot gases and soot, the transportation of aerosols (whether radioactive or not), the clogging of filters, the environmental conditions inducing the failure of electrical equipment and the mechanical damage on fire barriers such as firebreak doors and fire dampers. Based on a two-zone modelling, each compartment is divided into two zones of variable volume, in which the thermodynamic properties are uniform (temperature, combustion products, etc.). The ventilation network is modelled using a set of elements, such as ducts, filters, valves, fans, etc. Mass and heat exchange correlations (between zones, flames and walls) supplies the mass and energy balance equations performed in each zone. This software is especially designed to perform low time-consuming simulations that are required for safety assessments. SYLVIA is extensively validated on full-scale experiments of fire in confined and mechanically ventilated configurations, most of them being conducted in a fire tests platform of IRSN.

Fire Modelling (Cabinets and Cable Trays)

The cabinet fire source is considered to be a row of 5 electrical cabinets. The first cabinet of the row, where fire breaks out, is assumed open-door and is located at the centre of the row. The other cabinets have their doors closed. Since the SYLVIA software adjusts the mass loss rate of the fire in relation to the oxygen concentration, the time evolutions of Heat Release Rates (HRR) for open and closed-door cabinets are taken from the IRSN fire tests in free atmosphere which could lead to the most harmful effects on safety issues (CA02 test in [10] for a closed door cabinet and PXA.3.1 in [8] for an open door cabinet). Moreover, the fire spreading between cabinets is assumed all along the cabinet row. Consequently, the total heat release rate sums up the different HRR for each single cabinet already in fire. The fire spread from a cabinet to the adjacent one is modelled with the approach recommended by NUREG/CR-6850 [8] (see above). As the spreading of the fire from one cabinet to an adjacent one is a very complex problem and hard to connect with real fire scenarios, it is assumed that the fire spreads in any case (conservative approach). Based on these assumptions, the composite HRR of the cabinet row displayed in Figure 2 can be decomposed in three phases:

- During the first 900 s, the HRR curve follows exactly the HRR from the experimental open door cabinet fire showing a HRR peak at about 1.6 MW at 710 s.
- After 900 s, the fire propagates to the adjacent cabinet. In the same time, the HRR begins to decrease slowly to about 750 kW due to both HRR decrease of open-door cabinet and HRR increase from two adjacent closed-door cabinets.
- 900 s yet later, the cabinets located at the end of the row ignite and the HRR remains roughly constant.

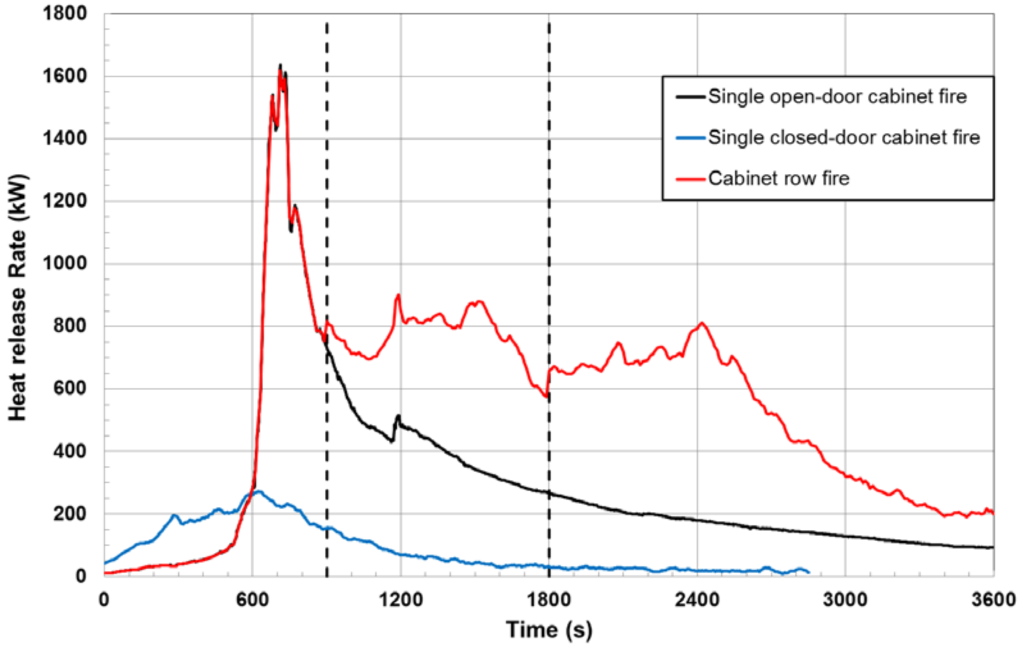

Figure 2 Modelling of HRR for a 5 electrical cabinet row fire

Based on the experimental campaigns conducted by IRSN in the framework of the OECD PRISME 2 Project, a semi-empirical model of horizontal cable trays fires in a well-confined enclosure has been developed. This model is partly based on the approach used in the FLASH-CAT model [14] and on experimental findings from the IRSN cables fire tests. It allows a dynamic determination of the burning surface of a cable trays fire to compute the corresponding HRR and includes oxygen depletion law based on the Peatross & Beyler model [16]. An article, describing this model and providing more technical detail, is currently being reviewed for publication [18]. For one cable tray, this model gives heat release rate up to roughly 200 kW with a fast fire grow.

For the cabinets, the fire is modelled as a pool fire in the SYLVIA code, the effect of oxygen depletion in the room is modelled, affecting the pyrolysis rate and the fire duration. This is done by using either an empirical oxygen depletion model built for pool fire or a classic fire extinguishing law. A sensitivity study is performed under the following two boundary conditions:

- A lower oxidant limit (LOL) model, which assumes a sudden fire extinguishment below a defined oxygen threshold; an oxygen threshold of 10 % in volume is considered in the computations;
- a Peatross & Beyler model ([16], P&B) which assumes a linear decay of pyrolysis rate with oxygen concentration; an oxygen threshold of 11.5 % in volume is considered in the computations. This threshold is deduced from IRSN full-scale experiments of an open door cabinet fire inside a mechanically-ventilated compartment [17].

Concerning the simplified combustion reaction defined for fire simulation, the major products of combustion are introduced following the chemical reaction hereafter:

$$\text{Fuel} + Y_{O2}\, O_2 \rightarrow Y_{CO2}\, CO_2 + Y_{CO}\, CO + Y_{H2O}\, H_2O + Y_{soot}\, C \qquad (1)$$

In this equation (1), Y_{O2}, Y_{CO2}, Y_{CO}, Y_{H2O} and Y_{soot} are the mass rate of oxygen consumption, the mass rate of production of carbon dioxide, carbon monoxide, water vapour and soot respectively. For each fire source, combustion products and oxygen consumption yields are determined from both experimental data (cabinet: [8], [9] and [10] | cables: [20]) and mass balance.

Modelling Rooms and Ventilation Network

A simplified approach considers that the inlet and exhaust of the ventilation network of each room are modelled as a fixed pressure boundary condition. Leakage resistances of closed-doors and closed dampers are taken from IRSN aeraulic experiments [5]. This simple model accurately assesses the fire development and propagation of hot smoke in the rooms and takes into account the success or failure of safety actions such as ventilation elements behaviour.

Sensitivity and Parametric Studies

Due to the purpose of the computations, the potential impact of some key parameters on the results has to be assessed. Regarding the fire itself, the oxygen depletion or extinction law has to be investigated. Since there is no safety requirement regarding the closure of the door between rooms 1 and 2 (as per scenario definition), a parametric study is also conducted on the state ("open" or "closed") of this door.

RESULTS

From the comprehensive modelling of fire scenarios detailed in the previous paragraphs, a set of fire simulations were performed with the SYLVIA code and the safety conclusions deduced from the numerical outcomes are summarized in Table 1.

As a reminding note, the purpose of this work is the illustration of the method on a sample case study. Therefore the design improvements proposed are not to be taken as general guidelines. In the frame of this exercise, the fire in an electrical cabinet row leads to several safety issues.

Concerning *issue a.*, the results show the closure of the fire dampers of both rooms 1 and 2 when the door between the rooms is left open. However, when the door is closed the hot gas are less prone to propagate to room 1 and the general temperature stays low enough to prevent the fuse-closure of the dampers.

Concerning *issue b.*, the same effect leads to a general malfunction of the electrical device in both rooms when the door is opened, while the room 1 is preserved when it is closed. These results show the side effect of a particular operating rule, as one configuration can for example both prevent a safety issue and allow another to occur. The thermal degradation of this non fire-proof door has not been considered in these computations.

Concerning *issue c.*, the code does not predict fire spreading to other cabinet rows. As the model does not take into account the case of the cabinets, and because the distance between two rows is short, this results seems surprising. Indeed, fire radiation in SYLVIA code is modelled with a point source model. This limits the accuracy of the radiation model in the vicinity of fire sources and a solid flame model would be more appropriate to evaluate radiative heat fluxes for short distances. To fix this limitation, HRR and flame height during the first 900 s computed by SYLVIA were used as input data of a solid flame model to assess a relevant radiative heat flux. This last method predicts that fire could spread to the closest cabinet rows in case of an open door cabinet fire. These results are consistent with measured heat fluxes of open-door cabinet fires [8]. In case of either facing open cabinets or cabinets equipped with combustible doors this results can lead to a propagation of the fire and an aggravated fire scenario. As a first approach, the computations were re-run to take into account the ignition of the adjacent cabinet row. Because the other safety issues had already occurred before this spread, these computations didn't raise any additional safety issue. Therefore, in the interests of simplification, the fire propagation between rows of cabinets is not presented in this work.

Table 1 SYLVIA computation results

	Cabinet fire oxygen law	Opened door between rooms 1 and 2	Closed door between rooms 1 and 2
Issue a.	LOL – 10 %	yes - [V1] yes - [V2]	no - [V1] yes - [V2]
	P&B – 11.5 %	yes - [V1] yes - [V2]	no - [V1] yes - [V2]
Issue b.	LOL – 10 %	yes - [T+S-R1] yes - [T+S-R2]	no - [T+S-R1] yes – [T+S-R2]
	P&B – 11.5 %	yes - [T+S-R1] yes - [T+S-R2]	no - [T+S-R1] yes - [T+S-R2]
Issue c.	LOL – 10 %	no	no
	P&B – 11.5 %	no	no
Issue d.	LOL – 10 %	yes - [CM-1] – room 2	yes - [CM-1] – room 2
	P&B – 11.5 %	no	no
Issue e.	LOL – 10 %	no	no
	P&B – 11.5 %	no	no

Concerning *issue d.* and issue e., the results differ depending on the choice of the oxygen extinguishing law. When the LOL model is used, the temperature rise is enough to make the cables malfunction, but not enough to ignite the tray, whereas a P&B model limits the HRR of the cabinet fire and does not lead to cable malfunction. Further investigation of these differences led to highlight that the validity of the P&B model, which is based on liquid pool fires, could be unsatisfactory for a cabinet fire source [17]. Investigations are ongoing at IRSN to find a more appropriate model for complex solid fire sources. In coherence with the general conservative approach required in safety assessment analysis, safety conclusions are only deduced from LOL computations. The non-ignition of cable tray 1 is expected despite its location in the fire plume. In SYLVIA software, as often in two-zones modelling [19], the plume model is used to assess the energy transfer from the fire to the gas layers and no energy exchange between the plume and a target can be directly taken into account. A closer analysis of the SYLVIA flame height output shows that the flame reaches the tray and probably leads to its ignition. This is also consistent with the temperature results of the PRISME 2 CFS tests [13], conducted in the IRSN DIVA experimental facility, showing that the temperature at the same position (and considering a cabinet of the same dimensions as primary fire) is sufficient to reach the ignition criterion of the cables. The computations are rerun taking into account the fire of the part of tray 1 located inside room 2. The results regarding *issues a.* to *d.* remain unchanged, since their criteria are reached, when applicable, before the ignition of the cable tray 1. The relevant results are summarized in Table 2.

Table 2 SYLVIA computation results taking into account the ignition of cables in room

	Cabinet fire oxygen law	Opened door between rooms 1 and 2	Closed door between rooms 1 and 2
Issue d.	LOL – 10 %	yes - [CM-1] (room 2)	yes - [CM-1] (room 2)
Issue e.	LOL – 10 %	yes - [CI-1] (room 2)	yes - [CI-1] (room 2)
Issue f.	LOL – 10 %	no	no

Concerning *issue f.*, the growth of the fire and its heat release rate doesn't lead to thermal effects exceeding the ISO-834 design curve. The pressure increase due to the fire also doesn't exceed the pressure threshold of 18 hPa. Thus, the fire compartment integrity is not compromised by either thermal aggression or pressure rise. Regarding fire duration, the ignition of the cable tray does lead to a fire still burning after 90 min. However, hot zone temperatures do decrease below 100 °C before the duration certification. A specific examination of this issue with civil engineers can lead to the conclusion that the fire compartment is not jeopardized by such low temperature levels.

Based on these results, and in the frame of a safety analysis, a number of design improvement leads can be determined. Regarding issues a. and b., the closing of the door between rooms 1 and 2 prevents the malfunction of electrical device in room 1 and partially avoid common mode failure. As the thermal degradation of this door isn't taken into account, drawing conclusions on the computations results imply its replacement with a fire proof door and the definition of room 2 as a safety fire compartment. Therefore, the mitigation of the consequences of issues d. and e. are also mandatory. This can be done by setting up a fire proof protection of the cable tray 1 in room 2. These modifications should avoid a common mode failure for this fire scenario.

CONCLUSION

The conjoint use of literature data, dedicated experimental tests and the SYLVIA software tool concerning both the characterisation of the fire or its environment (containment equipment or material fire resistance) allows IRSN to propose a simple and time efficient method for performing computations in order to assess fire scenarios and their consequences in the framework of fire safety analysis.

A simple and conservative approach for modelling the fire spread between cabinets or to a cable tray based on both fire tests and external literature has been proposed, along with the determination of several safety issues criteria regarding both failure modes of device or containment equipment. These criteria involve both IRSN experimental tests and literature data. The numerical outcomes of this case study were obtained with the SYLVIA zone code. This kind of modelling allows fast computations and the examination of several issues, but also puts an emphasis of the necessity a careful examination of the accuracy of numerical tools before drawing any safety conclusion. It also illustrates the relevancy to have experimental tests that can help in this critical post computations analysis. In this work, the impact on close targets at locations handled by specific sub models (radiative transfer, fire plume, etc.) had to be carefully assessed in order to formally conclude that a safety issue is raised or not.

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DEVELOPMENT OF AN INTEGRATED TOOL (FOCUS) FOR FIRE INFLUENCE APPRROACH ANALYSIS IN THE FRAMEWORK OF THE FIRE HAZARD ANALYSIS FOR THE BELGIAN NUCLEAR POWER PLANTS

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ABSTRACT

Following the introduction of the WENRA Reference Levels in the Belgian regulation at the end of 2011, a comprehensive Fire Hazard Analysis study became mandatory for all the Belgian nuclear power plants (NPPs). Seven units, representing altogether7500 rooms, needed to be assessed. The goal of the study was to demonstrate that the capabilities required to safely shut down the reactor, to remove the residual heat and contain the radioactive material are maintained in case of a single internal fire.

The developed FHA methodology is based on the IAEA's Fire Containment and Fire Influence Approaches (FCA and FIA):

- Fire Containment Approach (FCA) a global screening analysis, which allows a relative fast fire propagation assessment based on predetermined conservative assumptions;
- Fire Influence Approach (FIA): a detailed analysis which is performed on the fire issues identified in the FCA analysis or on the cases that are out of validation range of the FCA.

To perform the FIA analysis following an automated and repeatable approach, existing tools were integrated in a first of a kind java tool named FOCUS. It links the client's database to a two zones fire modelling tool. All the necessary input data (drawings, fire loads, safety equipment, libraries of materials, etc.), the defined fire scenarios and their associated calculation results are centralized in FOCUS. Nowadays more than 2.5 billion objects are handled automatically by the tool.

FOCUS was developed to integrate the followings functionalities:

- User interface allowing the data edition and the 3D visualization of input data;
- A full automatic process that generates fire scenarios by igniting sequentially each fire load inside a selected room;
- Calculation of fire generated conditions;
- Post-processor for 3D visualization of the fire growth inside the room;
- Automatic report generation to standardize and facilitate documentation of the fire simulations;
- Automatic inputs files generation for the most used fire modelling software such as CFAST, MAGIC[1] and FDTs (Fire Dynamic Tools [5]).

Furthermore, a mobile tablet version allows the use of FOCUS tool remotely or onsite during the inspection visit and therefore directly assists the engineer for a prompt decision making. The mobile tablet version also facilitates the data collection and allows a saving time of about 70 % and further limiting the risk of errors.

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[1] MAGIC - the EDF deterministic numerical simulation tool for fire safety assessment of NPP.

This paper will give a description of the developed algorithms and the functionalities of FOCUS.

INTRODUCTION

Fires represent a significant risk for the safety of Nuclear Power Plants (NPP's) and other nuclear installations. Therefore, the WENRA Reference Levels [1] were introduced in the Belgian regulation at the end of 2011 [3]. A comprehensive Fire Hazard Analysis study became mandatory for all the Belgian NPP's. Seven units, representing 7500 rooms, had to be assessed.

The goal of the study is to demonstrate that the capabilities required to safely shut down the reactor, to remove the residual heat and contain the radioactive material are maintained in case of a single internal fire.

The developed FHA methodology is based on the IAEA's Fire Containment and Fire Influence Approaches (FCA and FIA) [4]:

- Fire Containment Approach (FCA): a fast screening for simple geometries used to assessment the efficiency of physical barriers. It is based on conservative correlations with limited applicability, allowing to calculate the propagation of fire through compartment boundaries;
- Fire Influence Approach (FIA): a detailed calculation of local quantities generated by fire to assess the influence of the fire on safety equipment followed by the analysis of failure of redundant safety systems.

To perform the FIA analysis following an automated and repeatable approach, existing tools were integrated in a first of a kind java tool named FOCUS. It links the client's database to a chosen two zones fire modelling tool (MAGIC). The database contains all the data related to the NPP's which correspond to the plans of about 7500 rooms and 2.5 billion objects that have to be handled, transformed and finally used as input by the simulation software.

To perform the FIA analysis following an automated and repeatable approach, existing tools were integrated in a first of a kind of Java tool named FOCUS. It links the plant operator database to a chosen two zones fire modelling tool (MAGIC). The database contains all the data related to the entire NPP's to be analysed. These data correspond to the drawings of about 7500 rooms and 2.5 billion objects that have to be handled, transformed and finally used as input by the simulation software themselves.

CONTEXT

The first phase of the FHA project was performed with the FCA which is a fast screening approach based on conservative assumptions. The FCA analysis was performed in order to assess the capacity of physical barriers to avoid fire propagation and to prevent a common mode failure induced by a single internal fire. The FCA therefore assumes that:

- The redundant safety related equipment are located in different room/compartment
- The geometry of the selected rooms is such as the simple correlations from NUREG 1805 [5] (Mc Caffrey, Quintiere and Harkleroad, Foote Pagni and Alvares, Beyler, etc.) are applicable.

For the more complicated configuration (redundant safety related equipment located in the same space, complex geometry…) a more advanced and detailed fire analysis named FIA is performed. Three kinds of model have been used for the detailed fire modelling analysis in the FHA study:

- Algebraic model: Fire Dynamic Tool (FDT) used mainly to evaluate the Zone of Influence (ZOI) of an ignition source in unconfined environment.

- Zone model: CFAST tool (developed by NIST) and MAGIC tool (developed by EDF) used to calculate the fire generated condition in the multi-compartment configuration. These tools are used in the situation involving simple geometries. The preparation of input for a zone model, the computation time, and the amount of output data generated (hot gas layer temperature, gas composition, oxygen concentration, heat fluxes, etc.) are slightly more extensive than a simple algebraic model; however, the computational time remain still acceptable.
- Computational Fluid Dynamics model: FDS tool (developed by NIST) used to calculate the fire generated conditions for complex geometries and severe boundary conditions. CFD is also used to predict a more specific fire variable in precise locations. The main drawback of using CFD models is that they require an important effort to prepare the inputs, huge computational power and they are time consuming.

Taking into account the FHA challenging deadlines, the potential amount of FIA cases to compute and the need for reproducible, coherent and high-quality results, it was decided to create a new tool that could automatically create the input files for a chosen fire calculation model by using the available database. Indeed, the main constraint for the creation of this new tool was the development timeframe. A feasibility analysis showed it would be more efficient to use a validated existing two zones model (MAGIC tool) and rather focus the development mainly on the automatization of the input files preparation. The outcome is the development of the FIA tool named FOCUS.

DESIGN

Requirements

As FOCUS was developed in the framework of the FHA project for which the methodology was already defined and discussed with the Belgian safety authorities, some design constraints had to be taken into account:

- The main features implemented had to be defined according to the FHA methodology.
- The main source of data had to be the existing FHA database.
- The computing code had to be a validated and commonly accepted fire calculation tool.

Additionally, the technologies used for the source code had to be selected in order to facilitate the implementation and the interoperability of the tool with other software: UML, Java, Swing, Hibernate, Java FX2, Jasper Report, etc.

General Architecture

The general architecture of FOCUS is shown in Figure 1 below.

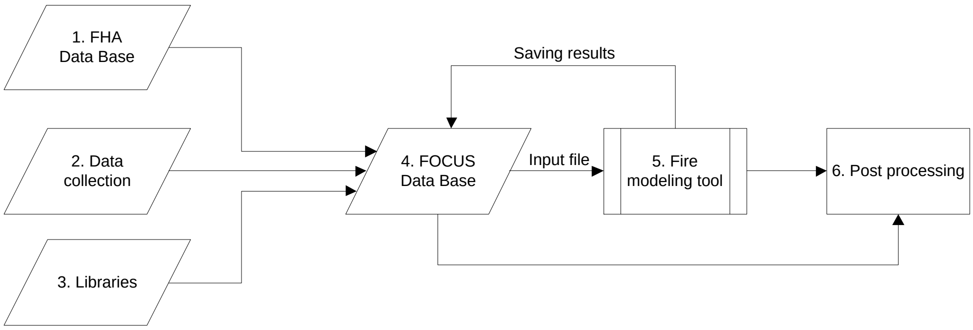

Figure 1 General architecture of FOCUS

1. FHA database: existing database built for the FCA analysis;
2. Data collection: as the FHA database was built for the FCA analysis, some additional information needed to be collected for the FIA analysis. A specific module was developed and the missing data can be directly uploaded in the FOCUS database;
3. Libraries: for quality assurance purpose, all the characteristics of material, the default setting of systems and equipment are predefined to avoid end-user's errors and ensure coherence over all FIA simulations;
4. FOCUS database: the tool has its own data base containing the specific data needed for the detailed fire modelling calculations;
5. Fire modelling tool: a computing code is integrated inside the tool to perform the fire modelling calculations using the appropriate input data;
6. Post processing: a post processing module is incorporated in the tool in order to visualize the outputs, make specific graphs or generate different kind of reports.

Flow of Data

There are two versions of FOCUS:

- Server version: this master version contains the complete data base and all the required functionalities. The FOCUS database contains data from FHA database, libraries of data for fire protection equipment, libraries of data for fire load characteristics, libraries of data for the materials characteristics. This version also allows the generation of a specific file (".focus") to be used by the client version. The ".focus" file contains the existing data for a selected set of rooms.
- Client version: this version looks like the server version but with some limited functionalities. It uses a copy of the main FOCUS database (which is stored on the server version) in order to collect the additional information necessary for the FIA calculations. This is done by the use of tablet PC's. The client version, after a data collection campaign, generates the ".walkdown-files" that can be uploaded to the server version. The ".walkdown-files" contain the additional data collected on site and also the fire scenario created during the data collection.

Figure 2 shows the flow of data between the server version and the existing database, libraries and client version. The user can connect remotely on server version to view data, create fire scenario, launch calculations, etc.

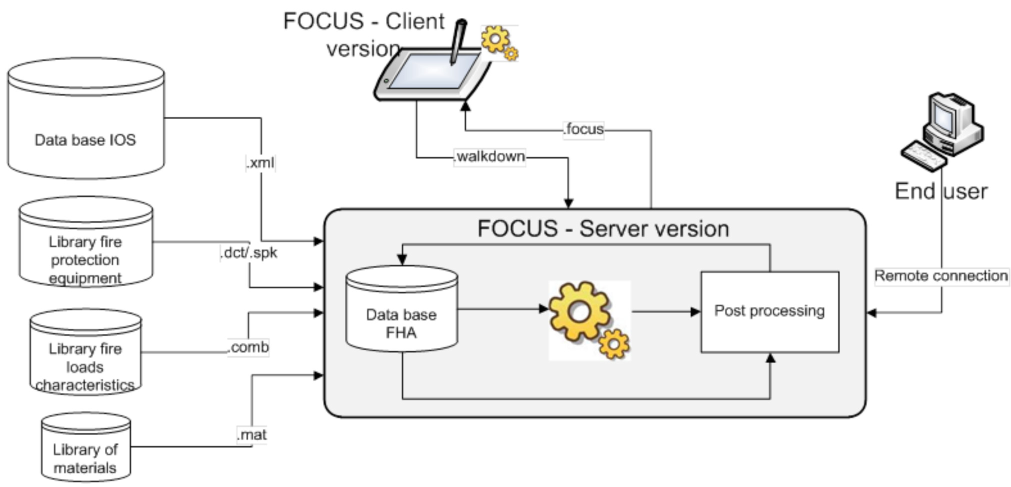

Figure 2 Flow of data exchange during the detailed fire modelling process

Functionalities

The functionalities of the tool are defined in order to save a maximum of time, decrease the risks of error, insure the traceability and the repeatability of the analysis. The main features contained in FOCUS are the following:

- Graphical User Interface (GUI) for data acquisition and editing;
- Fire scenario definition;
- Fire simulation in two calculation modes (explained more in detail in the paragraphs below related to the fire simulation);
- Generation of input file for a selected two zones model (MAGIC tool);
- Post processing;
- Reporting.

IMPLEMENTATION

Libraries

The accuracy of a model in predicting a particular quantity is determined by the verification and validation (V&V) studies. But the accuracy also depends on the precision of the input data that the modeller uses to predict the fire behaviour. Therefore, in the framework of the FHA study, a quality assurance document which provides the guidelines for the detailed fire modelling was elaborated: a step by step fire modelling process based on NUREG 1934 [1], generic parameters and methods to calculate the fire load, material properties, etc. All these methods and parameters are integrated in FOCUS through dedicated libraries. Therefore, all the characteristics of materials, methods to calculate the Heat Release Rate (HRR) of fire loads, characteristics of fire protection systems are predefined in FOCUS. Table 1 below shows an example of fire load model implemented in FOCUS.

Table 1 Model of Electrical cabinet implemented in FOCUS

Quantity	Method	Parameter	Source of data
Heat of combustion [kJ/kg]	constant	LHV [kJ/kg] – Lower heating value (or PCI)	libraries
MLR (t) [g/s] - mass loss rate	$= \min\begin{pmatrix} \frac{HRR_{peak}}{PCI} \cdot 1000 \\ \frac{alpha \cdot t^2}{PCI} \cdot 1000 \end{pmatrix}$ $t = \begin{bmatrix} 0; \Delta t;\ 2\Delta t;\ 3\Delta t;\ 4\Delta t; \\ 5\Delta t;\ \Delta t_{peak}; t_{end} \end{bmatrix}$ $\Delta t_{peak} = \sqrt{\frac{HRR_{peak}}{alpha}}$ $\Delta t = \frac{\Delta t_{peak}}{6}$	HRR_{peak} [kW] – Heat Release Rate	libraries
		PCI [kJ/kg]	libraries
		Alpha [kW/s²]	libraries
		t_{end} [s]	FOCUS
Mass [kg]	$=\frac{E}{PCI}$	HRR_{peak} [kW]	libraries
		PCI [kJ/kg]	libraries
		Alpha [kW/s²]	libraries

Quantity	Method	Parameter	Source of data
	$E = alpha \cdot \frac{\Delta t_{peak}^3}{3} + HRR_{peak} \cdot \Delta t_{steady} + \frac{HRR_{peak}}{2} \cdot \Delta t_{decay}$	Δt_{steady} [s]	libraries
		Δt_{decay} [s]	libraries
diameter of the base of the fire [m]	$= \frac{1}{100} \cdot \sqrt{\frac{4 \cdot l \cdot w}{\pi}}$	L [m]	database
		W [m]	database

The default values from the libraries can be changed by the user. However the software keeps track of the last modification and which user made it in order to insure a good traceability of all modification. The software also indicates if a user specified value is entered instead of a default one.

Figure 3 here next is a screenshot with the list of characteristics to be set up when a user creates a new fire load in FOCUS. It can be seen that most of parameters are filled up in advance with values from the FOCUS libraries. Only a few parameters (name and dimensions) request a user input.

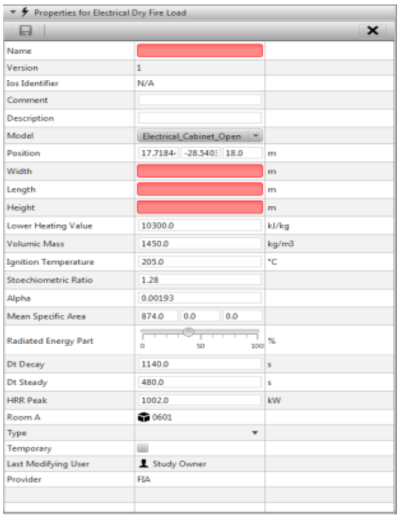

Figure 3 Screenshot of equipment properties window from FOCUS

Computing Code

The computing code used in FOCUS is MAGIC. It is a two zones fire model that calculates fire environment variables using control volumes, or zones, of a space. The zones correspond to a Hot Gas Layer (HGL) and a cooler lower layer. MAGIC can also predict the radiation heat flux, the gas composition, the thermal behaviour through the separation wall etc. In MAGIC, all data required to run the model are contained in an input data file which is a structured text file ".cas file". The ".cas-file" contains different groups of data [6], [7]: room geometry, ventilation, fire properties, specifications for fire protection systems and target. Each line of the ".cas-file" contains inputs related to a group and begins with a keyword label that identifies the input. The keyword labels are preceded by the symbol "#" as shown in Figure 4.

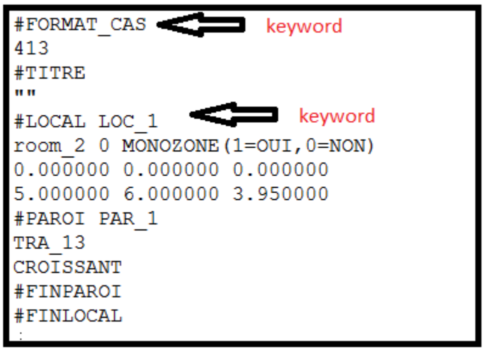

Figure 4 Example of input file of MAGIC

FOCUS has been designed to automatically generate the ".cas-file" with the necessary information to define the scenario under consideration and then to start the MAGIC computation. The tool also post-processes the data from the outputs files of MAGIC. As it can be seen in Figure 5, FOCUS can also provide an overview of the studied room in Magic's pre-processor.

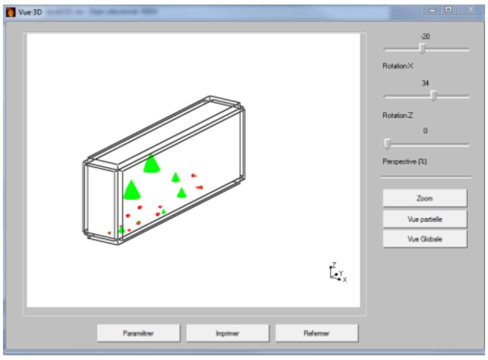

Figure 5 Example of a room overview with pre-processor of MAGIC

Construction of the Fire Scenario in FOCUS

In two zones model, the compartment studied needs to have a rectangular parallelepiped shape. However, in NPP's, most of the rooms do not meet this criterion. Therefore, before launching the calculation, the actual geometry has to be properly converted into an equivalent rectangular parallelepiped which represents the room under study. The geometrical transformation also implies that the items, equipment and openings located inside the room have to be repositioned. These manipulations are time consuming as the user has to create a representative equivalent parallelepiped room in accordance with the fire modelling goals taking into account its representability with respect to the physical phenomena.

To save time and to automate as much as possible the detailed fire modelling in FOCUS, the idea was to implement an automated room transformation algorithm. In this manner the user can modify the original geometry to its needs and should not waste time with any of the transformations or repositioning.

The algorithm defined for the room transformation considers the following constraints (not exhaustive) and is illustrated in Figure 6:

- The volume and height should remain the same: V1 = V2 and H1 = H2;

- The position of target should be such as the free volume between target and highest ceiling remains the same after room transformation: V1_cible1 = V2_cible1, V1_cible2 = V2_cible2;
- The distance between ignition source and target should remain the same[2]: d1_1 = d2_1, d1_2 = d2_2;
- The separation wall characteristics should be such that the heat losses are unchanged;
- All the adjacent rooms/spaces connected to the "burning space" with horizontal and vertical openings should be considered in the transformation.

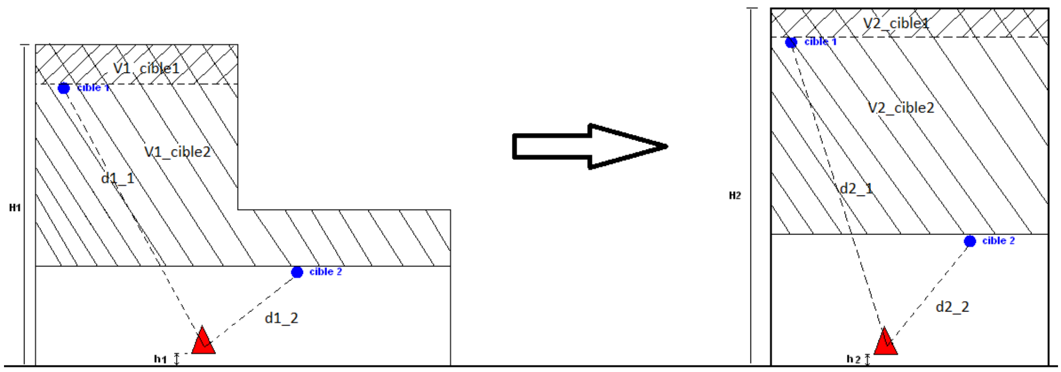

Figure 6 Illustration of a room transformation and some related constraints

Before applying the room transformation algorithm, the NPP's existing drawings were first digitalized and saved in our database. Each room was defined as a superposition of slices with uniform shape. Each slice is defined by the corners ($x_{i,j}$,$y_{j,j}$) and a height (H_{S_j}) as shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**. As the shape of a selected slice doesn't change in the vertical direction, the transformation into the equivalent rectangular parallelepiped is then much easier.

The transformed room is defined by its length (l), width (w), height and its centre of gravity (Gx, Gy, Gz). The calculation of these parameters is based on the contribution of each slice. All the slices are automatically repositioned at the calculated centre of gravity of the room before the computation of the length and width of each slice (based on unchanged volume constraint).

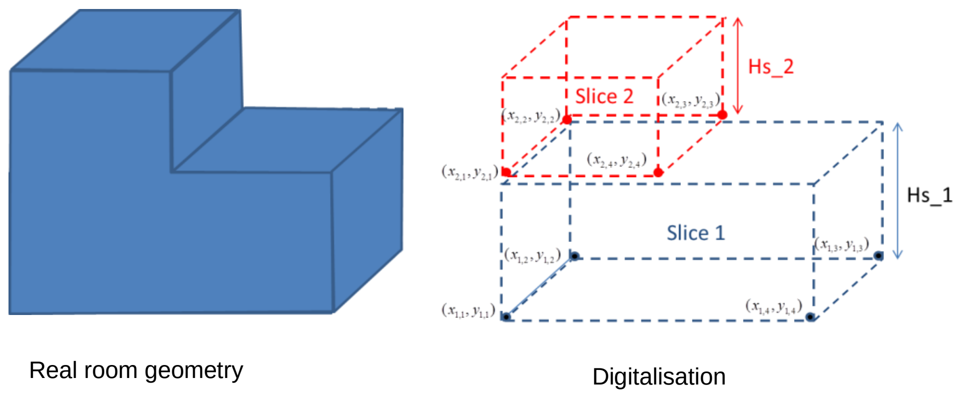

Figure 7 Illustration of digitalisation of the geometry

2 The radial distance between targets and ignition sources is also a constraint.

The surrounding rooms can influence the fire growth inside the selected fire room and therefore are considered in the room transformation process. In FOCUS the surrounding rooms connected by an opening with the selected fire room are considered as following (see an example in Figure 8): rooms in communication by an opening located on the ceiling, on the floor and on the side walls are transformed into equivalent parallelepiped rooms and placed respectively above, below and to the left side of the selected fire room.

The user can select a target room next to the fire room to assess the impact of fire (loss of safety equipment, smoke propagation, etc.). In this case, the target room will not be merged with other surrounding rooms, it will be transformed separately as shown in Figure 8.

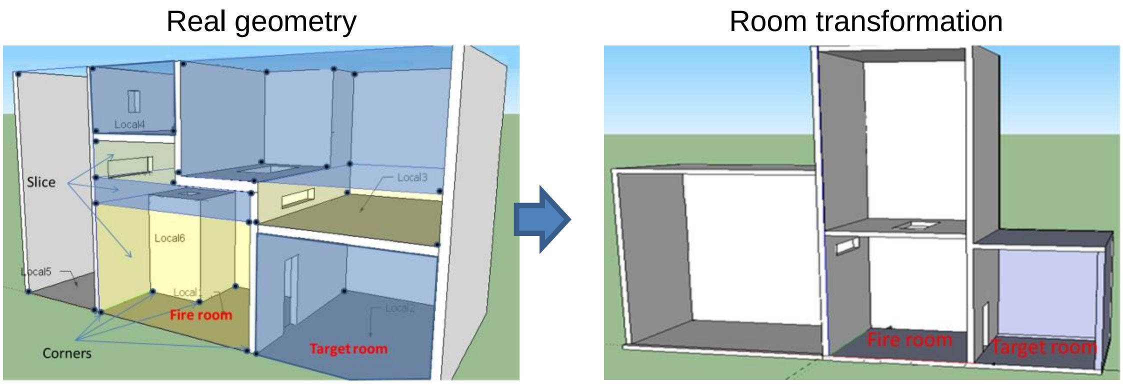

Figure 8 Example of room transformation

Graphical User Interface (GUI)

The GUI is organised into three different screens as it can be seen in Figure 9: Base Data & Scenario (left), room editor (middle), properties (right).

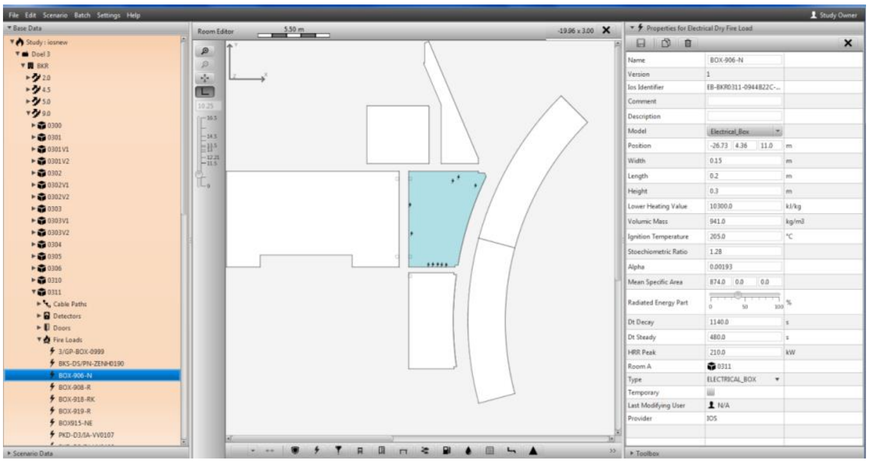

Figure 9 Graphical user interface

The first window (Base Data & Scenario) is structured in a top down tree of the power plant and consists of two parts:

- Base Data: allows for the modification, creation, (re)positioning of the objects;

- Scenario: allows for the creation of different scenarios in which different parameters and settings can be changed by the user in order to simulate the desired scenarios while the original data in Base Data remains unchanged.

The second window (Room editor) presents a “2.5D” view of the selected room and its adjacent rooms. The view is actually a 2D representation with a slider which allows the user to change the elevation. Not only the selected room, but also all the adjacent rooms are presented.

The third window (Properties) allows for the modification of the characteristics of a selected object.

Data Acquisition and Data Editing

One of the FOCUS needs is to add new elements or data to the existing database such as position of safety equipment, cable trays and new fire loads. The user must also be able to modify the existing data in order to assess if a plant modification might provide a solution to the identified issue. The additional data acquisition is done on tablet PCs during the inspection visits on site (see Figure 10).

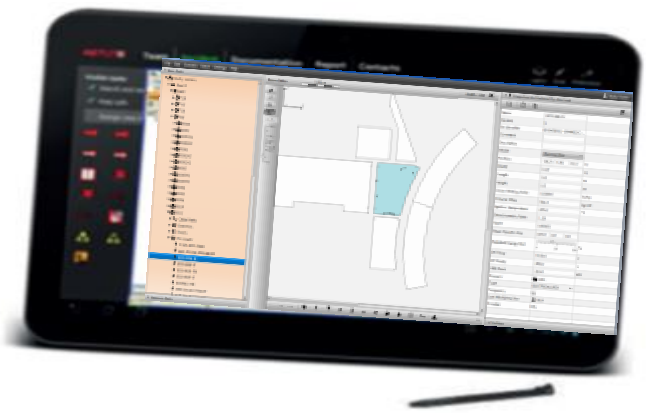

Figure 10 Photograph of FOCUS window on tablet PC

Room Editor

The Room Editor is designed to add and position objects by drag-and-drop. There are different types of fire loads which can be added to a room. FOCUS uses pre-defined libraries in which most of the physical parameters are defined and on which there is an agreement with the Technical Support Organisation (Bel V) of the Belgian Nuclear Safety Agency (FANC).

Cable Trays & Safety Equipment

One of the main conservative assumptions of the FCA analysis is that all the fire loads inside the volume of analysis are considered to be involved in the fire at the start of the simulation. The exact 3D location and trajectories of the cable trays are not considered. However for the more detailed FIA approach, this information plays an important role in the analysis. Therefore, the possibility to draw cable trays trajectories by using the “2.5D” representation was implemented in FOCUS.

FIRE SIMULATION

Before starting fire simulation, the assessor defines a fire scenario. In FOCUS as many things are already defined or are managed automatically, the definition of fire scenario is limited to: select the fire room, set the objectives, choose the ignition source and choose a target room. The tool creates automatically:

- The geometry with the rectangular parallelepiped rooms;
- Targets on each equipment present inside the fire room and inside the target room;
- The fire characteristics of all objects present inside the fire room.

The scenarios created by a user for a selected room are tagged as “main scenarios”. FOCUS can generate automatically additional scenario for a selected room. These second types of scenario are tagged as “son scenario”.

Once the main scenarios are defined, FOCUS can perform three types of calculation:

- Fast calculation mode (quick run) in which only one fire scenario is calculated with one ignition source and a limited amount of secondary fire loads;
- Full calculation mode (full run) in which several fire scenarios are performed automatically for a room selected by FOCUS;
- Batch calculation mode in which several fire scenarios are performed automatically for a set of selected rooms.

Quick Calculation

During on-site visits, there are some particular cases that need the support of a calculation tool to assess on-site if an issue is relevant and need to be thoroughly studied, for instance, to check if the combination of the hot gas layer temperature and radiation heat flux can cause a fire issue.

Full Calculation

In FOCUS when the assessor has defined the main scenarios for a selected room, the tool can create additional scenario (“son scenario”). The “son scenarios” are generated from a “main scenario” by changing the ignition source. Therefore for a given room, there are as much scenarios as there are fire loads inside the fire room. This process is done when the “full calculation mode” is activated.

Batch Calculation

The batch calculation is the application of the “full calculation” on several selected rooms. The amount of runs in the batch mode is then:

$$Number\_of\_calculation = \sum_{i=1}^{N_{room}} i \sum_{j=1}^{N_{FL,i}} j \qquad (1)$$

with:

$N_{FL,i}$: amount of fire loads inside the room “i”,

N_{room}: amount of selected rooms.

The batch calculation mode can involve several fire scenarios and can be run sequentially on a local computer. However to save time, the execution of these fire scenarios can be ran in parallel on different servers using a load management tool called CONDOR. All fire scenarios and their associated results are saved in the FOCUS database.

POST-PROCESSING

After the calculation, MAGIC generates an output file ".res-file" which is a structured text file with a keyword label that identifies each output. These files are organised by FOCUS in structured directories. The user interface of FOCUS allows to start the post-processing tool of MAGIC on those results and to draw the time evolution curves of different output quantities as it can be seen in Figure 11.

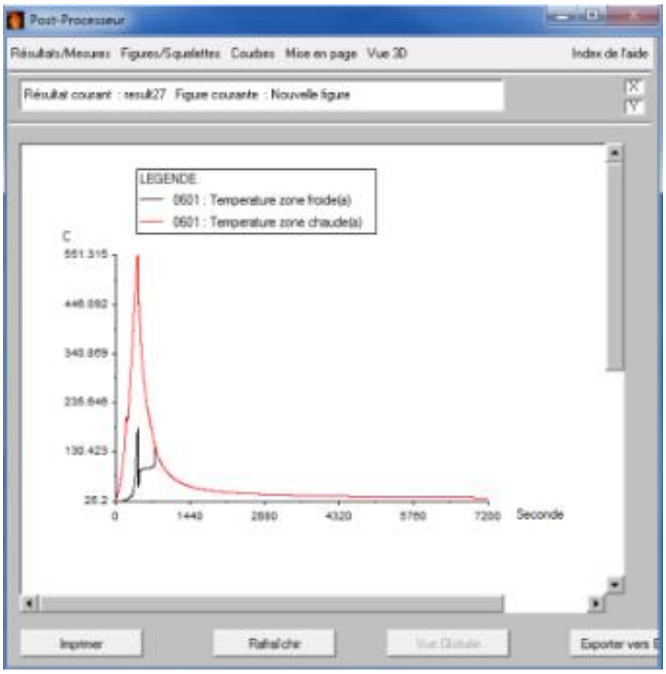

Figure 11 Example of time evolution temperature provide by the post-processor of MAGIC

REPORTING

To reduce the time spent on formatting graphs, tables and other time consuming tasks, an automatic reporting function has been included in FOCUS. Three different kinds of reports are generated on demand:

- Level 1: Provides an overview of the fire generated conditions inside the room;
- Level 2: Provides the fire generated conditions of the main fire scenario;
- Level 3: Provides the detailed fire generated conditions of all the fire scenarios (main fire scenario and "son scenarios").

To check the predictive capacity of the fire model used, all reports are provided with the normalized parameters for application of the validation results to NPP's fire scenarios (according to NUREG-1824/EPRI [2]). The model uncertainty is also calculated automatically and reported. The probabilities of exceeding a critical value x_c (temperature, heat flux, etc.) are then provided in reports. These probabilities are computed using the error function as follows:

$$P(x > x_c) = \frac{1}{2} erfc(\frac{x_c - \mu}{\sigma\sqrt{2}}) \quad (2)$$

MAINTENANCE AND SUPPORT

An issue tracking system, in the form of a server application, keeps track of the different issues, bugs and new specification. The use of this kind of system, commonly spread in IT development, allows for a good follow-up and ensures no issues are forgotten, overseen or treated twice.

CONCLUSION

FOCUS was developed in order to automate as much as possible detailed fire modelling calculations. The main challenge was to link a two zones computing code to the database of NPP's. With FOCUS, it is now possible to create a fire scenario, to start the two zones calculation and to generate the report in less than 15 min. FOCUS was already used successfully in the Belgian FHA project for the detailed fire modelling (i.e. FIA). The tool can also be used for the data collection with a significant time saving.

Recent developments of FOCUS allow now to generate also the input file for CFAST.

In future projects, FDS computing code could be incorporated in FOCUS. Also, the possible integration of Monte Carlo simulation could be considered as an improvement to increase the accuracy of the predictive tool capacity.

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DEVELOPMENT OF INTERNAL FIRE PSA FOR NEW BUILD UK GENERIC DESIGN ASSESSMENT

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ABSTRACT

Internal fire hazards can pose a significant threat to plant safety and can often contribute a significant portion of total plant risk. This level of contribution therefore warrants a probabilistic treatment to identify vulnerabilities and provide insights for design or procedural improvements. Such an analysis was conducted for a new build reactor design of the United Kingdom (UK) Advanced Boiling Water Reactor (ABWR) as part of the UK's Generic Design Assessment (GDA) licensing process. This analysis was conducted for both at-power and shutdown operating states to obtain a comprehensive understanding of the potential internal fire risk for different plant operating states and configurations.

The analysis was conducted for UK ABWR generic design according to the NUREG/CR-6850 method for internal fire probabilistic risk assessment using fire ignition frequencies from NUREG-2169 [2] in the absence of plant-specific ignition frequency data. The analysis included all buildings containing equipment with the potential to contribute to overall risk and had to overcome many challenges specific to new-build plant designs such as a lack of detailed design data including cable selection and routing information, evolving design reference points and coordination with other related studies ongoing as part of the GDA process. The analysis also included a novel method for performing multi-compartment fire analysis to reflect the design's unique features relating to fire compartment and fire barrier design. The analysis was also conducted in parallel with an internal flooding PSA and shared much of the same input data using an innovative data storage and manipulation tool to enable efficient generation of fire and flooding scenarios for use with the quantification software.

The insights for the design and possible solutions for generic design will be shared as part of this paper as well as insights from performing such studies in the context of the UK new build licensing process.

INTRODUCTION

The UK GDA Process and Use of PSA

The GDA process, like other international licensing regimes, requires a thorough understanding of the potential risk associated with the operation of any nuclear power plant design proposed for construction in the UK. The use of probabilistic safety assessment (PSA) is a fundamental part of demonstrating this understanding and a set of regulatory expectations [3] exists concerning the scope, level of detail and completeness of the PSA supporting the design for licensing.

An important part of any PSA, including those supporting the licensing process for new build designs in the UK, is appropriate coverage of hazards. Hazards are recognized as representing a unique threat to a nuclear plant's safety and operability and must be accounted for in the design process as part of the justification that the risk associated with the design has been reduced to a level that is as low as reasonably practicable (ALARP).

However, it should also be recognized that GDA is only a part of the overall licensing process for a new reactor build in the UK. A GDA is then followed by a post GDA process which reviews the implementation of the generic design at a specific site. From a PSA perspective, the post GDA activity effectively builds upon the GDA PSA to develop the full site-specific PSA including all elements that are specific to the proposed implementation site.

Internal Fire Hazards

Internal fire is recognized as one of the more risk significant hazards as next-generation reactor designs often rely on an increased safety systems reservation which comes at the expense of increased amount of equipment and cables resulting in higher fire loads.

It is important therefore to evaluate the performance of the design against internal fire hazards to provide valuable insights into design and procedural improvements such that the internal fire risk is well-understood, controlled and reduced to a level that is ALARP.

Internal Fire and the UK ABWR Design

ABWR design is a Generation III+ boiling water reactor [4]. The UK ABWR design is based on the Japanese ABWR (J-ABWR) design that has been built in Japan. However, there are some differences between the J-ABWR and UK ABWR generic design that were intended to meet UK specific expectations and adopt relevant good practices. As part of the process for UK ABWR generic design, a full-scope PSA has been developed, peer-reviewed and used to inform the design process in GDA [10]. From a safety assessment perspective, examples of the most significant differences are as follows (more are listed in Reference [5]):

- A Backup Building with an alternative power supply and coolant injection function is installed for use in the event of severe damage to the Reactor Building (RB).
- A number of design changes are proposed to increase protection against internal hazards. To reflect UK relevant good practice, a design change will be implemented to minimize the number of doors in the Class 1 safety barriers inside the R/B and to introduce double fire doors at the remaining locations where reasonably practicable.

It should also be noted that the UK ABWR generic design is evolving as necessary based on insights from the GDA process. This topic, and specifically insights from the internal fire PSA, will be revisited again later in this paper.

ASSESSMENT APPROACH

Use of Methods and Standards

As stated previously, the approach to the Internal Fire PSA was based on NUREG/CR-6850 [1] and more recently issued NUREG-2169 [2]. This approach is considered to represent the industry accepted approach to conducting fire PSA and moreover, was considered as an appropriate method for meeting the fire PSA assessment expectations listed in the ONR PSA Technical Assessment Guide (TAG) [3].

However, the NUREG/CR-6850 [1] (and also NUREG-2168 [2]) guidance is based on application to an operating plant rather than a plant in design. The application of the guidance within a GDA process where the focus of the assessment is on a *generic* design rather than a specific plant at a specific location brings certain challenges as discussed below:

- The scope of the design undergoing assessment within the GDA process is not the same as a typical operating plant as some plant specific elements are not assessed during GDA. This represents a scope limitation within the fire PSA as not all plant areas with the potential to lead to fire events have been included. On the other hand, the UK ABWR design includes some specific SSCs which are not typical for the existing operating plants. That represents an additional challenge because the available generic data is derived from existing plants operating experience which cannot cover the non-typical SSCs. An example of a plant area specifically designed for the UK ABWR is the Backup Building that houses and additional set of safety equipment that is not present in the existing operating ABWRs.
- A general lack of design detail during the generic design phase was present throughout the analysis both in terms of plant layout, cable routing and equipment characteristics. The approach to overcome this challenge without introducing excessive conservatism is discussed later in this paper although the significance of this lack of design detail is discussed further in the assessment insights section.
- A probabilistic assessment typically relies upon a comprehensive deterministic assessment to provide many of the data inputs and identify areas of potential concern for further probabilistic treatment. This information was not fully available at the GDA stage. These presented challenges in making effective use of the deterministic fire analysis. In many cases a detailed fire modelling was required to be performed in order to allow more precise probabilistic assessment.
- The operating procedures for the plant both under normal operation and during maintenance were not fully developed during the GDA process. This required the use of alternative Human Reliability Assessment (HRA) approaches and bounding judgements.

Each of these points, including their impact on the assessment and alternative approaches required, is discussed in more detail in the sub-headings below.

It is also relevant to note that the internal fire PSA was being conducted in parallel with an internal flooding PSA. A significant portion of the data collected for the Internal Fire PSA was shared with the Internal Flooding PSA including plant layout and room characteristics, initiating event and basic event identification and mapping and cable selection and location information. This information was stored in a proprietary Fire PSA database and used in both studies. This transfer of information represented a significant efficiency in the initial tasks of the Internal Fire and Flooding PSA. The use of the Fire PSA database will be discussed further in Section 2.3.

The Internal Fire PSA was structured into 16 tasks in accordance with NUREG/CR-6850 [1] guidance. For the purposes of practical implementation some of these tasks were performed in parallel as indicated in the list below:

- Task 1 - Plant Boundary Definition and Partitioning
- Task 2 - Fire PSA Components Selection
- Tasks 3 and 9 - Fire PSA Cable Selection and Circuit Failure Analysis
- Task 4 - Qualitative screening
- Task 5 - Fire- Induced Risk Model
- Task 6 - Fire Ignition Frequencies
- Task 7 - Quantitative Screening
- Task 8 and 11 - Scoping and Detailed Fire Modelling
- Task 10 - Circuit Failure Mode Likelihood Analysis
- Task 12 - Post-Fire Human Reliability Analysis
- Task 13 - Seismic-Fire Interactions Assessment
- Task 14 - Fire Risk Quantification

- Task 15 - Uncertainty and Sensitivity Analyses
- Task 16 - Fire PRA Documentation

In order to keep the focus on the design stage Fire PSA, this paper will only emphasize on the topics where particular challenges were faced and the ways to resolve them.

Finally, a key part of the assessment approach was the incorporation of a formal peer review process prior to submission of the final analysis. The peer review group comprised an independent group of experienced Internal Fire PSA personnel who provided comments on the methodology and a critical review of the results. The incorporation of a peer review process also provided additional confidence to key stakeholders that the analysis had been planned and executed according to the current industry consensus approach.

Plant Partitioning and Multi-compartment Fire Analysis

For the GDA of the UK ABWR design, the scope was limited to a number of structures which formed the basis of the generic design [6]. A number of structures for which the design is heavily dependent on plant-specific factors were excluded even though those structures, according to the ONR TAG and ASME/ANS standard [7], would not be candidates for exclusion based on potential contribution to initiating events and/or impact on accident mitigating equipment. This is a function of the GDA process which is only a part of the overall licensing regime for a new nuclear plant.

It has to be noted that there is a difference in the use of the terms “fire area” and “fire compartment” in different countries. In the text below these two terms and also “plant analysis unit” (PAU) are used with the same meaning as in the UK ABWR Fire PSA project. More specifically, the term fire area describes a space enclosed by rated fire barriers as it is defined in the UK ABWR Fire Hazard Analysis. The terms “fire compartment” is used as an equivalent to PAU meaning a plant subdivision resulting from the plant partitioning task. Therefore, multi-compartment fire should be interpreted as multi-PAU fire.

Usually the plant partitioning for the purposes of the Fire PSA is based on the plant partitioning applied in the FHA (Fire Hazard Analysis). For the UK ABWR design the FHA subdivided the plant into rather large fire areas consisting of a large number of rooms and housing large number of equipment. Even though this type of subdivision is suitable for the deterministic analyses, it was found not to be practical for the Fire PSA. Generally, if this type of rather coarse subdivision was to be applied, it would result in a very high ignition frequency per PAU along with an extensive target set within the PAU. On the other hand, if the plant is subdivided into a larger number of smaller PAUs, some of the PAU boundaries would consist of non-credited fire barriers, resulting in an increased complexity in the modelling of the multi compartment fire scenarios.

The balance between the conservatism in the single compartment fire analysis and the complexity of the multi compartment fire analysis was the key to overcome this challenge. It was found that a staged multi compartment analysis approach can help keeping a reasonable amount of effort while at the same time limiting the conservatism in the single compartment fire analysis. In order to provide the appropriate treatment of the multi compartment fires affecting the credited and non-credited fire barriers and impacting different type of equipment, the staged approach required the multi compartment scenarios to be categorized in four types:

- Type 1 – multi-compartment fire scenarios where the fire is not severe enough to cause any cable damage but can potentially impact the temperature sensitive equipment. These scenarios include multiple fire compartments (PAUs) within the same fire area - Type 1a - where no random credited barrier failure is required for the fire to progress from one PAU to another. Type 1 scenarios also include Type 1b scenarios where the fire could spread to the adjacent fire area by means of randomly failed fire barrier.

- Type 2 – multi-compartment fire scenarios where the fire is sufficiently severe to cause cable damage in multiple compartments but does not spread through a credited fire barrier.
- Type 3 – multi-compartment fire scenario where the fire is sufficiently severe in order to generate a damaging hot gas layer (HGL) capable of causing extensive damage in case of randomly failed credited fire barrier within the same safety division.
- Type 4 - scenarios are similar to Type 3, however they occur on the boundary between safety divisions and can cause more severe damage by significantly reducing the safety system redundancy.

These four types of multi compartment scenarios are related to either different fire conditions or different fire damage criteria. For example, Type 1 is associated with fire damage to temperature sensitive equipment with damage criteria 65°C or 3 kW/m^2 [1]; Type 2 is associated with local fire damage condition like target located in the fire plume or affected by flame radiation; Types 3 and 4 required a damaging HGL to form with a temperature exceeding the cable damage temperature.

The further calculation of the plant risk (expressed as CDF) resulting from multi compartment fires can be expressed as described below. Note that the calculation was similarly applied to large release frequency (LRF).

Type 1A: Temperature sensitive HGL - intra fire area scenario (barrier failure probability =1)

$$CDF_{MCS(i)\text{-}Type\ 1a} = IF_i \times SV_{330<HGL>65°C} \times CCDP(i, TSE\text{-}FA(A))$$

where:

IF_i is the frequency of a fire source in the exposing compartment (i),

$SV_{330<HGL>65°C}$ is the fraction of fires in the compartment capable of causing an HGL in the exposed compartment(s) of > 65°C but less than 330°C [1],

CCDP(i, TSE-FA(A)) is the conditional core damage probability given damage to all equipment and cable in the exposing compartment (i) and temperature sensitive electronics in any exposed fire compartments within the associated fire area A.

Since most ignition sources result in HGL temperatures in the exposing compartment of > 65 °C with no additional failures, this scenario will largely subsume the single compartment analysis.

Type 1B: Temperature sensitive HGL - inter fire area MCA scenario frequency (requires random barrier element failure). In this case there was one scenario for each interfacing fire area which contains temperature sensitive equipment.

$$CDF_{MCS(i)\text{-}Type\ 1\ b} = IF_i \times SV_{(330<HGL>65)i} \times pfBA\text{-}B \times CCDP(i, TSF\text{-}FA(A,B))$$
$$CDF_{MCS(i)\text{-}Type\ 1\ b} = IF_i \times SV_{(330<HGL>65)i} \times pfBA\text{-}C \times CCDP(i, TSF\text{-}FA(A,C))$$
$$CDF_{MCS(i)\text{-}Type\ 1\ b} = IF_i \times SV_{(330<HGL>65)i} \times pfBA\text{-}D \times CCDP(i, TSF\text{-}FA(A,D))$$

where:

IF_i is the frequency of a fire source in the exposing compartment (i),

$SV_{(330<HGL>65)i}$ **is** the fraction of fires in the compartment (i) capable of causing an HGL in the exposed compartment(s) of > 65 °C but less than 330 °C,

pfBA-B is the total probability of the random failure of a barrier element in a barrier separating fire area A compartments from fire area B,

CCDP(i, TSF-FA(A,B)) is the conditional core damage probability given damage to all equipment and cable in the exposing compartment (i) and temperature sensitive electronics in any exposed fire compartments within the associated fire areas A and B.

Since most ignition sources result in HGL temperatures in the exposing compartment of > 65 °C with no additional failures, this scenario will largely subsume the single compartment analysis.

MCA Scenario Type 2 includes all fire scenarios in an exposing compartment which did not produce a damaging HGL of > 330 °C in the exposing compartment but may expose PSA equipment/cables on the opposite side of a non-rated barrier to a damaging plume temperature or radiant heat flux. In this case a Local Severity Factor was evaluated ($SV_{LOCAL(i)}$) which was the fraction of fires in the compartment which can expose any of its associated barriers to damaging temperature or heat flux. In this case, Type 2 MCA scenarios assumed that the exposing and all of the adjacent exposed compartments were damaged as the conservative initial scenarios.

$$CDF_{MCS(i)-Type2} = IF_i \times SV_{LOCAL(i)} \times CCDP(ijk...)$$

where:

IF_i	is the frequency of a fire source in the exposing compartment (i),
CCDP(*ijk..*)	is the conditional core damage frequency given whole room damage in exposing compartment (i) and all susceptible adjacent exposed compartment(s) (j, k, ...).

Susceptible exposed adjacent compartments include those which are not separated by a fire rated barrier. In addition, an exposed fire compartment separated from an adjacent exposing compartment by a wall, floor or ceiling which is not fire rated but does not have any penetrations was not considered susceptible to Type 2 MCA scenarios. However, these compartments were considered susceptible to damage in Type 3 and Type 4 scenarios.

The extent of damage due to local barrier effects was refined if the scenario was determined to be risk significant under this conservative damage model.

Note:
Damage associated with Type 2 scenarios was also considered in combination with damage resulting from Type 1 scenarios.

MCA Scenario Type 3 includes all fire scenarios in an exposing compartment which produced a damaging HGL in the exposing compartment. In this case, it was conservatively assumed that all equipment and cable in the associated fire area, surrounded by fire barriers, was damaged. While an HGL scenario may also challenge the fire rated inter compartment fire area barriers, the Type 3 scenarios represent the case where such barriers do not fail.

$$CDF_{MCS(i)-FA(A)} = IF_i \times SV_{HGL>330(i)} \times CCDPFA(A) \times (1-\Sigma(pfBA\text{-}B + pfBA\text{-}C + \ldots..))$$

where:

pfBA-B	is the total probability of the random failure of a barrier element in a barrier separating fire area A compartments from fire area B,
pfBA-C	is the total probability of the random failure of a barrier element in a barrier separating fire area A compartments from fire area C,
CCDP*FA(A)*	is the conditional core damage frequency given whole room damage in all compartments the fire area associated with exposing compartment (i), i.e. fire area A.

MCA Scenario Type 4 like Type 3, includes all fire scenarios in an exposing compartment which produced a damaging HGL in the compartment but, in addition, included inter fire area barrier failures. Multiple Type 4 scenarios were developed, each considering a single barrier failure at a time. All equipment and cable in the exposing and exposed fire areas were conservatively assumed to fail.

$$CDF_{MCS(i)-GRP(A-B)} = IFi \times SVHGL(i) * pfBA\text{-}B * CCDPFA(A,B)$$

$$CDF_{MCS(i)-GRP(A-C)} = IFi \times SVHGL(i) * pfBA\text{-}C * CCDPFA(A,C)$$

$$CDF_{MCS(i)-GRP(A-\ldots)} = IFi \times SVHGL(i) * pfBA\text{-}\ldots * CCDPFA(A\ldots)$$

where:

CCDP*FA(A,B)* is the conditional core damage frequency given whole room damage in all compartments associated with exposing compartment (i), i.e. fire area A and the exposed fire area B,

CCDP*FA(A,C)* is the conditional core damage frequency given whole room damage in all compartments associated with exposing compartment (i), i.e. fire area A and the exposed fire area C.

The main purpose of the categorization of the multi compartment scenarios was to limit the fire modelling scope for each scenario only to the applicable fire conditions and damage criteria. For example, for a large number of multi-compartment scenarios it was sufficient to use fire modelling correlations instead of building a zone model such as CFAST.

The categorization of the fire scenarios applied along with the usual multi compartment screening analysis as described in NUREG/CR-6850 [1] represents an efficient way to optimize the effort required for detailed fire modelling.

Cable Routing and Data Processing

A particular challenge to the design stage Fire PSA was the lack of complete cable routing information. The Fire PSA for a typical operating power plant either relies on the existing cable routing database or includes the building of a cable routing database as a part of the overall fire PSA process, very often relying on walkdowns for filling in the gap or for confirmation of the data.

The UK ABWR cable routing data at the GDA stage was limited due to availability of detailed design. Since the specifics of cable routings, ignition sources, or target locations in each fire compartment were still in the design phase, a simplified, conservative, and bounding approach was used in the Fire PSA analysis. Cables associated with the components were identified by developing Cable Block Diagrams based on the circuit design of a surrogate J-ABWR plant. Assumed cable routing was conducted by Hitachi-GE electrical engineers on a room by room basis using the shortest route possible while maintaining divisional separation using conceptual raceway layout drawings.

The cable routing was updated iteratively by the electrical engineers starting with a high-level cable routing assuming all cables from one safety division to be located in all rooms associated with the same safety division.

From PAU perspective, that type of cable routing is focused on identification of the equipment which cannot be impacted by the fires initiated in that particular PAU, therefore it is known as “cable routing by exclusion”.

The main purpose of the risk quantification using the cable routing by exclusion was not to provide a reliable risk value but rather to allow for importance ranking of the cables and components. Then the list of cables identified to be of high importance was sent back to the cable routing team for more detailed cable routing.

This iterative approach resulted in two main achievements:

- Reducing the conservatism in the Fire PSA by obtaining more detailed cable data for the components with high importance in a very efficient way;
- Establishing of feedback chain with the electrical design team that effectively became a risk-informed design optimization [10].

In order to implement the iterative cable routing process in timely manner, the manual data processing had to be limited as much as possible. That was achieved by building a server based cable database as part of the UK ABWR Fire PSA database capable of generating quantification inputs. The main purpose of the database system was to minimize the manual data processing and to avoid generating any intermediate data tables. In this way, any update to the cable routing inputs resulted directly in a quantification inputs update.

Applicability of the Generic Ignition Frequency Data to the New NPP Designs

In order to address the specific UK expectations, some new features were added to the typical ABWR design. These new features include additional buildings (e.g. Backup Building) and additional equipment. Adding more equipment to the new plant design raises the question to what extent the generic ignition frequencies would be applicable to the new plant given that they were derived from operating nuclear power plants that may have a significantly different number of components. The methodology for ignition frequency calculation in NUREG/CR-6850 [1] groups the plant equipment in 37 ignition frequency bins, according to the ignition source type and plant location, and provides a generic ignition frequency corresponding to the total ignition frequency of the bin. The generic ignition frequencies in NUREG-2169 [2] were updated accounting for new input data but the methodology and binning scheme were kept generally the same with some bins split in sub-bins. One of the main assumptions bounding this methodology is that the bin frequency does not depend on the equipment count. The individual component frequency is derived from the generic frequency divided by the equipment count. This assumption can be considered acceptable for the operating plants as long as the count of the equipment falling into a particular bin does not vary too much from plant to plant. However, for UK ABWR having additional set of safety equipment such as pumps, valves, electric cabinets and diesel generators, a direct implementation of the ignition frequency calculation methodology would lead to a significant underestimation of the types of equipment.

After comparing the UK ABWR design and general equipment inventory with a typical US BWR, certain differences between the US BWR and the UK ABWR generic design have been identified. It is concluded that the generic ignition frequencies of the fixed ignition sources for the US BWRs are, in general, applicable to the UK ABWR design with some exceptions. Additional structures, such as the Backup Building, are included in the analysis by either excluding the area from the count of both fixed and transient ignition frequencies per component, or by assigning the area to the matching generic plant location.

The Equipment in Backup Building was not included in calculations for the ignition frequency per component. The equipment from the Backup Building is mapped to the corresponding generic plant locations, the default being the plant-wide location. In general, a plant specific location is not mapped to a unique generic plant location, as this mapping is equipment dependent. For example, mapping of the batteries in battery rooms in the Backup Building is made to Battery Rooms generic plant location. Hence, the battery ignition frequencies from two Backup Building battery rooms are calculated using the generic frequency for Bin 1 without diluting the total frequency of that bin. This also means that the total ignition frequency for Bin 1 of the UK ABWR is set to exceed that of the average BWR. The same approach was applied to the other ignition sources in the Backup Building such as pumps, motors, electric cabinets, diesel generators and transient fires.

Human Reliability Assessment

The HRA activity was focused on three tasks:

- Modification of the existing internal events human failure events (HFEs) to reflect the potentially adverse impacts of a fire;
- Development of fire specific operator actions and their respective human error probabilities;
- Dependency analysis to recognize potential dependencies between multiple operator actions in a single sequence.

The first activity recognizes that operator performance may be adversely impacted by the need to simultaneously address the fire event as well as implement a reactor trip and affect a safe shutdown should this be required. The approach used in this assessment recognizes that instrumentation used to provide the operators with the necessary cues for the different actions may also be fire impacted and derives different Human Error Probabilities (HEPs) for the following three cases:

- All instrumentation available (nominal case);
- Partial instrumentation available;
- No instrumentation available (trivial case).

Each case is directly implemented in the plant response model as can be seen in Figure 1. This approach ensures that any fire impacts to the instrumentation are captured explicitly in the plant response model and the appropriate HFE applied.

A screening approach was applied to the development of the human error probabilities (HEPs) for the all / partial instrumentation case whereby a factor of 10 was applied to the internal events HEP for the all instrumentation available case and a minimum value of 0.1 applied to the partial instrumentation case. The trivial case of insufficient instrumentation used an HEP of 1.0.

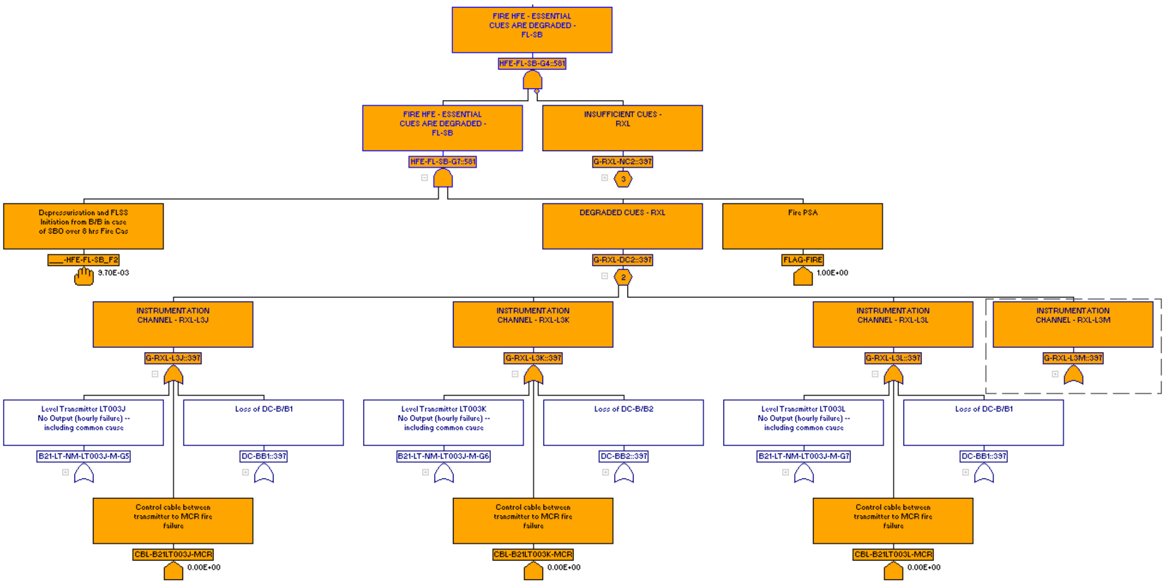

Figure 1 Example of plant response model showing modelling of an operator action under fire conditions

The second task of the HRA required the development of new HFEs to represent the fire specific actions; however, at the GDA stage no additional operator actions to respond to a fire were identified.

The third activity was to conduct a dependency analysis once the final results (and associated cut sets) had been developed. The purpose of the dependency analysis is to (1) systematically identify HFE combinations in the cut sets, (2) evaluate HFE combinations for dependencies and (3) address dependencies. The underlying concern is that risk metrics can be underestimated when all basic events are assumed to be independent when they are not. The scope of the dependency analysis was limited to post-initiator HFEs as it was assumed that pre-initiator HFEs are independent and any potential dependencies are captured within the same HFE. The dependency approach as described in NUREG-1921 [8] was applied to evaluate dependencies and dependent joint HEPs added to the cut sets using recovery rules.

Plant Response Model Development and Quantification

The quantification activity involved two specific aspects, namely the development of the plant response model for both Level 1 and Level 2 end states and the quantification of the models themselves.

The plant response model was based on the internal events model but incorporated additional logic to represent the fire induced initiating events, the fire affected operator actions along with their instrumentation dependency. Importantly, the changes made to the base internal events model were identified in a different colour so that it was clear where the fire changes had been made to the underlying model. Given that the plant response model was a combined fire and flooding model then it was clearly beneficial to reviewers and maintainers to be able to easily identify the fire and flooding related changes.

Additional changes included the addition of mutually exclusive logic under the top gate selected for quantification.

Following the quantification and review of results several sensitivity studies were carried out to quantify the impact of selected assumptions that were made during the development of the previous tasks. Assumptions were explicitly tracked during the development of those tasks and it was therefore straightforward to identify them for consideration within the sensitivity analysis task.

ASSESSMENT INSIGHTS

The assessment produced some valuable insights into the fire risk associated with the design submitted for assessment under the UK GDA process. It is also important to acknowledge and distinguish between, conservative assumptions made due to lack of detailed design information which yield some conservative results and, actual design/procedural issues which may require design modifications to reduce potential risk. Ideally, the presence of the former would be eliminated at the stage of plant specific design so that the insights reveal true design issues and are not masked by conservatism in the model. It is therefore fundamental that significant efforts are made to avoid overly generic and conservative assumptions. This is of particular relevance in assessments conducted at the design stage where actual plant-specific operating experience is not available or very limited.

However, even given the issues identified above, this analysis enabled insights to be gained that demonstrated which assumptions were significant and, with appropriate analyst judgement, where potential improvements in the design against fire hazards were sensible. Although the proprietary nature of this information prevents a detailed discussion of the insights, it became clear that the following aspects were significant:

- Identification of actual cable locations instead of assumed ones;
- Identification of fire barriers that may not be credited for the purposes of deterministic analyses but can adequately contain the fire.

CONCLUSIONS

The assessment of the fire risk for the UK ABWR design as part of the GDA process provided valuable insights into the design process. The methodology/approach of the fire PSA to overcome many challenges specific to new-build plant designs such as a lack of detailed design and operational information significantly contributed to the development and use of the full scope PSA for the UK ABWR generic design development [10]. The fire risk assessment also highlighted the fundamental need for comprehensive, detailed and plant-specific design and procedural information to be made available as early as possible in the design process to facilitate a best-estimate assessment of the fire risk. The extent of this information as the design evolution progresses demonstrates how the process of risk assessment and feedback of insights into the design process is both iterative and progressive and this should be acknowledged and accommodated as part of the overall licensing process of any new reactor design.

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FIRE PROTECTION FOR NUCLAER POWER PLANTS DURING DISMANTLING AND FOR SITES WHERE RADIOACTIVE MATERIALS ARE HANDLED (OUT OF APPLICATION AREA OF ATOMIC ENERGY ACT)

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ABSTRACT

The construction, use and demolition of buildings is subject to authorisation in Germany. Generally, the local building authorities are responsible for these approvals.

As per the Regulation (EU) No 305/2011 [1], the building must be designed and performed according to the following regulations, namely that in the event of an outbreak of fire:

- the load-bearing capacity of the construction can be assumed for a specific period of time;
- the occurrence and spreading of fire and smoke within the construction works are limited;
- the propagation of fire to neighbouring construction works is limited;
- occupants can leave the construction works or be rescued by other means;
- the safety of rescue teams is taken into consideration.

Detailed regulations are outlined in the German federal states laws. Moreover, there are additional rules for buildings with extended hazards (e.g., Ministry for the Environment, State Office or District Government).

In addition to these general requirements for the construction of buildings, the handling of radioactive materials is also subject to authorisation. The superior authorities of the German federal states (e.g., regional authorities or regional council) are responsible for such approvals.

According to the German Radiation Protection Ordinance (StrlSchV) [2], provisions for firefighting have to be taken for the eventuality of a fire. The objective of these measures is to protect fire fighters against radiation. Detailed requirements on manual firefighting are specified in the German guideline for fire brigades FwDV 500 [3]. The StrlSchV specifies requirements for the limitation of the release of radioactive materials to the environment in case of any hazardous incident. The required measures are determined by the authorities. The occurrence frequency of an incident shall be considered. For quantification, the limits and planning levels of the radiation exposure of persons shall be taken into account.

Nuclear as well as non-nuclear regulations with respect to the necessary fire prevention measures have been promulgated (e.g., KTA 2101 [4] or DIN 25425 [5]) for single institutions that work with radioactive materials. Fire safety measures mostly consider the inventory of readioactive materials, which is described as a multiple of exemption levels according to the StrlSchV. The implementation of these measures assumes that the precautions required by the StrlSchV have been approved instead of given.

This paper discusses the aspects of building code requirements and the requirements of the protection against radiological consequences. It also examines the existing approach of considering the (radiological) hazard potential to determine fire safety measures, particularly for the protection of fire fighters and the environment.

INTRODUCTION

The construction and use as well as the demolition of buildings are subject to authorisation in Germany. Depending on the type of permission, the responsibility lies at the German federal, state or communal level. The building code legislative competence is at the state level (for example Bavaria or North Rhine-Westphalia) in Germany. The states therefore have passed their own state building code (BauO), for which the permits are issued by the local authorities.

In addition to the requirements for the approval procedure (procedural law), general technical requirements as well as detailed rules for the implementation of fire protection means (substantive law) have been taken into account in the state building code.

The aforementioned general requirements are also reflected in the state building code, according to which buildings are to be built and operated such that

- the occurrence of a fire is prevented;
- the spreading of fire and fire by-products such as smoke are prevented;
- the rescue of people and animals is ensured;
- effective firefighting is possible.

Supplementary regulations are issued by each German federal state for special building constructions the purpose of which is to provide minimum requirements for fire protection, taking into account structural characteristics, special risks or operational requirements. Many of the German federal states have separate regulations, e.g., for high-rise buildings, assembly occupancies and industrial buildings.

Apart from these general state building code requirements and supplementary regulations, the handling and storage of radioactive substances, among other things, may be subject to regulatory licensing and supervision. In Germany, further detailed requirements are given by the Atomic Energy Act (AtG) [6] and the StrlSchV [2]. The nuclide-specific exemption level of the radioactive substances is defined there. The license requirements are determined by the exemption levels for the radioactive substances.

Superior state authorities (e.g., Ministry for the Environment, State Office or District Government) are responsible for such permissions. Personnel must be authorised to handle radioactive substances. This relates to not only the nuclear power plants for energy production but also nuclear medicine and research buildings The AtG and the StrlSchV also specify the essential requirements that have to be met by the applicant during the approval procedure, construction, operation and dismantling.

According to the regulations mentioned above, preventive and protective measures must be taken with regard to the overriding objectives of radiation protection (protection of humans and the environment against ionizing radiation) that avoid unnecessary radiation exposure and reduce the dosage. From this, we deduce the following additional general requirements (in addition to Regulation (EU) No. 305/2011 [1]) with respect to fire safety:

- exposure to radioactive material has to be limited for a certain period of time;
- the spread of radioactive material via smoke or via an extinguishing agent has to be limited within the construction work;
- the release of radioactive materials to the environment of the plant has to be limited;
- measures for radiological safety at work have to be provided for the fire brigade.

The overriding and detailed requirements for fire protection in German nuclear power plants are derived from the Safety Requirements for Nuclear Power Plants [7] as well as from the KTA Standard Series on Fire Safety, KTA 2101 [4]. These regulations are taken as a reference when dismantling nuclear power plants, including nuclear fuel, as well as for the research reactors. Fire protection means for buildings in which radioactive substances are handled other than installations of the nuclear fuel cycle are regulated in various DIN standards (e.g., DIN 25422 [8], DIN 25425-3 [5], DIN 25460-3 [9]).

The fire protection means are determined separately as per DIN standards. The fire protection measures are defined in DIN 25425-3 (Radionuclide laboratories - Rules for preventive fire protection) [5] on the basis of hazard levels. These hazard levels are determined by the multiple of the exemption levels from the StrlSchV [2]. The hazard levels refer to the maximum activity values, whereby a differentiation is made between radioactive substances that are encapsulated and those that are not. The fire protection measures are defined in DIN 25422 (storage and keeping of radioactive materials) [8] depending on the activity classes. The activity classes are defined as in DIN 25425-3 [5] by multiplying the exemption levels defined in the StrlSchV [2]. The requirements also apply here according to the maximum overall activity. In DIN 25460-3 [9] (Hot cells, preventive fire protection), the fire protection measures are defined by protection classes. The assignment of the protection class to the fire protection measure depends on the releasability of the activity inventory and not on the maximum overall activity, as is the case in DIN 25422 and 25425-3.

The radiological risk potential, the physical and possibly the chemical properties of radioactive materials have to be considered when implementing these requirements in a fire protection concept.

In order to meet the aforementioned regulatory requirements and the additional general requirements for fire protection in an appropriate form, the installation must be classified on the basis of the radiological hazard potential. Furthermore, the effects on fire prevention as well as on firefighting (manual fire control) have to be taken into account accordingly. Regulations exist in Germany for all of these three areas that we discuss and examine in the following section.

Examination of the Existing Approach for the Definition of Fire Protection Measures

Classification

Nuclear power plants with light water reactors, where nuclear fuels are present in considerable quantities, require licensing according to the Atomic Energy Act [6]. The necessary fire protection measures are not specified in the high level Safety Requirements [7] and the KTA series 2101 [4] by the activity inventory of the available radioactive substances or their releasability. The entity of fire protection means shall ensure that the required safety functions of items important to safety including those for meeting radiological safety objectives in accordance with [7] are maintained, even in the event of a fire. To achieve this, the fire load and the ignition sources, the structur-related and system-related conditions, as well as the possibilities for fire detection and fire fighting have to be considered. In addition, fire protection means for personnel available on site are also provided, taking into account international standards. This protection goal-oriented procedure is maintained according to the requirements set out in the Decommissioning Guidelines [10] by the federal German regulatory body until the plant or parts thereof are no longer ppart of the application area of the Atomic Energy Act [6].

According to the German StrlSchV [2], humans and the environment have to be protected against the harmful effects of ionizing radiation resulting from radioactive materials used in nuclear facilities or installations. This protection goal also comprises protection against ionizing radiation caused by the release of radioactive materials during fires. A graduated approach is used here.

In order to quantify this protection goal, the StrlSchV [2] defines limits (for normal operation) or planned reference levels (for the accidental release of radioactivity) for human exposure to radiation. Regulations that define fire safety measures exist so as to prevent radiation doses above these limits during fires. With respect to the necessary fire prevention measures in nuclear facilities or installations, these regulations include, for example DIN 25422 [8], DIN 25425 [5], DIN 25460 [9] or FwDV 500 [3].

In these regulations, the amount of radioactive material permitted for use in a nuclear facility or installation is assigned to risk levels that are usually based on multiples of exemption levels according to the German StrSchV [2] and/or the volatility of the radioactive material. The exemption level defines how much Bq of a nuclide is subject to handling or storage.

An explicit validation of compliance with the limits or planning reference levels is usually carried out only in certain cases, for example when using a radioactive material with a high radiological risk.

Our experience has shown that the use of multiples of exemption levels to estimate the radiological risk potential of fires in nuclear facilities or installations is impractical in some cases. This is because exemption levels are based on exposure scenarios associated with the normal and safe use of radioactive materials, with accidents and with the disposal of radioactive materials. Basic dose limits of 10 µSv/a are assumed for the public. Since exemption levels are based on a variety of different scenarios, they only partially reflect the radiological risk potential of fires. This has been proven by an analysis we carried out for a radiochemistry laboratory.

In this analysis, we calculated the radiation dose for the public for approximately 400 radionuclides in different physical/chemical forms caused by the release of radioactive material due to a fire in the radiochemistry laboratory. This meant we had to derive the activity (so-called "risk potential limit") of each radionuclide at which the accident planning reference levels according to § 50 and § 49 StrlSchV [2] (50 mSv for the effective dose) are reached. The risk potential limit thus quantifies the radiological risk of a radionuclide in the radiochemistry laboratory being released in the fire scenario used in the analysis. Figure 1 shows the maximum risk potential limit plotted against the exemption level of all radionuclides used in the analysis. Hence, every point in Figure 1 corresponds to the ratio of the risk potential to the exemption level of a single radionuclide.

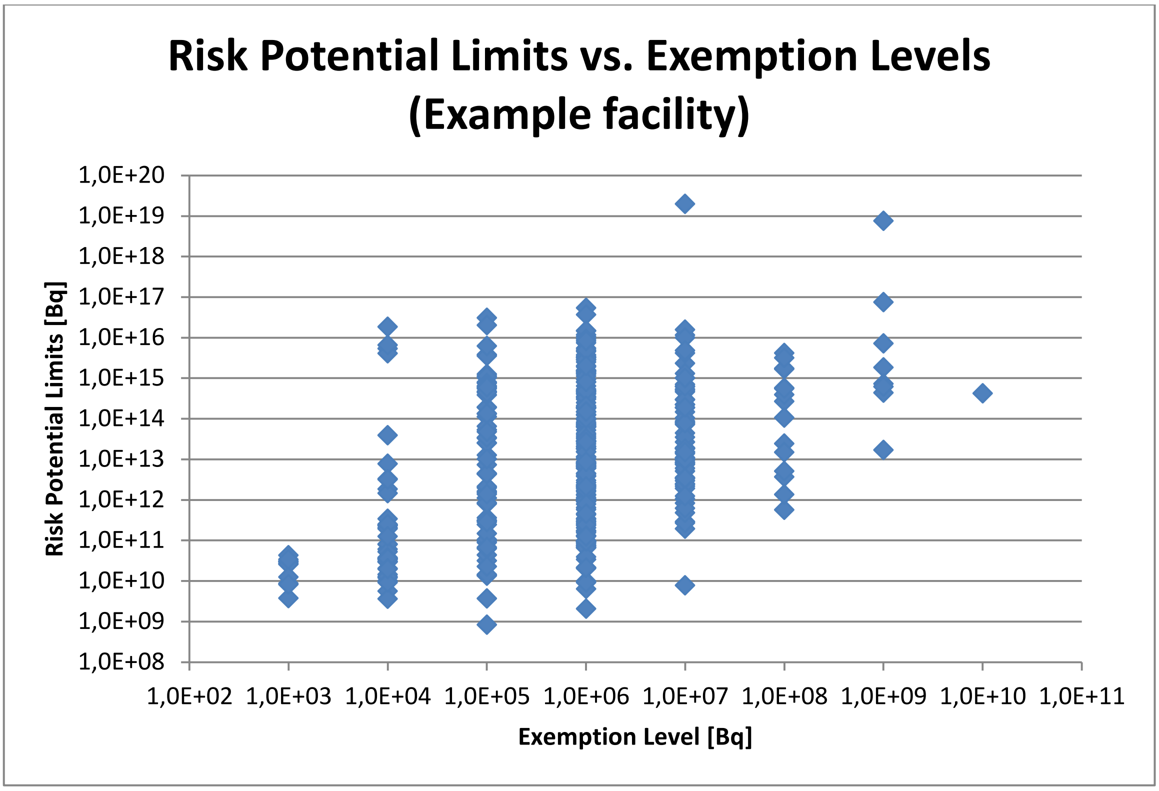

Figure 1 Risk potential limits (see text for explanation) vs. exemption levels

Figure 1 shows that for radionuclides of a certain exemption level, the radiological risk due to a fire in this radiochemistry laboratory can differ in many orders of magnitude. For example, the nuclides of the exemption level 1.0 E+06 Bq have risk potential limits in the range from roughly 1.0 E+09 Bq to 1.0 E+17 Bq, although they are treated as equal in DIN 25422, DIN 25425 [5], DIN 25460 [9] and FwDV 500 [3].

The exemption levels only reflect the potential radiological risk of a radionuclide in the event of a fire to a limited extent.

In order to avoid an underestimation as well as an overestimation of the radiological risk of radioactive materials in nuclear installations, fire safety means should be derived not only from the multiple of the exemption levels of the radionuclides used but also from a radiological dose analysis that considers the radionuclides used in individual fire scenarios.

Integrated standard scenarios and limit values for dose loads have to be defined to determine the limitations of the inventory. However, since the general approach does not take plant-specific boundary conditions into account, site-specific boundary conditions should be included. These could be, for example, the mobilization of radioactive substances, accounting for the specific form, the restraint facilities / characteristics and the location of the installation in relation to the surrounding facilities (danger to further persons).

Fire Prevention

The risk of a fire should always be assumed (cf. Higher Administrative Court Münster 10A 363/86 [11]). Adequate fire protection measures must therefore be defined that meet the aforementioned general requirements of Regulation (EU) No 305/2011 [1] as well as the additional general requirements derived from the protection objectives of the StrlSchV [2]. According to [7], priority is given to passive measures over active measures in principle. The structural fire protection means are therefore of particular importance. Structural fire protection means are important for storage rooms or laboratory areas where radioactive substances are handled as well as for escape and rescue routes.

The respective regulations also include provisions regarding the implementation of plant-specific fire protection measures, for example fire detection features, smoke and heat extraction equipment, considering the hazard level, along with the structural fire protection means.

In order to define a fire protection concept with adequate fire protection means, the radiological risk potential as well as the physical, and possibly chemical properties of the radioactive material have to be considered. These requirements are more stringent than the normal building code designed to help reduce the release of radioactive materials by mitigating the effects of a fire.

If the fire protection means implemented in a given nuclear facility or installation comply with the requirements provided by the DIN-standards, it can safely be assumed that the radiological risk of a fire is sufficiently minimized, even without any direct validation.

A limit value from the additional requirements is indispensable for the development of a fire protection concept. In the previous DIN-standards, there is no direct reference to individual fire protection means required to minimize the radiological consequences of a fire. The identification of an appropriate of a measure is based on the quantity of radioactive substances. The advantage of this approach is a simple and general determination of additional fire protection means for a plant without analysis of individual case considerations. The disadvantage is that the specific boundary conditions are not addressed here. It is not possible to make an optimal assessment with regard to the protection goals of the StrlSchV [2] and the additional general requirements. A further protection goal-oriented approach, similar to KTA 2101 [4], which takes into account those scenarios that are likely in reality, should be discussed.

Fire Defence

Fire defence comprises a variety of active measures. According to the terms of the radiation protection ordinance, the necessary measures for the preparation of fire-fighting shall be planned with the relevant state law. According to the German requirements for decommissioning, tasks and responsibilities of the onsite fire brigade may change as soon as decommissioning has started and demolition of the plants has started. During this phase, the public fire brigade may be responsible for several activities the onsite fire brigade has carried out before in case an onsite fire brigade is no longer available.

The required performance and the corresponding equipment of the public fire brigade have to be ensured by the local authorities. However, the attendance time (cf. Proceedings of SMiRT 20, 11th International Seminar on Fire Safety in Nuclear Power Plants and Installations [12]) can change considerably. It is therefore particularly important that the public fire brigade will be alerted in due time.

Additional aspects have to be considered in installations handling radioactive substances in Germany. According to the requirements provided in the StrlSchV [2], preparative measures for firefighting have to be taken into account. § 52 of the StrlSchV stipulates that the operator and the responsible authority, according to federal German state law, have to plan the corresponding measures. Areas containing relevant quantities of radioactive substances must be assigned to a hazard group and marked accordingly. A hazard group is classified based on the restrictions pursuant to the StrlSchV [2]. In this case, hazard group I is assigned to areas in which the total activity is no higher than 10^4 of the exempted level, hazard group II refers to a total activity not exceeding 10^7 of the exempted level and hazard group III to a total activity of more than 10^7 of the exempted level.

The general procedure during firefighting interventions is regulated by diverent German guideline for fire brigades FwDV. Tactical planning for an ABC application (A for operations with radioactivity, B for operations with biological dangers and C for operations with chemical hazards) is required by FwDV 500 [3] and depends on the operation scenario. Basically, a differentiation is made between operations to minimise the spread of damage and operations for human rescue. Depending on the hazard group and the expected danger in the fire location (e.g., thermal steam, contamination by solid substances, impact by dangerous gases or steams), different types of protective clothing have to be provided to the fire brigade in charge. A normal protective suit can basically be used for applications in rooms that are classified in hazard group I. A contamination protection hood for the neck and head area has to be worn in addition to the normal protective equipment in rooms that have been classified as hazard group II. Extended contamination protection becomes necessary in rooms that have been classified as hazard group III. In addition to the protective suit, at least one personal dose meter and a dose warning device have to be carried during the application as special equipment.

The objective of this approach is to provide adequate fire protection means for the fire brigade. As in the case of preventive fire protection, the chosen hazard group should also represent the real risk potential of the existing radioactive substances. It is useful to not only include the general classification in a hazard group but also specific considerations of the real situation (see section “Classification”) for an optimum determination of radiological safety measures for the fire brigade at the workplace. This is determined on the one hand by the general properties of the radioactive substances and, on the other hand, by the real conditions.

If radiation exposure within the scope of fire control cannot be avoided, dosage references are defined in the FwDV 500 [3] to protect the operating forces against ionizing radiation. Rescue measures may only be carried out by volunteers over the age of 18. To avoid dangerous situations for a person, the effective dosage shall not exceed 100 mSv in any particular calendar year and 250 mSv over an entire lifetime. The aforementioned reference values must be taken into consideration for any protective equipment.

CONCLUSIONS

In summary, it can be concluded that the applicable regulations and therefore the requirements with respect to fire protection as well, do change during decommissioning of nuclear power plants. The respective regulations, which also serve for establishments, in which radioactive substances are being treated, have to be considered for nuclear power plants during shut down, which are released from the German Atomic Energy Act (AtG). These provisions include a procedure that allows to take appropriate and reliable measures for fire prevention and defence.

A classification of the radioactive substances provided for treatment or storage is important to determine the necessary fire protection means. The orientation on the multiple exemption levels give a valid value for protections means, but the conclusions are often not so definitely with respect of fire protection means. The categorization for fire protection means could be specified on basis of nuclide-specific determination. Thereby the appropriateness of the fire protection means could be improved with respect to the radiological consequences for humans and the environment and therefore also for the life of the working operatives of the on-site fire brigade. Furthermore, location specific basic conditions should be considered when determining additional fire protection means for areas with radioactive substances as well as for the measures for radiological labour protection for the fire brigade.

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DEVELOPMENT OF A LOW PRESSURE WATER MIST SYSTEM TO ENSURE FUNCTIONALITY OF LOW VOLTAGE CABLES

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ABSTRACT

Complete physical separation of normal and low voltage cables with fire barriers is often rather difficult to implement and complicates the installation of new cables. Therefore, the option of significantly enhancing the fire protection effectiveness by adding or improving existing protection with fire detection and automatic suppression systems is developed.

An existing low pressure water mist system initially developed for the protection of cable trays in cable tunnels has been adapted to protect cable trays (high voltage cables were not considered). Actuated with early warning detection, the engineered low pressure water mist systems is tested for its ability to extinguish a fire on a cable tray, and, most importantly, is successfully tested to cool sufficiently ‘protected’ cable trays from a nearby fire in order to ensure cable functionality. In order to set up a life test case for the latter, a four step methodology and Computational Fluid Dynamics (CFD) simulations have been used.

After extensive engineering development and testing it can be concluded that fast detection in combination with a low pressure water mist system can be considered as a trustworthy alternative to ensure cable functionality when compared to classic physical separation systems.

In this paper, the approach used to define test conditions and facility for a low pressure water mist system as new automatic fire suppression system is presented.

INTRODUCTION

Adding passive protection (fire barriers) to cables is often a challenging task when retrofitting such passive protection systems in existing situations. Moreover, the installation of new cables in the cable trays with passive fire protection is complicated. Therefore, adding or improving active protection with fire detection and automatic fire suppression systems (low pressure water mist) in order to protect the functionality of cables is investigated. It will be shown that such approach provides an alternative to the installation of fire barriers.

The development of the approach and testing of the low pressure water mist system is further depicted.

The remaining of this paper is dedicated to the challenging development of the physical protection which is based on the use of fire detection and automatic suppression systems. To test these systems, a design fire is depicted based on fire engineering insights and CFD simulations. The Society of Fire Protection Engineers (SFPE) Conceptual Design Procedure for Fire Protection design is used as coherent backbone for outlining this performance based fire protection strategy.

Define Project Scope

A fire impairing the functionality of cables must be avoided. The fire can originate from a nearby cable or from a remote fire source (fire exposure).

Identify Goals

The main goal is to ensure the physical separation in case of a single fire.

An advantage of this easy to install system is that it can be helpful to physically separate cables with different polarities or functions.

Define Stakeholder and Design Objectives

Since the use of fire barriers to maintain the functionality of cables with different function or polarities in case of fire is rather difficult to implement and complicate the future installation of new cables on the protected cable trays, it is preferred to significantly enhance the fire protection effectiveness by adding or improving existing protection with fire detection and automatic suppression systems.

Fire Detection Technology Selected

Often rooms are only equipped with automatic fire detection systems with point detectors. These systems can detect a fire due to the presence of smoke and/or abnormal heat or flames. In addition to these systems, fast and adequate fire detection systems are needed to activate early a suppression system. The combination of the following types is considered to protect cable trays:

- Linear heat fire detection systems for cable routes: these systems detect an increase in temperature due to a fire;
- Flame detectors: this is an optical device (sensor) for detecting fire flames;
- Aspiration smoke detection (ASD): this is an active smoke detection system that operates on air suction. The air is passed through a piping system to a central detector which analyses the smoke particles present in the sample. Due to the active suction, detection will take place much quicker than with point detectors;
- Video smoke detection (VSD) system: this is a system using special software to transform a surveillance camera to a highly reliable smoke detection system.

The additional fire detection systems relate to the separation of cables. Such fire detection systems have to be installed in combination of the low pressure water mist system to achieve the above mentioned goals.

Definition of the Test Configurations for the Low Pressure Water Mist System Used as Additional Fire Suppression System

In the framework of the investigation to find an alternative for physical separation, an existing low pressure water mist system initially developed for the protection of cable trays in cable tunnels has been adapted. Such system was initially not designed for this purpose. Therefore, specific engineering and testing were required.

The main idea was that such system, activated with early warning detection, is:

(1) Able to extinguish a fire on a cable tray (with additional functionality test);

(2) Able to cool sufficiently ‘protected’ cable trays from a nearby fire in order to ensure cable functionality.

Both conditions were successfully proven by test.

The approach used to define the test configurations is detailed in the following sections.

System “Suppression” Test (1)

The test configuration for the first testing (1) was composed of a steel framework test rig. The ceiling was realized by means of aerated concrete slabs that were applied between the flanges of steel H-shaped beams. At one side, the configuration was closed by means of a wall composed of aerated concrete bricks. A schematic side view of the general configuration is depicted in Figure 1.

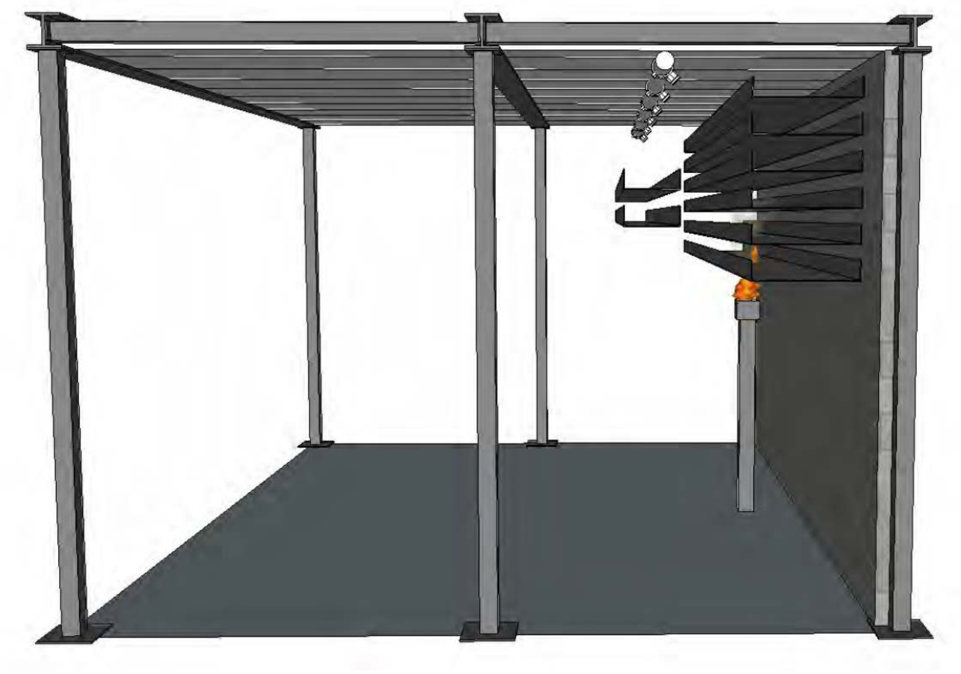

Figure 1 Side view of the test configuration

In total eight steel cable trays were installed. Six steel cable trays (width 600 mm; height 110 mm) were installed above each other with a hart-to-hart distance of 200 mm. The six steel cable trays were installed at a distance of 80 mm from the wall made out of aerated concrete. The distance between the bottom of the upper cable tray and the ceiling was 210 mm. Two steel cable trays (width 300 mm; height 110 mm) were installed above each other with a hart-to-hart distance of 200 mm. These two cable trays were installed at a distance of 300 mm from the above mentioned six cable trays. The distance between the bottom of the upper cable tray to the ceiling was 750 mm. The latter cable trays block the sprinkler pattern on the six cable trays. A calcium silicate board was fixed to the underside of each cable tray (thickness 8mm; width of the cable tray), blocking the spray pattern and counteracting the formation of mist. No such board was present on the lowest cable tray, as such promoting ignition and initial burning.

Figure 2 Build-up of the test configuration

At a distance of 1200 mm from the aerated concrete wall, the pipe of a low pressure water mist system, including six nozzles (K-factor 10, spray angle 120°, hart-to-hart distance 1100 mm), was fixed to the aerated concrete ceiling in such a way that the axis of the nozzles was situated at 1110 mm from the wall, oriented under an angle of 45 °C to the horizontal. The water supply was assured by means of a water tank and a pump in order to obtain a pressure of 4 bar at the moment the nozzles are activated and a total volume flow of the water of approx. 120 l/min (i.e. 20 l/min per nozzle).

All the cable trays were completely filled with cables of different types (50 % PolyVinylChloride (PVC), and, 50 % PolyEthylene (PE)). The load was approx. 75 kg/m.

For the first testing (1), the fire source was a propane burner controlled according to the requirements in ISO 9705-1:2016 [8] (Room Corner Test).

The Heat Release Rate (HRR) of the burner is set to 250 kW. The fire source (100 x 100 mm²) was applied in the middle of the test configuration and the surface of the burner was located 300 mm below the lowest six cable trays configuration. The procedure and pass/fail criteria are based upon the Technical Specification CEN/TS 14972:2011 [9]. After 5 min, the burner was switched off and the water mist system was switched on. The end of the test was set at 20 min.

The test method to evaluate the ability to maintain circuit integrity of the PE-electrical cables under fire conditions is based upon the Belgian Standard NBN 713.020 add.3 [10] (Edition 1994) and the European Standards EN 50577:2015 [11] (non-protected electrical cables) and prEN 1366-11:2017 [12] (protected electrical cables). The applied circuit diagram is given in the figures below.

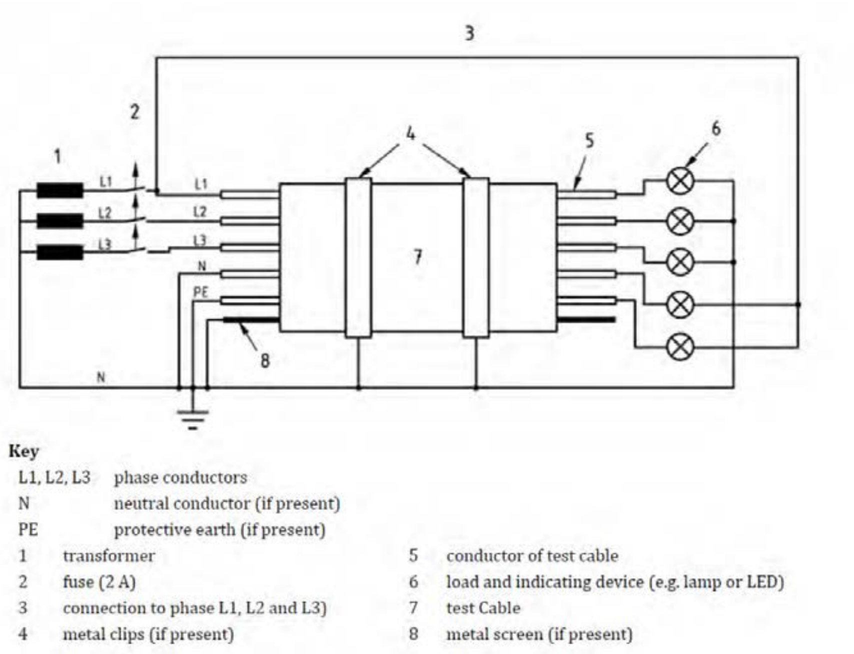

Figure 3 Basic circuit diagram (Figure 6 in EN1366-11:2017 [12])

Figure 4 Circuit control rack of the fire test

The following results were obtained:

- The circuit integrity of the electrical cables is maintained during the complete duration of the fire test.

- 5 min after activation of the low pressure water mist system, the gas temperature 100 mm below the ceiling is less than 100 °C.
- No flaming at either ends of the cables.
- No visible flames at the end of the test.
- No re-ignition of the cables during 15 min after the test is terminated.

After 5' 00" | 1' 30" after activation of the water mist system

Figure 5 Observations during test

System Test to Verify the Ability to Cool the Cables (Keep Functionality) in Case of Fire Exposure (2)

The remaining of this paper deals with the development of the test setup for (2). The development of the configuration and the design fire was done using CFD modelling and pre-testing of the fire source. It was done independently of the application of the water mist system.

For the presented example situation, selected based on considered worst case fire scenario's, a total of 13 cable trays are considered to burn simultaneously (i.e. the fire source) as illustrated in Figure 6. More details regarding the cable trays are presented in Table 1. It must be pointed out that high voltage cables were not considered.

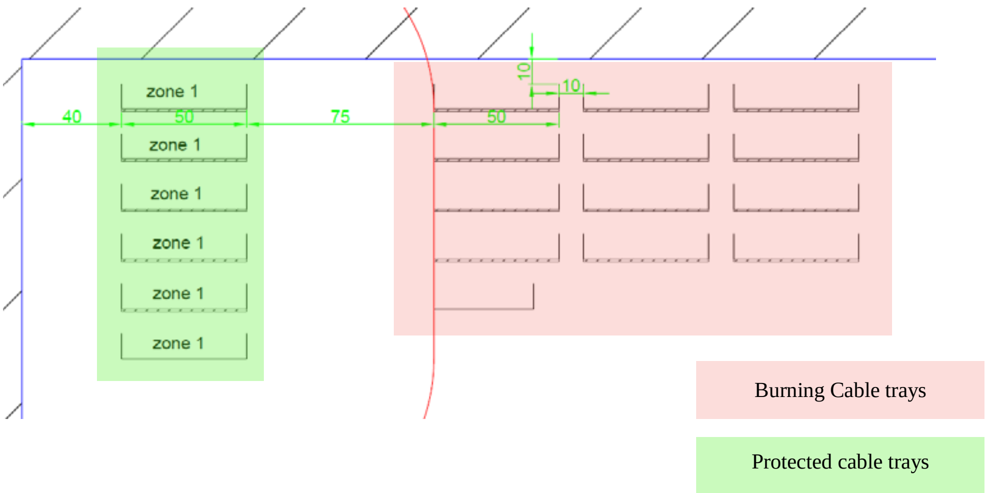

Figure 6 Cable trays configuration for the example case

Test Specifications

After the equivalent burning behaviour was shown between the real full scale situation (example case above) and the test case (without considering water mist), a test procedure and pass/fail criteria based upon the Technical Specification CEN/TS 14972:2011 [9] was developed. After a conservative time period of 2 min the water mist system was switched on. The test ended at 53 min and 20 s. The latter timing is based on the complete burning of the burning cable trays.

The test was successful because the circuit integrity of the electrical cables was maintained during the complete duration of the fire test.

DETERMININITION OF THE TEST CONFIGURATION FOR THE LOW PRESSURE WATER MIST SYSTEM IN ORDER TO KEEP FUNCTIONALITY IN CASE OF FIRE EXPOSURE

A four step methodology has been used for this study, as illustrated in Figure 7.

As a first step, cable tray fires were studied in more detail in order to determine the representative cable tray configuration and to determine the parameters values for the CFD (FDS) input. As a second step, a large scale simulation was conducted which represents a real scale fire scenario. Within step 3, a test facility construction was proposed so that the heat impact on the target cables is similar with that of the large scale simulation. In the final fourth step, a pool fire was dimensioned in order to replace the cable fire source during the real test.

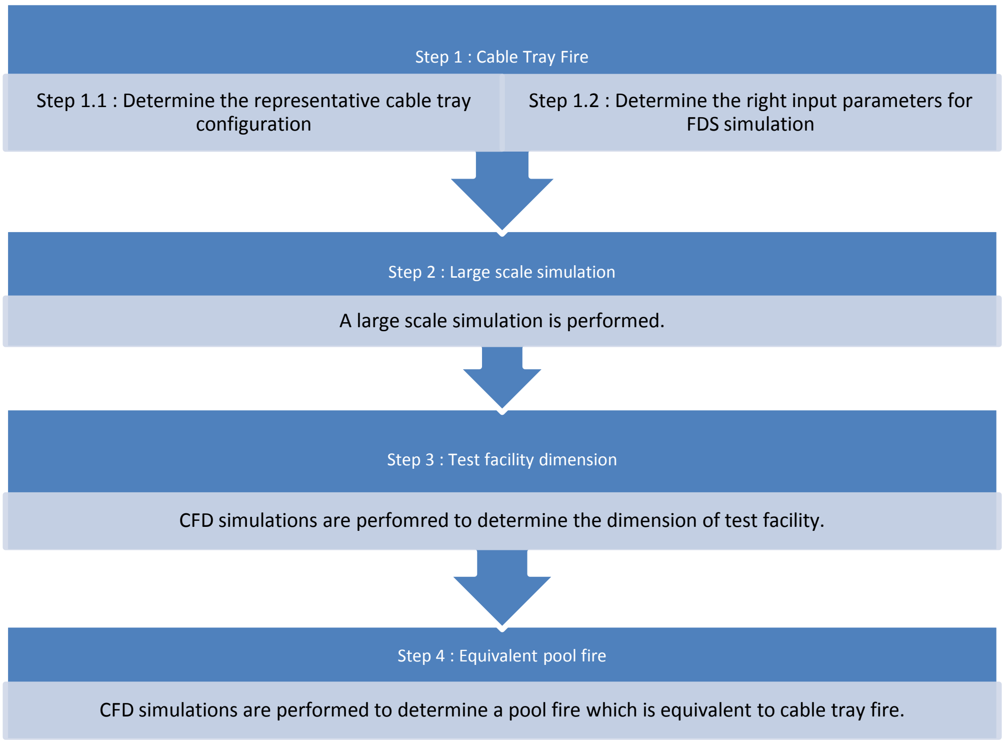

Figure 7 Overview of the main steps in developing the fire design scenario

Develop Design Fire Scenarios (Step 1)

As a first step, a cable tray fire is considered where the suppression system can be installed to protect selected cables from a nearby cable tray fire (step 1.1). The number, width and location of the cable trays can have a large impact on the HRR. As such, a representative cable tray configuration is determined when considering the system description (Figure 6). Based on fire load mapping and visits on the example location, the cable tray configuration representing the most severe fire scenario can be determined.

Besides the cable trays configuration, the heat of combustion, flame spread rate and cable insulation materials have a large impact on the HRR. Small scale simulations were performed in order to make conservative choices of these parameters (step 1.2). These values were used as input for the large scale CFD simulation.

Table 1 Characteristics of burning cable trays for the typical case (step 1.1)

Parameter	Value
Number of cable trays	13
Width of cable trays	12 x 50 cm-wide cable trays, 1 x 40 cm-wide cable tray
Horizontal distance between cable trays	10 cm
Vertical distance between cable trays	75 cm
Minimum distance to the protected selected cable trays	75 cm
Loading	Fully loaded
Cable insulating material	50 % PVC + 50 % PE

Cable Trays Simulation (step 1.2)

The first step is to determine the best method to model cable trays fire. Various scenarios are performed to determine the right input parameters. The input parameters are always chosen from a conservative perspective to avoid the influence of uncertainties.

<u>List of Scenarios</u>

Table 2 Scenario description

Scenario No.	Description
Scenario 1	Base case scenario: All the input parameters are taken from literature study for cable fire.
Scenario 2	Flame spread rate is taken as 9 mm/s for cable fires in confined space.
Scenario 3	HRR per unit area (HRRPUA) from the OECD PRISME 2 tests [1], [2] is used. Flame spread rate of 9 mm/s is used.
Scenario 4	The cable tray fire is modelled using ignition temperature.

Geometry

The geometry of the FDS model is shown in Figure 8. As the purpose of this step is to find the applicable input parameters for FDS simulation, other geometry details such as walls and ceiling are not considered in sensitivity studies.

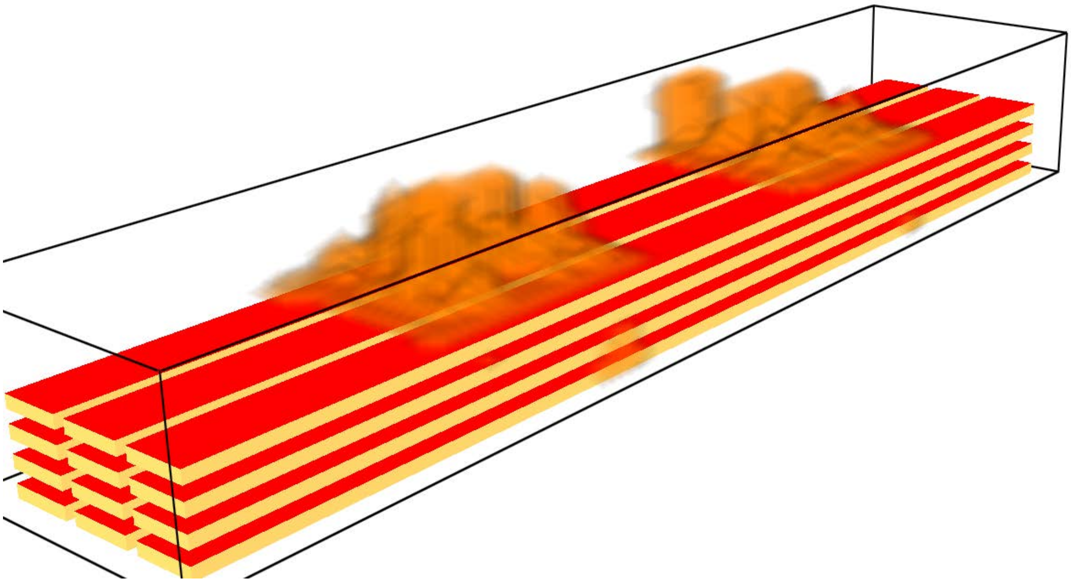

Figure 8 Geometry of the cable trays model

For all simulated scenarios, the validation is checked according to an internal quality assurance system based on the FDS User's Guide [6] and NUREG/CR-1934 [7] recommendations. Sensitivity was performed accordingly.

Scenario 1

Input

The input for the HRR includes:

- The HRRPUA: 250 kW/m² [3]
- The HRRPUA developing curve (Each FDS cell burning surface will have the HRRPUA curve after ignition) [4] shown in the following Figure 9:

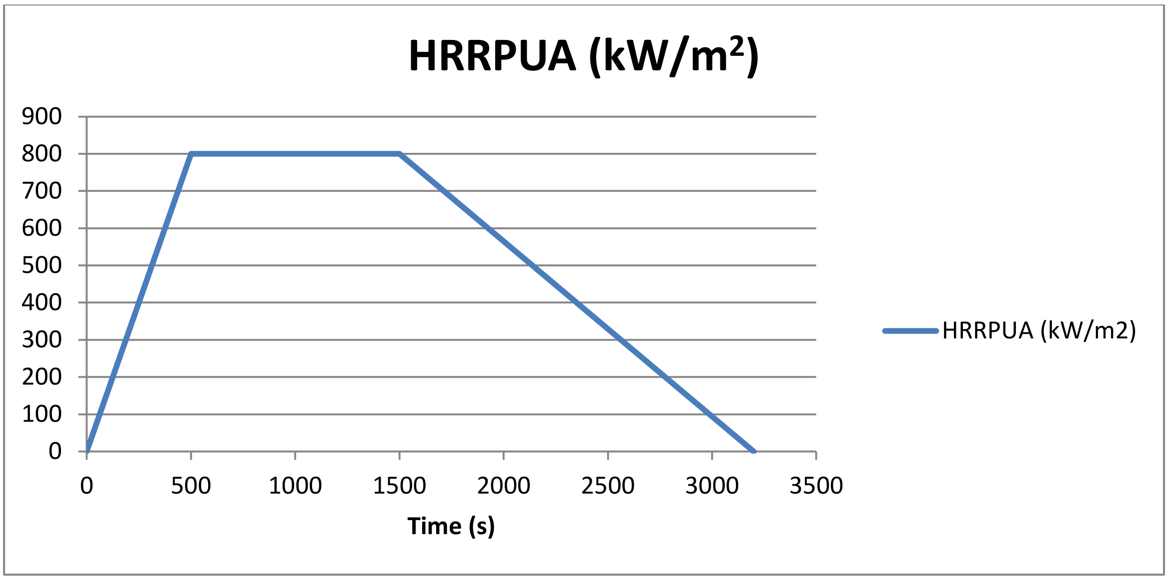

Figure 9 HRRPUA for Scenario 1

- Free burning cable trays with horizontal flame spreading rate of 0.9 mm/s [3];
- Geometry: 3 * 4 cable trays;
- The cable fire is defined as 'spreading fire', which means that cables are ignited at the specified location and then flames spread horizontal to both sides at a rate equals to 0.9 mm/s.
- Boundary condition: open boundaries.

Results

The heat release rate of Scenario 1 is presented in Figure 10. The HRR reaches a steady state after about 2500 s.

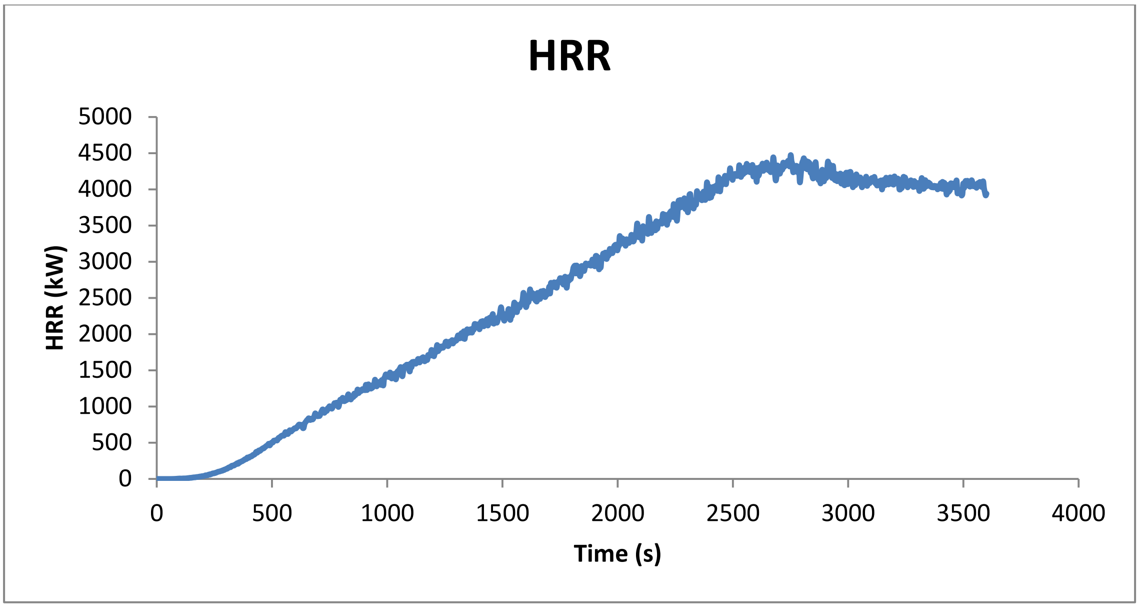

Figure 10 HRR - Scenario 1

Scenario 2

<u>Input</u>

The horizontal flame spread rate depends on cable insulating material and burning environment. Higher flame spread rate will lead to larger area of cable trays to burn simultaneously. Scenario 2 aims to investigate the effect of horizontal flame spread speed on the HRR.

The input remains the same as in scenario 1, except that the horizontal fire spreading rate is taken as 9 mm/s.

The recommended value given in NUREG [5] for flame spread rate is given in Table 3 for reference.

Table 3 Flame spread rate for cable trays

	Thermoplastic	Thermoset
Open atmosphere	0.9 mm/s	0.3 mm/s
Confined space	9.0 mm/s	3.0 mm/s

<u>Results</u>

The heat release rate of Scenario 2 is presented in Figure 11. Compared to Scenario 1, the HRR is 220 % higher. A higher flame spreading rate can be observed for cable fires in confined spaces, where smoke and heat can be contained and heat up the cable trays. As such, a higher flame spread rate can take into account cable fires in a compartment, which is the case for the test.

Based on the comparison of Scenario 1 and Scenario 2, the horizontal flame spread rate to be used in FDS simulation should be 9 mm/s instead of 0.9 mm/s.

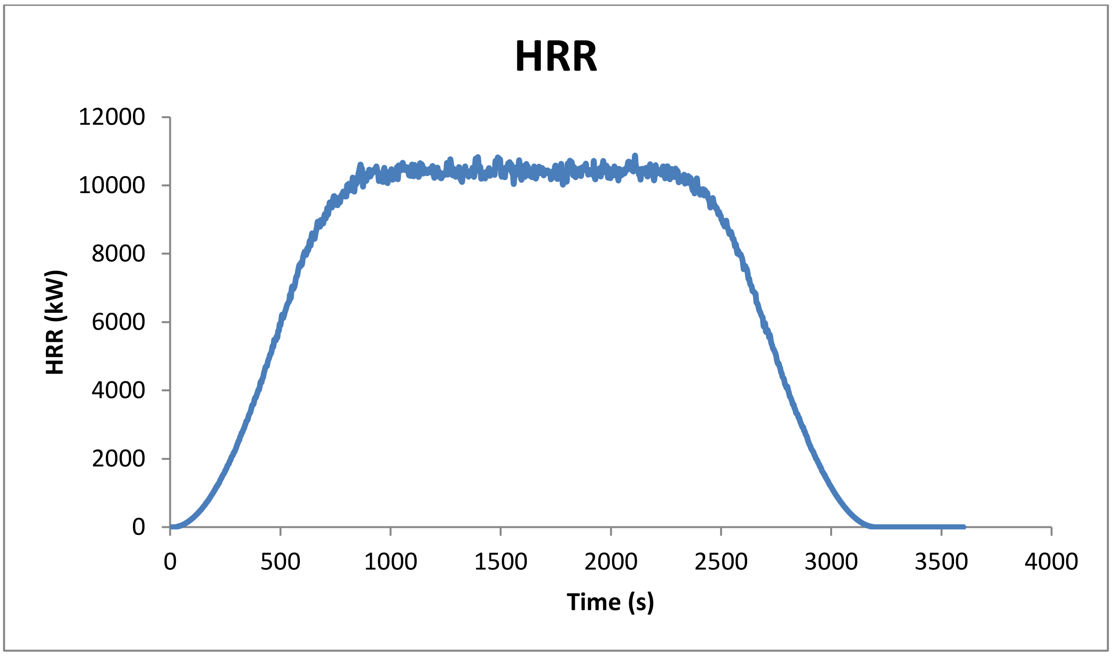

Figure 11 HRR - Scenario 2

Scenario 3

Input

The horizontal flame spread rate is taken as 9 mm/s.

NUREG [5]) recommends the following HRRPUA values: 250 kW/m² for thermoplastic cable tray fires and 150 kW/m² for thermoset cable tray fires. These values are representative values for all types of cables. Some cable tests have been conducted within the framework of PRISME 2 Project [1], [2]. The type of cables used in the PRISME 2 tests is more representative of the NPP cables. Therefore, the HRRPUA values from PRISME test were used.

Four different types of cables were tested within the PRISME 2 tests, their HRR/HRRPUA are shown in Table 4.

Table 4 Maximum HRR and HRRPUA from PRISME 2 cable fire tests

Test	CFSS-1	CFSS-2
HRR [MW]	3.2	2.2
HRRPUA [kW/m2]	592	407

It is conservatively assumed that there is perfect mix of thermoset and thermoplastic cables. The resulting HRRPUA is shown in Figure 12.

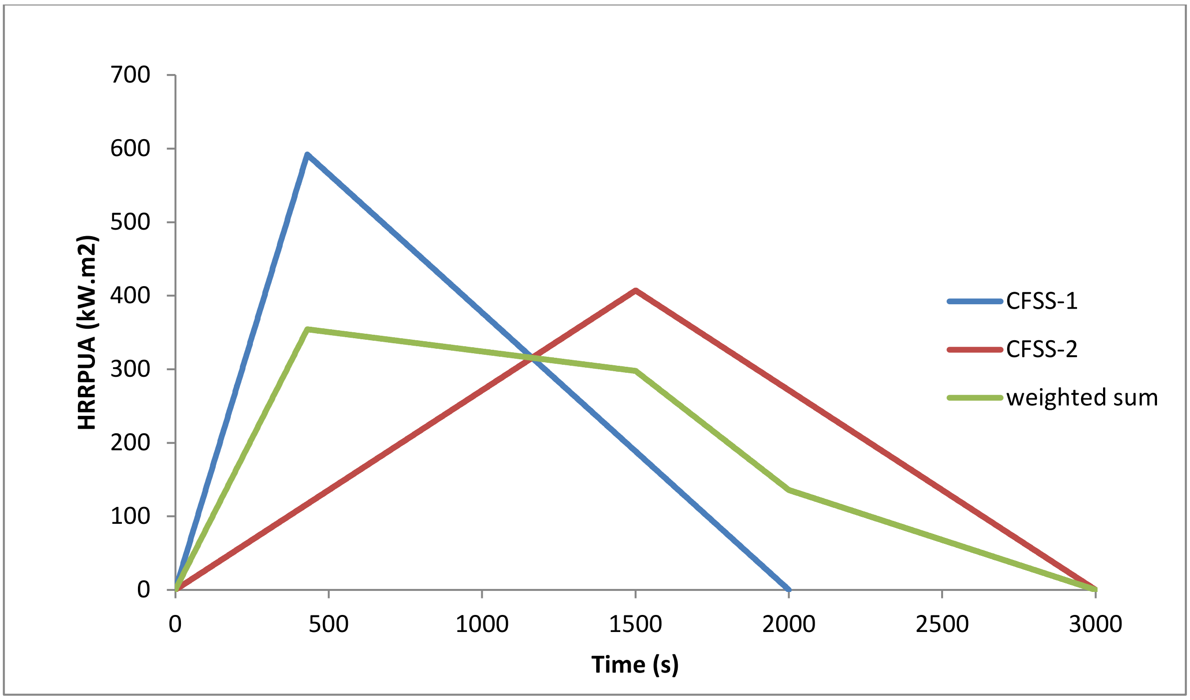

Figure 12 HRRPUA for Scenario 3

Results

The HRR of Scenario 3 is shown in Figure 13. With the adjusted HRRPUA, the HRR is higher and thus more conservative. The HRRPUA derived from the PRISME 2 Project will be used for further simulations.

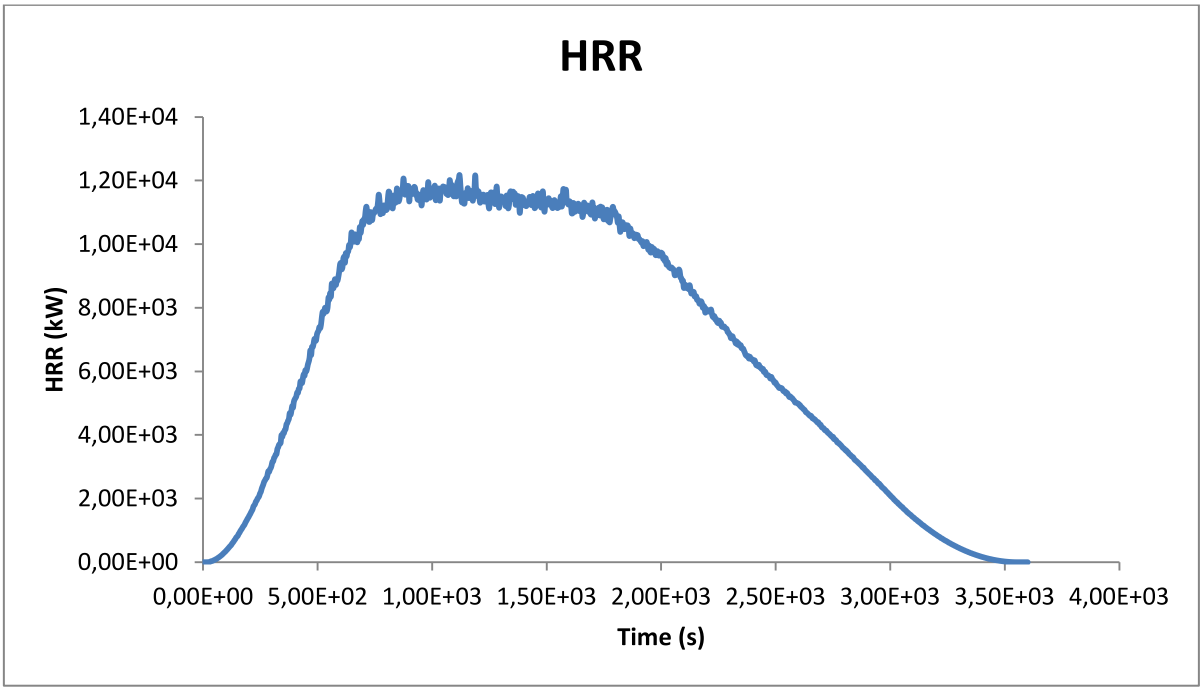

Figure 13 HRR - Scenario 3

Scenario 4

Cable trays fire can also be modelled by assigning ignition temperature. This method will use the pyrolysis sub-model of FDS. Scenario 4 uses this sub-model for CFSS-1 test. Figure 14 shows the fire development of CFSS-1 test.

This method is not suitable for predicting the HRR for the following reasons:

- The burning behaviour (spreading mode) is different from observations during the CFSS-1 test.
- There are several input parameters which are selected such that the FDS prediction and the test result match.

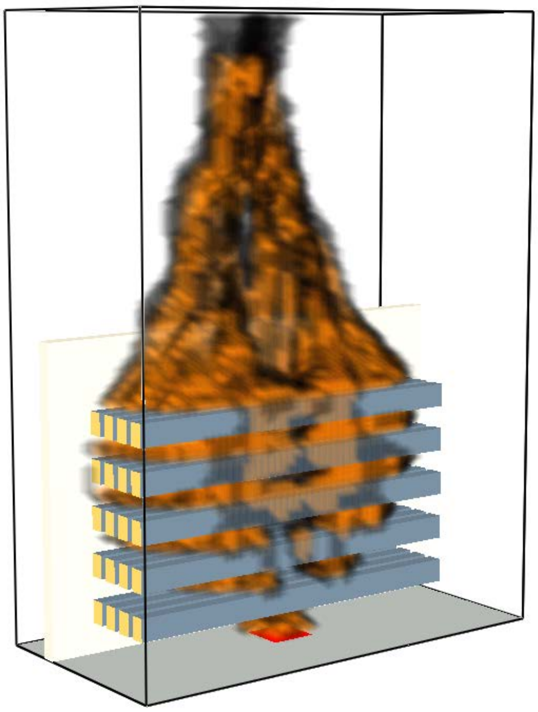

Figure 14 FDS simulation of CFSS-1 using pyrolysis sub model

Summary of Step 1.2

Based upon the above mentioned simulation results, the following cable CFD modelling approach was proposed:

- Spreading fire mode is selected to simulate cable trays fire.
- The HRRPUA input is determined based on the PRISME 2 tests.
- The PRISME test involves cables which are used in NPP and as such provide more representative data.
- The PRISME 2 test data are more conservative than the recommended value given in NUREG (250 kW/m²).
- The burning characteristics of thermoplastic and thermoset cables are different. It is assumed that the simulated cable tray contains a perfect mix of each type of cable. The HRRPUA is calculated considering both cables.
- Horizontal cable fire spreading rate is taken equal to 9 mm/s.

Develop Trial Designs (Step 2)

In this step, CFD tools were used to propose a test configuration which is representative real scale configurations.

A large-scale CFD simulation was required to assess the heat impact of a real cable tray fire on the selected cable trays.

The full length of the cable trays, as well as typical surroundings selected based on considered worst case fire scenario's, is included in the simulation. All parameters have to be considered in the simulation to predict an accurate smoke layer depth.

The results obtained from this simulation were then used as a benchmark to determine test facility characteristics.

The following outputs were in depth analysed:

- HRR;
- Maximum air temperature around the target cable trays;
- Maximum radiative heat flux on the cable trays;
- Maximum target cable tray temperature.

Evaluate Trial Designs (Step 3)

As it is impractical to build a test facility with the same dimensions of the rooms and annexes to be considered, extra walls were placed in such a way that smoke and heat can be contained within the test facility. By doing this, the heat impact on the target cable is similar to the one obtained using a large scale test facility.

Computer simulations were thus performed to define a test facility setup (Step 3) which can produce similar heat impact on the target cable trays.

The following parameters were studied:

- Location of a wall in order to determine a wall configuration which yields the highest heat impact on the target cable trays which was used for further simulations;
- Determination of the size of smoke barriers. Additional smoke barriers were investigated to be present around the facility to help containing smoke and heat. The dimensions of the smoke barriers were determined using the CFD simulations.

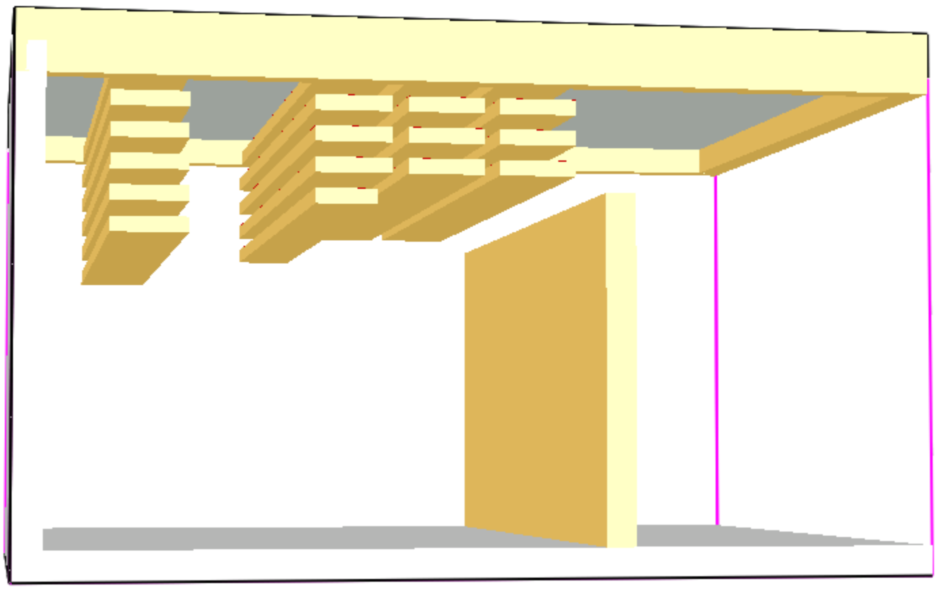

Figure 15 Illustration of wall and smoke barriers for the test facility

Definition of the Fire Source (Step 4)

As a 4th step, an equivalent pool fire (hexane on water pool with air injection representing a natural low velocity fire source) was used to safely operate the test, to control the HRRPUA and to ensure the repeatability of the tests. The dimension and location of the pool fire were determined such that the heat impact is similar to that of cable tray fires. Using CFD and pre-testing on the burner itself, the pool fire with adjustable HRRPUA was calibrated. This pool fire is shown to be equivalent to the cable tray fire using CFD simulations. It helps determining the location, size and HRRPUA of such pool fire under test conditions. Different scenarios were considered as shown in the following table. The burner is somewhat closer to the target cable trays in location 1 than it was for location 2 (the inverse hold for the distance between the burner and the added wall).

Table 5 List of scenarios - equivalent pool fire

Scenario No.	Location	HRR
Pool 1	Location 1	3400 kW
Pool 2	Location 1	3200 kW
Pool 3	Location 1	2900 kW
Pool 4	Location 1	2700 kW
Pool 5	Location 2	3400 kW
Pool 6	Location 2	3200 kW
Pool 7	Location 2	2900 kW
Pool 8	Location 2	2700 kW

<u>Results</u>

The results from the pool fire were compared to those from large-scale simulation in order to demonstrate the equivalence. “Pool 2” provided the best match.

For this scenario, the computed air temperature is slightly lower when the equivalent pool fire is used instead of cable tray. Nevertheless, this is compensated by a higher radiative heat flux. As a result, a similar cable surface temperature is obtained.

The fire intensity of the large scale simulation is higher during the delay phase (after 2000 s). However, since the steady state lasts for a long period (1500 s), a prolonged delayed phase was claimed not to have any influence on the functionality of the target cable trays.

Based on the CFD study result, the following test configuration is proposed:

The heat release rate of the pool fire is shown in Figure 16 (maximum HRR 3200 kW). In practice, the HRR of the pool fire is controlled by regulating the HRRPUA as shown in Figure 17.

In the FDS simulation no combustion efficiency was considered. In reality, the pool will burn with a given combustion efficiency α (~ 1 as determined by the laboratory). As such, the fuel supply rate was slightly adjusted accordingly so that the effective HRR from the pool fire is equivalent to the value used within the CFD simulation.

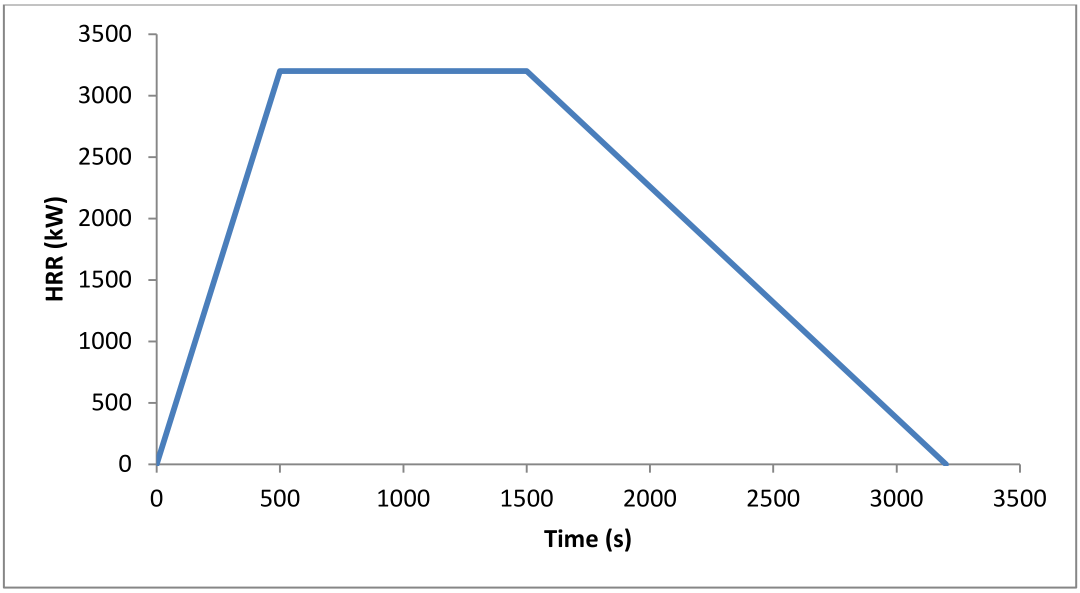

Figure 16 HRR of the pool fire to be used for test

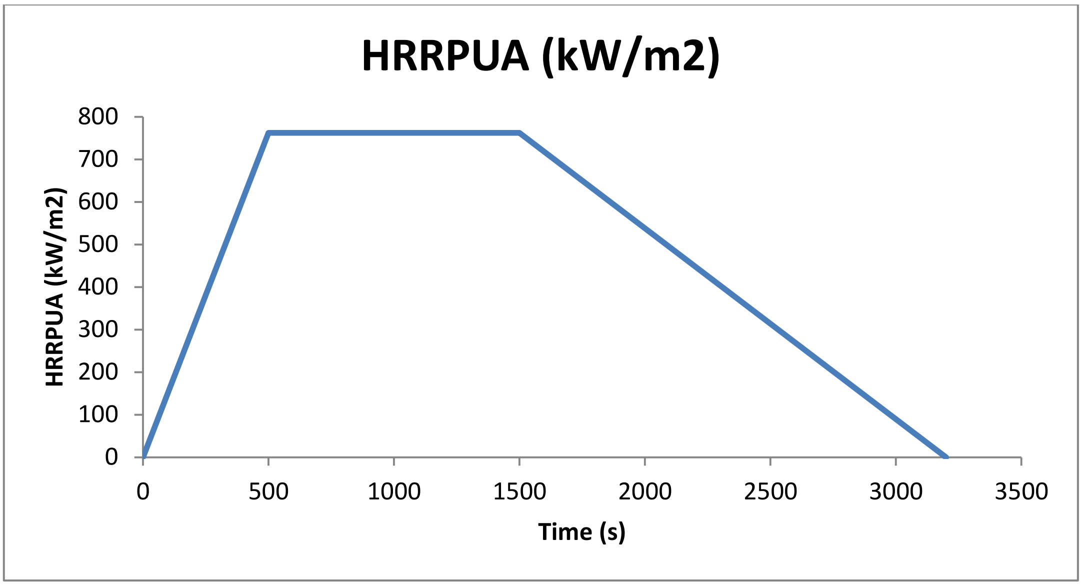

Figure 17 HRRPUA of the pool fire to be used for test

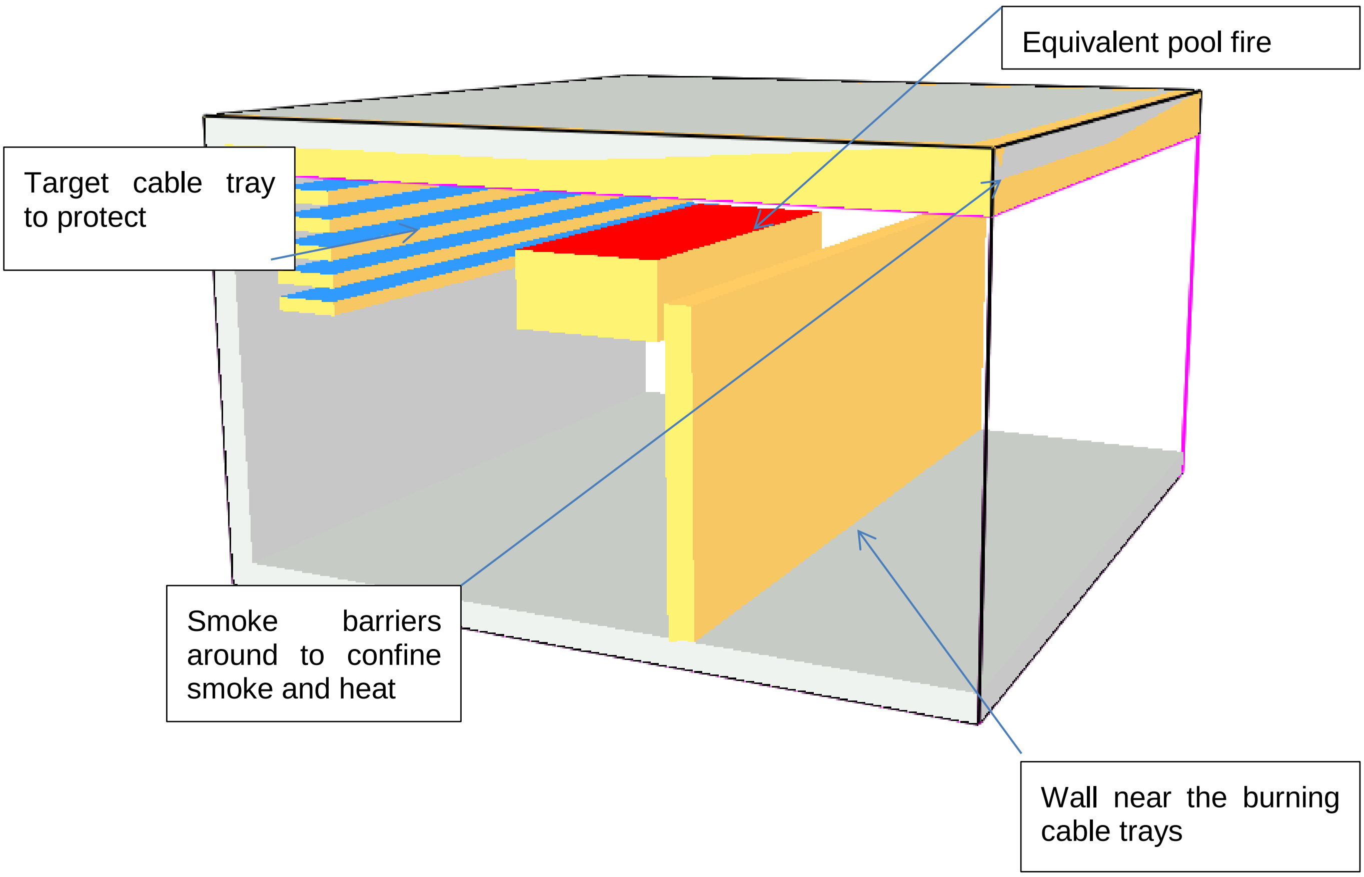

Figure 18 Proposed test configuration (The spray system is not shown in the figure.)

Test Configuration

A schematic view of the test configuration is given in the Figure 19 below.

The test configuration for the testing was composed of a steel framework test rig. The ceiling was realized by means of aerated concrete slabs that were applied between the flanges of steel H-shaped beams. At one side, the configuration was closed by means of a wall composed of aerated concrete bricks. The other three sides were open.

A smoke barrier of calcium silicate board (height 200 mm) was applied at the boundaries of the ceiling. An additional wall (width 6 m; height 2.5 m) composed of aerated concrete bricks (thickness 200 mm) was installed at a distance of 3.6 m from the wall closing off one of the side openings.

Six steel cable trays (width 500 mm; height 110 mm) were installed above each other with a hart-to-hart distance of 200 mm. These six steel cable trays were installed at a distance of 400 mm from the wall closing one of the opening sides. The distance between the bottom of the upper cable tray and the ceiling was 210 mm. A calcium silicate board was fixed to the underside of each cable tray (thickness 8 mm; width of the cable tray – joints between adjacent boards approx. 3 mm), blocking the spray pattern and counteracting the formation of mist.

At a distance of 1600 mm from the side wall, the pipe of a low pressure water mist system, including six nozzles (K-factor 10, spray angle 120°, hart-to-hart distance 1100 mm), was fixed to the aerated concrete ceiling in such a way that the axis of the nozzles was situated at 1510 mm from the wall, oriented under an angle of 45 °C to the horizontal. The water supply was assured by means of a water tank and a pump in order to obtain a pressure of

4 bar at the moment the nozzles are activated and a total volume flow of the water of approx. 120 l/min (i.e. 20 l/min per nozzle). This water mist system is switched on at 2 min from start.

In each of the six cable trays, two PE (PolyEthylene) cables of different type were tested on their ability to maintain circuit integrity.

The fire source is a liquid pool fire composed of hexane pumped into a steel tray filled with water. Since hexane is lighter than water, hexane floats on water. Pressurised air is also fed into the water and mixes with the hexane vapour directly above the fuel surface.

In order to obtain the required HRR, hexane was pumped into the water with a constant mass flow rate. The mass flow rate during the maximum HRR, i.e. 3200 kW, was 6.51 l/min (heat of combustion 44,752 kJ/kg, volumic mass 0.659 kg/dm³). Since it was practically not possible to follow the HRR curve (Figure 16), the mass flow rate of hexane was increased every minute (every 2 min during the decay phase) to follow the HRR curve as close as possible as shown in Figure 20 below.

The test method to evaluate the ability to maintain circuit integrity of the concerned electrical cables under fire conditions is the same as for the system "suppression" test (1).

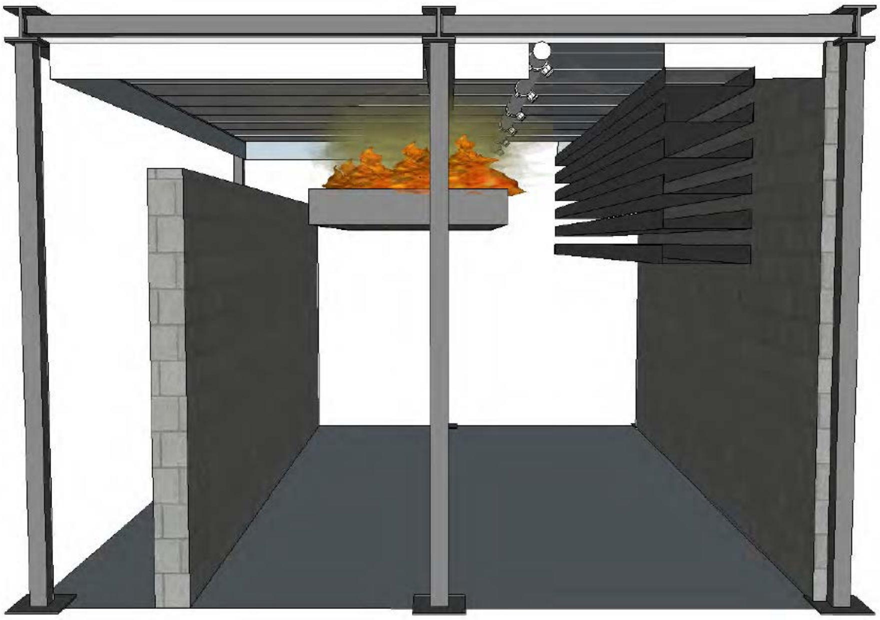

Figure 19 Side sketch of the obtained test configuration

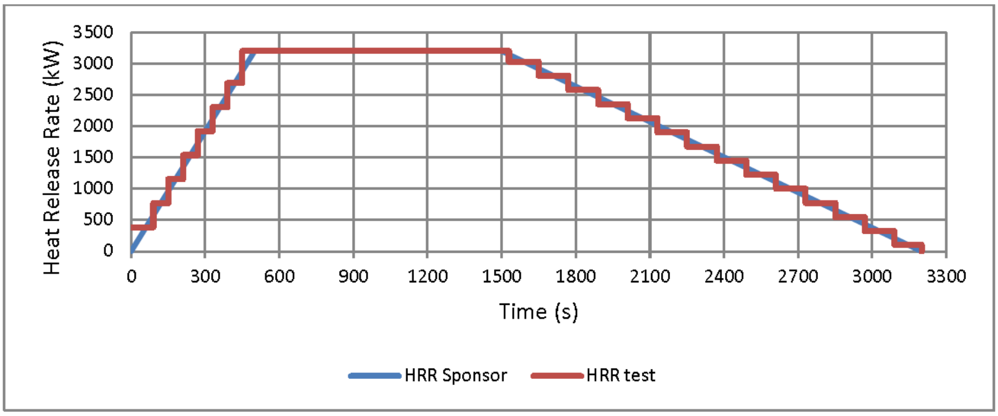

Figure 20 HRR of the burner during the test

The build-up of the test configuration is shown in Figure 21. Some observations during the test are depicted in Figure 22.

Side view of the test configuration

Side view of the test configuration

Figure 21 Side view of the test configuration

After 2' 00" (activation of water mist system)

After 15' 00" (left side)

Figure 22 Observations during the test

CONCLUSIONS

Since a complete physical separation of cable trays with fire barriers is rather difficult to implement and complicates the installation of new cables on these cable trays, the option of significantly enhancing the fire protection effectiveness by adding or improving existing protection with fire detection and automatic suppression systems was shown to be a trustworthy alternative.

Indeed an existing low pressure water mist system initially developed for the protection of cable trays in cable tunnels is adapted to protect cable trays (high voltage cables were not considered). Actuated with early warning detection, the engineered low pressure water mist systems is tested for its ability to extinguish a fire on a cable tray, and, most importantly, is successfully tested to cool sufficiently 'protected' cable trays from a nearby fire in order to ensure cable functionality. In order to set up a life test case for the latter, a four-step methodology has been used. First, cable tray fires were studied in more detail in order to determine the most representative cable tray configuration and to determine parameters values for the CFD input. As a second step, a large-scale simulation was conducted which represents the real scale fire scenario. Thereafter, a test facility construction was proposed so that the heat impact on the target cables is similar with that of the large scale simulation. In the final fourth step, a pool fire was dimensioned in order to replace the cable fire source during the test. The life test succeeded as the circuit integrity of the tested electrical cables (not done for high voltage cables) is maintained during the complete duration of the fire test.

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EVENT COMBINATIONS WITH FIRES – UPDATE FROM THE OECD FIRE DATABASE

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ABSTRACT

Operating experience from different types of industrial installations has shown that combinations of different types of hazards occur during the entire lifetime of the installations. Typically site specific occurring hazards cause or induce other hazardous events (cascade effects) to occur. In particular, natural hazards rarely happen alone.

Thus, it is very important to note that almost any event combination of hazards is possible and that it is necessary to identify these interactions specifically for each type of industrial facility and to determine ways to mitigate as far as possible the effects of hazard combinations.

Operating experience from nuclear installations has shown that combinations of fires and other anticipated events do occur during the entire lifetime of these installations. The required function of systems, structures, and components important to safety may be impaired in case of the occurrence of such event combinations.

Therefore, it was decided to investigate combination of fires and other events or hazards in more detail. For this investigation, three types of combinations have to be distinguished: fire and consequential event, event and consequential fire, and fire and another event occurring independently at the same time.

For each of these groups of event combinations it has to be systematically checked which types of internal or external hazards can be correlated to fire events.

As a result, a complete list of possible combinations has been elaborated and will be the basis for future assessments, even though only some of them have been observed in the operating experience reported to the OECD FIRE Database up to now.

Basis for the investigation presented hereafter is the updated OECD FIRE Database in the most recent version 2016:01 containing in total 491 fire events up to the end of 2016. 56 of these fire events have been identified as event combinations of fires and other events. The vast majority of such event combinations are consequential fires after a high energy arcing fault.

Eight combinations are combinations of multiple events (so-called event chains) which show cascade/domino effects comparable to situations also known in other industrial installations, in particular in process and chemical industry, as recent accidents in 2017 have also shown.

INTRODUCTION

The complexity of domino and cascading effects requires the application of a proper risk assessment methodology. In the common practice, the risk evaluation is performed for independent events where single risk indexes are determined.

Cascading effects are the dynamics present in accidents in which the impact of a hazard or the development of an initial technological or human failure generates a sequence of events. Thus, an initial impact can trigger other phenomena leading to severe consequences. Cascading effects are complex and multi-dimensional and evolve constantly over time. They are associated with a high degree of vulnerability.

However, when considering domino and cascading effects which are often induced by external hazards, the resulting risk may be higher than the simple aggregation of the individual risk. For this reason, multi-risk assessments should be carried out taking into account all possible interactions of risks due to cascading effects [1]. A domino effect can occur in various types of scenarios. Moreover, an essential aspect is whether it is confined to a single installation or area or progresses to others.

The domino effect occurs in many major accidents, increasing significantly both their complexity and their final effects and consequences. The significance of domino effects in chemical accidents is described in [2].

Combinations of events have already been investigated in process and chemical industry for many years because several major accidents occurred, often damaging equipment enclosures. Operating experience from different types of industrial installations has shown that event combinations of fires and other events occur throughout their entire lifetime.

The domino effect of event combinations can be investigated by different methods [3]. The specific aspect of damage probability exposed to fire is addressed in [4].

The nuclear operating experience from the recent past also underlines the necessity to take into account event combinations in the safety assessment of nuclear power plants, because the required function of systems, structures and components (SSCs) important to nuclear safety may be impaired in case of the occurrence of event combinations of fires and events. For example, combinations of causally related events such as earthquakes and consequential fires may significantly impair or even totally disable SSCs and even may not be limited to one reactor unit at multi-unit sites [5].

On this background, a document of the International Atomic Energy Agency (IAEA) [6] regarding the design of nuclear power plants requires that combinations of events which could lead to anticipated operational occurrences or to accident conditions shall be considered in the design basis (as so-called design basis accidents, DBA) or shall be included as part of design extension conditions (DEC) and that such consequential effects shall be considered to be part of the originally postulated initiating event (IE).

CURRENT STATUS OF EVENT COMBINATIONS WITH FIRES IN THE RECENT OECD FIRE DATABASE

Operating experience from nuclear installations has shown that combinations of fires and other anticipated events do occur during the entire lifetime of these installations. Therefore, it was decided to investigate in more detail such combinations of fires and other events or hazards.

For this investigation, three types of combinations have to be distinguished:

1. Fire and consequential event,
2. Event and consequential fire, and
3. Fire and another anticipated event occurring independently at the same time.

Thereby the first two bullets define causally related event combinations. For each of these groups of event combinations it has to be systematically checked which types of internal or external hazards can result from such combinations with fire events. As a result, the following list (cf. Table 1) of possible combinations has been identified within the OECD FIRE Database Project. This list contains combinations which have already been observed in the operating experience as well as combinations which are considered possible.

Table 1 List of the different types of event combinations with plant internal fires

1. Fire and consequential event:		
	Fire and consequential fire	
	Fire and consequential (internal) flooding	
	Fire and consequential component failure (including high energetic ones, such as high energy arcing faults (HEAF)) of mechanical, electrical or pressurized components	
	Fire and consequential drop of heavy loads	
	Fire and consequential collapse of structural elements	
	Fire and consequential explosion	
	Fire and consequential multi-unit impact	
	Fires and consequential releases of dangerous substances	
	Event chains of multiple events with fires and more than one consequential event	
2. Event and consequential fire:		
	Internal hazard and consequential fire:	
		Internal flooding and consequential fire
		Failure of (including high energy ones) fault of mechanical, electrical or pressurized components potentially impairing items important to safety and consequential fire
		Drop of heavy loads and consequential fire
		Collapse of structural elements and consequential fire
		Internal explosion and consequential fire
		Releases of dangerous (e.g., combustible, explosive) substances and consequential fire
		Other internal hazard and consequential fire
	Natural external hazard and consequential fire:	

		Earthquake and consequential fire;
		Weather induced natural hazard and consequential fire, e.g., hydrological impact (from rain, flooding), lightning
		Biological impact and consequential fire
		Wildfire (if not man-made) and consequential fire
		Other natural hazard and consequential fire
	Man-made external hazard and consequential fire:	
		External fire and consequential fire
		External explosion pressure wave and consequential fire
		Aircraft crash and consequential fire
		Other man-made hazard and consequential fire
	Event chains with fires as one of the consequential events	
3. Fire and another event occurring independently of each other, but simultaneously, one during the mission time of the other:		
	Internal hazard and independent fire:	
		Fire and independent fire
		Explosion and independent fire
		Other internal hazard and independent fire
	External hazard and independent fire:	
		Earthquake and independent fire
		Hydrological impact (e.g., external flooding, precipitation) and independent fire
		Other external hazard and independent fire

Having identified all potential event combinations, the international OECD FIRE Database on fire events in nuclear power plants has been investigated regarding the operating experience in the participating member countries with respect to the different types of event combinations of fires and other events.

Although the combinations listed above are considered possible or have been observed in the operating experience from other industries as well as in the Fukushima Dai-ichi reactor accidents, the investigation has shown that only a few of these potential event combinations have been so far reported to the Database from those member countries participating in the FIRE Database Project.

This first comprehensive investigation of 448 event records including 49 event combinations has been presented in [7]. This study was based on the OECD FIRE Database version 2014:01 [8].

This investigation has recently been updated based on the OECD FIRE Database version 2016:01 with fire events reported up to the end of 2016 [9]. This updated analysis has shown that 56 of the 491 event records have been identified as event combinations of fires and other events (see Figure 1). This contribution of approximately 11 % is non-negligible.

Eight of these combinations (more than 14 % of the entire 56 event combinations) are combinations of multiple events (so-called event chains). One example of an event chain is shown in Table 2 for fire and consequential events.

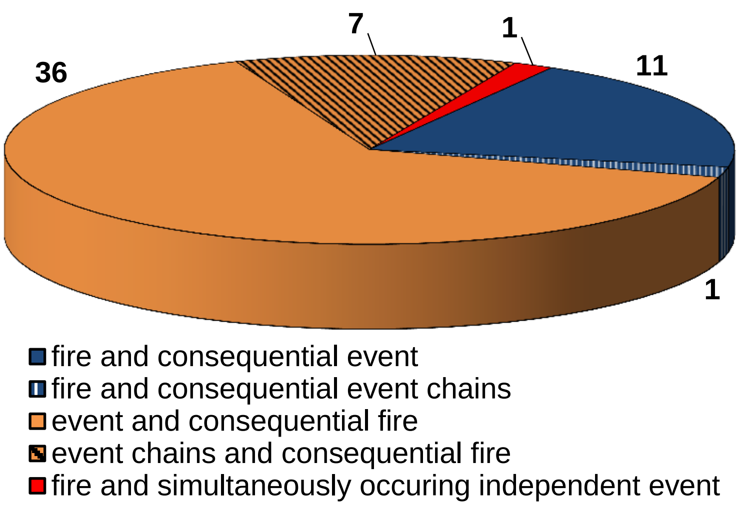

Figure 1 Fire event combinations in the OECD FIRE Database version 2016:01 [9]

In the following Table 2 to Table 5, the following abbreviations are used:

PO: power operation	SD: shutdown mode	HS: hot standby
E: equipment	H: human	P: procedures

Both events in Table 22 (event IDs 59 and 94) were fires of electrical cabinets, resulting in HEAF of the cabinet inducing a consequential fire in an electrical building.

Information similar to Table 22 is provided for all combinations of fires and other events in the OECD FIRE Database, version 2014:01 [8]. Details can be found in [7] for 49 event combinations of fires and other events.

The seven new event combinations in the most recent OECD FIRE Database version 2016:01 [9] are briefly characterised in Table 3 to Table 5.

Table 2 Fire with consequential high energy arcing fault (HEAF) and subsequent fire

Event Title	ID	Plant state before / after fire	Component where the fire started	Fuels	Plant area / building where the event combination occurred	Root causes	Extinguished by (all means involved)	Duration [h:min]
Fire in an electrical cabinet in a switchyard room. Converter in cabinet – 2 NXA201 is affected by the fire. Cause is overheating of affected component. An arc started a second fire	59	PO / PO	electrical cabinet: low voltage (non-HEAF, < 1 kV)	other solid material	electrical building	E	on-site plant fire brigade	> 00:05
Fire at 6.6 kV switchgear	94	PO / SD	electrical cabinet: high or medium voltage (HEAF, ≥ 1 kV)	cable insulation materials; other insulations	electrical building	E, H	on-site plant fire brigade	00:37

Table 3 Explosion and consequential fire

Event Title	ID	Plant state before / after fire	Component where the fire started	Fuels	Plant area / building where the event combination occurred	Root causes	Extinguished by (all means involved)	Duration [h:min]
Fire at 5.5 kV switchboards	466	unknown / unknown	electrical cabinet: high or medium voltage (non-HEAF, ≥ 1 kV)	other solid material	turbine building	E	unknown	< 00:05
Generator hydrogen desiccation station on fire	468	PO / HS	turbine generator: hydrogen	hydrogen	turbine building	E	unknown	unknown

Event Title	ID	Plant state before / after fire	Component where the fire started	Fuels	Plant area / building where the event combination occurred	Root causes	Extinguished by (all means involved)	Duration [h:min]
Main generator hydrogen explosion and fire	488	PO / SD	turbine generator: hydrogen	hardly inflammable liquid, hydrogen, other solid material	turbine building	E	fixed system – automatic actuation	< 00:15
Explosion in moderator cover gas oxygen addition line	497	PO / PO	valve	other gases, oxygen	reactor building, outside containment	E, H, P	people available in the fire area	< 00:05

Table 4 HEAF and consequential fire

Event Title	ID	Plant state before / after fire	Component where the fire started	Fuels	Plant area / building where the event combination occurred	Root causes	Extinguished by (all means involved)	Duration [h:min]
Arc fire in power distribution box in turbine building	458	SD / SD	electrical cabinet: low voltage (HEAF, < 1 kV)	cable insulation materials	turbine building	E	people available in the fire area	< 00:05
Potential transformer panel fire	477	PO / SD	electrical cabinet: high or medium voltage (HEAF, ≥ 1 kV)	cable insulation materials	turbine building	E	on-site plant fire brigade	< 00:05

Table 5 HEAF with consequential explosion and subsequent fire

Event Title	ID	Plant state before / after fire	Component where the fire started	Fuels	Plant area / building where the event combination occurred	Root causes	Extinguished by (all means involved)	Duration [h:min]
Loss of offsite power (LOOP) as a consequence of main step-up transformer fire during plant outage[1]	478	SD / SD	high voltage transformer (voltage ≥ 50 kV): oil involved, catastrophic	flammable liquid	main transformer area (not bunkered)	E	fixed system – automatic actuation, on-site plant fire brigade	< 00:30

1 The event occurred in the recent version of the Database [9], but the coding as an event chain was implemented after its distribution.

In the following, two examples of event combinations are described in more detail.

The first event (event ID 478) is an event chain and consequential fire. A short to ground occurred on one of the main step-up transformers, causing arcing (HEAF), an explosion and subsequent fire in the transformer enclosure. This event chain including consequential fire led to a loss of offsite power (LOOP) at the affected plant site with the impaired unit under shutdown for an outage. The unit was in cold shutdown, the reactor vessel was unloaded and fuel was stored in the spent fuel pool. Because the start-up transformers were undergoing maintenance, the electrical buses of the unit were powered through the step-up transformers connected on the 380 kV grid. This is a specific configuration required by the technical specifications in such a case. The three single-phase main transformers of the unit are located outside of the turbine building in an adjacent building and separated from each other by concrete walls. The transformers are not completely bunkered, each transformer is protected by a spray water deluge system.

The ground fault occurred inside one of the transformers, causing a high energetic arc and an explosion of the transformer enclosure. The arcing occurred close to the transformer oil causing a dramatic pressure increase and the failure (rupture) of the transformer vessel. Several findings support an arcing fault:

- The vessel ruptured along a weld, suggesting a failure following a pressure peak from inside.
- The fault occurred at the most distant point from the pressure relief valve (design flaw, reducing the efficiency of the pressure relief system).
- The electrical fault and the vessel rupture did not occur at the exact same place.
- Evidence of arcing was found on the transformer windings conductors and on the vessel walls (multiple black/burnt spots), but not directly at the location of the vessel failure.
- No evidence was found of a significant amount of conductor material being vaporized.

The explosion caused the oil of the transformer to ignite. The deluge system activated instantaneously as a consequence of the transformer explosion and started to suppress the fire around the transformer location. Debris and burning oil were projected at a distance from the transformer and required the intervention of the on-site fire brigade to be completely extinguished – an intervention of the off-site fire brigade was not needed. Water and foaming additive was used for manual extinguishing of the burning transformer. The total event duration was 20 min because of the extinguishing of all burning items.

The loss of the power source and the unavailability of the start-up transformers caused the diesel generators to start and power the unit.

2 h and 30 min after the event, the power supply was re-established through the electrical systems of the twin unit. The recovery of the incident implied the immediate stop of all ongoing maintenance work, and reconnection of the start-up transformer to the 150 kV grid and the electrical buses of the unit. The step-up transformer was replaced by a spare piece of equipment and, as a preventive measure; the two other transformers were also replaced by newer equipment bought by the licensee for another unit.

Similar pieces of equipment had to undergo increased monitoring. The replacement of older surge arrestors was planned to increase the protection of the transformers against transients on the power grid and reduce stresses on the windings.

The actual safety impact for the unit was small because of the cold shutdown mode and the storage of all fuel assemblies in the spent fuel pool (SFP).

The second event (event ID 497) has been identified as a combination of an explosion with a consequential fire. The unit was in full power operational mode when an operator was requested to add oxygen to cover gas[2] in the addition line. The operator opened the oxygen

[2] Cover gas - or shielding gas - is used to prevent rapid oxidation of the weld zone due to atmospheric oxygen.

bottle valve fully, checked the position of the manifold valve[3] (found it open) and started the open supply valve. When the supply valve was opened about ¼ of a turn, this valve erupted into an orange fireball explosion. The supply valve failed as a result of an internal combustion mechanism wherein the stainless steel material of the valve body and the associated tube were burned or oxidized by the high purity oxygen gas. The original design configurations did not follow the oxygen system design guidelines, e.g., the use of combustible soft seat material in high pressure oxygen systems, is inappropriate. Hence, the system layout was not designed to minimize the occurrence of adiabatic compression.

As a result of the explosion the operator was thrown three meters from the valve station, with his coverall on fire. He extinguished the flames by patting them and rolling on the floor.

Then he called the plant emergency number using a local rotary phone, advised that there was a fire and that he had sustained burns. Unfortunately, the injured operator gave the wrong elevation for the fire location when he phoned for help. As a result, the fire and rescue crew were dispatched to the wrong location thus increasing their response time. Additionally, the operator who accepted the call used a procedure that branched to either a fire response or a rescue response. Unfortunately, he chose the fire response path without initially notifying the emergency response team (ERT) captain of the person´s injury. Thus, attempts to reach the ERT captain to inform him were not successful.

The injured operator was transported to the hospital by ambulance approximately 25 min after the accident. The operator was badly injured; he was treated for second degree burns to his hands and forearms as well as first degree burns to his face and neck.

Thus, the root causes comprise equipment, human and procedures as addressed in Table 33. ID 497 is only the second of the 56 event combinations where all three types of root causes affected the course of the event.

As a consequence, the following corrective actions have been identified and implemented by the utility:

- The oxygen addition system of all utility generation facilities had to be redesigned to meet all applicable standards.
- Operating and maintenance procedures and training had to be reviewed to ensure that precautions for handling high pressure, high purity oxygen are adequately addressed.
- The technical surveillance program has been reviewed, with particular emphasis on systems whose failure could have a significant impact on employee safety.

The corresponding distribution of all 56 event combinations is provided in Figure 2.

It has to be mentioned that for most of the possible types of combinations, only few events have been reported so far to the OECD FIRE Database.

The vast majority of these combinations have been identified as combinations of HEAF events. 27 out of 56 (i.e. nearly 48 %) event combinations are fires consequential to HEAF; additional seven event sequences (i.e. approximately 12 %) are HEAF induced by an initial hazard (including fire) with subsequent fire. Thus, in total nearly 60 % of the combinations are HEAF related indicating the need for special attention regarding preventive measures for this type of event combinations. The occurrence probability of a combination of HEAF events is in the range of 4.3 E-03 per reactor year.

Only one event combination of a fire and another event occurring independently but concurrently with the fire has been recorded. This event is an external flooding and a simultaneously, however independently occurring fire, demonstrating that such combinations do occur. In principle, this combination of events shows the need to be aware of the possibility of a fire and an independently occurring event. In case of external flooding plant accessibility is needed, even under such extreme circumstances, in order to enable technical

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[3] Valve manifolds are functionally installed to isolate, vent and equalize the gases and fluids.

support from outside the plant, e.g., to allow for a change of the on-site personnel or access of the external local fire brigade.

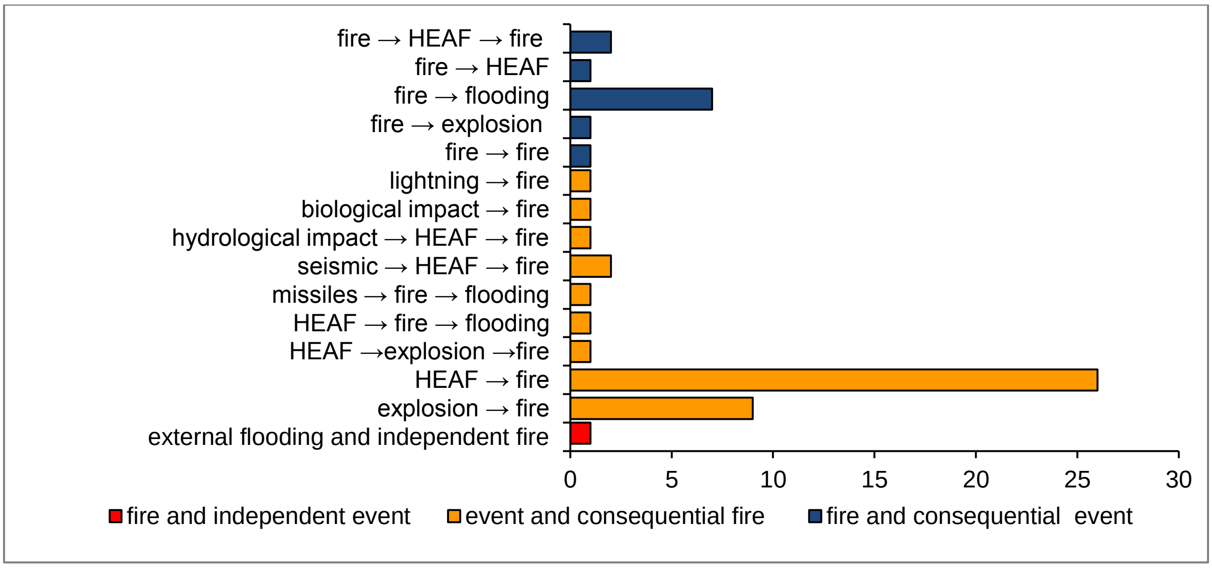

Figure 2 Event combinations observed in the updated OECD FIRE Database [9]

Figure 3 shows the components where in case of the event combinations the fires started analysed.

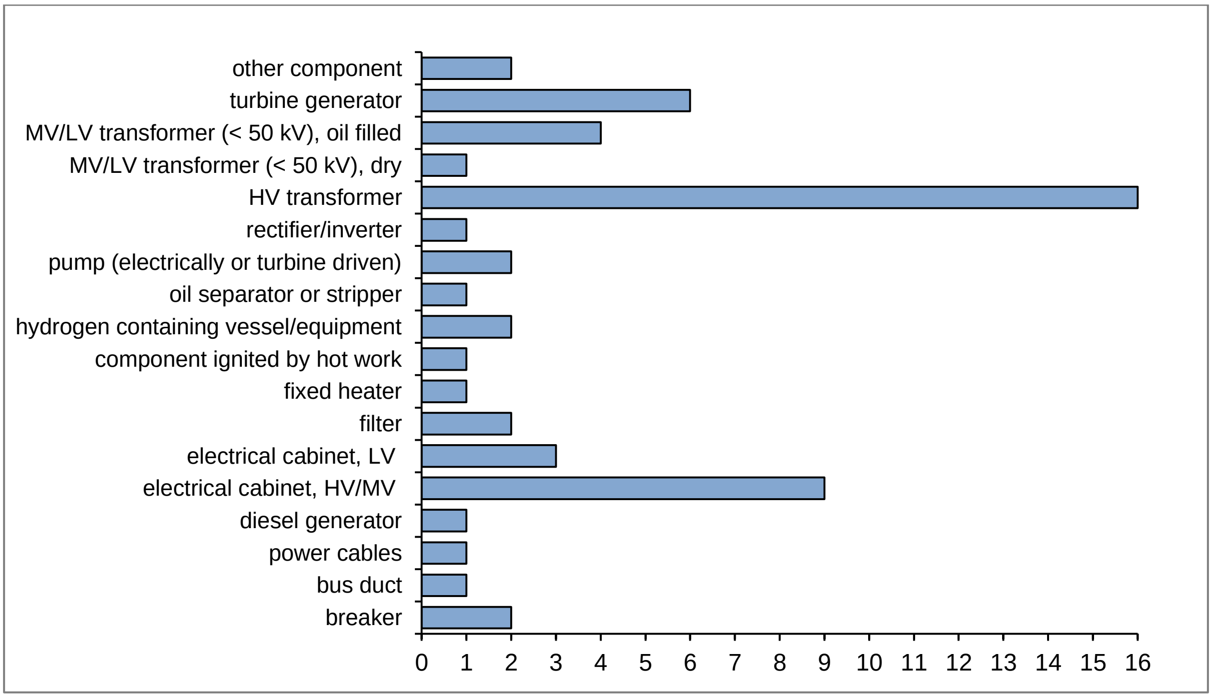

Figure 3 Event combinations - component where the fire started according to [9]

A majority of the events recorded occurred at transformers (nearly 36 %) and electrical cabinets (approximately 21 %).

With regard to the severity of the events, there are indications either provided by information on how many safety trains were affected or lost or by the information on change of the plant operational mode as a consequence of the event sequence. In case of eight of the 56 event combinations recorded in the Database, one safety train and in case of two event sequences more than one safety train was lost. In no case all safety trains were lost.

The plant operational mode changed in 36 cases (approximately 55 % of the entire event combinations). This contribution is even higher when considering that for plants under construction or in shutdown the plant mode cannot change.

CONCLUDING REMARKS

Operating experience from nuclear power plants has shown that combinations of fires and other anticipated events do occur during their entire lifetime as it is valid in case of installations of process industry. As a consequence, in the last years national and international activities resulted in updating respective regulations and standards to properly address event combinations.

The German "Safety Requirements for Nuclear Power Plants" as issued recently [11] include only high level requirements with regard to the consideration of plant specifically possible internal hazards and their potential combinations with internal hazards, such as fires, or external hazards including emergency cases. Therefore, the revised German Nuclear Safety Standard KTA 2101.1 for Fire Safety in Nuclear Power Plants [12], which provides more detailed technical requirements, covers this aspect systematically and exhaustively.

On international level, the two safety standards of the International Atomic Energy Agency regarding internal hazards [13] and [14] are currently in a merging and updating process to one safety guide on protection against internal hazards in the design of nuclear power plants; this new guide will also address that possible combinations of hazards and their cascading effects should be considered.

Although the combinations listed above are considered possible or have already been observed in the operating experience from other industries as well as in the Fukushima Dai-ichi reactor accidents, only a few of these potential event combinations have been reported to the OECD FIRE Database so far. Moreover, there is still an amount of remaining simultaneously occurring independent events that could be considered, which are not listed above. However, their probability of occurrence is very low. The increasing number of reported events shows that event combinations are non-negligible and their investigation is helpful to identify the needs for improvements of operating nuclear power plants and to design new plants in an adequate manner taking into account site-specific conditions in a conservative manner.

About 11 % of the entire fire events recorded in the OECD FIRE Database up to the end of 2016 [9] have been identified as event combinations of fires and other events. 27 out of 56 events combinations are fires consequential to HEAF. Thus, HEAF events resulting in fires are the most important contributors to event combinations, among them HEAF at transformers and at electrical cabinets representing the highest contributions.

One of the lessons learned from this result is that HEAF phenomena were not well known at the time when a majority of the existing nuclear power plants were designed. The relevance of HEAF events for fire safety and the need to address these in probabilistic fire safety assessments has been recognized on an international level. This was the reason for starting an OECD Nuclear Energy Agency (NEA) experimental project in order to perform in-depth investigations. The results are of the experiments have been presented in detail in [10].

The experience from event combinations also indicates that only a few explosions caused a consequential fire and that most of these did not result in a change of the plant operational mode indicating that the plant design against internal explosions has already considered the possibility of such consequential fires and their potential effects on plant safety. This is in contrast to experiences in process industry [15].

Nine out of 56 fire events in the [9] resulted in internal flooding. In most of these events the flooding was due to fire extinguishing activities. The non-negligible contribution of event combinations finally resulting in subsequent internal flooding events indicates that some improvements may be possible in the plant design regarding the protection against fire and consequential flooding.

Only one example of a fire and a simultaneously, but independently occurring hazard (one during the mission time of the other) has been observed up to now; however, this underlines that the list has to contain even this type of event combinations, although the occurrence frequency of such an event combination is low.

In total six event sequences in the OECD FIRE Database show a domino effect: fire with consequential HEAF causing another fire, HEAF causing explosion and subsequent fire, missiles causing a fire resulting in subsequent flooding, two event sequences with seismically induced HEAF and subsequent fires, and, last but not least, rain causing HEAF and subsequent fire.

It has also to be mentioned that none of event combinations observed in the FIRE Database resulted in a loss of all safety trains. Moreover, in contrast to accidents in the process industry, the events in the nuclear power plants were limited to one plant unit in case of multi-unit sites. However, this may be due to the fact that a majority of the event records in the Database represent events without safety significance and that in most cases passive fire protection means have ensured that fires occurring inside buildings are at least limited to the respective building.

The investigations of the operating experience collected in the OECD FIRE Database clearly underline that event combinations of events from internal as well as external hazards with fires need to be more systematically analysed. Moreover, they should be addressed in the site specific plant design as one has seen from the post-Fukushima reactor accident analyses.

Cascading/domino effects are an important in process and chemical industry, as also two recent accidents have shown.

On June 5, 2017, eight people were killed and nine injured in an explosion and consequential fire at a chemical plant in eastern China's Shandong province. The accident was triggered by an explosion of a liquefied gas tanker in a loading area at the Linyi Jinyu Petrochemical Co. plant at about 1 a.m. The blast set ablaze several fuel storage tanks at the site. The fire was brought under control in the late afternoon after more than 900 firefighters were needed to extinguish the fire.

Another accident happened in Crosby, Texas, on August 31, 2017. Hurricane Harvey brought several days of torrential rains over Texas. It was the strongest hurricane in Texas for more than 50 years. The chemical plant Arkema in Crosby, which is about 40 km northeast from Houston, was shut down a few days ahead of the storm. Up to 2 m of floodwater lead to a power cut of refrigerators and swamped backup generators, leaving the facility without power.

The facility's coolant system and inundated backup power generators as well as the primary power at the plant failed on Sunday 27, and two sources of emergency backup power were lost shortly thereafter. Ahead of Harvey's arrival, "*the plant made extensive preparations", bringing extra backup generators to the facility, along with diesel-powered refrigerated tank trailers"*, Arkema stated. But the generators were inundated by water and failed.

As a result of the missing cooling, the chemicals at Arkema caught fire in a tractor-trailer and sent up to 9 – 12 m high flames and black smoke. The detailed investigation is ongoing; thus, there are still discussions if it should be called explosions, small pops or a chemical reaction and an overpressure of the container.

In describing what happened at the plant, Arkema officials declared that this was not an industrial accident and cited the unprecedented nature of the storm: the problems that resulted from the hurricane and the torrential rains that fell upon Texas and more particularly on Crosby.

In 2008, when Hurricane Ike made landfall over Galveston, Arkema identified floods and hurricanes in the following year – as well as power failure and loss of cooling – as threats to its Crosby site. However, the plans, which the company must file with the United States Environmental Protection Agency every four years, did not include measures to raise critical equipment such as backup generators above possible flood levels. Nor did the plans call for isolating hazardous materials from high wind or water.

This accident underlines the need to assess natural hazards in detail and to be aware of their consequences even if their occurrence frequency seems to be low.

Moreover, as the recent accidents in China and USA have shown, it is a basic task to investigate and assess relevant combination of hazards not only for a single installation but for the respective site and/or industrial park. In that context, domino and cascading effects pose particular challenges for risk management to prevent industrial accidents.

The propagation of fire in chemical plants – also known as fire domino effects – largely depends on the performance of add-on passive and active protection systems. Although such safety barriers are widely employed to prevent or delay the initiation or escalation of fire domino effects, their inclusion in the modelling and risk assessment of fire domino effects has hardly been taken into account. Recently, the dynamic behaviour of fire protection systems has been investigated. In order to quantify the changes over time and their impact on the escalation of fire domino effects, a dynamic Bayesian network methodology has been developed [16].

Therefore, multi-hazard assessment has to be performed to determine the probability of occurrence of different hazards either occurring at the same time or shortly following each other, because they are dependent from one another or because they are caused by the same triggering event or hazard, or merely threatening the same elements at risk without chronological coincidence.

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VULNERABILITY ASSESSMENT OF DIESEL GENERATORS AGAINST FIRE/EXPLOSION FUMES

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ABSTRACT

The vulnerability of emergency diesel generators against fire/explosion fumes was assessed in a generic study. For a diesel engine operating at $\lambda = 1.7$ under normal conditions $\lambda = 1.3$, representing 65 % nominal oxygen supply, was considered as one failure criterion together with a combustion air temperature exceeding 170 °C. CFD parameter studies of fires in front of a diesel generator building were performed in order to define the boundary conditions under which the criteria fail. In the simulations, the fire area, the heat release rate per unit area and the wind speed orthogonal to the building wall were varied. The resulting correlations show that the failure criterion based on oxygen supply does fail earlier than the temperature criterion.

INTRODUCTION

German nuclear power plants (NPPs) are equipped with two emergency electrical grids that are fed by emergency diesel engine generators (EDG). The EDGs of the first (“D1”) grid are located in the Emergency Diesel Generator Building. The smaller EDGs of the second (“D2”) grid are located in the Independent Emergency Building. This building is designed against external events such as earthquake, releases of hazardous substances (mainly gases), fires and explosions. According to the Safety Requirements for German NPPs “*the effects of plant external fires on ventilation systems and the intake air of the emergency diesel generators as well as the potential ingress of combustion products into buildings shall be considered*” [1], Section 4.2.3.2 (3)). One basic argument for the robustness of the emergency grids against external fire and explosion fumes is that the two buildings hosting the EDGs are separated from the reactor building which ensures a minimum distance and serves as an obstacle for several external impacts like aircraft crashes. A detailed assessment by the operators of German NPPs with respect to the behaviour of the EDGs in case of impacts from fire and explosion fumes is not known to GRS. Therefore an assessment is performed on a generic basis.

BEHAVIOUR OF DIESEL ENGINES

External events such as extreme external fires or explosions can lead to different composition and temperatures of the combustion air. Since the exact behaviour of the diesel engines under such conditions is not known to GRS, engineering judgement has been applied for the assessment based on open information.

For fire and explosion fumes the combustion air is changed by

– increased temperature and
– reduced oxygen content by depletion and displacement.

Increased Combustion Air Temperature

If there is no effective cooling between the inlet pipe and the turbocharger, the efficiency of the turbocharger is probably reduced, because the standard point of operation shifts to a less efficient one. This will lead to reduced air charging pressure for the diesel engine. For turbochargers of ship engines it is reported [2] that the maximum output pressure is reduced by 2.2 % for every 10 K the turbocharger air intake temperature is raised. Since this statement is valid for maximum air temperatures below about 50 °C, it is not known if it can be extrapolated to temperature levels of combustion fumes of up to several hundred degrees.

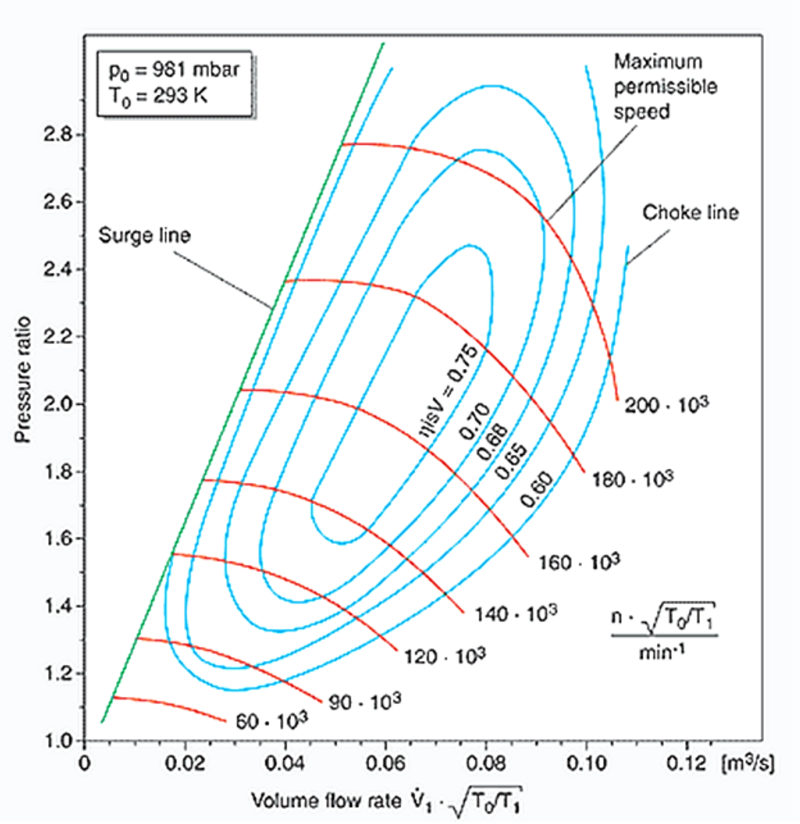

Figure 1 Sample operation diagram of a turbocharger of a diesel engine (not to scale) (image source: BorgWarner, http://www.turbos.bwauto.com/img/products/compressorMap.gif)

A reduction of charging pressure results into reduced engine power. For a sample engine installed in a German NPP the reduction shows a nearly linear behaviour for larger load levels. A reduction of 20 % of the charging pressure leads to a power reduction of about 15 %. The fraction of power reduction which leads to failure of an engine depends on the actual load conditions. Based on expert judgement under normal conditions, the power reserve of the engine is about 25 %. If 25 % engine power reduction is taken as failure criterion, this represents about 35 % reduction of the charging pressure. If the above-mentioned correlation between temperature increase and charging pressure reduction is extrapolated, the criterion becomes about 150 K increase of the turbocharger inlet temperature or 170 °C. Conservative load conditions, that are achieved e g. when large pumps are under run-up conditions, may lead to earlier failure.

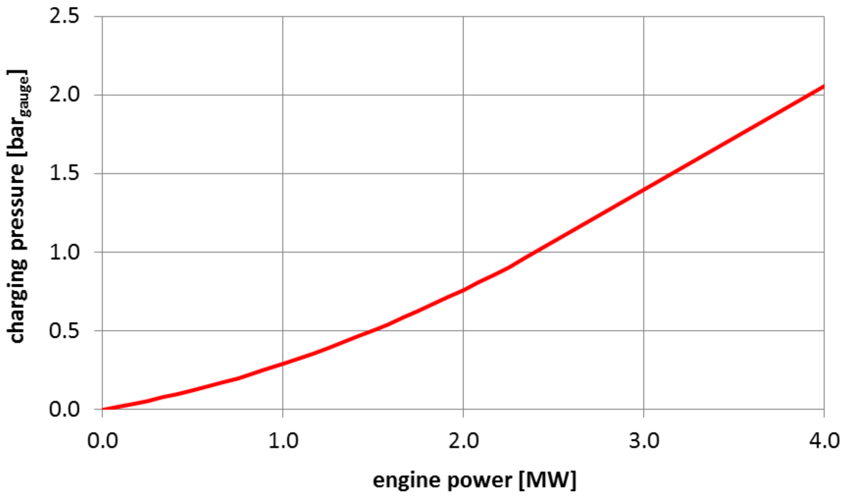

Figure 2 Sample correlation between charging pressure (air cooled behind the turbo-charger) and engine power

The intake gas duct may (1) be directly connected to the turbocharger or (2) openly ends in the engine compartment, from where the combustion air is sucked in by the turbocharger. The gas intake may either (2a) be used completely for combustion or be (2b) much larger than required for combustion, because most of the intake is needed for the purpose of engine cooling.

For design type (1) there is typically no cooling system installed in front of the turbocharger, but only behind it. With regard to the temperature based failure criterion, cooling of combustion fumes only occurs by heat losses to the intake gas duct.

For design type (2a) typically a recirculation air cooling system is present. This removes the heat which is lost by the engine and which is not removed by the water cooling system from the engine room. To the knowledge of GRS the radiative and convective heat loss of hot engine parts is less than 10 % of the nominal power output of the engine. With regard to the temperature based failure criterion it has to be checked whether the convective heat by the combustion fume inflow is large compared to the cooling capacity. Additional cooling of combustion fumes occurs by heat losses to the intake gas duct and the engine compartment walls.

Design type (2b) does not have an additional cooling capability. Because of the large air intake and high air exchange rates, credit from passive cooling by heat losses to ducts and compartment boundaries will be small. In Germany, this design type is not used for EDG that are designed against external hazards.

Reduced Oxygen Content by Depletion and Displacement

The reaction of organic fuel in air has a twofold effect on the composition of combustion air: The oxygen (O_2) content (23.2 % by mass in dry air) is depleted and combustion products like carbon dioxide (CO_2) and water vapour (H_2O) are produced. Given a fuel with a typical ratio carbon to hydrogen of 1 to 2, for any 1 molecule of oxygen depleted, 1.5 molecules of combustion products are produced. Since the heat capacities of CO_2 and H_2O are larger than the one of nitrogen (N_2), the inhibition effect of the combustion products is also larger, therefore reducing the willingness of the mixture to ignite.

The combustion products are mixed with ambient air before they are sucked into the inlet duct of a diesel engine. For external fires below the inlet, mixing of combustion products with ambient air takes place by entrainment into the rising fire plume.

A failure criterion based on the oxygen supply is not known to the GRS; therefore this was derived based on open information. The diesel engines in the bunkered independent emergency buildings are known to run under full power operation (100 % nominal power) with an air excess of about $\lambda \approx 1.7$. The minimum air excess for (undisturbed) operation is reported to be about $\lambda \approx 1.2$, which is about 70 % of the normal value. As a criterion for a disturbed operation we assume $\lambda \approx 1.1$, which is about 65 % of the normal value. Such a reduction is expected to lead to inoperability of the engine because the ignition of the fuel-air-mixture is less reliable and/or the combustion process is more incomplete. The exhaust gas flow is also significantly reduced compared to the normal value because of less air excess and incomplete combustion. This in turn reduces the power available for the turbocharger. Finally, the rotational frequency of the EDG is decreased. The control system of the engine will commonly increase the fuel supply rate when the frequency declines, which leads to a further decrease of air excess number λ and worsens combustion.

Discussion of Failure Criteria

As failure criteria a turbocharger intake gas temperature of 170 °C or a decrease of the oxygen mass flow to 65 % of the nominal level were derived. The second criterion is the more decisive one, because it affects the capability of the engine to run at all, whereas the first affects the power output that depends on the power demand.

Practically increased temperature and decreased oxygen mass flow will appear together such that a combination of both criteria is relevant. It is not known whether there are synergetic effects of both criteria for the turbocharger or the diesel engine.

Synergetic effects for the intake ducts are obvious: The increase in temperature leads to a reduced density of the mixture, which leads to a reduction of the mass flow through intake ducts: under the assumption of a constant pressure drop the volume flow will roughly increase by the square-root of the ratio of the Kelvin-temperature of the mixture divided by the Kelvin-temperature under ambient conditions. The mass flow will decrease by that factor. Under the assumption of a constant volume flow the mass flow will decrease by the ratio of the Kelvin-temperature of the mixture divided by the Kelvin-temperature under ambient conditions.

Since in most cases the combustion air flows downwards from the level it is sucked in to the level where the engine is located, there is a pressure difference by buoyancy that is against the flow direction and therefore increasing the pressure drop. At a gas temperature of 220 °C (assumed 200 K temperature increase) the pressure is Δp = 4.8 Pa/m.

REFERENCE INDEPENDENT EMERGENCY BUILDING AND FIRE SCENARIO

As reference independent emergency building a concrete building with four redundant and structurally separated diesel engines is taken (cf. Figure 3). The cubic building is 15.2 m high and 26 m wide. On the wide side four combustion air inlets are installed at a mean elevation of 11.6 m. Each inlet is 3.6 m wide and 2.4 m high. Since there is a grille in front of the inlets, they jump ahead the plane wall about 0.4 m. The volume flow through each inlet is 0.665 m^3/s.

Fire scenarios were studied with the CFD model Fire Dynamics Simulator (FDS), version 6.5.3 [3],[4]. Since the scenarios are intended to represent a wide range of conditions to achieve generic results, different parameters are varied. These are:

1. the depth of the fire area, which extends from the building wall to distances of 1 m, 3 m, 6 m, and 9 m in front of the building,
2. the heat release rate per unit area that is varied from 0 to 1200 kW/m^2, and

3. a wind condition directed orthogonal to the building wall with a constant velocity of 1 m/s, 3 m/s, or 9 m/s.

1. Under normal conditions no relevant fire loads should be located below the inlets of combustion air or the ventilation system. However this may occur due to any maloperation, temporary construction work, or accidental situation. Accident scenarios typically analysed in the frame of nuclear safety assessment are aircraft crashes. In case of an aircraft crash it is assumed that the fuel splashes against the building wall and is poured down to build a spill of liquid fuel and solid debris. To represent different conditions and to study the sensitivity of this parameter the depth of the fire area beginning at the building wall was modelled as 1 m, 3 m, 6 m, and 9 m. The width of the fire was alongside the building wall.

2. The heat release rate per unit area (HRRPUA in kW/m^2) shows a highly considerable variation over potential fire scenarios involving different types and geometric formations of fuels. Therefore the value was increased during the simulations from 0 to 1200 kW/m^2. This variation is assumed to cover the potential range of a low heat release rate of, e.g., a fire of solid fuel to the heat release rate of kerosene fires [5]. Because in the simulations the increase of the heat release rate is performed quite slowly, steady state conditions are achieved concerning the gas concentrations and temperatures at the air inlets of the building. The first seconds of the simulations with very small heat releases are also used to establish the wind field. For the combustion model a typical organic fuel is considered with a C to H mole ratio of 1 to 2. The effective heat of combustion of the fuel mixture is HOC_{eff} = 39 MJ/kg. The fuel is always located at an elevation of z = 0.40 m above ground level.

3. For fire plumes, the air entrainment is increased by wind. It is assumed that all possible wind parameters like direction, velocity, gustiness, and turbulence, which are very location-specific, are not covered by the simulation. To get a clue of the possible influence, a constant wind directed orthogonal to the building wall is considered in the simulations. The velocity is changed to 1 m/s, 3 m/s, and 9 m/s.

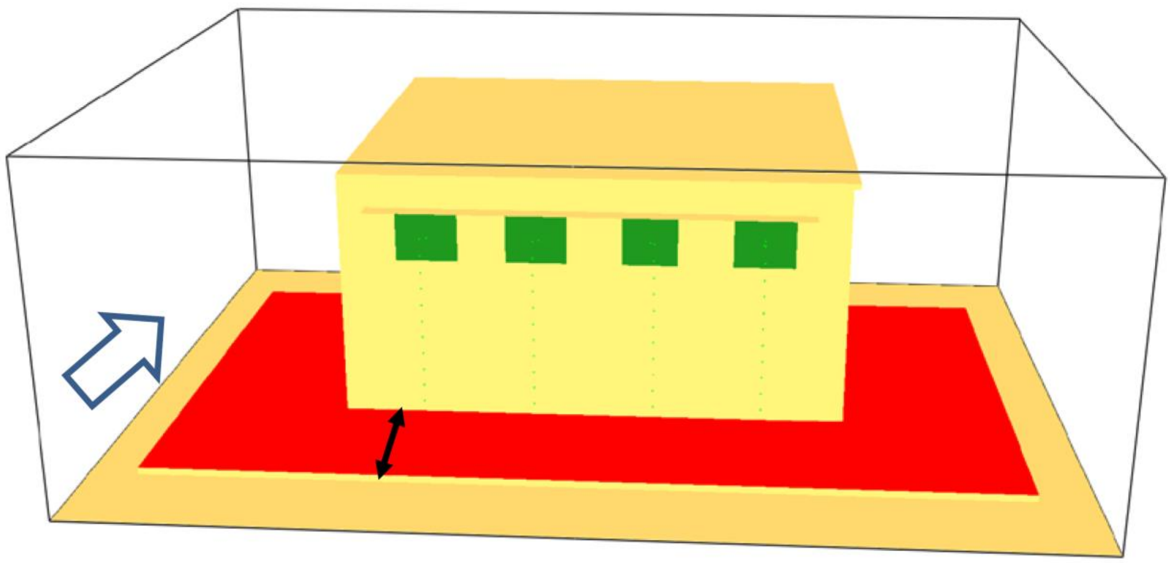

Figure 3 Snapshot of the modelled reference building with the varying extensions of the fire area (double arrow) and wind speeds orthogonal to the building wall

The independent emergency building modelled is axisymmetric. For the simulations only one half was modelled using the mirror function of FDS.

SIMULATION RESULTS

The building with four redundant trains is quasi axially symmetric with two inner and two outer inlets. As someone would expect, air entrainment in the fire plume below the outer inlets was larger than below the inner inlets. Since oxygen concentration is larger and gas temperature is lower in front of the outer inlets, the slightly more conservative results from the inner inlets are presented in this paper.

Temperature at the Combustion Air Inlets

The gas temperature of the different parameter variations is shown in Figure 4 a-c. The heat release rate per unit area is correlated with the gas temperature taken in front of the inlet. The top diagram (a) is for 1 m fire area extension of the building wall, the middle diagram (b) for 3 m extension, and bottom (c) for 6 m extension. Each diagram depicts lines for three wind speeds (1 m/s, 3 m/s, 9 m/s). There is significant fluctuation in the diagrams when the HRRPUA rise, that was partly smoothed. It is believed that the criterion is fulfilled when the average value of the criterion is fulfilled. The temperature criterion of 170 °C is only fulfilled for fire areas of $\geq$ 3 m extension. For 3 m extension it requires HRRPUA of about 1 MW/m^2 and relatively little wind (1 to 3 m/s). For 6 m extension HRRUA of approximately 600 kW/m^2 are needed with little wind (< 3 m/s) or about 1 MW/m^2 with 9 m/s wind.

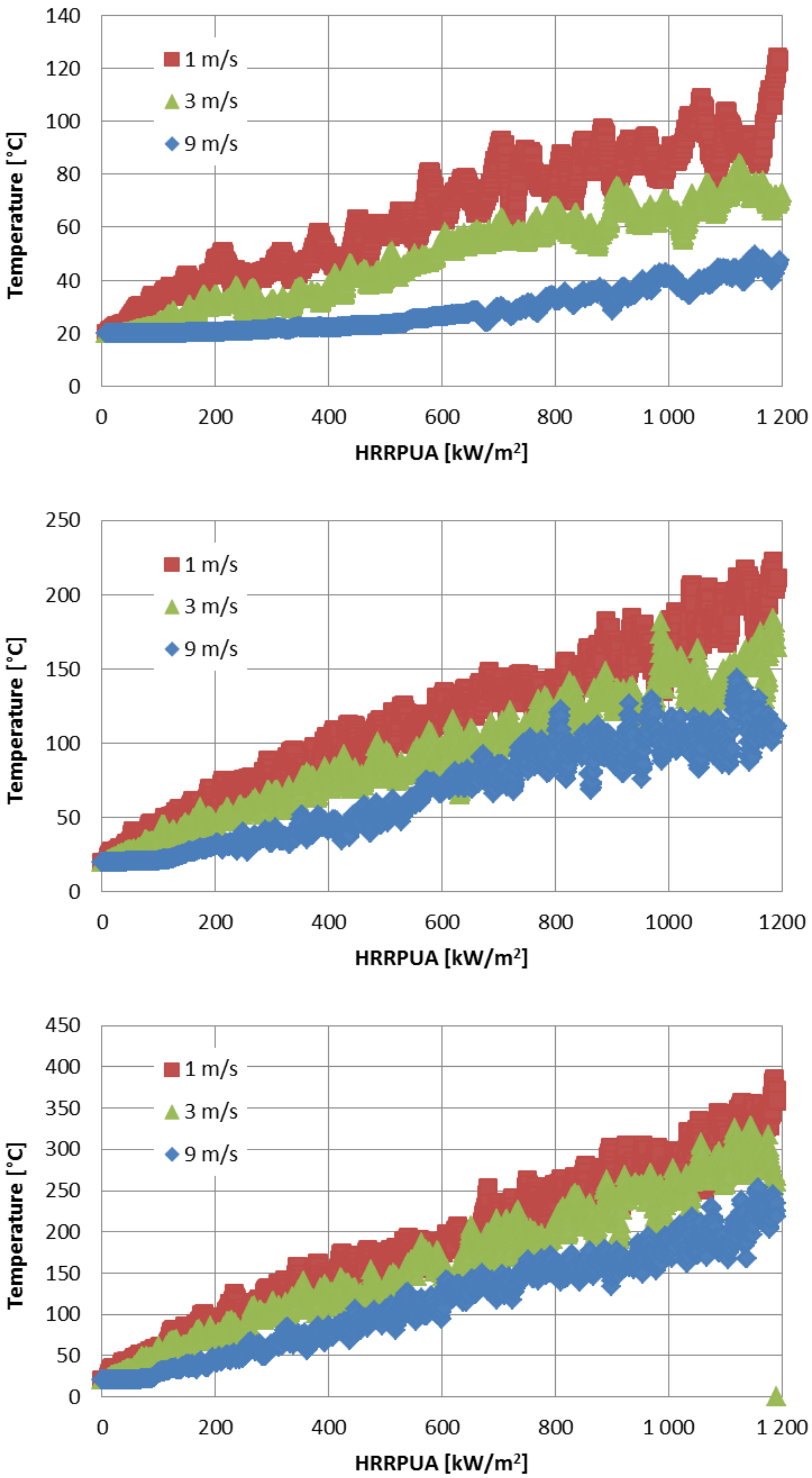

Figure 4 Inlet gas temperature for fire area extensions of a) 1 m, b) 3 m, and c) 6 m of the building wall

Heat Flux into the Combustion Air Inlets

The heat flow into the inlet duct is shown in Figure 5 a-c. The top diagram (a) is for 1 m fire area extension of the building wall, the middle diagram (b) for 3 m extension, and bottom (c) for 6 m extension. The heat flow is calculated based on a volume flow of 0.655 m^3/s. The heat flow has to be compared to the heat losses of the inlet duct and additional cooling capacities from walls or from cooling systems. As described above, these cooling capacities are design specific.

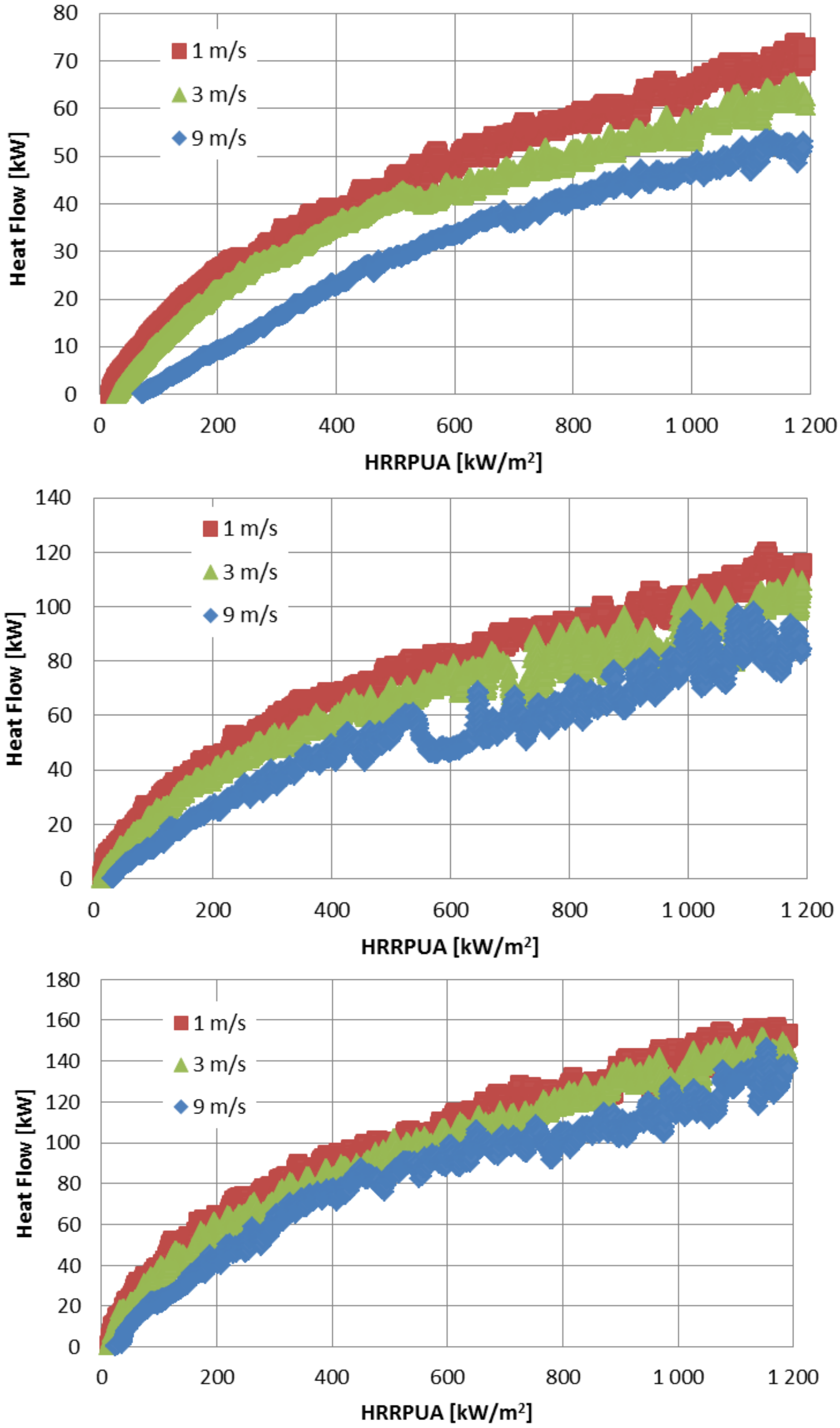

Figure 5 Heat flow into the inlet duct for fire area extensions of a) 1 m, b) 3 m, and c) 6 m of the building wall

Oxygen Mass Fraction at the Combustion Air Inlets

The heat release rate per unit area correlated with oxygen mass fraction in front of the inlets is shown in Figure 6 a-c. The top diagram (a) is for 1 m fire area extension of the building wall, the middle diagram (b) for 3 m extension, and bottom (c) for 6 m extension. For pure air the oxygen mass fraction is 0.23 kg/kg. The decrease results from oxygen consumption and displacement by combustion products. Air entrainment that enriches the oxygen fraction is increased by wind. The reduction of oxygen mass flows (see below) depends on reduced oxygen mass fractions together with reduced gas mass flows from density reduction.

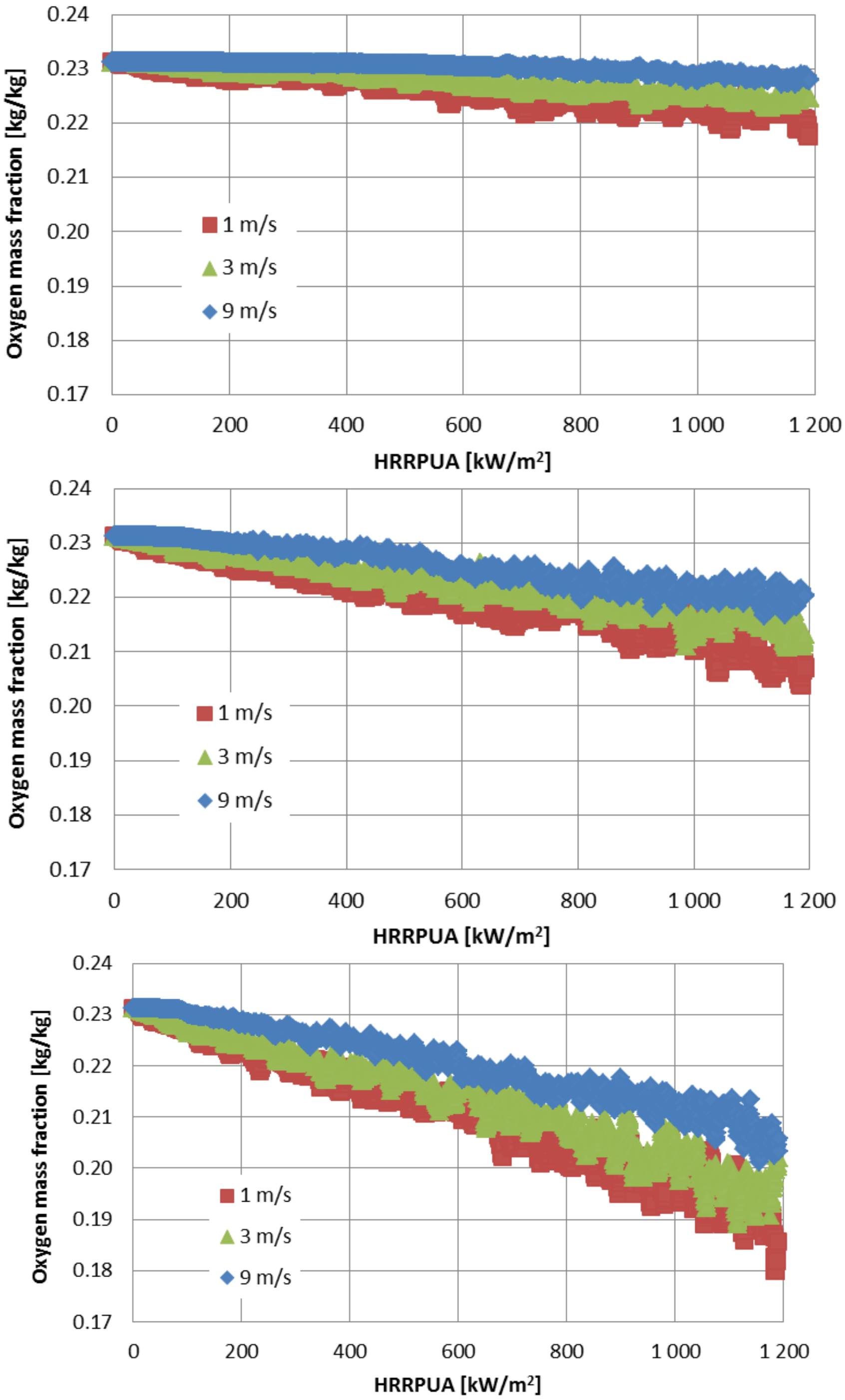

Figure 6 Oxygen mass fraction at the inlet duct for fire area extensions of a) 1 m, b) 3 m, and c) 6 m of the building wall

Oxygen Mass Flow into the Combustion Air Inlets

The heat release rate unit area correlated with oxygen mass into the inlets flow of the different parameter variations is shown in Figure 7 a-c. The top diagram (a) is for 1 m fire area extension of the building wall, the middle diagram (b) for 3 m extension, and bottom (c) for 6 m extension.

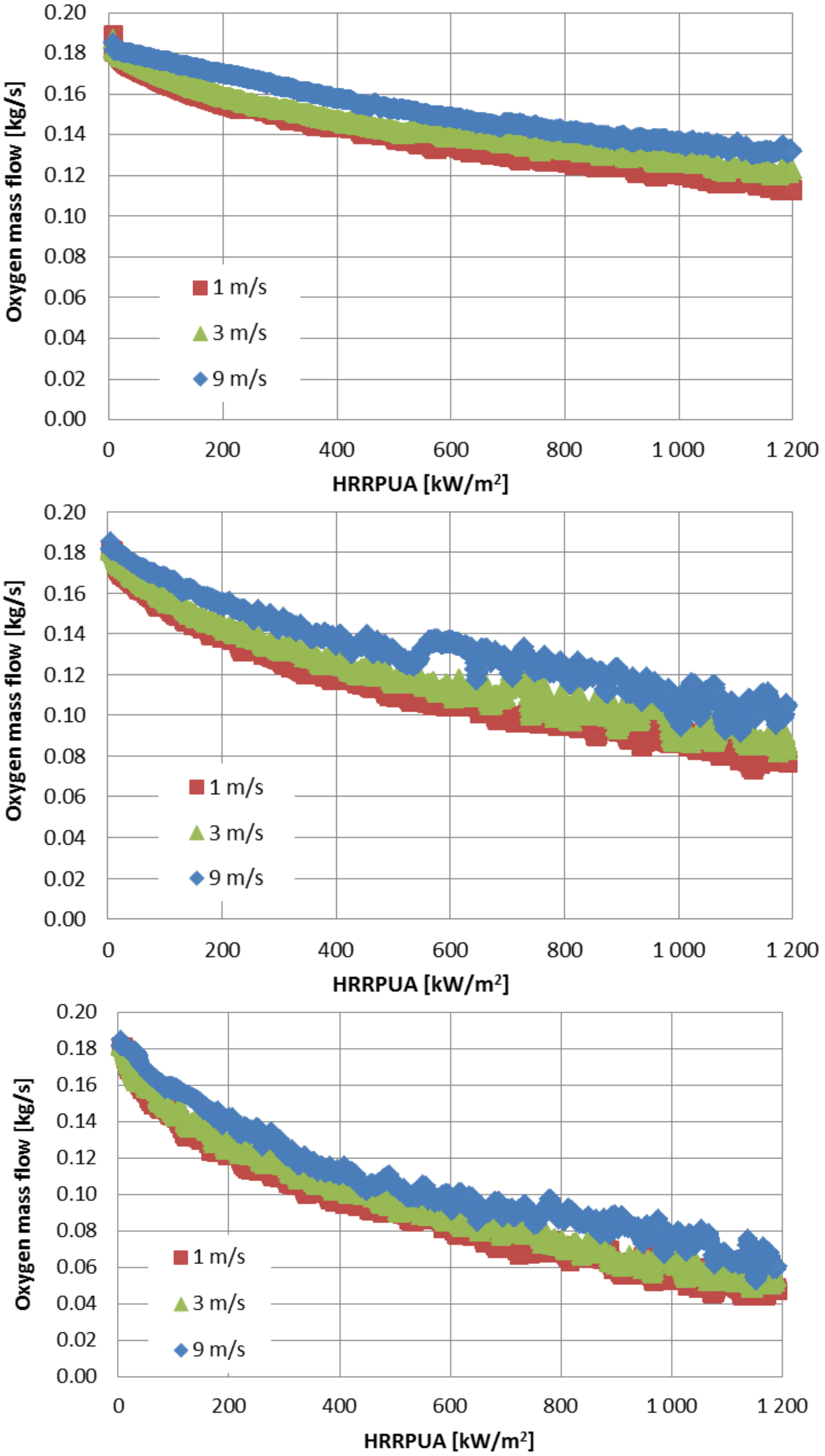

Figure 7 Oxygen mass flow into the inlet duct for fire area extensions of a) 1 m, b) 3 m, and c) 6 m of the building wall

Each diagram depicts lines for three wind speeds (1 m/s, 3 m/s, 9 m/s). The gas volume flow through the inlet is fixed to 0.655 m^3/s which equals 0.196 kg/s oxygen mass flow at 20 °C. The reduction of the oxygen mass flow is due to decreased density and oxygen concentration. The 65 % failure criterion represents an oxygen mass flow of 0.128 kg/s. This criterion is met for fire areas of 1 m extension at a HRRPUA of approximately 750 kW/m^2 with 1 m/s wind speed at a HRRPUA of about 1 MW/m^2 with 3 m/s wind speed, and at a HRRPUA exceeding 1.2 MW/m^2 with 9 m/s wind speed. For fire areas of 3 m extension it is met at a HRRPUA of about 300 kW/m^2 with 1 m/s wind speed, at a HRRPUA of about 370 kW/m^2 with 3 m/s wind speed, and at a HRRPUA of about 700 kW/m^2 with 9 m/s wind speed. For fire areas of 6 m extension it is fulfilled at a HRRPUA of about 170 kW/m^2 with 1 m/s wind speed, at a HRRPUA of about 200 kW/m^2 with 3 m/s wind speed, and at a HRRPUA of about 300 kW/m^2 with 9 m/s wind speed.

It should be kept in mind that the assumption of a constant volume flow may be too conservative. However, as described above, since the influence of temperature increase on the pressure drop is twofold (decrease because of reduced density, increase because of buoyancy effect), a detailed generic assessment is impossible.

CONCLUSIONS

All fire simulation results mentioned above, together with simulations with 9 m fire area extension, were evaluated concerning the failure criterion “inlet temperature above 170 °C” (cf. Figure 8) and “oxygen mass flow below 65 % of nominal value” (cf. Figure 9). In the diagrams the dots were connected by smoothed lines. The oxygen mass flow criterion, which is found as the more decisive one (see above), fails earlier than the temperature criterion. For the temperature criterion it is remembered that cooling effects are conservatively ignored. Concerning the fire area, the oxygen supply criterion already shows an asymptotic behaviour for the studied extensions.

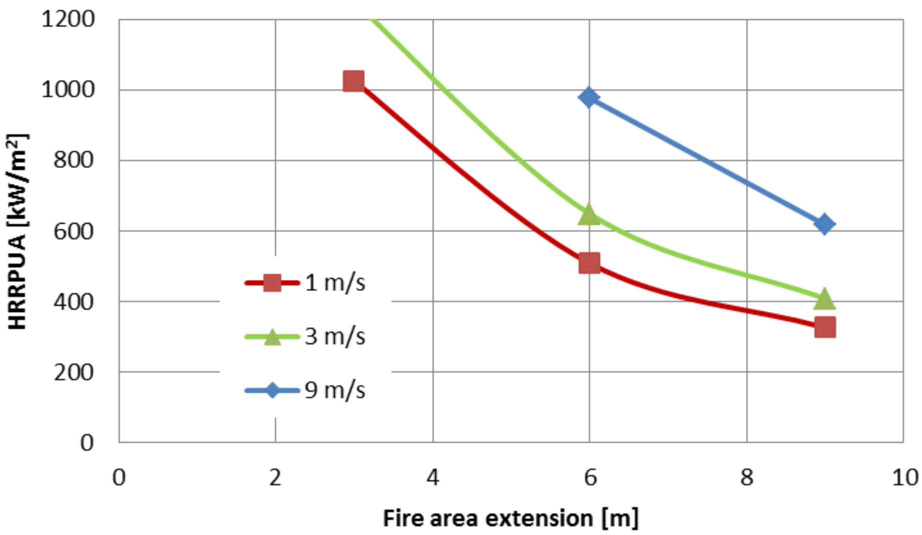

Figure 8 Resulting correlation of HRRPUA with the fire area extension of the building wall for the failure criterion inlet temperature above 170 °C

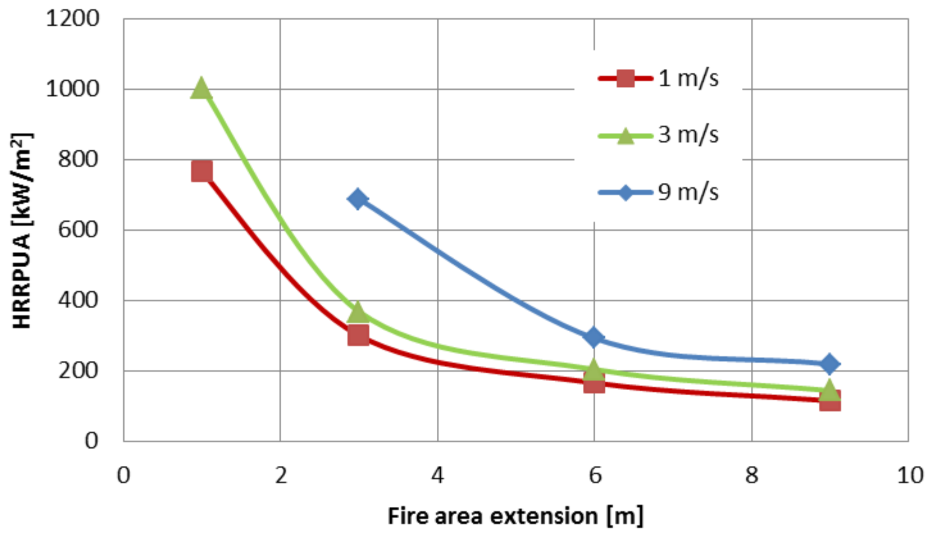

Figure 9 Resulting correlation of HRRPUA with the fire area extension of the building wall for the failure criterion oxygen mass flow below 65 % of nominal value

The influence of an orthogonal wind of constant speed on the results is reasonable; however, as someone would expect, the influence decreases for larger fire area extensions. Wind effects are surely not studied in full complexity. For low wind speeds, heat release rates of several hundred kilowatts per square meter are capable for diesel engine failure for fire area extensions of several meters. These heat release rates are achieved for fires of liquid fuels or, e.g., piles of wood pallets.

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