SMiRT 22
13th International Seminar on FIRE SAFETY IN NUCLEAR POWER PLANTS AND INSTALLATIONS

Proceedings

Columbia, SC, USA
September 18-20, 2013

GRS-A-3731

Gesellschaft für Anlagen-
und Reaktorsicherheit
(GRS) mbH

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Kurzfassung

Im Rahmen des vom Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU) beauftragten Vorhabens 3610R01375 wurde im September 2013 das mittlerweile dreizehnte internationale Seminar “Fire Safety in Nuclear Power Plants and Installations“ als Post-Conference Seminar der 22nd International Conference on Structural Mechanics In Reactor Technology (SMiRT 22) in Columbia, South Carolina (USA) veranstaltet.

Die vorliegenden Proceedings des Seminars enthalten alle achtzehn Fachbeiträge des zweitägigen Seminars mit insgesamt sechsundzwanzig Teilnehmern aus neun Ländern aus Asien, Europa und Nordamerika.

Abstract

In the frame of the project 3610R01375 funded by the German Ministry for the Environment, Nature Conservation and Reactor Safety (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, BMU) the meanwhile thirteenth international seminar on "Fire Safety in Nuclear Power Plants and Installations" has been conducted as Post-Conference Seminar of the 22nd International Conference on Structural Mechanics In Reactor Technology (SMiRT 22) in September 2013.

The following seminar proceedings contain the entire eighteen technical contributions to the two day seminar with in total twenty-six participants from nine countries worldwide.

Contents

1 Foreword

The meanwhile 13th International Seminar on 'Fire Safety in Nuclear Power Plants and Installations' was held as Post-conference Seminar of the 22nd International Conference on Structural Mechanics In Reactor Technology (SMiRT 22) in Columbia, South Carolina, USA in September 2013. In total twenty-six participants from Belgium, Canada, France, Germany, India, Japan, Sweden, United Kingdom and the United States of America followed the eighteen presentations in the different scientific sessions and participated actively in a round table expert discussion on the challenges of fire safety in nuclear facilities at the end of the seminar.

A broad majority of the participants could also participate in a fire related technical study tour of the VC Summer nuclear power plants' site.

The first presentations gave insights in general aspects of fire safety concepts and their challenges and provided recent enhancements in nuclear fire safety related regulations and standards.

The further sessions of the first seminar day strongly focused on ongoing research with respect to fire safety in nuclear installations starting with the ongoing real scale experimental activities. Several presentations on fire modeling and actual developments in simulation tools and their results demonstrate the progress made in the recent past in this field. However, these presentations also clearly indicated that there are still gaps to be closed and that continuous research and development activities are strongly needed. It is still not possible to predict all fire scenarios relevant for nuclear installations (e.g. fires of vertically routed cables and their consequences) with high certainty. Fire hazard analysis as well as probabilistic fire risk analysis (Fire PRA) need these improvements for adequately modeling different phenomena as well as fire suppression in an as far as possible realistic but still enough conservative manner. These challenges have to be considered in future R&D activities.

The second seminar day with in total four sessions focused on fire safety analysis in the frame of the regulatory oversight and supervision of the plant operation first. Practical examples of still not completely resolved and challenging issues to be addressed in the analysis, such as fire modeling of the main control board or fire induced cable and circuit failure modes analysis. The second session particularly addressed the differences in the approaches for rating of fire barriers and their elements being significant not only for nuclear installations design but also in case of changes in the use of fire compartments and plant operation. This session was explicitly aiming on getting a better understanding of the differences which do not become visible from the regulation. The third session provided valuable insights on fire related post-Fukushima improvements of nuclear power plants and lessons learned with respect to fire induced spurious operation, its probability and duration

The focus of the final discussion involving all participants´ perspectives on the recent challenges with respect to nuclear installations´ fire safety provided insights on what has to be addressed in a better way in the future. This concerns in particular electrically induced fire including spurious operation of items important to safety, a systematic and comprehensive consideration of event combinations with fire events and uncertainties in human response in the event of fire in a nuclear installation.

From the first seminars of this series starting in 1987 when the safety significance of fires in nuclear installations had just been recognized up to today fire safety in nuclear reactor facilities as well as in other nuclear installations has significantly increased. This does concern design as well as operation, all areas of assessment, inspections and maintenance, active and passive means. Over more than three decades, methodological approaches and analytical tools have been and are still continuously being enhanced.

Nevertheless, new challenges do arise, affecting analysis of fire hazards and their consequences in nuclear installations. Nuclear fire risk assessment needs permanent research and development on a theoretical as well as experimental basis. New as well as further enhanced methods and analytical approaches need validation and verification for the area of application. The existing data have to be updated and adapted to the state-of-the art.

From the operating experience in the recent past, indications to also cover fire not only as a single event, but also in causal relationship to other hazards and anticipated events have posed new aspects to be considered. The major goal of this thirteenth seminar on ‘Fire Safety in Nuclear Power Plants and Installations’ was to reflect the most recent challenges and to provide insights in how to resolve fire safety issues. The Seminar was hosted with great hospitality by Frederick A. Emerson (F. Emerson Consulting LLC) and Dennis Henneke (GE Hitachi) in Columbia, SC, USA. The organizers are indebted to the invitation and support by the hosts during the two days seminar.

Furthermore, the organizers and the participants are grateful to the management of the VC Summer Nuclear Power Plant having invited all the seminar participants to a technical study tour of the plant mainly focusing mainly on different aspects of fire protection. The organizers want to express their particular thanks to Duane Twining and Gerald Loignon Jr. and their colleagues guiding the tour group considering explicit wishes and interests of the participants as well as answering all the upcoming questions with high expertise and in a very open minded manner.

Last but not least the organizers want to thank all participants, speakers, authors and chairpersons for their active and fruitful participation as well as for the many high level contributions during the 13th International Seminar on 'Fire Safety in Nuclear Power Plants and Installations' which made this thirteenth venue within twenty-six years again a very successful one.

The next, 14th seminar of this series is intended to be held as SMiRT 23 Post-conference Seminar in Manchester, United Kingdom in late summer 2015.

Dr. Marina Röwekamp

\- Scientific Chairperson and Organizer -

2 Seminar Agenda

13th SMIRT Post-Conference Seminar on Fire Safety in Nuclear Power Plants and Installations

Columbia, South Carolina, USA; September 18-20, 2013

AGENDA

Wednesday, September 18, 2013

	Pre-Seminar NPP Study Tour **(transportation arranged)**		
11:00 h	***Lunch (Sheraton Hotel)***		
12:00 h	Bus transport to NPP		
13:00 h	Arrival at VC Summer NPP		
13:30 h	NPP study tour		
17:00 h	Bus transport back to Columbia		
18:00 h	Arrival at Sheraton Hotel		

Thursday, September 19, 2013

09:30 h	***Introduction by Hosts***	F. Emerson	
	Welcome	D. Henneke	
	General Aspects of Fire Safety Programs in Nuclear Installations	***Chairperson: Frederick Emerson (F. Emerson Consulting LLC)***	
09:45 h	IRSN Global Process for Conducting a Comprehensive Fire Safety Analysis for Nuclear Installations	T. Vinot, et al.	IRSN, France
10:15 h	Legal Aspects of Current Technical Issues: U. S. Nuclear Power Plant Fire Protection	S. Trubatch	The Regulatory Strategy Group LLC, USA
10:45 h	***Coffee Break***		
	Regulation, Standards and Guidelines	***Chairperson: Frederick Emerson (F. Emerson Consulting LLC)***	
11:15 h	Ongoing Enhancements in the German Nuclear Regulatory Framework with Respect to Fire Safety	M. Röwekamp, H.-P. Berg	GRS, Germany BfS, Germany

	Nuclear Fire Research - Experiments and Simulation	***Chairperson: Laurent Audouin (IRSN)***	
12:00 h	Experimental Studies on Electric Arc Explosion Events Using the 6.9 kV Switchgears Subjected to High Energy Arcing Fault	K. Shirai, et al.	CRIEPI, Japan
12:30 h	***Lunch Break***		
	Nuclear Fire Research - Experiments and Simulation (continued)	***Chairperson: Laurent Audouin (IRSN)***	
13:30 h	OECD PRISME 2 Fire Research Project (2011-2016) - Current Status and Perspectives	L. Audouin, et al.	IRSN, France
14:00 h	Recent Fire Research Related to Swedish Nuclear Power Plants and European Spallation Source	J. Wahlqvist, et al.	Lund University, Sweden
14:30 h	Validation of CFD Code ISIS for Compartment Fires with Leakage	F. Bonte, et al.	BEL V, Belgium
15:00 h	***Coffee Break***		
	Nuclear Fire Research - Experiments and Simulation (continued)	***Chairperson: Laurent Audouin (IRSN)***	
15:30 h	Determining Compliance of Experimental Data and Numerical Results Using FDS	M. Siemon, et al.	iBMB, Germany
16:00 h	Computational Approach for Sodium Fire Phenomenon in Sodium Cooled Fast Reactor	T. Takata, et al.	Osaka University, Japan
16:30 h	Application of Fire Modeling and Simulation for Fire Hazard Analysis	P. Roy	TATA Consulting Engineers Ltd., India
17:00 h	***Adjourn of the first day***		
19:00 h	***Hosted Dinner***	All participants enscribed and spouses	

Friday, September 20, 2013

	Fire Safety Analysis and Modelling	***Chairperson: Dennis Henneke (GE Hitachi)***	
09:15 h	Fire PRA: Detailed Fire Modeling of Main Control Board	G. Georgiev, et al.	Jacobsen Analytics, United Kingdom

09:45 h	Development of the Methodology for Analysis of Cable Failure Modes and Effects (FMEA) for the Purpose of Fire PSA	E. Piljugin, et al.	GRS, Germany
	Fire Barrier Qualification	***Chairperson: Marina Röwekamp (GRS)***	
10:15 h	Need for Prudent Use of Resources for Passive Fire Protection in Nuclear Power Plants and Installations	P. Roy	TATA Consulting Engineers Ltd., India
10:45 h	***Coffee Break***		
11:05 h	Load and Deformation Redistribution Following Column Removal	E. Zalok, et al.	Carleton University, Canada
11:35 h	Qualification of Fire Barriers in U.S. Nuclear Power Plants	R. Sims	Hughes Associates, USA
12:05 h	***Lunch Break***		
	Fire Barrier Qualification (contd.)	***Chairperson: Marina Röwekamp (GRS)***	
13:05 h	Recent Considerations on the Fire Barrier Resistance Rating for German Nuclear Power Plants	B. Forell	GRS, Germany
	Operating Experience and Lessons Learned	***Chairperson: Marina Röwekamp (GRS)***	
13:50 h	Improvements of German Nuclear Power Plants after the Fukushima Dai-ichi Reactor Accidents	M. Beesen, et al.	TÜV SÜD, Germany
14:20 h	Recent Lessons Learned in Fire-induced Spurious Operation Probability and Duration	D. Henneke	GE Hitachi, USA
14:50 h	***Coffee Break***		
15:05 h	**Discussion**	***Chairperson: Frederick Emerson (F. Emerson Consulting LLC)***	
16:00 h	***Seminar Adjourn***		

3 List of Participants

22nd International Conference on Structural Mechanics in Reactor Technology (SMiRT 21) -
13th International Post-Conference Seminar on
"FIRE SAFETY IN NUCLEAR POWER PLANTS AND INSTALLATIONS"

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4 Seminar Contributions

In the following, the seminar contributions prepared for the 13th International Seminar on 'Fire Safety in Nuclear Power Plants and Installations' held as Post-conference Seminar of the 22nd International Conference on Structural Mechanics In Reactor Technology (SMiRT22) are provided in the order of their presentation in the seminar.

5 Seminar Conclusions and Outlook

The 13th International Seminar on 'Fire Safety in Nuclear Power Plants and Installations' demonstrated significant progress in nuclear fire safety with respect to experiments, analysis, and assessment. However, there are still challenges since the knowledge on several fire related phenomena is not yet as mature as expected two decades ago and due to the continuous need of further enhancing the analytical tools.

The excellent presentations provided an added value to the state-of-the-art in nuclear fire protection highlighting the recent, partly still unsolved issues in this field.

The following conclusions have been drawn from the seminar:

The participants concluded that significant progress has been achieved with respect to fire safety in nuclear installations and its assessment within the last more than twenty-six years after the first of these seminars. However, fire safety is still a 'hot' issue which has to be addressed in nuclear facilities from their construction throughout all their operational lifetime until decommissioning. The question, therefore, is where we are now and what are the more recent challenges.

While fire behavior has been widely resolved to be modeled more accurately, realistically predictions of solid fires, typically of cable insulation materials representing more frequent fires, e.g. in nuclear power plants, are still difficult and bear remarkable uncertainties. Further uncertainties do still exist in the human response to fire. Efforts are ongoing to reduce these uncertainties to be able to quantify them, in particular for probabilistic analyses.

For demonstrating the robustness of the fire protection in nuclear facilities, post-Fukushima issues such as consideration of potential 'cliff-edge'-effects or combinations of fires and other anticipated plant internal and external events, being either correlated in cause or time, are gaining more and more significance. In particular with respect to seismically induced fires, progress is needed to better understand which components can catch fire and why. In this context, mobile equipment for ensuring adequate protection becomes more important. Tsunamis and consequential fires also have not been adequately addressed in safety analyses in the past. Accident mitigation is essential, resulting in the availability of accident mitigation equipment needed to be reliably operable after the event, even in case of consequential fires. Risk assessment has also to address these new fire sources resulting from the event interactions. In this context, fire related plant walk-downs seem to be essential.

With respect to research activities focusing on real case fire scenarios in nuclear installations´ fire safety there is a strong expert opinion that the actually ongoing experimental nuclear fire research programs provide valuable insights on the behavior of the nuclear facility in the case of fire. A typical example is the international OECD PRISME Project, which is being continued in a second phase with as far as possible realistic nuclear power plant specific scenarios to close still existing knowledge gaps. The intended experiments should assist to resolve specific questions important for the analysis, such as the consideration of under-ventilated conditions, the effects of specific conditions by forced ventilation, or the effects of fire extinguishing systems on fire sequence course.

In respect of the validation of fire models, the heat release rate for electrical cabinet fires represents a still unsolved issue. The existing databases on fire events in nuclear installations do only provide information on the amount of such fires in comparison to other types of fire, and on the event sequence as far as this could be concluded after the event. The do not provide enough information on the energy released during the event. Here, further investigations to reduce uncertainties in the fire characteristics are needed.

From the U.S. point of view, spurious and multiple spurious operation of equipment of the instrumentation and control (I&C), in particular the effects of smoke and soot on digital circuits need further investigation.

Shutdown fire PSA is another topic of interest, mainly in front of aging nuclear power plants and long-term operation. Fire frequencies vary strongly over time and plant location. In the context of fire PSA; new insights from the operating experience, inspection and maintenance practice and corresponding findings providing insights on how to improve reliability and effectiveness of active and passive fire protection features become more and more important.

Moreover, there is a need to address the non-negligible hazard fire in full scope PSA up to Level 2 in order to enable the analyst to also predict fire induced large release frequencies.

Last, but not least, the nuclear accidents as a result of earthquake and Tsunami.at the Fukushima Daiichi nuclear power station in Japan in March 2011 revealed further questions, in particular on combinations of fires with external or internal hazards. In principle, the fire protection standards and design cover these aspects and especially seismically induced fires and explosions. However, the operating experience has shown vulnerabilities in this respect. As already observed in the previous, 11th International Seminar on 'Fire Safety in Nuclear Power Plants and Installations' the most recent earthquakes having impaired the safety of nuclear installations have re-started the discussion on fires consequential to external hazards between regulators and analysts in several countries. The existing regulations and standards have to be adapted to the state-of-the art in this respect.

For beyond design basis accidents with consequential fires there is nevertheless a need for further investigations. The results from international stress tests and other national in-depth investigations resulting from the above mentioned nuclear accidents will show in the near future, where research and analytical effort is needed and what could be done to improve the safety of operating installations further. However, the more frequent fire events have to be analyzed with highest priority.

The participants from all over the world, representing the different parties involved in nuclear fire safety, nuclear industry as well as regulators, research institutions as well as technical expert and support organizations (TSO), strongly emphasized the value and benefits of the information provided in this experts' seminar to be shared inside the nuclear fire community. They expressed their wish of continuing this series of fire safety seminars on a regular basis in time intervals of approximately two years. The next, 14th seminar of this series is therefore planned to be conducted in late summer 2015 in conjunction with the 23rd 'International Conference on Structural Mechanics In Reactor Technology' (SMiRT 23), which will take place in Manchester (United Kingdom) in August 2015 (cf. http://www.smirt23.org/).

Attachment

CD of the 13th International Seminar on ‘Fire Safety in Nuclear Power Plants and Installations’ held as Post-conference Seminar of SMiRT 22

IRSN GLOBAL PROCESS FOR CONDUCTING A COMPREHENSIVE FIRE SAFETY ANALYSIS FOR NUCLEAR INSTALLATIONS

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ABSTRACT

A fire safety analysis (FSA) is requested to justify the adequacy of fire protection measures set by the operator. A recent document written by IRSN outlines a global process for such a comprehensive fire safety analysis.

Thanks to the French nuclear fire safety regulation evolutions, from prescriptive requirements to objective requirements, the proposed fire safety justification process focuses on compliance with performance criteria for fire protection measures. These performance criteria are related to the vulnerability of targets to effects of fire, and not only based upon radiological consequences outside the installation caused by a fire.

In his FSA, the operator has to define the safety functions that should continue to ensure its mission even in the case of a fire in order to be compliant with nuclear safety objectives. Then, in order to maintain these safety functions, the operator has to justify the adequacy of fire protection measures, defined according to defense in depth principles.

To reach the objective, the analysis process is based on the identification of targets to be protected in order to maintain safety functions, taken into account facility characteristics. These targets include structures, systems, components and employees important to safety. Facility characteristics include, for all operating conditions, potential ignition sources and fire protections systems.

One of the key points of the fire analysis is the assessment of possible fire scenarios in the facility. Given the large number of possible fire scenarios, it is then necessary to evaluate "reference fires" which are the worst case scenarios of all possible fire scenarios and which are used by the operator for the design of fire protection measures.

INTRODUCTION

This document presents the IRSN (Institut de Radioprotection et de Sûreté Nucléaire) process for a comprehensive analysis of fire hazards in nuclear installations as outlined in [1].

The purpose of the analysis process described in this document is to provide the required steps to prove that the fire protection measures in the facility are acceptable and sufficient. The justification of the measures retained should be based on the fulfilment of technical criteria considering the fire hazard analysis. On the basis of the safety functional requirements in combination with the protection requirements for safety targets[1], the operator shall there-

1 The elements needed to perform a safety function or to protect against the effects of a fire. Targets can be diverse in nature: radioactive materials, radioactive materials containment systems, criticality units, material and human resources that play a role in the safety functions, escape routes and access routes to equipment which has to be operated to put and keep the installation in safe conditions.
Structures that accommodate or support safety targets are to be protected against the fire. Equipment and

fore determine the performance criteria that shall be met by the fire protection measures. Compliance with these criteria ensures that the safety objectives will be met.

This guide is a tool explaining the analysis process of the fire hazards in nuclear installations. Considering its general nature, the process described in this document may require to be adapted to very specific configurations.

FIRE AND NUCLEAR SAFETY CONSIDERATIONS

In the room where a fire breaks out, the fire will cause a temperature increase as well as a change in the room gas pressure. Hot gases and combustion aerosols toxic, corrosive and possibly flammable will be generated by the fire. Fire is often the source of opaque and explosive atmospheres.

It is important to consider all the effects of the fire in the analysis, on the one hand to assess the vulnerability of the targets that need to be protected against the effects of fire and, on the other hand, to establish the fire protection measures.

Considering only fire characteristics is not enough to determine and design the fire protection measures needed for a satisfactory level of safety. It is also essential to consider the unfavourable effects of the fire extinguishing systems selected (excess pressure due to the release of an extinguishing agent, malfunction of safety equipment due to the extinguishing agent used, criticality accident caused by a mechanical or moderating effect, etc.) and the mechanical effects induced (behaviour of confinement barriers, etc.).

Fire in the Presence of Radioactive Materials

In the presence of radioactive materials, a fire can scatter the materials, thereby producing a situation in which the workers' exposure cannot be controlled and even not a release of radioactive materials into the environment. A fire can also trigger a criticality accident by damaging the measures and systems used to control the criticality units. Furthermore, specific measures are necessary to deal with the effluents produced by the extinguishing systems or the fire fighting, which could lead to a contamination (dispersion of radioactive materials) or criticality accidents.

Fire in the Presence of Safety Equipment

The fire and the extinguishing systems used can significantly damage safety equipment. Even at a distance from the fire and in different ways, the corrosive materials and the soot contained in the smoke may produce equipment malfunctions which differ from those caused by the simple thermal effects of a fire. Because of the toxicity and visibility effects for employees, smoke may jeopardize actions to tackle the fire and to put the installation in safe conditions.

Structural Stability in Case of Fire

In nuclear installations, the structural stability of buildings containing targets shall be guaranteed to lead and maintain the facility in safe conditions. This stability is requested for a fire occurring inside or outside these structures. Consideration also has to be given to the consequences of any interactions between buildings caused by a fire that grows up in a contiguous building.

To demonstrate that the structural stability in case of fire is sufficient, the actual stress (temperature and pressure fields) that these structures are likely to experience, including the

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structures, different from those mentioned above, are also to be protected against the fire and its effects if their deterioration (in the form of a domino effect) caused by a fire could affect the safety of the installation.

cooling phase after extinction, and the structures' behavioural requirements during a fire have to be known.

The analysis process defines the fire scenarios, leading to the worst effects on the structures.

HAZARD ANALYSIS PROCESS FOR A FIRE IN A NUCLEAR INSTALLATION

According to the defence in depth, the safety of a nuclear installation in case of fire shall be demonstrated for all of the operating states, including shutdown states, with the operating ranges associated to each operating state. The measures retained to meet the safety objectives have to be described. However, the measures` adequacy has to be justified in particular.

The analysis process shall be based on the verification of the fulfilment of the technical performance levels which are justified through a fire and safety hazard analysis. The operator has to define the safety functions to be protected, the associated functional requirements, the technical performance levels of fire protection measures (FPMs) retained, and to demonstrate the adequacy of these performance levels in relation to the needs and how they are assured by the design adopted. Justification of the measures therefore concerns compliance with technical performance criteria. Calculation of the potential radiological consequences of a fire will only be carried out in a verification step of the safety demonstration.

Principles to be met

Goals of the Fire Protection Measures

The control of hazards linked to an event such as a fire in a nuclear installation requires the examination of both plausible fires and targets to be protected as part of nuclear safety.

The goals of the protection measures implemented on the basis of this examination are to:

- Prevent fires and limit their number, spread and duration,
- Maintain functional safety requirements,
- Limit the radiological consequences of the fire.

Defense in Depth Applied to Fire Protection

To fulfil the aforementioned goals, the fire protection is defined and designed according to the defence in depth principle. These measures are therefore implemented and organized in successive levels that are as independent as possible. Each level of defence against the fire shall prevent the situation from deteriorating and moving to the next level and limit the consequences of the failure of the previous level.

Applied to fire hazards, the levels of defence in nuclear installations can be defined according to the definition for nuclear power plants by IAEA in [2] as:

- 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.

It may also be necessary to have additional levels of defence including the ultimate protection measures inside the installation and the protection of the population in case of a radioactive materials release. These last levels are generally specified in the installation´s internal emergency plan and the corresponding external emergency plan. These levels are not covered in this document because fire is not the only initiating event to be considered when defining the corresponding measures.

Fire protection means shall be designed and dimensioned to meet the goals of the aforementioned defence in depth levels as well as possible.

Combination of Events

A combination of events is the occurrence that several events are able to affect the same installation in the same period of time. If there is no link between these events, they are independent events. Otherwise, depending on the strength of the correlation, the dependence of the events is potentially proven.

This section looks at the combination of fires with other events to be considered when designing and dimensioning fire protection measures (FPMs). These events may be internal events caused by the failure of equipment involved in a safety function or caused by internal or external hazards.

As a general rule, the combinations shall be explicitly considered whenever there is a proven dependency and no design solution can rule out such a dependency. Any absence of dependency shall be justified. Excluded combinations of events shall be specified and their exclusion shall be justified with regard to their frequency and consequences.

Combinations with a potential dependency shall be examined to determine whether they should be considered. The following situations are to be examined, in particular, lightning and fire, airplane crash and fire, explosion and fire, earthquake and fire.

Furthermore, an independent fire is to be considered

- in conjunction with each event with a high frequency that is likely to affect the fire protection measures (freezing, loss of external power supply, etc.),
- after an event that undermines the safety of the installation over a long period without any compensatory measures.

For the entire combinations of events considered, all of the direct and indirect effects brought about by the initial event are to be studied. Therefore, the effects of these events on the fire protection measures and the associated back-up elements as well as the possible intervention of the external emergency services shall be assessed. If necessary, these fire protection measures will have to be protected against the associated hazards and qualified on the basis of the specific conditions induced.

Margins and uncertainties

The hazard analysis process needs an assessment of the different effects of fire and a comparison with the performance criteria while taking into account the failure conditions of the targets to be protected.

The modelling of the fire scenarios and the evaluation of the scenarios´ effects comprise uncertainties that are linked to the input data used to model the scenarios, the values associated with the data, the tools used to determine the effects, the models implemented, etc. These uncertainties shall be assessed and taken into consideration. Furthermore, the margins considered when defining the performance criteria of the fire protection measures shall cover the variability of the situations examined in the installation´s safety analysis, which are finally represented by a small number of studied scenarios (‘reference’ fire scenarios).

The margins selected and the parameters used to determine them shall be presented and justified in the analysis.

Fire Hazard Analysis

The fire hazard analysis shall prove that the performance level of the FPMs meets the safety objectives and prove the robustness of the operator´s safety demonstration. For the ‘reference’ fire scenarios, this means that the operator will have to show that:

- the fire protection measures (defined according to the defense in depth process) are adapted to the fire hazards,
- their global design ensures, despite the failure of one of these measures, that the consequences for the installation´s safety are controlled and the consequences for individuals and the environment remain acceptable.

The performance level of the FPMs is defined according to specific conditions. The hazard analysis shall be updated in case of modification of the installation or for the safety reassessments required by regulations.

The analysis shall reveal the key parameters of the safety demonstration. Then, minor modifications and those likely to significantly undermine the safety demonstration´s conclusions can be easily pointed out.

As part of the final verification of the design, the operator shall show that consequences would remain acceptable, even in case of fire in a given room despite the FPMs taken.

Demonstration of the Sufficiency of the Fire Protection Measures

<u>Elements Required for the Analysis</u>

This chapter lists the elements which shall be known in addition to the description of the installation's characteristics (dimensions, organization of rooms, layout, procedures, etc.) for the fire hazard analysis.

Functions to be safeguarded and associated functional requirements

The operator identifies the safety functions and the associated support functions to be maintained or to be restored within a relatively short period in case of fire. The operator associates the functional requirements needed to ensure that the corresponding systems and components work correctly during the various operating states.

Targets to be protected against the fire and its effects

The operator identifies the targets to be protected so that the functions defined previously can be safeguarded in case of fire. These targets include, in particular: radioactive materials, material confinement systems, criticality units, SSCs (structures, systems and components) important for safety, material and human resources that play a role in the safety functions to be safeguarded in the event of a fire, escape routes and access routes to equipment which have to be operated to put and keep the installation in safe conditions.

Structures that accommodate or support safety targets are to be protected against the fire. Equipment and structures, different from those mentioned above, are also to be protected against the fire and its effects if the safety of the installation can be affected due to domino effects.

Performance criteria to be met

A nuclear installation operator shall demonstrate by a fire safety analysis that the functional safety requirements are met thanks to the fire protection measures put in place. Considering the process, the effectiveness of these measures has to be compared with quantitative performance criteria. These technical criteria may be threshold values based on, for example, data on the failure of equipment (temperature and thermal flux values that trigger a malfunction, soot particle or toxic particle concentration levels, etc.); whenever possible, they shall include a margin in relation to the experimental or theoretical data.

These performance criteria vary according to the goal of the operator's demonstration. For example, if the operator seeks to demonstrate the resistance of the last stage filter, the performance criteria can be defined in relation to the failure criteria of the filtering system during a fire (i.e. the maximum temperature values and the difference in pressure at the filter terminals).

Furthermore, specific attention shall be given to the fire stability requirement for structures that accommodate or support safety targets. Attention shall also be given to the associated performance criteria, because this functional requirement is generally a priority condition for the compliance with all of the other requirements.

Fire hazards

The fire hazards within the installation, which are likely to impact on the targets, have to be identified for all of the installation's operating states (normal, maintenance, shutdown states, etc.). These fire hazards are linked to the products and materials used and also to the installation's equipment and operating conditions.

The fire hazards outside of the installation, which form part of the industrial, human activities or natural environment (such as lightning, external road or railroad hazards, etc.) shall also be identified in order to define the fire protection measures needed to control external fire hazards.

Fire protection measures

The operator specifies the reliable FPMs for its safety demonstration. The operator justifies the fire protection measures' ability to fulfil their functions (fire detection, heat insulation, smoke tightness, access and extinction of the fire in a room, etc.). The justification of these measures can be based on the fact that they comply with different reference documents or standards, as long as the associated conditions and qualification criteria are adapted to the situation.

With regard to the response to a fire, whether it relies on human or technical actions, the response time to be used for the safety demonstration is the sum of all of the amounts of time needed for the effective implementation of the intervention means.

<u>‘Reference’ Fire Scenarios</u>

The selection of ‘reference’ fire scenarios is an important part of the safety demonstration. These scenarios justify the suitability and the sufficiency of the fire protection measures retained, considering the fire hazards, by comparing the performance levels of these fire protection measures with the performance criteria.

In practice, numerous fire scenarios could arise in an installation. Nevertheless, it is usually necessary to reduce the possible fire scenarios to a manageable number of credible “reference” fire scenarios.

Two stages are therefore necessary:

- Identification of the fire scenarios,
- Selection of "reference" fire scenarios for the design of the fire protection measures.

Definition of fire scenarios

The definition of deterministic fire scenarios is carried out by room or group of rooms. Conservative assumptions are to be retained with regard to the parameters used in the scenarios' development (ventilation flow rates, diagnosis and response times, etc.). As part of a deterministic approach, the outbreak of a fire will always be considered.

Selection of ‘reference’ fire scenarios

The fire scenarios thereby identified may be grouped in accordance with their specific characteristics and similarities as long as the fire hazards are of the same nature. The rooms or groups of rooms concerned are covered by the same type of fire protection measures (similar nature and performance levels) and their fire effects are alike.

For each fire scenario group, one or more representative scenarios are selected if they are likely to have the most harmful direct or indirect effects on the targets. These scenarios will be used to check the design of the fire protection measures. They are specified as "reference" fire scenarios. Each ‘reference’ scenario shall be chosen to ensure that the fire protection measures can also ensure compliance with these objectives for all of the other scenarios of the group.

The conclusions issuing the examination of each reference scenario apply to all of the rooms or groups of rooms covered by a same ‘reference’ fire scenario.

Quantification of the Effects of ‘Reference’ Fire Scenarios

For each ‘reference’ fire scenario, a quantitative assessment of the characteristic factors of the fire is necessary to assess the effects that the fire can have on targets and the effectiveness of the fire protection measures.

The methods and tools used for this quantification process shall be adapted to the scenarios and the parameters studied. The input parameters and groups of hypotheses shall be reasonably inclusive.

Selection of methods and tools

When the assessment of the characteristic factors under investigation is based on a numerical tool or an analytical calculation method, the capability of the selected tool to match the degree of complexity of the phenomenon studied must be proven. The accuracy, the physical factors to be characterised and the performance criteria are also to be considered. For these tools, a validation and a demonstration of their use in the relevant area shall be provided.

If quantification is carried out on the basis of experimental results, the experimental results shall be presented if they were obtained under conditions that are sufficiently representative of the scenarios. The test results shall be analysed to make sure that the conclusions drawn apply to the cases considered.

In certain specific cases (for example, in case of a lack of adapted calculation method or experimental data), the opinion of experts can be sought. However, a prudent approach should guide the reflexion. In any case, resorting to an expert's opinion shall be clearly mentioned and justified.

Characteristic factors investigated

The characteristic factors to be quantified vary with the "reference" fire scenario(s) retained and the requirements. Aside from the temperature reached in the room and the duration of the fire, factors such as room gas pressure, thermal flux received by the targets, the quantities of soot and unburned materials produced, the toxicity of the smoke, etc. and their associated uncertainties (inherent to the input data, the modelling tool, etc.) may be factors to characterise.

Input data and groups of hypotheses

Regardless of the quantity of input data needed to forecast the characteristic factors of the fire under investigation, some of them may significantly affect the results. They shall be identified and their values justified (physical parameters, values of thresholds for automatic actions, criteria for manual actions, time required for manual actions, etc.). The uncertainties associated with these values shall be assessed.

Verification of the Performance Level of the Fire Protection Measures

The characteristic factors of fire effects in the 'reference' scenarios shall therefore be compared with the criteria retained. Then, two situations can ensue:

- One or more criteria are not met: corrective measures shall be taken (new design of fire protection measures, additional measures, modification of initial project, etc.) and the demonstration shall be reconsidered,
- All of the criteria are met: justification of the performance level of the fire protection measures is provided for the reference scenarios; the robustness of the demonstration shall now be proven.

Verification of the Robustness of the Safety Demonstration

The robustness of the safety demonstration, and therefore the sufficiency of the fire protection measures and their design, is proven on the basis of the fire scenario study whose effects could prove to be more harmful than the 'reference' scenarios retained at the dimensioning stage; this involves:

- "aggravated" scenarios based on a fire protection measure failure,
- one or more "maximum possible fire" scenarios.

Within the scope of checking whether the consequences for safety, people and the environment remain acceptable.

Aggravated Scenarios Based on a Fire Protection Measure Failure

The failure of a fire protection measure can result in fire scenarios that are more harmful than those retained during the dimensioning stage. Consequently, the performance criteria of some of these measures may no longer be respected. This stage therefore consists of checking the robustness of the safety demonstration while making sure that the consequences remain acceptable despite the hypothetical failure of a fire protection measure.

The acceptability of the demonstration is assessed on a case by case basis, while taking the installation, its specific characteristics and its environment into consideration. To test the robustness of the demonstration, two approaches are possible:

- a deterministic approach,
- a probabilistic approach.

Deterministic Approach

On the basis of the "reference" fire scenarios, this approach aims to determine the plausible failures of the fire protection measures. Then these failures, considered separately, shall not allow the development of a fire whose effects would result in unacceptable consequences. It is important to recall that in certain cases, the lack of effectiveness of one fire protection measure can impact on the effectiveness of one or more of the other fire protection measures. These cases shall be clearly identified and considered in the demonstration.

The failure can concern material that may belong to an active system, such as the automatic fire detection (failure of a sensor, for example) or an extinguishing system (failure of a valve, for example), or a passive system, such as fire area elements (doors, fire dampers, in particular).

Failure may be the result of human actions, such as the failure of an action or diagnosis or a delayed intervention (incorrect diagnosis by an operator, slow response and slow implementation of equipment by the emergency team).

If the operator provides proof of the robustness of certain fire protection measures, their failure may be ruled out. The operator shall, nevertheless, provide proof that the level of performance of the measures concerned and the measures' functional characteristics are maintained during the fire scenario conditions and for the period required.

Probabilistic Approach

This approach allows situations comprising complex events and an accumulation of events to be studied. In particular, situations in which redundant systems are lost and situations involving the occurrence of an external or internal hazard such as a fire. The hazard in terms of the probability of occurrence of the undesirable event is assessed. It includes both failures of a material and of a human or organizational action.

The event tree method is commonly used to represent fire scenarios. It shows how each scenario will develop, determine the events to be studied, assess the influence of measures (fire protection measures, systems and support systems, behavioural procedures, etc.) and consider time-related and functional dependencies between events.

The addition of the values of the frequencies calculated for each sequence of the event tree that leads to the undesirable event gives then the total frequency of the undesirable event for the "reference" scenario. The frequency associated with the reference scenario is then applied to all of the scenarios covered by this reference scenario in order to exhaustively assess the hazard associated with this group of scenarios.

To assess the robustness of the demonstration, the following factors are cross-referenced:

- the total frequency associated with the group of scenarios considered,
- the contribution of the failure of each fire protection measure to the total frequency,
- the corresponding level of consequences.

The approach adopted to create the event trees and the input data retained shall be presented and justified as the robustness of the results of the probabilistic approach chiefly depends on the quality of the input data.

Worst Case Fire Scenarios

Eventually, the robustness of fire compartmentation shall be assessed with a final stage in order to check that a fully developed fire in one room or a group of rooms cannot result in unacceptable consequences for safety, people and the environment,.

The rooms or groups of rooms concerned by this stage are those that accommodate mobile radioactive material and that contain - or are likely to contain for a transient period - permanent combustible loads.

The spreading of a fire to all of the loads is to be considered separately from any consideration of the quantity of air available (air tightness or possible ventilation) and fire extinguishing systems that may be present.

The boundaries of the rooms or groups of rooms to be retained for the maximum possible fire study are those for which a fire resistance and a radioactive material confinement capacity are justified. Where a facility is not subdivided by these areas, the maximum area should be defined by the exterior walls and roof of the facility.

Assessment of Consequences for Safety, People and the Environment

The consequences of a fire are to be assessed by considering:

- the functional damage brought about by equipment failures,
- the radiological impact.

The failure of any equipment important for safety or the loss of back-up systems requested for the functioning of such equipment due to the effects of a fire shall induce the operator to carry out a functional analysis in order to check the operability of safety functions required in case of fire.

If the time needed to recover a function is below the lead times needed to recover and maintain the installation in a safe state or if there is a possibility of a functional redundancy, the safety demonstration is acceptable.

The assessment of the radiological consequences of a fire combined with the dissemination of radioactive materials or irradiation exposure concerns both workers, surrounding population, rescue team and the environment.

The quantification of the effects of the fire scenarios shows the quantities of radioactive materials that could be involved. The fractions of the airborne materials are estimated while taking into account the nature of the radionuclides involved, as well as their physicochemical form and volatile character. For each radionuclide or each group of radionuclides, the retained airborne release fraction shall be justified. If results from experiments are used, it shall be guaranteed that the experiment conditions are sufficiently close to the case considered.

The various modes of transfer and deposition mechanisms in the buildings and ventilation systems are to be considered with specific attention to leakages into the environment.

If the radiological consequences thereby assessed are considered to be tolerable, the safety demonstration in the event of a fire is acceptable.

CONCLUSION

This document presents the process by IRSN for a comprehensive analysis of fire hazards in nuclear installations.

This document gives the required steps to prove that the fire protection measures in the facility are acceptable and sufficient. On the basis of the safety functional requirements in combination with the protection requirements for safety targets, the operator shall determine the performance criteria that shall be met by the fire protection measures. Compliance with these criteria ensures that the safety objectives will be met in case of a fire.

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NUCLEAR POWER PLANT FIRE PROTECTION: LEGAL ASPECTS OF RECENT TECHNICAL ISSUES

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ABSTRACT

Fire protection issues at nuclear power plants (NPP) are still being actively pursued by the nuclear industry and the Nuclear Regulatory Commission (NRC). A review of these activities suggests that they present legal vulnerabilities which could interfere with resolutions of these issues. Although the NRC has, for the most part, successfully defended its program against legal challenges, that success may have resulted in part from ineffectual legal opposition. Because more effective lawyering by opponents may be more successful in the future, consideration needs to be given to developing more sophisticated defensive legal and regulatory strategies. Four examples of these concerns are presented: (1) the recent adverse court decision on the NRC's compliance with the National Environmental Policy Act (NEPA) for the Indian Point 3 (IP3) Hemyc exemption for reduced fire barrier capability, (2) exemptions for Operator Manual Actions (OMAs) in lieu of Thermo-Lag fire barriers, (3) enforcement discretion for licensees transitioning to the new NFPA 805 licensing basis, and (4) consistency of the NFPA 805 frequently asked questions (FAQ) process with Administrative Procedure Act (APA).

INTRODUCTION

This paper presents my views on legal vulnerabilities associated with several aspects of the Nuclear Regulatory Commission's (NRC) fire protection program at nuclear power plants (NPP). Although the NRC has successfully defended most of its fire protection program for many years, that success may have resulted in part from ineffectual legal opposition. A review of some essential ongoing aspects of that program indicates that the NRC's continued success in fending off challenges may depend on its adoption of more sophisticated legal strategies.

Four legal issues are discussed in detail:

- Indian Point 3 (IP3) Hemyc exemption for reduced fire barrier capability;
- Exemptions for Operator Manual Actions (OMAs) in lieu of Thermo-Lag fire barriers;
- Enforcement discretion for licensees transitioning to new NFPA 805 [1] licensing basis; and
- Consistency of NFPA 805 FAQ process with Administrative Procedure Act (APA).

BACKGROUND

The NRC's fire protection requirements for NPP's, 10 C.F.R. Part 50, Appendix R (Appendix R) [2], became effective in 1981. Since then, the NRC has granted over 900 exemptions. Exemptions continue to be granted 32 years later.

In 2004, the NRC adopted 10 C.F.R. 50.48(c) [3], a risk-informed, performance-based alternative regulation for NPP fire protection based on NFPA 805 [1]. NRC continues actively to interpret the rule through the Frequently Asked Questions (FAQ) process. So far very few NPPs have implemented the transition to the new fire protection licensing basis. Other NPPs are actively working on license application requests (LAR).

Coupled with the NRC's adoption of 10 C.F.R. 50.48(c) is the agency's grant of enforcement discretion to LAR applicants. Non-compliances with Appendix R [2] are excused from agency enforcement action to encourage licensees to transition to the new licensing basis. NRC has subsequently extended its enforcement discretion four times. Some plants may not comply fully with either fire protection regulatory regime for several more years. Kewaunee, which began operation in 1974, was shut down in 2013 without ever having attained full compliance.

INDIAN POINT, UNIT 3 (IP3) HEMYC EXEMPTION

To understand the NRC's grant of an exemption for Hemyc, it is useful to briefly review the history of the NRC's regulation of fire protection in the affected plant areas. In 1984, the NRC granted an exemption from the requirement that redundant safe-shutdown trains either be separated by 20 feet without intervening combustibles or separated by a one-hour fire rated barrier in an area protected by automatic fire detection and suppression systems. The exemption permitted a separation of twelve feet between the redundant safe-shutdown trains based on minimal fire hazards in the area, the use of asbestos-jacketed flame retardant cables, and the installed automatic fire detection and cable tray suppression systems.

Subsequently, the licensee determined the need for additional separation measures and installed one-hour Hemyc fire-rated wraps on several redundant safe-shutdown raceways in the area. In 1987, the NRC accepted the use of these wraps and confirmed the continuing validity of the previously granted exemption.

In 2005, testing revealed that Hemyc did not provide a one-hour fire-rated barrier. In response, the licensee declared the Hemyc inoperable and implemented temporary compensatory measures, including an hourly fire watch and verification of the operability of the fire detection systems. In 2006, the licensee committed to modifying the installed Hemyc to provide a twenty-four minute fire-rated barrier and requested another exemption. In 2007, the NRC granted the exemption based on the existing features in the affected fire zones.

In summary, Hemyc was installed in Indian Point, Unit 3 (IP3) to establish compliance with the Section III.G.2 requirement in Appendix R [2] for protecting one train of safe shutdown equipment from fire damage. Before it was discovered that Hemyc did not meet its fire barrier capability, exemptions were sought and granted in areas containing Hemyc for other non-compliances with Appendix R.

Twenty-five years after it was installed, Hemyc was found to be inadequate. Licensees reacted by seeking additional exemptions for its reduced fire barrier capability. In 2006, IP3 requested revised exemptions from the III.G.2 one-hour fire barrier requirement because Hemyc was found to provide only 24 minutes of fire barrier protection. The exemptions were granted in 2007. Notice was published at 72 FR 56798 (October 4, 2007) [4]. In 2013, after a long court battle, the NRC issued an Environmental Assessment (EA) for the exemptions. Notice was published at 78 FR 20144 (April 3, 2013) [**5**]. A summary of the court battle is given in the following.

Members of the public (petitioners) requested a hearing on the exemptions. In 2008, the NRC rejected the petition. A lawsuit followed. The Federal District Court sustained the exemptions in *Brodsky v. United States Nuclear Regulatory Commission* WL 797497 (S.D.N.Y., 2011) [**6**].

The District Court rejected all of petitioner's arguments. The District Court found that:

1. The NRC has inherent exemption authority based, in part, on the unique nature of nuclear safety regulation.
2. Fire protection exemptions are legal because the Court of Appeals for the District of Columbia Circuit (D.C. Circuit) had ruled in 1980 that exemptions were a critical element of flexibility necessary for upholding Appendix R [2].
3. Hearings are not required for exemptions.
4. The EA was properly found by the NRC to be sufficient; an Environmental Impact Statement (EIS) was not required.
5. The NRC applied agency expertise to conduct an adequate, detailed safety evaluation.

This decision by the District Court was understandably based on many years of precedent. No legal challenge to a NRC safety decision has ever succeeded because courts always defer to the NRC's technical expertise. Also, the NRC knows how to "paper" an issue by creating massive documents.

Petitioners' apparently were not sufficiently aware of the strength of this precedent and, so, made legal arguments that were unnecessarily broad. They should not have challenged the NRC's exemption authority because it was clearly established many years ago. They should not have pressed for a hearing because that procedural issue had also been resolved long ago. Finally, petitioners' challenge to fire protection exemptions was not well formulated in terms of basic administrative law. Petitioners' reliance on the 30-day period in rule was superseded by years of the NRC's practice of freely granting exemptions.

Petitioners appealed to the U. S. Court of Appeals for the 2nd Circuit (2nd Circuit) in New York, not far from IP3. The 2nd Circuit, in *Brodsky v. U.S. Nuclear Regulatory Commission* (Decided January 13, 2013) [**6**] upheld NRC actions against almost all challenges recognizing the NRC's broad powers to:

(1) ensure that NPPs do not threaten public welfare;
(2) grant exemptions from specific fire protection requirements if no undue risk results; and
(3) continue the exemption process as critical element of flexibility for cumbersome fire safety requirements.

Although the 2nd Circuit simply followed precedent in deferring to the NRC's technical expertise, it was not comparably self-restrained regarding the NRC's compliance with NEPA.

Petitioners did not argue the exemption case well. They should have focused on the NRC's ongoing reliance on exemptions for over 30 years because that raises significant administrative law issues. As a general matter, exemptions from rules are to be limited because they do not provide for public input as does rulemaking. In this case, the wholesale grant of almost 1,000 exemptions has led to the situation hoped to be avoided, the exemptions swallowed the rule.

Petitioners should also have focused on the NRC's exemption for Hemyc as contrary to the purpose for which exemptions were permitted. Exemptions focused on initial compliance problems. Plants that had been built could not be stretched to accommodate increased separations between redundant trains of safe shutdown equipment.

The installation of Hemyc was not undertaken because the separation criteria could not be met at IP3. Rather, Hemyc was installed in an attempt to comply with the separation requirements in Appendix R by installing a fire resistant barrier. Hemyc's failure 25 years later should have led to a new attempt to comply by installing appropriate materials, not by granting an exemption. The NRC should not have acceded to the utility's replacement cost concerns.

The only issue on which the 2nd Circuit reversed was the lower court's implicit rejection of the claim the claim that the NRC was required to let the public participate in the EA. Well-established precedent required the NRC to provide for public participation where appropriate and practicable. However, the 2nd Circuit found that "on the record presented in this case, we cannot conduct even deferential judicial review of plaintiff's claim that the NRC granted the challenged exemption in violation of NEPA's public participation provisions." (Slip Opinion at 24) because nothing in the NRC's record of decision was found by the 2nd Circuit to give it the information it deemed necessary to determine whether the NRC had a reasoned basis for not including public participation. Thus, the NRC's decision was remanded to the District Court to remand to the NRC for either an explanation or for public participation in the EA.

To understand the 2nd Circuit's decision it is necessary to understand that a basic element of NEPA is public participation. The NEPA procedures require agencies to make environmental information available to the public and to give the public an opportunity to respond, before the agency acts. The Courts do recognize that an agency could structure how to provide for public interaction regarding a specific proposal. However, on several occasions, the courts have observed that the NRC has acted as if the public, because it is not expert in matters nuclear, has nothing to contribute to agency decisions. In this case, the NRC relied on a correct legal position that no hearing was needed but failed to explain why no other means for public participation was practicable.

Clearly, this NRC position annoyed the court, so it reached for a reason to enable the public to participate in the NRC decision. Why was the 2nd Circuit so concerned? Indian Point 3 is near New York City. It has always been controversial. Democracy works only if the public can participate meaningfully in decisions that affect it. Because of the lingering history of the atomic mystique, the NRC failed to appreciate the potential consequences of an increasingly disenfranchised public. Courts, in general, are much more sensitive than is the NRC of the need to meaningfully address public concerns.

The 2nd Circuit's negative view of the NRC's lack of concern for public participation is clear in the decision. NRC's claim that public was indifferent to the grant of Hemyc exemptions by pointing to petitions to the NRC requesting license suspensions due to Hemyc failures was rejected by the court. Also rejected was the NRC's claim that public petitions for exemption reconsideration were simply an opposition to a use by noting that petitioners had raised a specific controversy about the sufficiency of a 24-minute fire barrier to protect IP3.

For these reasons, it is clear that the 2nd Circuit was clearly not impressed by the NRC's transparently inadequate excuses for not providing for public participation. The NRC's feeble arguments likely exacerbated the 2nd Circuit's frustration with the NRC's behavior. Finally, the 2nd Circuit was not persuaded by the NRC's claim that because there would not be any environmental risk from granting exemption there is no possible substantial environmental controversy. The 2nd Circuit observed that the NRC could not, through its conclusory statement, prove the absence of a controversy, when it was precisely the petitioners' issue.

Other courts have been similarly annoyed by the NRC's limited implementation of NEPA. But the impacts of such court decisions are limited. NEPA is a procedural statute. It only requires a federal agency to prepare an environmental analysis and give the public an opportunity to comment on that analysis. NEPA does not force an agency to adopt a particular decision. Theoretically, an agency can approve an environmentally damaging action it that action can be justified for other reasons. Therefore, all that a reviewing court can do under NEPA is require the agency to revise an environmental analysis that the court finds deficient and require the agency to give the public more opportunities to comment on that analysis. After the agency revises the analysis and gives the public an opportunity to comment, the agency can proceed to approve the proposed action.

In this case, the NRC published an EA on remand. This is an example of how a NEPA issue can only delay NRC action. Delay rarely translates into change in an agency's position on a proposed action. The NRC reiterated its finding of no significant radiological environmental impacts from granting the exemption, no significant increase in amounts of effluents released off-site or radiation exposures, and no significant increase in consequences from a fire in the fires zones with exemptions. A successful safety challenge is the only real clout.

EXEMPTIONS FOR OPERATOR MANUAL ACTIONS (OMAs) IN LIEU OF THERMO-LAG (TL) FIRE BARRIERS

Thermo-Lag (TL), another fire-retardant barrier material, has also had a history similar to Hemyc's. TL was installed as a fire-retardant barrier to provide the fire-barrier protection required by Appendix R for a redundant train of safe-shutdown equipment. Subsequent testing showed that Thermo-Lag did not have the claimed fire-barrier rating and, in fact, was itself combustible. Between 1991 and 1995 the NRC issued fourteen Information Notices, one Generic Letter, and two Bulletins on TL's failures. Starting in 1998, the NRC began issuing a series of Confirmatory Orders requiring licensees to replace the non-functioning TL fire barriers and restore fire barrier operability at nuclear power stations. Licensees responded that they would come into compliance by restoring operability to the fire barriers. However, between 2000 and 2004, renewed NRC fire inspections discovered that a large number of nuclear power station operators had instead adopted Operator Manual Actions (OMAs) without obtaining the NRC's approval.

As with the installation of Hemyc, the installation of TL showed that licensees could comply physically with the separation requirements in Section III.G.2 of Appendix R [2] for redundant safe-shutdown trains. Those, licensees also did not need the transition "safety valve" of exemptions. Thus, the grant of exemptions for the use of OMAs to substitute for fire protection inadequacies in TL is similarly not justified by the reasoning relied on by the D.C. Circuit when it upheld Appendix R.

For example, the NRC granted the Peach Bottom Atomic Power Station (PBAPS) exemptions for the use of OMAs instead of TL on March 30, 2011, 30 years after NRC made Appendix R effective. In its exemption request, PBAPS discussed the financial implications of the plant modifications necessary for compliance. The NRC's exemption criteria permit the NRC to consider compliance costs if they are "significantly in excess of those contemplated at the time the regulation was adopted, or are significantly in excess of those incurred by others similarly situated." The NRC stated that it did not consider the costs of plant modifications for lack of their substantiation by the licensee. This implies that the NRC may have considered such costs had they been substantiated. Such consideration would be difficult to support legally because the costs of replacing failed fire barrier material with effective fire-barrier material should be borne by the licensee, who failed properly to determine the fire-barrier rating of the material before it was installed. The cost of replacing defective fire-barrier material with effective fire-barrier material is not a regulatory cost but a management failure cost.

So what is really wrong with the NRC's grant of OMA exemptions? The NRC's Commissioners modified Appendix R at last minute before its promulgation to require reliance on passive protection by adequate separation of redundant safe shutdown trains. OMAs are inherently less reliable: (1) humans fail; (2) procedures are not always followed; and (3) response times cannot consider unknowns. The clear initial Commissioner intent was disregarded.

Can't an agency change its mind? Sure it can. But it is basic administrative law under the Administrative Procedure Act that the public has a right to participate in federal agency rule-making proceedings. Because this basis right is not observed by the agency when it grants an exemption from a rule, and because an exemption is really a modification of a rule for a particular party, it is also basic administrative law that the exemptions are to be granted sparingly. Otherwise, if exemptions were to be granted liberally, they would substantially change the rule, without the necessary public participation. It is also true that the fire protection rule is exceptional because the court, which sustained it against industry challenge, expected the NRC to grant exemptions liberally right after it was adopted in recognition of the circumstance that nuclear power plants, which were already build, could not physically comply with the new requirements. However, that time is long past and exemptions are now being granted to compensate for failed attempts to comply with Appendix R [2]. Arguably, such exemptions are inconsistent with the court's reasoning which led to the reliance on exemptions as an initial "safety valve" adopted as a practical alternative for affirming the rule.

ENFORCEMENT DISCRETION FOR TRANSITION TO 10 C.F.R. 50.48(c)

The NRC's Enforcement Policy states that it intended to support the NRC's mission to ensure_adequate protection of public health and safety, which presumptively is attained by licensees' compliance with the NRC's rules. The Enforcement Policy is designed to:

(1) deter non-compliance; and

(2) encourage licensees' prompt identification and correction of violations of NRC requirements.

NRC's application of the Enforcement Policy ensures that public health and safety are maintained.

NRC's enforcement authority is derived from its organic statutes: (1) the Atomic Energy Act of 1954; and (2) the Energy Policy Act of 1974. The authority in these statutes is so broad that it has been found to include an inherent authority to exercise enforcement discretion. That discretion has been recognized by courts and enables the NRC to permit the continued operation of an NPP despite a violation, if there is no undue risk to public health and safety.

To encourage licensees to transition to NFPA 805 [1] as a way of resolving long-standing compliance issues, the NRC granted enforcement discretion not to take enforcement action for certain existing Appendix R non-compliances and new ones which might be found during the licensing basis transition process. The NRC justified this exercise of enforcement discretion to permit non-compliances to remain unfixed for extended periods of time based on:

(1) licensees' and NRC's resource limitations to implement transitions to alternative fire rules;

(2) interim compensatory measures; and

(3) licensees' threats to flood the regulatory process with exemption requests if the NRC attempted to force compliance.

Thus, the NRC exercised its discretion for non-safety reasons, contrary to the Enforcement Policy's stated intent. Moreover, the NRC never claimed that fire safety in the nuclear power plants would improve by transitioning to the new licensing basis. Rather, the NRC acknowledged that there would be a slight increase in fire risk possible with new rule.

Since the NRC first granted enforcement discretion in 2004, that discretion has been modified and extended four more times. For over nine years, the NRC has encouraged licensees to transition to NFPA 805 [1] through enforcement discretion:

- 2004 - NRC initial exercise of discretion
- 2005 - Extension granted at industry request
  - Licensees need time to budget/plan for transition
- 2006 - Licensees need more time to transition
- 2008 - Administrative efficiency if NRC waits
  - Until finalize transition guidance from pilot plants
- 2011 - NRC needs extended review schedule
  - Insufficient resources to simultaneously review large number of contemporaneous submittals

A recent example involves Beaver Valley, a plant operated by the First Energy Nuclear Operating Company (FENOC). In 2005, FENOC notified the NRC of its intent to transition to NFPA 805 [1]. Accordingly, the NRC exercised its enforcement discretion for existing and newly identified non-compliances. FENOC committed to submitting license amendment request (LAR) by September 30, 2011. Then, in 2012, almost one year later, FENOC asked for an extension. NRC granted an extension to December 31, 2013, justified in part by FENOC's modification schedule. One can question at what point in time the NRC might be seen as abusing its enforcement discretion.

CONSISTENCY OF THE NFPA 805 FREQUENTLY ASKED QUESTIONS (FAQ) PROCESS WITH THE ADMINISTRATIVE PROCEDURE ACT (APA)

The NRC established the FAQ process in 2006 with the Nuclear Energy Institute's (NEI) support. It was intended to resolve interpretation issues from NEI-04-02 [7] – guidance for implementing 10 C.F.R. 50.48(c) as adopted by the NRC in Regulatory Guide 1.205 [**8**]. It is implemented by incorporating FAQ answers into the NRC endorsed version of NEI-04-02. The FAQ process is a public process available to all stakeholders, licensees and public. It is not intended to be as a process to modify 10 C.F.R. 50.48(c) [3].

As an early example, consider FAQ 06-0021. This FAQ interprets Section 3.3.5.2 of NFPA 805 [1], which provides:

- Only metal tray and metal conduits shall be used for electrical raceways.
- Thin wall metallic tubing shall not be used for power, instrumentation, or control cables.
- Flexible metallic conduits shall only be used in short lengths to connect components.

Clarification was requested for previously approved bare cable runs (exposed cable air drops) no longer than three feet without conduit. Are they still acceptable under the new rule? The requester was concerned that this NFPA provision could be interpreted to prohibit the use of air drops and, so, suggested that this was not intent of the provision. But no technical basis was provided. The requester relied solely on history under the superseded rule.

The NRC agreed with requester to find that the intent of the provision is to prohibit use of long runs (greater than 3 feet) of flexible metal conduit. Note that this position is not a clarification of the guidance in RG 1.205 [**8**], but an interpretation which modifies a provision in the rule. This raises the question whether this FAQ response is an interpretation clarifying the rule or a change modifying the rule without rulemaking?

NFPA 805/3.3.5.2 [1] established a protection hierarchy:

- Metal tray conduits <u>shall be used</u> for electrical raceways.
- Thin wall metallic tubing <u>shall not be used</u> for power, instrumentation, or control cables.
- Flexible metallic conduits <u>shall only be used</u> in short lengths to connect components.

Bare cable runs of any length are not included. Thus, the intent of hierarchy could be read as requiring appropriate protection for various types of cables

A more recent example is provided by proposed FAQ 12-0063. It addresses NFPA 805/3.41(a), which requires that a fully staffed, trained, and equipped fire-fighting force (at least five members) <u>shall be available at all times</u>. Currently approved fire protection programs permit up to 2-hour absence by one team member. This FAQ requests inclusion of this exception for the purposes of accepting a LAR under NFPA 805 [1]. Is this an interpretation or a change?

In both cases, if the rule is being changed through a process which does not comport with the requirements of the notice and comment provisions of the Administrative Procedure Act (APA), the NRC has engaged in rulemaking without rulemaking. Such agency actions are vacated by the courts for compliance with the necessary procedures. Although the legal principles here are different from those required by NEPA, the NRC's actions are based on the agency's belief that the public has nothing to contribute to the regulation of nuclear power.

In *Appalachian Power Company v. Environmental Protection Agency* 208 F.3d 1015 (D.C. Cir. 2000) [**9**], EPA published guidance which the court determined was being treated as a rule by the agency. In addition to finding that the EPA's action violated the APA, the court also wondered if the EPA had called the action guidance so as to avoid judicial review. Not surprisingly, the court was not amused.

The legal situation with the FAQs is potentially even worse for the following reasons. In *Appalachian Power*, the court was concerned that EPA tried to expand its authority without rulemaking by calling rule guidance. In *Connecticut Light & Power*, the court upheld Appendix R despite rulemaking issues because there was a clear safety concern from the Browns Ferry fire. If a court is reluctant to let an agency expand its power without rulemaking unless a safety issue is involved, how will court respond to the NRC's acceptance of industry's requests to limit its power when safety issues are involved?

CONCLUSION

Four examples of the NRC's potential vulnerability to legal challenge for actions taken regarding the fire protection requirements have been discussed. These actions have all been described as reducing fire safety in the nuclear power plants regulated by the NRC. Smart lawyers may pursue these issues to force the NRC to be more vigorous in its enforcement of its fire protection regulations. NRC defenses against legal challenges to these actions are simple. Be more sensitive to possible legal challenges and act defensively to avoid them.

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ONGOING ENHANCEMENTS IN THE GERMAN NUCLEAR REGULATORY FRAMEWOK WITH RESPECT TO FIRE SAFETY

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ABSTRACT

In general, the regulatory framework for nuclear power plants (NPP) in Germany is a deterministic one comprising comprehensive and partly very detailed regulatory documents such as, safety requirements, guidelines and recommendations of the regulatory and advisory bodies, nuclear safety standards and rules incorporated in a corresponding legal structure.

The mainly deterministic German nuclear regulation has recently been significantly enhanced promulgating state-of-the-art "Safety Requirements to Nuclear Power Plants" in 2013. The enhancements also address the adequate consideration of internal hazards including fires, in particular with regard to event combinations of fires and other anticipated events, underlining the need for an appropriate fire protection design. Moreover, they focus on safety demonstrations by deterministic as well as probabilistic safety assessment in more detail.

One reason for fire protection remaining an important issue for nuclear power plants in Germany is that the spent fuel elements will remain either in the containment or in the spent fuel pool for further year requiring suitable fire protection means being in place.

INTRODUCTION

In general, the regulatory framework for nuclear power plants (NPP) in Germany is a deterministic one comprising comprehensive and partly very detailed regulatory documents such as "Safety Requirements for Nuclear Power Plants" [1], guidelines and recommendations of the regulatory body and advisory bodies, but also nuclear safety standards and rules incorporated in a corresponding pyramid type legal structure as shown in Figure 1.

This is the main reasons that in the past in Germany the NPP safety concept and licensing decisions by the regulatory authorities and their experts in charge were based on deterministic safety principles, such as prevention and control of abnormal plant operational conditions and incidents by various technical in-depth means such as passive barriers, redundancy and diversity of safety systems to ensure high reliability.

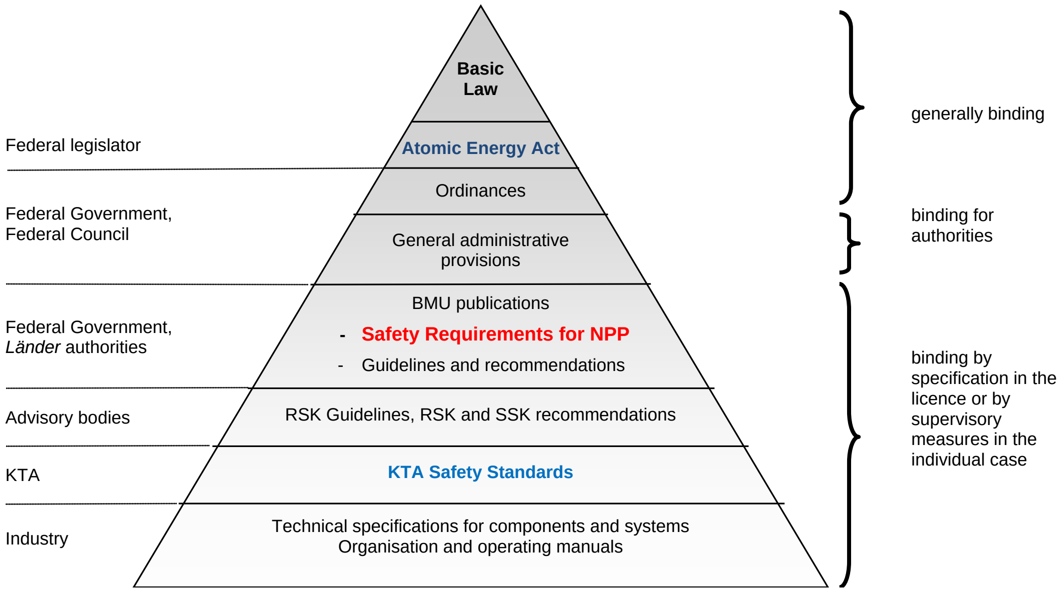

Figure 1 Nuclear regulatory framework in Germany

Moreover, safety decision making within the design and licensing process was principally based on demonstrating compliance with pre-described technical requirements as provided, e.g., in the German nuclear safety standards by the Nuclear Safety Standards Commission (German: Kerntechnischer Ausschuss, KTA). On the level of technically detailed KTA standards in total four standards are available with respect to fire and explosion safety:

– KTA 2101.1: Fire Protection in Nuclear Power Plants, Part 1: Basic Requirements [2],
– KTA 2101.2: Fire Protection in Nuclear Power Plants, Part 2: Fire Protection of Structural Plant Components [3],
– KTA 2101.3: (Fire Protection in Nuclear Power Plants, Part 2: Fire Protection of Mechanical and Electrical Components [4], and
– KTA 2103: Explosion Protection in Nuclear Power Plants with Light Water Reactor [5].

The German nuclear regulation has recently been significantly enhanced promulgating state-of-the-art "Safety Requirements to Nuclear Power Plants" as published in January 2013 [1]. These enhancements also address the adequate consideration of internal as well as external hazards including fires, in particular with regard to event combinations of fires and other anticipated events.

Moreover, they concern safety demonstrations by deterministic as well as probabilistic safety assessment in more detail. In this context, probabilistic safety analyses (PSA) shall supplement deterministic safety demonstrations with regard to the balance of the safety related plant design. PSA shall also supplement deterministic safety demonstrations to evaluate the safety significance of modifications in plant SSC (systems, structures and components), measures or procedures as well as of insights from incidents or phenomena important to safety being applicable to other NPPs, if their effects on the PSA results are expected to be significant. This procedure has, of course, also to be applied for modifications with respect to fire protection.

Details with regard to the actual fire safety requirements are provided in the following sections.

SAFETY REQUIREMENTS FOR NUCLEAR POWER PLANTS

The recently published “Safety Requirements for Nuclear Power Plants” [1] represent legally binding requirements with respect to nuclear safety of the existing German nuclear power plants on a high level. They are systematically structured and follow the safety approach of defense-in-depth coincident to the safety principles of IAEA SSR-2/1 [7].

In the Section on the “scope of application” the protection against internal and external hazards including fires is already addressed stating that detailed guidance is provided in a specific annex as follows:

“… In Annex 2, requirements regarding postulated events are substantiated, while those regarding the protection against internal and external hazards including very rare human induced (external) hazards are specified in Annex 3.”

Section 2 regarding the “technical safety concept” provides the most important principles of nuclear safety, also including hazards such as fires:

“2 (1) In order to meet the radiological safety objectives, the radioactive materials present in the nuclear power plant shall be confined by multiple technical barriers and/or retention functions, and their radiation shall be sufficiently shielded.
The effectiveness of the barriers and retention functions shall be ensured by fulfilling fundamental safety functions.
A defense-in-depth concept shall be realized to ensure that the fundamental safety functions and the preservation of the barriers and retention functions on several consecutive levels of defense as well as in the case of any internal and external hazards are fulfilled.”

Subsection 2.1 on the principle requirements regarding the “defense-in-depth concept” provides the basic requirements for meeting defense-in-depth. In this context, it is important to keep in mind the most important terms being used in [1].Therefore the safety related terms frequently repeated and used in the safety requirements are highlighted in the following in alphabetic order:

- *Component:* Part of a system defined separately according to structural or functional aspects. Components consist of operating materials. Operating materials consist of component parts; *see also structures, systems and components (SSCs).*
- *Component part: Part of equipment or the smallest part of a design group manufactured from product forms. In construction engineering, a component part is a part of a building.*
- *Emergency equipment*: Measures and equipment required for the control of an event sequence due to a very rare human induced external hazard or in the event of the postulated complete unavailability of the main control room.
- *External hazard*: Impact caused by ambient conditions, natural events or by civilization (according to Annex 3 Section 4.2.3) from outside the plant site.
- *Fire protection means*: Structural, plant engineering, operational sand administrative measures and equipment to prevent the occurrence and propagation of fires, to detect and effectively extinguish fires and to enable escape and rescue of humans.
- *Initiating event:* An identified event that leads to anticipated operational occurrences (AOO) or accident conditions and challenges safety functions.
- *Internal hazard*: Impact resulting from events at the plant site inside or outside buildings (e.g. fire, plant internal flooding).
- *Item important to safety*: An item that is part of a safety group and/or whose malfunction or failure could lead to radiation exposure of the site personnel or members of the public. Items important to safety include:
  - those structures, systems and components whose malfunction or failure could lead to undue radiation exposure of site personnel or members of the public,

  - those structures, systems and components that prevent anticipated operational occurrences from leading to accident conditions,
  - those features that are provided to mitigate the consequences of malfunction or *failure* of *structures, systems and components*.
- *Level of defense*: Category of plant conditions with defined boundary conditions of similar type:
  - Level of defense 1: normal operation
  - Level of defense 2: abnormal operation
  - Level of defense 3: accident
  - Level of defense 4: very rare events (4a),
events with multiple failure of safety equipment (4b),
accident involving severe fuel assembly damages (4c).
- *Measure*: Action, instruction or organizational activity or organizational process.

  Note:

  If no action, instruction or organizational activity is referred to, the measure is further specified, e.g.: *accident management measure*, *disaster control measure*, etc.
- *Postulated initiating event (PIE)*: An event identified during design as capable of leading to anticipated operational occurrences or accident conditions. The primary causes of postulated initiating events may be credible equipment failures and operator errors (both within and external to the facility), human induced or natural events.
- *Precautionary measure*: Measures and equipment, if being in place, the occurrence of an event has been demonstrated to be so unlikely that it does not have to be postulated.
- *Prevention (to prevent)*: Events or event sequences for whose control there are no higher level designed measures or equipment on a subsequent level of defense shall be prevented. Thus, the progression of events and event sequences on level of defense 3 to level of defense 4 shall be prevented.
- *Equipment of the safety system*: Measures and equipment of the safety system serving the control of design basis accidents.
- *Safety system*: The entirety of all equipment that has the task to protect the plant against undue impacts and, in case of design-basis accidents, to keep their effects on the operating personnel, the plant and the environment within specified limits
- *Structures, systems and components (SSCs)*: A general term encompassing all of the elements (items) of a facility or activity which contribute to protection and safety, except human factors. Structures are the passive elements: buildings, vessels, shielding, etc. A system comprises several components, assembled in such a way as to perform a specific (active) function. A component is a discrete element of a system. Examples of components are wires, transistors, integrated circuits, motors, relays, solenoids, pipes, fittings, pumps, tanks and valves.
- *Structural element*: Structures are parts (elements) of structures assembled from (civil) construction products (building materials and components) and connected to the ground. Synonyms: structure, building structure.
- *System*: Synonym for plant component (see structures, systems and components)

One particular requirement on the principles of defense-in-depth also covers hazards and thus fires:

"2.1 (5) The safety system as well as the emergency equipment shall be designed such that they will remain effective in the event of internal and external hazards.

Impacts resulting from very rare human induced external hazards or the postu-

lated inoperabilty of the main control room shall not lead to failures of *equipment of the safety system* in a way that the required safety functions are no longer effective.
Otherwise, specifically designed equipment shall be provided for this case so that event sequences of level of defense 4b are prevented."

Particular focus on barriers is given in subsection 2.2 "Concept of the multi-level confinement of the radioactive inventory (barrier concept)":

"2.2 (1) The confinement of radioactive materials present inside the nuclear power plant shall be ensured by sequential barriers and retention functions.
…
The barriers and retention functions in their entity shall be reliably effective to meet the radiological safety objectives according to Section 2.5 in case of events resulting from any internal or external hazard including very rare human induced ones or the postulated inoperability of the main control room."

Hazards are more specifically addressed in subsection 2.4 on the "protection concept against internal and external hazards including very rare human induced (external) hazards", providing systematic guidance for meeting the fundamental safety goals:

"2.4 (1) All equipment required for the safe shutdown of the nuclear reactor, for maintaining it in a shutdown state, for residual heat removal or the prevention of a release of radioactive materials shall be designed as and constantly kept in a condition that they can fulfill their safety related functions even in the event of any internal or external hazard including very rare human induced ones (see Annex 3).

2.4 (2) Internal or external hazards including very rare human induced ones that might inadmissibly impair the required functions of equipment of the safety system shall either be reliably prevented limited in their consequences according to Subsection 2.1 (5). In this context, passive protection means shall be preferred. If inadmissible consequences cannot be reliably prevented by passive means, reliable active means shall be in place.

2.4 (3) Redundant parts of items important to safety shall be either installed in physically separated plant areas or protected such that in the event of any internal hazard, a failure of more than one redundant train is reliably prevented."

Last but not least also subsection 2.5 "Radiological objectives" provides explicit guidance for internal hazards including fire:

"2.5 (2) *All items important to safety* in a nuclear power plant shall be designed against impacts from internal and external hazards including very rare human induced ones, maintained in such a condition and protected in such a manner that they fulfill their required safety related functions."

Subsection 3.1 providing "general requirements" also covers hazards in view of accident management and mitigation:

"3.1 (11) Measures and equipment provided for internal accident management shall remain effective even in the event of internal and external hazards including very rare human ones if these may lead to multiple failures of equipment of the safety system needed in these situations and if these contribute to the mitigation of the effects of the respective hazards."

The "requirements for the reactor core and for shutdown systems in subsection 3.2 of [1] implicitly requires to ensure control of reactivity in the event of fire for all plant operational states (POS) on different levels of defense I depth:

"3.2 (1) The control of reactivity in the reactor core shall be ensured for all operational modes on levels of defense 1 to 4a as well as in the event of internal and external hazards including very rare human induced ones."

As a result of insights after and from the reactor accidents of Fukushima Dai-ichi, subsection 4.2 with the title “Internal and external hazards including very rare human induced external hazards” contains strict and explicit requirements on the precautions of nuclear power plants against hazards and their potential combinations:

“4.2 (1) The design of systems, structures and components against internal and external hazards shall be based on:

a) those natural hazards with the most severe consequences or other external hazards to be postulated at the site under consideration;

b) the special characteristics of external hazards of long duration;

c) combinations of several external hazards (e.g. earthquake, flood, storm, lightning) including vary rare human induced ones (aircraft crash, or combinations of these hazards with plant internal events (e.g. pipe break, internal fire, loss of offsite power); these combinations shall be postulated, if the combined events or hazards show a causal relationship or if their simultaneous occurrence has to be postulated according to its probability and the expected extent of damage.”

4.3 Events Involving Multiple Failures of Equipment of the Safety System

“4.3 (2) The plant specific spectrum of event sequences on which the planning of preventive measures of the internal accident management shall be based shall comprise at least events from the following groups of events:

- Transients,
- LOCA inside the containment as a result of the maximum postulated leaks in the reactor coolant system,
- LOCA with containment bypass, an
- Internal and external hazards if these can lead to multiple failures of equipment of the safety system.

Based on a postulated multiple failure of equipment of the safety system, the representative event sequences to be referred to for the planning shall be defined.”

Safety Requirements for NPP, Annex 3: Requirements for the Protection against Internal and External Hazards Including Very Rare Human Induced Hazards

Annex 5 of the “Safety Requirements for Nuclear Power Plants” [1] provides in a systematic and exhaustive manner detailed requirements with respect to the protection against plant internal as well as site specifically to be considered natural as well as human induced hazards. These requirements also cover the very rare human induced hazards of an accidental aircraft crash, plant external explosions and the impact from hazardous, mainly gaseous materials, such as toxic, combustible and explosive gases or gas mixtures. The list of hazards for which detailed requirements are given in [1], Annex 3 is provided grouped according to the types of hazards in Figure 2.

Hazards from malevolent actions are out of scope of the German safety requirements [1].

In Annex 3 the basic requirement is a complete and systematic consideration of all hazards to be analyzed. Moreover, event combinations of different hazards and or hazards with other anticipated events need to be addresses systematically and considered as far as they cannot be excluded according to probability reasons Annex 3, Subsection 3.1 “General requirements” therefore provides guidance on the safe installation of protection mean against internal hazards such as fires:

Hazards			
Internal Hazards	**External Hazards**		
	Natural Hazards	**Human Induced Hazards**	
		Very Rare Human Induced Hazards	**Other Human Induced Hazards**
Fires	Earthquake	Aircraft crash	Flotsam, dam failures; and ship accidents
Flooding	External flooding	Plant external explosion	Plant external fires
Component failure with impacts on items important to safety	Extreme meteorological conditions	Hazardous materials	Electromagnetic impacts (except lightning)
Leak/break in the main steam/feedwater system, etc.	Biological hazards		
Drop and impact of heavy loads			
Electromagnetic hazards:			
Collision of vehicles on site			
Multi-unit plant interactions			
Explosions			

Figure 2 Hazards including fires as addressed in the German Safety Requirements for Nuclear Power Plants [1], Annex 3

"3.1 (1) Plant specifically identified and evaluated internal hazards as well as their potential combinations or their combinations with external hazards including very rare human induced ones shall be fully considered.

3.1 (2) For each hazard or combination of hazards according to Subsection 3.1 (1), the safety related impacts on the plant under consideration shall be determined considering the consequential impacts to be expected.
In particular, the effects listed in the following shall be considered:

- Plant internal flooding,
- Plant internal fires and explosions,
- Increased radiation levels,
- - …

3.1 (3) Features for the protection against internal hazards shall preferably be installed close to the potential source of an internal hazard unless any other location is more advantageous with regard to safety."

Subsection 3.2 "Hazard specific requirements" contains, besides others, a fire hazard specific paragraph 3.2.1 on "plant internal fire with respect " providing in total 23 high level requirements on protecting a nuclear power plant adequately against fires. These requirements can also be found, particularly with some additional, more technical details in the comprehensive and very detailed German nuclear safety standard KTA 2101, Part 1-3 [2], [3], and [4]. These requirements are completely listed hereafter:

3.2.1 (1) Protection means for the protection against plant internal fires and their consequences shall be in place both inside and outside of buildings. Inadmissible impacts of fires and their consequences shall be prevented by active and passive fire protection means.

3.2.1 (2) Fire protection means shall be planned and implemented such that defense-in-depth is realized:

- Suitable protection means shall be in place to prevent the occurrence of incipient fires.
- Fires which have nevertheless occurred shall be quickly detected and extinguished.
- The propagation of any fire neither extinguished nor self-extinguished shall be limited.

3.2.1 (3) A fire protection concept shall be developed and documented. The documentation shall be kept up to date. In case of any plant modification, its effects on the existing fire protection concept shall be assessed and, if necessary, enhanced.

3.2.1 (4) A fire hazard analysis shall be performed and documented. The documentation shall be kept up to date.

3.2.1 (5) The entire fire protection means shall ensure that even in the event of a random failure of a single fire protection means the required safety functions are not inadmissibly impaired.

3.2.1 (6) An ignition of combustibles should be postulated. Deviations from this requirement are admitted, if the combustible is encapsulated and it has been demonstrated that the encapsulation maintains its operability during specified normal operation and in the event of any accident.

3.2.1 (7) Fire loads and potential ignition sources shall be limited to the extent necessary for safe operation.

3.2.1 (8) For prevention of an ignition by potential ignition sources, fire loads needed for plant operation shall be sufficiently physically separated from these ignition sources at any location, where permitted by design and requirements for the operation of items important to safety.
Plant areas containing considerable fire loads should be separated by sufficiently rated fire barriers.

3.2.1 (9) Redundant trains of the safety system should be separated by sufficiently rated fire barriers to prevent a loss of more than one redundant train in case of fire.
If the protection required in the event of fire cannot be ensured by structural protection means due to systems engineering or operational reasons, an equivalent level of protection shall be ensured by other (compensatory) fire protection means or by a combination of different fire protection means.

3.2.1 (10) For transient combustibles in connection with maintenance work special protection means shall ensure that the plant safety is not inadmissibly impaired.

3.2.1 (11) Passive structural fire protections means shall ensure the fire safety of buildings and structures.

3.2.1 (12) Only non-combustible constructions and structural elements should be used.
The use of combustible materials is only permissible, if the use of such materials cannot be avoided, e.g. insulation materials for cooling pipes, decontaminable coatings.
Only non-combustible operating supplies should be used.
Exceptions are control and lubricating fluids as well as other combustible materials that cannot be avoided for operational reasons.

3.2.1 (13) I&C wires and cables should be routed separately from heated pipes or pipes carrying combustible media.
Power cables shall be sufficiently separated from signal and control cables.
In the exceptional case of unavoidable crossings of I&C wires and cables with

high-temperature pipes or pipes carrying combustible media or with power cables, particular protection means shall be in place.
Adequate protection means shall ensure that even in the event of fire cables for power supply or I&C cables are not inadmissibly impaired.

3.2.1 (14) The restrictions for the controlled area shall be considered in the selection and installation of active and passive fire protection means.

3.2.1 (15) In the event of fire, particularly in plant areas with equipment of the safety system and in controlled areas, adequate protection means shall ensure a reliable and fast fire detection and alarm.

3.2.1 (16) Adequate protection means for fire detection, alarm and suppression shall ensure that fires in the containment can be quickly and reliably detected and extinguished efficiently, even without smoke removal.

3.2.1 (17) Adequate protection means for a timely detection and alarm of any hazard and appropriate precautions for rapid escape and rescue activities via escape and rescue routes shall ensure that in case of danger persons can reach the outside quickly and can be rescued from the outside.

3.2.1 (18) Escape and rescue routes shall be provided within the buildings. These shall be protected against fire effects for an appropriate time period to allow for self-rescue, rescue of persons, fire extinguishing as well as for personnel actions required for safety reasons.

3.2.1 (19) Stationary fire extinguishing systems should be actuated automatically.
Remote controlled or local manually actuated extinguishing systems are permissible, if the fire effects are controlled until these extinguishing systems come into effect.

3.2.1 (20) Automatically actuated stationary extinguishing systems shall be designed and secured in such a way that neither disturbances occurring at them or at parts of them nor faulty actions / maloperations do neither impair the required function of equipment of the safety system nor of structural elements for separation of fire compartments.

3.2.1 (21) The entire fire protection means shall regularly be subject to in-service inspections with respect to their required function.
Test intervals shall be specified according to the safety significance of the equipment to be protected.

3.2.1 (22) For fire suppression, an efficient professional on-site fire brigade shall be established, equipped and maintained according to the existing non-nuclear regulations.
In addition, the local off-site fire brigade shall be familiarized with the plant and the different plant areas as well as with the specific boundary conditions at a nuclear power plant. The corresponding instructions shall be repeated at regular intervals.
Fire drills shall be conducted at appropriate time intervals.

3.2.1 (23) It shall be ensured that all means required for ensuring safe operation and control of events on levels of defense 3 and 4a can also be taken in the event of fire extinguishing."

NUCLEAR SAFETY STANDARD KTA 2101: FIRE PROTECTION IN NUCLEAR POWER PLANTS

Recently the existing German nuclear fire safety standards of the Germans Safety Standards Commission (KTA), KTA 2101 "Fire Protection in Nuclear Power Plants", Parts 1-3 as published end of 2000 [2], [3], and [4] are being updated.

All the three parts of KTA 2101 are interrelated (cf. Figure 3). Therefore, one intention of the update is to harmonize the structure to provide the fundamental requirements in Part 1 and the technical details for design and operation of structures, systems and components with respect to fire safety in Part 2 and 3 accordingly, avoiding duplications.

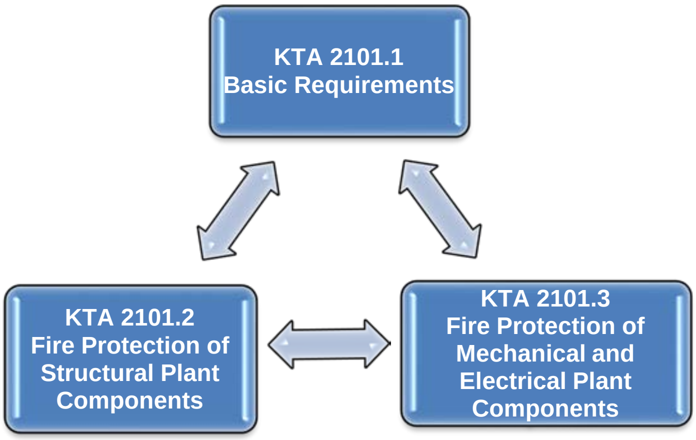

Figure 3 German nuclear safety standards KTA 2101 "Fire Protection in Nuclear Power Plants" [2], [3], [4]

Major goals of the update of KTA 2101, Part 1-3 [2], [3], [4] are the following:

- Adapting requirements to the actual state-of-the-art:
  - corresponding to the most recent, also non-nuclear standards and norms,
  - providing specific compliance with requirements regarding the fire brigade,
  - considering low power and shutdown plant operational states better and more systematically, and
  - covering event combinations of fires and other anticipated events more systematically (post-Fukushima requirement).
- Compliance with the (new) "Safety Requirements for NPP" [1] in respect of the following aspects:
  - Better consideration of the defense-in-depth concept,
  - Specific compliance with requirements for the safety demonstration, in particular requiring
    - a systematic and comprehensively documented deterministic fire hazard analysis (FHA) to be kept up to date,
    - an adequately documented probabilistic fire risk analysis (Fire PSA) for all plant operational states (full power as well as intended as well as unintended low power and shutdown states including the post-commercial shutdown phase of longer duration) to be kept up to date, and
    - deterministic safety demonstrations supplemented by probabilistic assessment in case of plant modifications.
  - A more systematic approach and outline of the standards covering only nuclear specific requirements and deviations from non-nuclear standards and norms, in particular with respect to combinations of fires with other anticipated events have to be assumed, if they occur as consequence of the initial event or if their occurrence at the

same time has to be accounted for due to their occurrence frequency and the extent of damage.)n this context, the following event combinations have to be considered:

- Fire and consequential event,
- Anticipated event and consequential fire, and
- Fire and independently occurring anticipated event.

The recent update of the KTA standard KTA 2101, Part 1 to 3 is ongoing. The enhanced standards are intended to be issued in 2014.

CONCLUSIONS

Nuclear power plants in Germany are mainly designed and licensed on the basis of deterministic fire safety assessment and according to the existing fire protection safety standards.

Meanwhile, Fire PSA is required as part of the PSA within periodic safety reviews (PSR) required in Germany [8]. Fire PSA have been conducted for all nuclear power plants in Germany within the second PSR. Thus, Fire PSA has become an additional tool to supplement deterministic assessment of the fire protection for supporting decision making.

However, according to the German PSA Guideline and its corresponding technical documents on PSA methods [9] and data [10], in the past Fire PSA has mainly focused on full power plant operational states. In the frame of the second PSR the scope was extended to low power and shutdown states. This extension has to be particularly applied to those plants, for which a third PSR is required by the German regulations [6] to be conducted.

The recently issued state-of-the-art “Safety Requirements to Nuclear Power Plants” [1] also underline the need for an adequate fire protection design and the demonstration of the reliability of the selected equipment by deterministic and probabilistic safety assessments.

Fire protection remains an important topic for nuclear power plants in Germany, even though eight out of seventeen plant units have been finally shutdown in 2011. One reason is that the spent fuel elements will remain either in the containment or in the spent fuel pool for further years; this still requires appropriate fire protection means being in place. Moreover, there are considerations or already practical actions to remove equipment not needed anymore for nuclear power plants under post-commercial shutdown, although the formal decommissioning process has not yet started. In this context, different aspects related to fire protection have always to be taken into account.

This was one of the reasons to continue the update of the three parts of the German nuclear fires safety standard KTA 2101. It is intended to complete the draft updates in March 2014, which are expected to be issued at the end of 2014.

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EXPERIMENTAL STUDIES ON ELECTRIC ARC EXPLOSION EVENTS USING THE 6.9 KV SWITCHGEARS SUBJECTED TO HIGH ENERGY ARCING FAULT

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ABSTRACT

High Energy Arcing Faults (HEAFs) 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 (hereinafter, 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, the Tohoku District-off the Pacific Ocean Earthquake attacked the Onagawa Station of Tohoku Electric Power Co., Inc. on March 11, 2011, and the successive fire incident due to HEAF occurred in the electrical cabinet in which the overhang-type high voltage breakers were used. Moreover, the remarkable thermal and structural damage to the cables and equipment of the adjacent cabinets were recognized due to the release of the hot gas propagation and high inner pressure. In order to understand the critical condition for the successive fire occurrence of the non-arc proof electrical cabinets due to HEAFs, a series of electric arc explosion tests with 6.9 kV switchgears were executed using the high power test facilities located in high power testing laboratory of Central Research Institute of Electric Power Industry in Japan. This paper presents the recent test results and the status of the damage of the switch gears, and the fire occurrence condition from the released arc energy point of view was discussed.

INTRODUCTION

Large electrical discharges, referred to as HEAF, have occurred in nuclear power plant (NPP) switching components throughout the world [1]. In general, HEAFs 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 the OECD report [2], by analyzing the OECD FIRE Database [3] with regard to HEAF fire events, a total of 48 out of 415 events collected in the Database, representing a contribution of 11.5 %, have been found to be HEAF events with fires as recent tendencies.

In Japan, the Tohoku District-off the Pacific Ocean Earthquake attacked the Onagawa Station of Tohoku Electric Power Co., Inc. on March 11, 2011, and the successive fire incident due to HEAF occurred in the electrical cabinet as shown in Figure 1, in which the overhang-type high-voltage breakers were used.

Figure 1 Electric cabinet with the sector where the fire started and others impaired [4] (Onagawa NPP in Japan on March 11, 2011)

HEAF has the potential to cause extensive damage to the failed electrical components and distribution systems along with adjacent equipment and cables within ZOI and passively lead to secondary fires. These incidents have been increasing as a result of the aging infrastructure and increasing energy demands. Nuclear Regulatory Commission (NRC) in the USA released NUREG/CR-6850 in 2005 [4] and the detailed methodology to quantify ZOI from a HEAF as shown in Figure 2 was introduced to apply for fire probabilistic risk assessment. This guide provides the comprehensive technical basis for subsequent damage, which may result from an arc induced fire. However, it seems that there is still remarkable uncertainty associated with the energetic arcing fault and subsequent fires, which should be resolved to quantify the fire effects at common voltage levels.

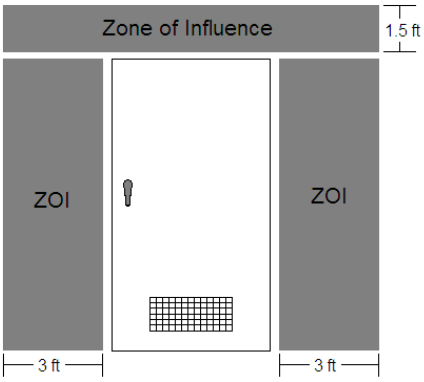


Figure 2 ZOI recommended in NUREG/CR-6850, Appendix M (2005) [5]

Therefore, it is very important to obtain scientific fire data on the HEAF phenomenon known to occur in NPP through experiments and improve the state of knowledge and develop a mechanistic model to account for the failure modes and provide better characterization of HEAF for the fire prevention countermeasures. The objective of our experimental studies is to clarify the Initial impact of the arc to primary equipment and the subsequent damage created by the initiation of an arc (e.g., secondary fires) on secondary combustibles (e.g., electrical control cables) and to investigate the numerical approach to estimate the damage of the electrical cabinets.

EXPERIMENTAL APPROCAH

In order to resolve the uncertainty associated with the energetic arcing fault and subsequent fires and quantify the fire effects at common voltage levels, the HEAF experiments using high voltage switchgears were conducted at the High Power Testing Laboratory of the CRIEPI by the request of the Federation of Electric Power Companies of Japan.

The HEAF test program consists of two phases as follows. The equipment considered in our study consists of non-seismic-proof and seismic-proof switchgears.

- Phase I (FY2012) : Primitive Arc Explosion Tests
  - Ten HEAF tests using non-seismic, non-arc-proof switchgears
- Phase II (FY2013) : Demonstrative Arc Explosion Tests
  - Three HEAF tests using seismic, non-arc-proof switchgears

Test Facility

The Electric Power Engineering Research Laboratory of the CRIPEI, located in the south of about 65km from the center 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.

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.

Figure 3 shows the overview of the high power test facilities. In this test facility, short-time withstand current and peak withstand current tests for circuit-breakers, disconnectors, earthling switches, load break switches, metal-enclosed switchgear and gas insulated switchgear can be conducted with the test capacity of current up to 60 kA and duration up to 2 seconds.

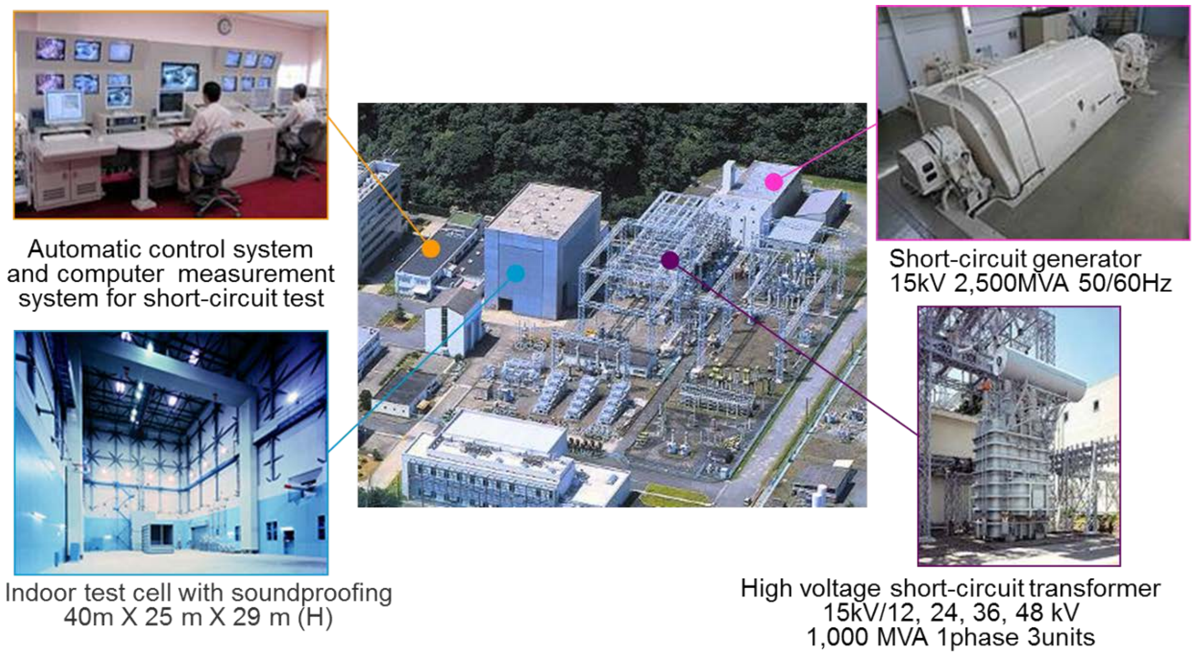


Figure 3 Overview of the High Power Testing Facilities in CRIEPI

Test Matrix

The total number of HEAF tests was thirteen, varying the type of switchgears, rating voltage, current and the arc discharge locations. Test matrix was setup referring "JEM1425-2011, Appendix A - Internal Fault -" [5] as shown in Table 1.

For the HEAF tests, eight 6.9 kV non-seismic/non-arc-proof switchgears and two 8.0 kV seismic/non-arc-proof switchgears were tested in the unloaded condition (no primary load attached to them). Arcing current was set to 20 kA considering maximum 3-phase short circuit current from the designated power system. Referring the standard of JEM1425-2011, arc duration was set to the range between 0.1 and 1.0 s. Moreover, from the safety point of view, the longer arc duration of 2.0 s was also considered. As arc discharge points, secondary bus in the cable room and VCB terminal were selected and the arc was initiated by means of a copper wire of 0.5 mm in diameter. The cabinet doors were closed to represent events that may occur under normal operation.

The test switchgears 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.

Table 1 HEAF test matrix and results

<table>
<tr><th rowspan="2">Test No.</th><th colspan="3">Arc Discharge Location</th><th rowspan="2">Current* [kV]</th><th rowspan="2">Voltage [kA]</th><th rowspan="2">Duration [sec]</th><th rowspan="2">Fire</th></tr>
<tr><th>Cabinet</th><th>Room</th><th>Location</th></tr>
<tr><td colspan="8">Phase 1 : Use of eight non-seismic, non-arc-proof switchgears</td></tr>
<tr><td>1-1</td><td>A</td><td>Upper</td><td>Secondary bus</td><td rowspan="10">6.9</td><td rowspan="10">18.9</td><td>0.1</td><td>No</td></tr>
<tr><td>1-2</td><td>B</td><td>Upper</td><td>Secondary bus</td><td>0.3</td><td>No</td></tr>
<tr><td>2-1</td><td>C</td><td>Upper</td><td>Secondary bus</td><td>0.5</td><td>No</td></tr>
<tr><td>2-2</td><td>D</td><td>Upper</td><td>VCB Terminal</td><td>0.5</td><td>No</td></tr>
<tr><td>3-1</td><td>E</td><td>Upper</td><td>Secondary bus</td><td>1.0</td><td>No</td></tr>
<tr><td>3-2</td><td>F</td><td>Upper</td><td>VCB Terminal</td><td>1.0</td><td>No</td></tr>
<tr><td>3-3</td><td>E</td><td>Lower</td><td>Secondary bus</td><td>1.0</td><td>Yes**</td></tr>
<tr><td>3-4</td><td>F</td><td>Lower</td><td>VCB Terminal</td><td>2.0</td><td>Yes***</td></tr>
<tr><td>4-1</td><td>A</td><td>Lower</td><td>VCB Terminal</td><td>2.0</td><td>Yes***</td></tr>
<tr><td>4-2</td><td>B</td><td>Lower</td><td>VCB Terminal</td><td>1.0</td><td>No</td></tr>
<tr><td colspan="8">Phase 2 : Use of two seismic, non-arc-proof switchgears</td></tr>
<tr><td>5-1</td><td>I</td><td>Upper</td><td>Secondary bus</td><td rowspan="3">8.0</td><td rowspan="3">20.0</td><td>0.2</td><td>No</td></tr>
<tr><td>5-2</td><td>I</td><td>Lower</td><td>VCB Terminal</td><td>0.2</td><td>No</td></tr>
<tr><td>5-3</td><td>J</td><td>Lower</td><td>VCB Terminal</td><td>0.5</td><td>No</td></tr>
</table>

Remarks:

* Arcing current: Max. 3-phase short circuit current from the designated power system

** Self-extinguished after 20 min

*** Extinguished by portable fire extinguisher using water as suppression agent at 7 - 10 min after ignition

Test Equipment

Phase-1

The total eight units of non-seismic-proof and non-arc-proof “3 - 6.9 kV metal-clad switchgears” were prepared as shown in Figure 4 and three series of the HEAF tests were executed as follows.

- Series1: Cabinets A+B
- Series2: Cabinets C+D
- Series3: Cabinets E+F+G+H
- Series4: Cabinets A+B (reused)

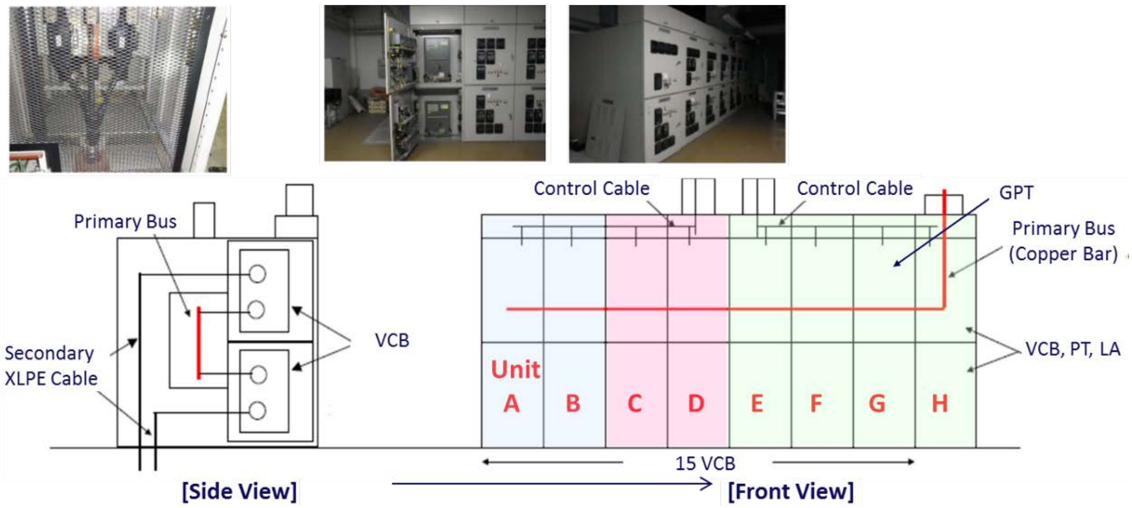


Figure 4 Non-seismic and non-arc-proof “3 - 6.9 kV metal-clad switchgears” for Phase-1

Phase-2

The total two units of seismic-proof and non-arc-proof “3 - 8.0 kV metal-clad switchgears” were prepared as shown in Figure 5 and one series of the HEAF tests were executed as follows.

- Series5: Cabinets I+J

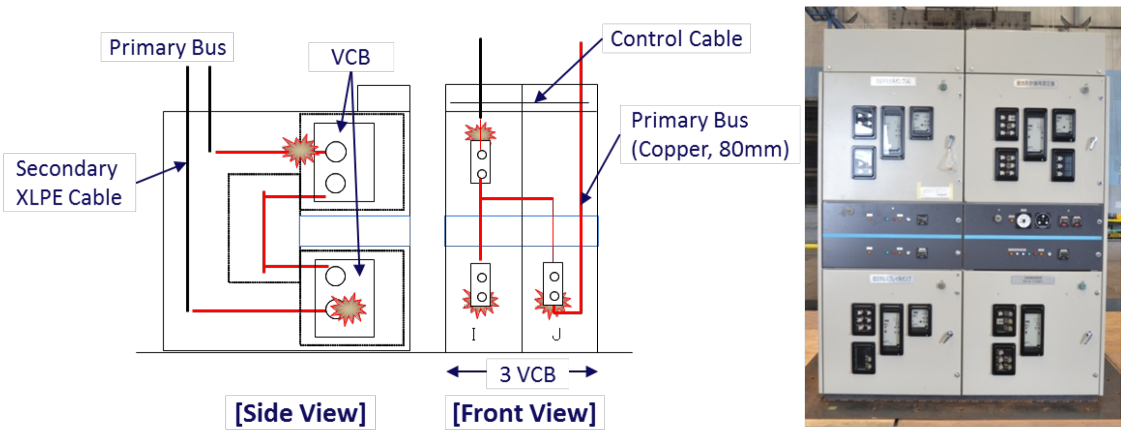
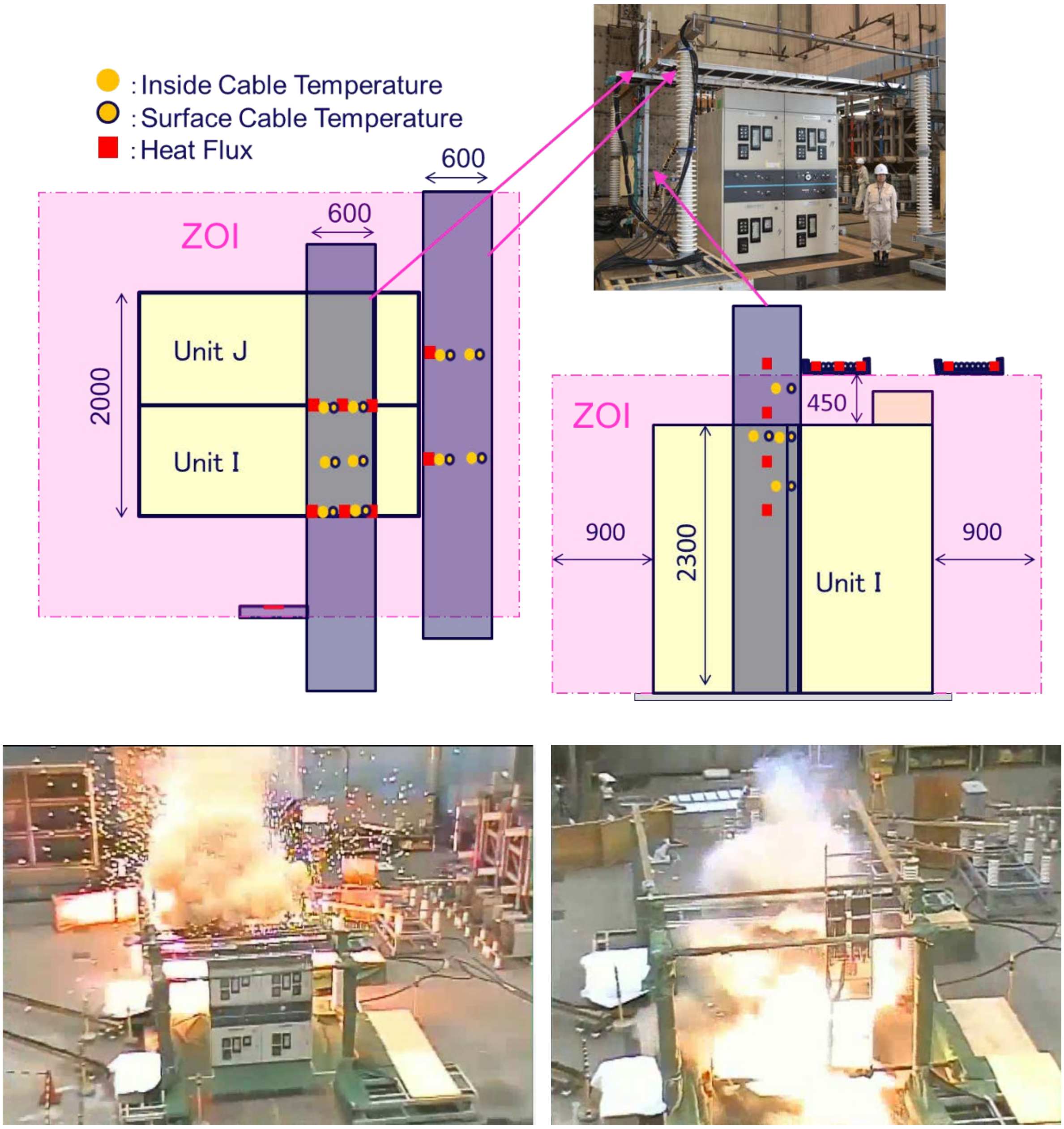


Figure 5 Seismic-proof and non-arc-proof “3 - 8.0 kV metal-clad switchgears” for Phase-2

Measurement

During the tests, arc intensity (e.g., arc power, current and voltage), arc duration, inner pressure inside the cabinet by pressure sensors, surface temperature of the cabinets by thermography and the passive temperature within ZOI were measured. Additional instrumentation included the high-speed video cameras.

Moreover, in case of Test Series 5, the instrumented cable trays were placed in the vicinity of switchgear as shown in Figure 6 to investigate the thermal damage or the potential fire resulting from the arc event.



(Test 5-1: Upper/ Secondary bus) (Test 5-3: Lower/ VCB Terminal)

Figure 6 Test equipment layouts for HEAF Test Series 5 and test images

HEAF TEST RESULTS

Damage to Components

Figure 7 shows the damage of the components observed in the Phase-1. In case that the arc was ignited in the upper cable room or at the VCB terminal located in upper layer with duration 1.0 s, there was no remarkable damage of the control cables in the upper duct although highly pressurized hot gas was released from deformed roof and side panels. On the other hand, in case that the arc was ignited at the VCB terminal located in lower layer with duration 2.0 s, the door opening due to the high pressure and the melting of the front panel of VCB were observed. After 15 min, fire was extinguished by portable fire extinguisher using water as suppression agent according to the safety procedure of the test facilities.

Figure 8 shows the damage of the components observed in the Phase-2. In case that the arc was ignited in the upper cable room with duration 0.2 s, the roof and rear panels were came off and the cable tray were deformed remarkably due to the impact of the detached roof panel.

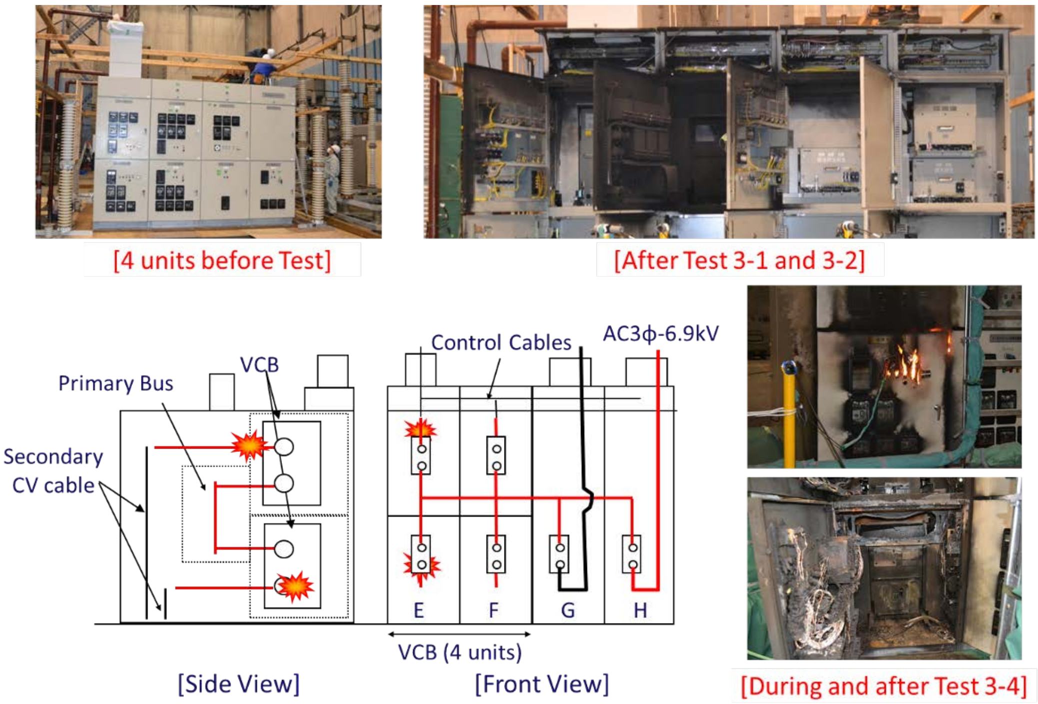


Figure 7 Typical damage of equipment observed in Phase-1

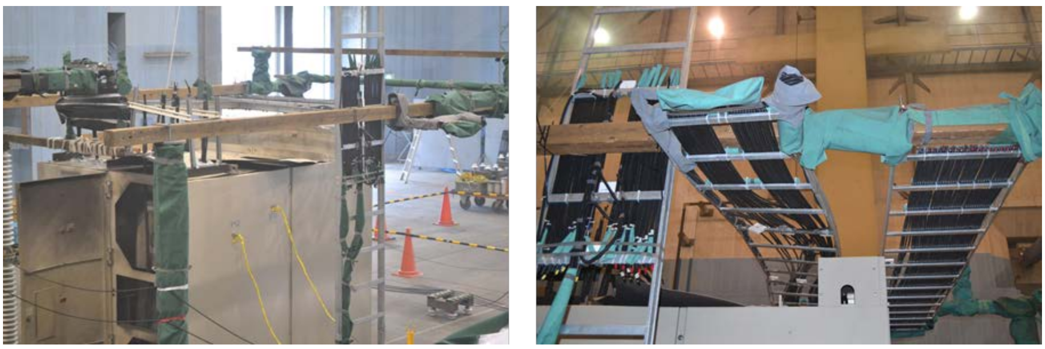


Figure 8 Damage of equipment observed in Phase-2 (Test No. 5-1)

Arcing Energy

Figure 9 shows the relationship between arc duration and measured arc energy. Arc energy in case of discharge in the cable room was 20 % larger than that in case of discharge at the VCB terminal. In both cases, below the total arc discharge energy 25 MJ (below arc duration 1.0 s), as highly pressurized hot gas was released from detached roof and side panels, there was no remarkable damage of the control cables in the duct and within the zone of influence, and the successive fire was not detected. On the other hand, over the total arc discharge energy 25 MJ (longer arc duration 2.0 s), the fire occurrence was detected and the fire extinguishment activities to remove the toxic gas release were needed. From these test results, it seems that the prevention of the successive fire or the mitigation of the influence for the equipment within ZOI may be accomplished if the arc duration or release energy is properly controlled.

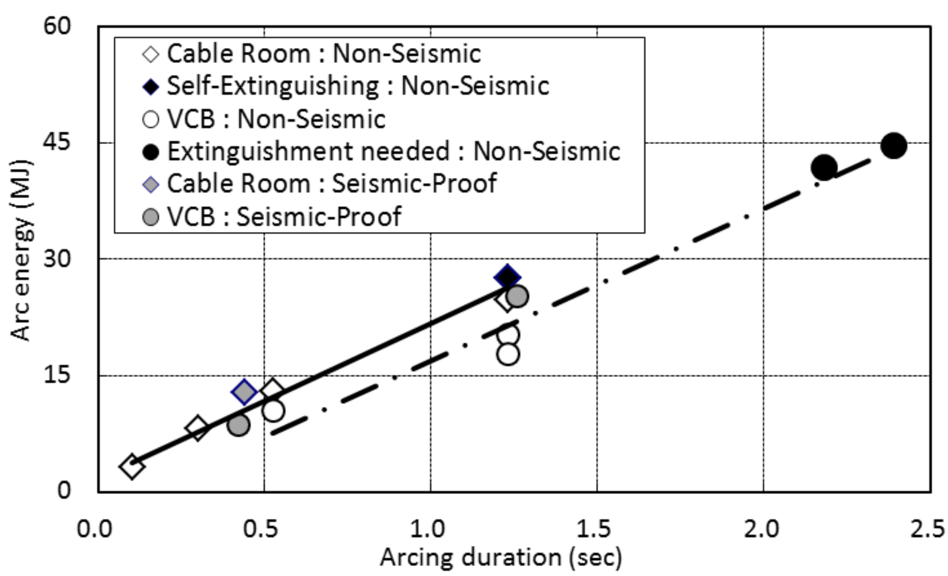


Figure 9 Relationship between arc duration and measured arc energy

Inner Arc Pressure

Neglecting all transient and hydrodynamic effects, the discharge of an arc in a cabinet can be treated as an ideal gas within constant volume system. If an amount of energy *ΔQ* is injected into the volume, the change in pressure *Δp* is expressed as follows [6]:

$$\Delta p = (\gamma - 1) \cdot \frac{k_p \Delta Q}{V}$$

with volume *V*, and adiabatic coefficient $\gamma = 1.4$, which is often used in high voltage switchgear application [6]. Thermal transfer coefficient k_p is the fraction of energy going into raising the gas pressure, while for copper bus bar $k_p = 0.53$ [7]. In case of Test No. 1-1, at arc duration of 0.1 s, arc energy of 3 MJ was found. Therefore, at a volume of 4 m^3, the above theoretical pressure of 159 kPa was obtained.

Figure 10 and Figure 11 show the relationship between arc duration and measured inner pressure and pressure time histories. Although the structure of the seismic-proof cabinet was strengthened to bear the severe seismic force, it could bear pressure at most up to 70 kPa. As only one peak was appeared in any time history, it seems that the panels (roof or side or rear) were highly deformed or opened or partially detached just after the first arrival of the shock wave due to the arc discharge. Moreover, as the several pieces of the broken bolts were scattered at least 15 m away from cabinet, they should be considered as a projectile which might induce the local damage to the surrounding equipment.

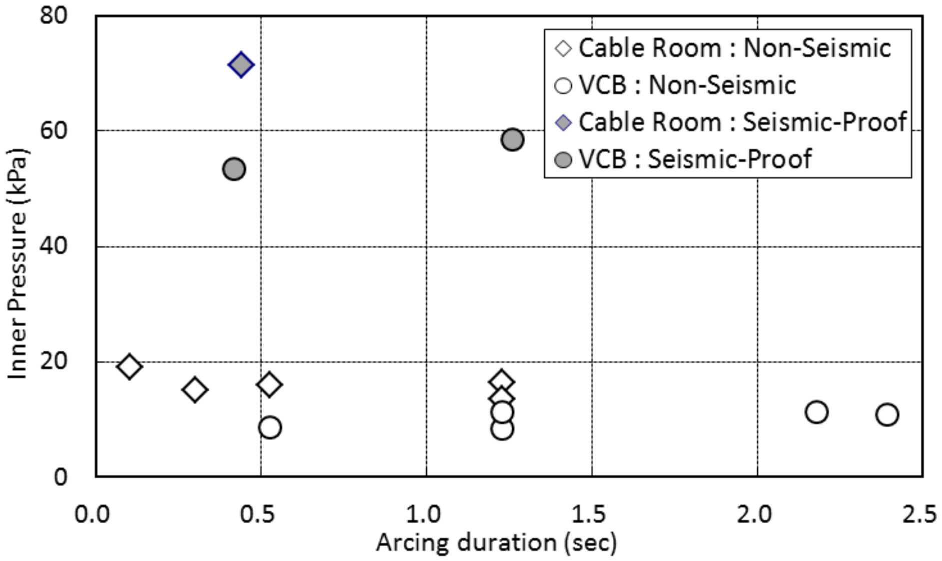


Figure 10 Relationship between arc duration and measured inner pressure

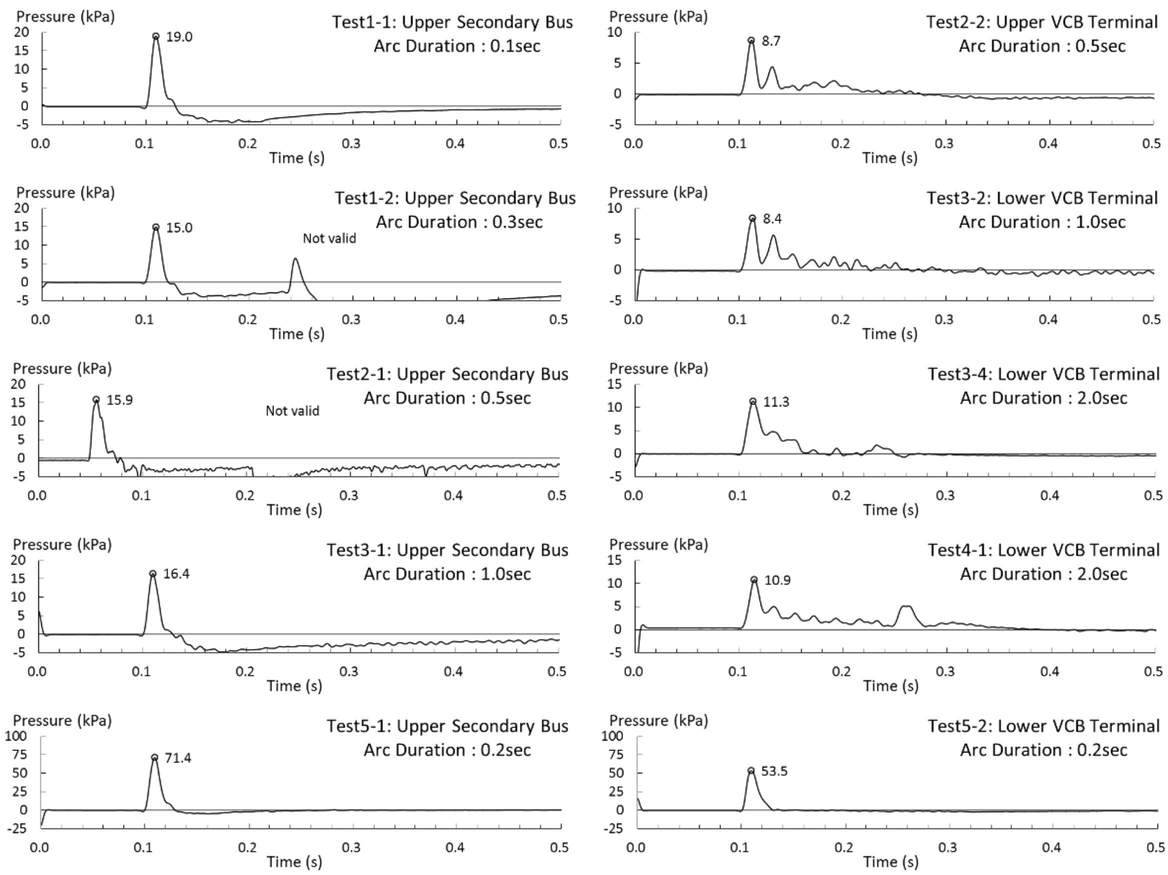


Figure 11 Time histories of measured inner pressure

NUMERICAL APPROACH

Verification of Numerical Tools

In order to estimate the pressure rise in the cabinet, the structural weakest point and the thermal propagation of the hot gas through the damaged cabinets to the environment numerically, impact analysis code "AUTODYN (Ver.13)" was applied considering the interaction between arc pressure and panel deformation. The in-house subroutine was developed and installed to AUTODYN to represent designated arc energy by pulse function accumulation as shown in Figure 12 and energy release of secondary combustible materials (e.g. control cables, etc.).

To verify this methodology, the benchmark calculation was executed for our previous works related to the internal AC arcing tests in a closed container[8-9] as shown in Figure 13. The test condition is summarized in Table 2.

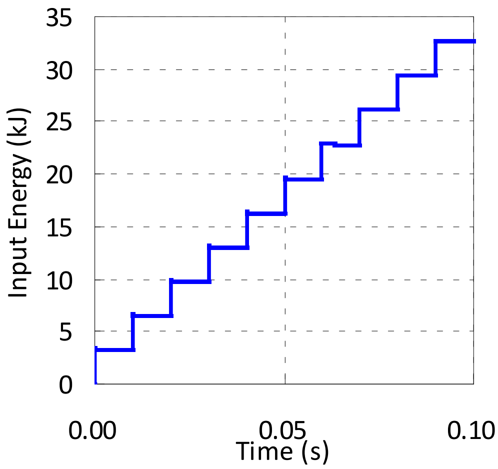


Figure 12 Example of the equivalent arc energy input for AUTODYN

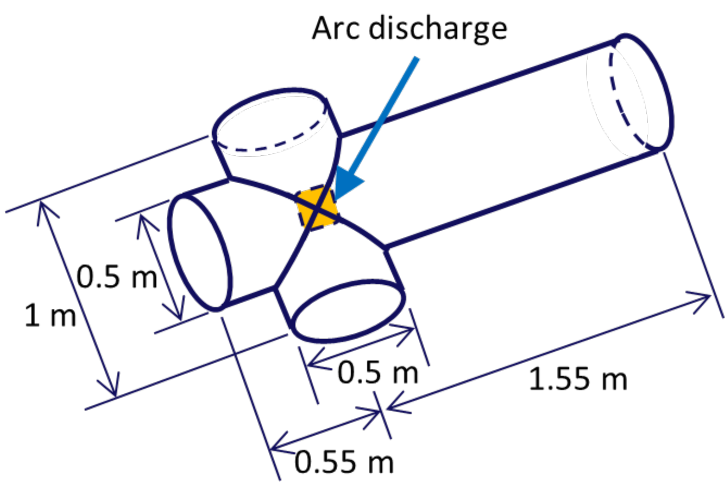


Figure 13 Schematic view of experiment arrangement

Table 2 Internal AC arcing analysis condition in a closed container

Item	Remarks
Container volume	0.52 m^3
Inert gas	Air
Initial pressure	0.1 MPa
Arc discharge condition	AC50Hz (Single phase)
Arc current	12.5 kA_{rms}
Arcing duration	0.1s
Material of electrode	Copper (Cu)
Gap between electrodes	50 mm
Arc energy	252 kJ
Thermal transfer coefficient k_p	0.53

Figure 14 shows the comparison between the calculation result and measured values as to the container pressure rise. Although pressure oscillation amplitude larger than Iwata's case due to the pulse function input was found, it seems that the maximum pressure value is good agreement with Iwata's results.

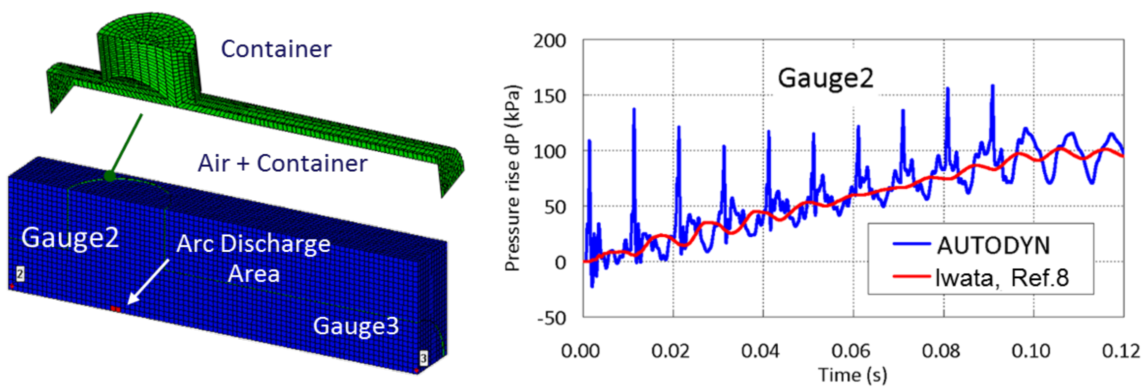


Figure 14 Benchmark of the pressure rise

Application to HEAF Tests

To investigate the accuracy of the numerical approach describe above for the realistic pressure rise due to AC arc ignition, the numerical model for Test No. 2-1 with two-full scale electric panels (Units C and D, non-seismic, non-arc-proof type) with upper cable duct was developed as shown in Figure 15.

Table 3 shows the analysis condition. Thermal transfer coefficient k_p described above was set to 0.53 considering the copper bus bars.

Figure 16 and Figure 17 show the deformation of the cabinet and the pressure profile obtained from numerical analysis. Calculated mean pressure value of cabinet C was 21.5 kPa higher than the measured value 15.9 kPa. Moreover, as the detachment of the roof panel and the rear panel deformation due to the collision of the tightening bolts were well represented, the structural weakest point, pressure increase and heat release can be interpreted by the numerical analysis.

However, it should be noted that huge elapsed time (5 days for 0.1 s) is necessary to accomplish total arc duration with a standard PC system.

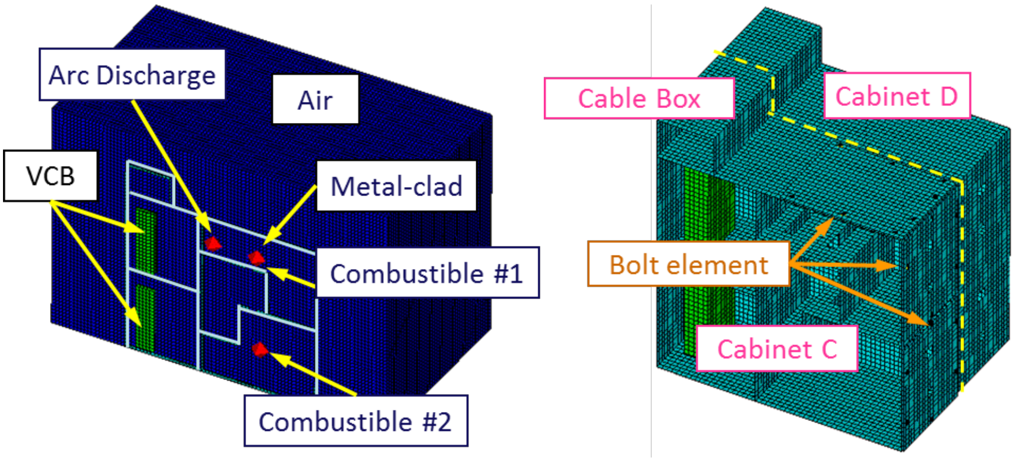


Figure 15 Numerical model for HEAF Test No. 2-1 (Units C and D, non-seismic, non-arc-proof type)

Table 3 Analysis condition for HEAF Test No. 2-1 with AUTODYN

Item	Amount
Arc current and voltage	19.1 kA x 7.19 kV
Arcing duration	0.5 s
Arc discharge location	Secondary bus in cabinet C
Arc discharge volume	1000 cm^3
Arc energy (thermal transfer coefficient) Combustible #1* in upper cable room Combustible #2* in Lower Cable Room (Ignition temperature)	12.9 kJ (k_p = 0.53) 50 kJ** 50 kJ** (230 °C)
Material of Electrode	Copper (Cu)
Gap between electrodes	50 mm
Arc Energy	252 kJ
Remarks: Lagrange solver: Metal-clad Plates (2.3-3.2 mm) Euler solver: Inner and Circumferential Air Fill solver : VCB (rigid) Twenty bolts on the top and side panels: Beam rupture element * Representative combustible materials, such as installed cables ** Ignition temperature 230 °C	

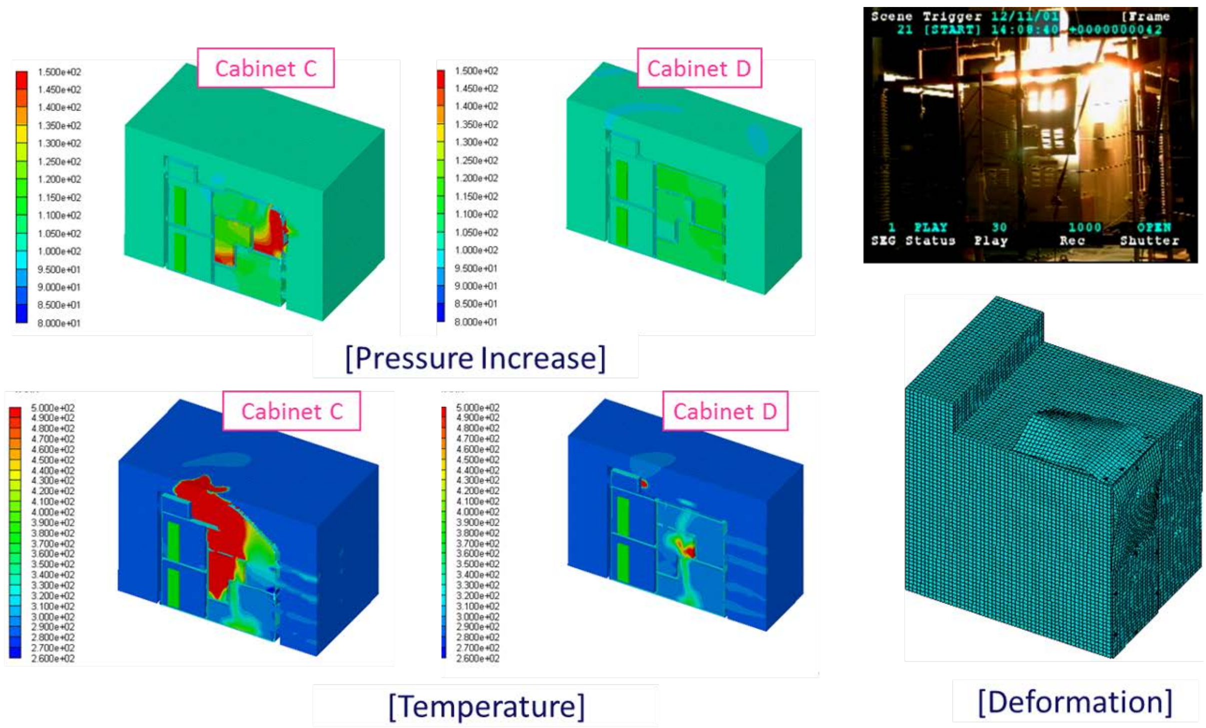


Figure 16 Deformation (Test No. 2-1: Units C and D, non-seismic, non-arc-proof type)

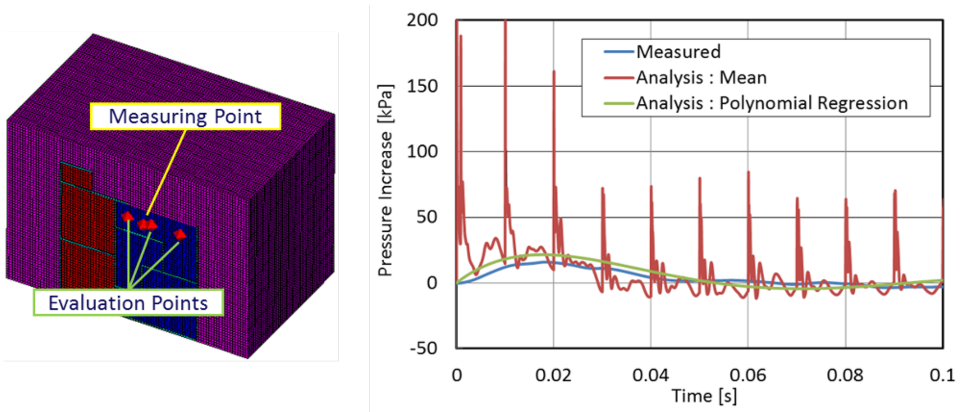


Figure 17 Pressure profile (Test No. 2-1: Units C and D, non-seismic, non-arc-proof type)

CONCLUSION

Electric arc explosion tests were executed to reflect on the countermeasures to mitigate the influence for the surrounding equipment by arcing fire in the electric cabinets.

In Phase-1 program during FY2012, in order to clarify the mechanism of pressure rise in the cabinet and thermal propagation through cabinets due to arcing fire and evaluate the zone of influence for the neighboring cabinets and surrounding equipment, ten HEAF tests (arcing duration from 0.1 to 2.0 s) using eight non-seismic, non-arc-proof cabinets at High Power Testing Facility in CRIEPI (Yokosuka, Japan) had been executed. As a result, successive fire was observed in case of long arc duration (2 s). Moreover, according to the test results, numerical tool using the impact analysis code AUTODYN to estimate the pressure increase was verified.

In Phase-2 program during FY2013, demonstrative HEAF tests using two seismic, non-arc-proof cabinets have been executed in order to set up the countermeasures for the mitigation of the HEAF influence. The detailed interpretation is actually ongoing.

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OECD PRISME 2 FIRE RESEARCH PROJECT (2011-2016) – CURRENT STATUS AND PERSPRCTIVES

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ABSTRACT

For many years (cf. [1] to [8]), the French "Institut de Radioprotection et de Sûreté Nucléaire" (IRSN) has conducted fire experiments in confined and mechanically ventilated compartments representative of fire scenarios occurring in nuclear facilities. Following the outcomes of the first PRISME Project 0 and on the basis of the needs expressed by partners, the PRISME 2 Project was proposed to investigate fire scenarios of interest in nuclear power plants including multi-compartment fires with mechanical ventilation, flame propagation on real fire sources, under-ventilated combustion regime and extinction systems. Indeed, three main topics of interest were identified by partners: smoke and hot gas propagation through a horizontal opening between two superposed compartments, fire spreading on real fire sources such as cable trays and electrical cabinets and fire propagation from a fire source to another, and fire extinction studies of the performance of various extinguishing systems. Up to now, the first experimental campaign, called Vertical Smoke Propagation (VSP), was carried out in 2012 and the second campaign concerning fire propagation on cable trays is underway in a confined and ventilated two-room enclosure. This paper presents contents and current status of the PRISME 2 Project as well as the perspectives concerning the next fire experiments.

INTRODUCTION

Fire safety in nuclear installations is a key topic involving many actors of the nuclear industry as nuclear licensees, Technical Safety Organizations (TSO) and academic research institutes. The need to exchange knowledge and participate to international projects dedicated specifically to fire safety for nuclear installations is consequently fully shared by numerous actors in the world [10]. In this context, a first international programme named PRISME has been carried out by IRSN under auspices of OECD.

The PRISME Project was an OECD five years project (2006-2011) carried out by IRSN in its experimental facilities and performed in the international framework of fire research for the safety of nuclear installations. This project has been motivated by the need of improving the knowledge on smoke and heat propagation for the specific nuclear fire scenarios involving confined and mechanically ventilated rooms. Such scenarios have implied phenomena as under-ventilated combustion regime, interaction between strong fire source and ventilation network, thermal stress effects on nuclear safety equipment (as electrical cables), effects of the ventilation devices (fire dampers) on smoke propagation and the depletion of oxygen in fire compartment, and the study of sprinkler systems on the cooling of a fire compartment. Papers and reports on this work are available as, for instance, [4], [5], [6], [7], [8], [9] and [11].

On the basis of the first PRISME conclusions and in the perspective of strengthening the collaborative activities and work built during this first project, most of the PRISME partners have contributed to impulse the definition of a new nuclear fire safety project named PRISME 2, giving their priorities and rationales for some remaining issues in nuclear fire safety.

This paper proposes an overview of this new experimental programme taking into account the needs of PRISME partners concerning fire scenarios of interest. It presents the contents of the PRISME 2 Project, a brief description of experimental facilities and instrumentation, the experimental campaigns foreseen in the project, the current status of the project including some first experimental outcomes, and finally the ongoing and future work.

CONTENTS OF THE OECD PRISME 2 PROJECT

The experimental PRISME 2 programme has been elaborated on the basis of the needs expressed by all PRISME partners and of the conclusions coming from an Expert Meeting of the OECD PRISME 2 Project held in February 2010 (in Cologne, Germany). Several topics addressed during this meeting focus on fire scenarios of interest in nuclear power plants including multi-compartments fire, ventilation system, real fire sources with flame propagation, under-ventilated combustion regime and extinguishing systems.

From thorough and fruitful debate concerning the needs of each partner for fire safety in nuclear installations, three main topics of great interest have emerged as open issues remaining to deal with:

- Smoke and hot gases propagation through a horizontal opening between two superposed compartments. This type of smoke flow [12] is poorly validated in large-scale facilities controlled by ventilation systems and remains a challenging task for computer codes.
- Fire spreading on real fire source as cable trays and electrical cabinet and fire propagation from a fire source to another one. These scenarios are identified by most of partners because they occur commonly in control panel and switchgear rooms of nuclear power plants.
- Fire extinguishing with study of performance of various extinguishing systems. Modeling the fire suppression system is still a great challenge and experimental database of full-scale fire tests representative of typical scenarios in nuclear power plants is needed.

From these issues, an experimental programme composed of original large-scale fire tests was built and the content of this PRISME 2 project is detailed hereafter.

In order to achieve the objectives defined just above, the experimental programme is divided into four experimental campaigns of fire tests:

- Three campaigns corresponding to typical fire scenarios (vertical propagation of smoke and hot gases through a hopper, cable fires and fire extinguishing by water systems) identified thanks to the analysis in-depth of partners' needs;.
- One fourth campaign, in which the fire scenarios and the experimental configurations are set after discussion with Project participants, on one hand based on the experimental outcomes from the first three fire tests campaigns and on other hand on numerical simulations.

Each campaign includes a set of three to six large-scale fire tests in the DIVA facility. Each set of experiments leads to an in-depth analysis (physical/chemical phenomena, data processing, uncertainties …). Additionally, extra support tests (e.g., fire characterization of material properties in open atmosphere …) are performed all along the experimental programme.

DESCRIPTION OF THE EXPERIMENTAL FACILITIES AND INSTRUMENTATION

The DIVA Facility

The DIVA facility is a large scale multi-room facility (see Figure 1 and Figure 2) representative of nuclear installations. It includes four compartments (labeled 1 to 4) and a corridor. All the walls are 0.3 m thick and are built with reinforced concrete designed to withstand a gas pressure ranging from – 100 hPa to 520 hPa. The compartments labeled 1 to 3 are 6 m in length, 5 m in width and 4 m in height. The room 4 (length × width × height = 8.8 × 5 × 4 m^3) is designed to study the vertical hot gas propagation from a lower (room 3) to an upper room (room 4) through a hopper having a surface of about 1 m^2. The corridor (length × width × height = 15 × 2.5 × 4 m^3) is located along the rooms 1 to 3.

All rooms of the DIVA facility can be connected with a mechanical ventilation system by means of inlet and outlet ducts, which can be set up at any height in each room depending of the fire scenarios. In this project, all ducts are foreseen to be located in the upper part of each compartment (about 0.75 m from the ceiling). The lower rooms (compartments 1 to 3 and corridor) can be connected through a single doorway (0.7 m × 2.1 m) or different types of elements (simple openings, fire door …).

The possibilities offered by DIVA allow investigating complex confined/ventilated fire scenarios, as encountered in real situations, and involving real fire source as for instance electrical cabinets and cables. Some targets, such as electrical equipment or cables can be set up in the DIVA facility in order to study thermal stress or electrical failures of such equipment during a fire scenario.

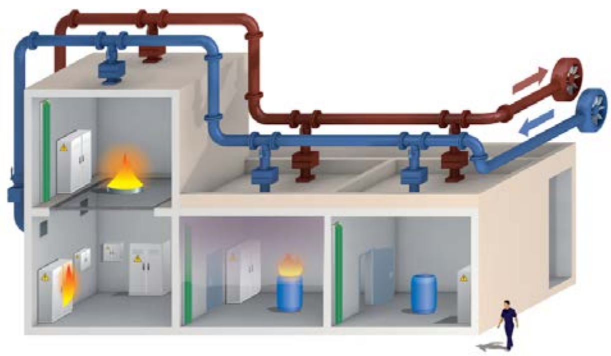


Figure 1 Schematic of the DIVA facility and its ventilation network

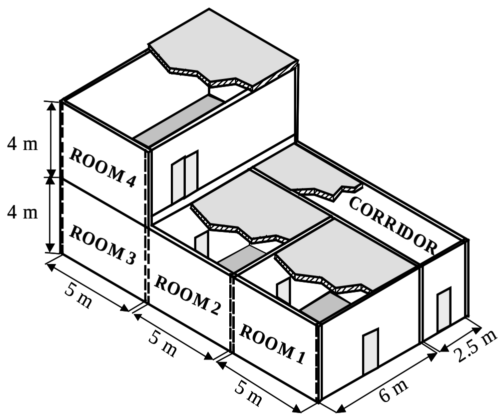


Figure 2 Main geometrical dimensions of the DIVA facility

The DIVA installation is highly instrumented (up to 800 possible measurement channels on the data acquisition system) and its ventilation network allowed it to simulate ventilation configurations representative of NPP (Nuclear Power Plant) as well as nuclear laboratories and nuclear reprocessing plant.

The SATURNE Facility (Calorimeter)

The SATURNE facility (see Figure 3) is a large enclosure of 2,000 m^3 volume (length × width × height = 10 x 10 x 20 m^3), in which is located a large scale calorimeter. The air intake goes from the top of this enclosure through large openings placed on all sides of the upper part of enclosure.

The fire tests, carried out under this calorimeter hood (see Figure 3 and Figure 4), are devoted to determine the fire behavior in open atmosphere for simple and complex fuels as liquid pool, electrical cabinet and cable trays. These tests are included in the PRISME Support tests (like characterization of heptane pool fire and of cable fire), in which are mainly investigated combustion products (O_2, CO, CO_2), soot concentration, pressure, flow rate, temperature and mass of fuel and so on. These experimental results allow in particular assessing the heat release rate, the mass loss rate, the effective heat of combustion and the effective chemical reaction of fire source in free atmosphere (i.e. without no effect of oxygen depletion on the fire source as met very often in well-confined and ventilated compartments). The design characteristics of this large-scale calorimeter are summarized just below:

- Hood dimension: 4.5 m (side of the square hood collector);
- Height from floor: The height between the floor and the bottom rim of the hood is about 4 m.;
- Ventilation system: The smoke exhaust system is connected to a ventilation network (fan, ducts, high efficiency soot filters, ventilation damper assembly and chimney). Its exhaust flow rate can be ranged from 1,000 to 25,000 m^3/h;
- This facility is designed for studying fire source up to about 3.0 MW.

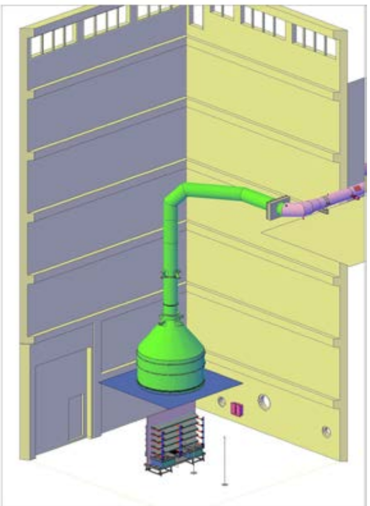


Figure 3 Hood of the SATURNE facility (large-scale calorimeter)

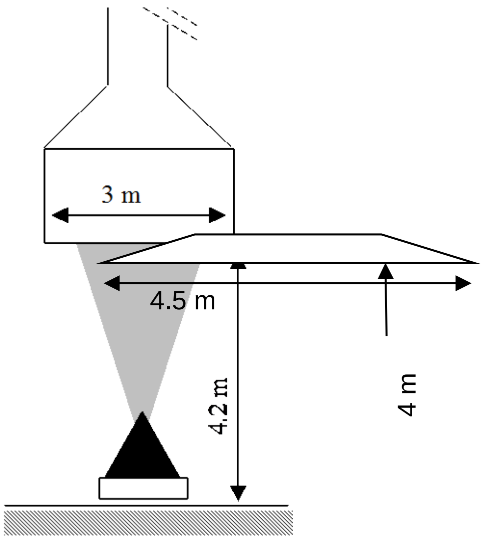


Figure 4 Main geometrical dimensions of the hood

Instrumentation

For most of PRISME 2 fire tests, more than 500 measurements are performed in order to fully describe the fire scenarios and to propose a high quality database for code validation. The measurements obtained in fire tests focus on the following variables: fuel mass loss rate (using precision balance), gas and wall temperatures (or other as inside of cables) with K-type thermocouples, gas species concentrations (CO, CO_2, O_2 and total hydrocarbons) by means of gas analyzers, soot concentrations (bank filters and tapered element oscillating microbalance systems), radiative and total heat fluxes (with MEDTHERM heat flux transducers and CAPTEC heat flux sensors) received by the walls or various targets, pressures and flow rates (using Rosemount sensors) in all compartments and in ventilation network.

For the SATURNE hood, the measurements available in exhaust duct are those usually available in calorimeter system such as fuel mass, pressure, gas flow rate, temperature, gas concentrations of O_2, CO, CO_2 and HCT and soot concentration. Additional quantities can be also determined nearby the fire source as temperatures, radiative and total heat fluxes (nearby and far from fire source) and video system.

DESCRIPTION OF EXPERIMENTAL CAMPAIGNS FORESEEN IN THE PRISME 2 PROJECT

Campaign1: Vertical Smoke Propagation (VSP)

The general objective is to investigate the vertical smoke propagation through a horizontal opening (or hopper) for mechanically ventilated fire room scenarios. The tests are focused on the study of the flows going through the vent. Indeed, these types of flows are complex in nature (typically, mono or bi-directional) because of the competition between the buoyancy force due to the density difference on one hand and, on the other hand, the inertia force due to the relative pressure induced by the operation of the ventilation system. Moreover, the flows could be significantly more complex if fire plume is located just below through the hopper (i.e. direct effect of plume momentum). The basic scenario for fire tests comprises two rooms (one lower compartment as fire room and one upper room connected by a horizontal opening of 1m² in area) with mechanical ventilation, except the first fire test devoted specifically to investigate the behavior of fire source under conditions of oxygen depletion. This fire source is a liquid pool fire of the well-known heptane. The ceilings of lower and upper rooms are insulated with panels of Thermipan material as well as the walls of the lower room except in the first test (VSP_1). In this fire test, only one wall (i.e. the North wall) is insulated by means of this insulation material.

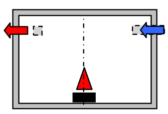
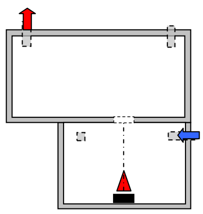
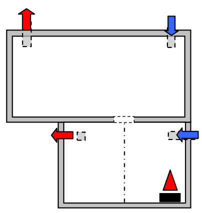
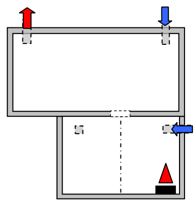
	PRS2_VSP_1	PRS2_VSP_2	PRS2_VSP_3	PRS2_VSP_4
Ventilation adj room	-	OUT/-	OUT/IN	OUT/IN
fire Room	IN/OUT	-/IN	OUT/IN	-/IN
Fire location	Centre	Centre	Off centre	Off centre
Objective	•Heptane MLR in vitiated environnment	• Axial momentum due to fire • ΔP high • ΔT free	• Radial momentum due to ceiling jet • ΔP low • ΔT free	•Radial momentum due to ceiling jet • ΔP medium • ΔT free
Configuration				

Figure 5 Fire test matrix for VSP experimental campaign

Based on a wide consensus among PRISME partners, four fire tests (see Figure 5) are carried out in this first campaign:

– The first one (VSP_1) is a one-room reference test with a given fire source and ventilation rate (here, the upper compartment is not used). The main goal is to determine the fire behavior of heptane in vitiated environment and to compare it to the outcomes previously obtained in PRISME 1 programme [1,], [4], [5], [8], and [13]). In this test, the pool fire area is only 0.3 m² and the renewal rate for ventilation is 16.6 h^{-1} (i.e. about 2000 m^3/h).

- The second test (VSP_2), deals with propagation of smoke and hot gases from fire compartment to a superposed room through a hopper. The inlet duct for fresh air is connected to the lower room and the exhaust duct for combustion products (gas and smoke) is located in the upper compartment. The renewal rate is 8 h^{-1} considering both volumes of lower and upper rooms (i.e. 2340 m^3/h). The pool fire area is 0.4 m². It is situated in the center of fire room as VSP_1 experiment and so the fire plume is just under the horizontal opening.
- The third test, VSP_3, is close to the configuration VSP_2. Inlet ducts for fresh air and exhaust ducts for combustion products are available in both compartments. The ventilation rate is in the whole the same as previously (i.e. 2340 m^3/h) but shared as 960 m^3/h for lower room and 1360 m^3/h for upper room. The pool fire is the same but is located in the off-center of fire room, nearby to a corner of the lower compartment (North-West location).
- Finally, the fourth test, VSP_4, is very similar to the configuration VSP_3. The only change concerns the exhaust duct in the fire room that is no longer open to exhaust the smoke and hot gases. Consequently, only the exhaust duct in the upper room can extract the combustion products from both compartments. The ventilation rate is the same as previously (i.e. 2340 m^3/h) and shared in the same way (960 m^3/h and 1360 m^3/h). The pool fire is again located in the off-center of the fire compartment, as in VSP_3 fire test.

This first series of fire tests were fully carried out in 2012.

Campaign 2: Cable Fire Spreading (CFS)

This test series concerns the fire spreading on five superposed cable trays and the fire propagation from cabinet fire to three overhead cable trays. The overall aims of this second experimental campaign (see Figure 6 and 7) consist of:

- Firstly, fire spreading along five horizontal cable trays (cf. Table 1) is investigated in confined and ventilated facility. The fire scenario involves two compartments connected by a doorway with the inlet duct located in the fire room and with the exhaust duct located in the adjacent room. Two levels of ventilation are used for these fire tests: 4 h^{-1} (i.e. 960 m^3/h) and 15 h^{-1} (i.e. 3600 m^3/h). Two types of cables provided by partners are tested: Cables with halogenated fire retardant (H) and with non-halogenated fire retardant (NH). Ignition of cable material is carried out with a fire source fire located just below and at the center of the lower cable tray. This fire source is a gas burner of propane having a fire power of about 80 kW.
- Secondly, fire spreading from electrical cabinet fire to three overhead cable trays (cf. Table 2) is studied in confined and ventilated facility. The fire scenario involves three compartments such as the fire compartment and its adjacent rooms are connected by a doorway as previously. In the same way, the ventilation system for inlet and exhaust ducts is identical with CFS-1 to CFS-4 fire tests. The initial level of ventilation used for these three fire tests in these two rooms is 15 h^{-1} (i.e. 3600 m^3/h). In this fire scenario, a fire door is located between the second and the third compartments. The ventilation system for this last compartment consists of one inlet and one outlet ducts, the renewal rate of this room being 15h^{-1} (i.e. 1800 m^3/h). As previously; two types of cables provided by partners are tested: Cables with halogenated fire retardant (H) and with non-halogenated fire retardant (NH). Ignition of electrical cabinet is carried out by means of line source located in the lower part of cabinet, all along the first electrical components. This line source is a propane burner having a fire power of about 10 kW.
- An additional fire test (CFS_7, see Table 2) investigates the closure of fire dampers (150 s after start of fire), particularly to assess the effect of pressure due to highly-

confined condition in such fire scenario. The type of cables and the ventilation system (inlet/outlet ducts, flow rates) are the same than in the CFS-6 fire test.

- A last objective is to assess the malfunction of electrical/electronic components of interest for partners in real fire conditions, i.e. when the electrical equipment undergoes both smoke and thermal stress effects. This topic is of great interest for fire safety of nuclear installations, particularly in probabilistic safety analysis (PSA).

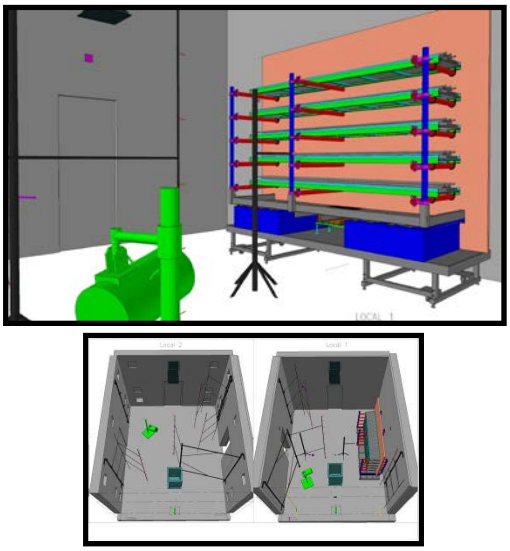
Fire Tests	Main Objective	Additional Objective
CFS-1 to CFS-4	Fire spreading along five horizontal cable trays in confined facility 	- Malfunction of electrical / electronic components

Figure 6 Experimental configurations for CFS 1 to 4

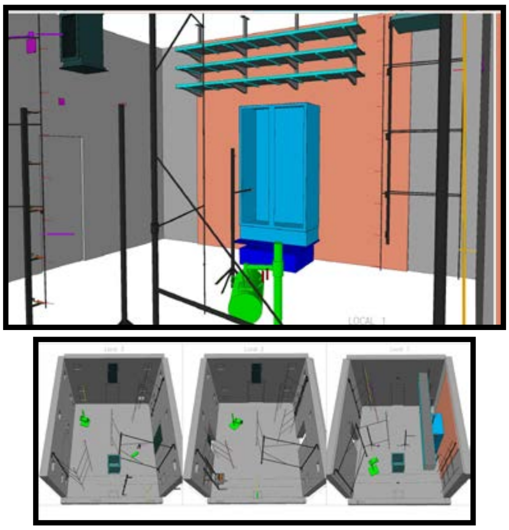
Fire Tests	Main Objective	Additional Objective
CFS-5 to CFS-7	Fire spreading from electrical cabinet to overhead cable trays in confined facility 	- Malfunction of electrical / electronic components - Spreading of smoke and hot gases through fire door - Effect of pressure due to closure of fire dampers

Figure 7 Experimental configurations for CFS 5 to 7

Under the SATURNE large-scale calorimeter, four support tests were carried out to determine the behavior of fire spreading along five horizontal cable trays. Some experimental results are discussed later. Now, the CFS campaign in DIVA facility is underway all along the year 2013 and will allow us to understand more thoroughly the effect of air depletion on flame spreading during cable fires.

Table 1 Fire test matrix for CFS-1 to 4

Test	Cables	Renewal Rate [h^{-1}]	Objectives
CFS-1	H cable	4 (960 m^3/h)	– Effect of low renewal rate (4 h^{-1}) on fire spreading over five horizontal trays filled with H cable – Malfunction of electrical / electronic components
CFS-2	H cable	15 (3600 m^3/h)	– Effect of high renewal rate (15 h^{-1}) on fire spreading over five horizontal trays filled with H cable – Malfunction of electrical / electronic components
CFS-3	NH cable	4 (960 m^3/h)	– Effect of low renewal rate (4 h^{-1}) on fire spreading over five horizontal trays filled with NH cable – Malfunction of electrical / electronic components
CFS-4	NH cable	15 (3600 m^3/h)	– Effect of high renewal rate (15 h^{-1}) on fire spreading over five horizontal trays filled with NH cable – Malfunction of electrical / electronic components

Table 2 Fire test matrix for CFS-5 to 7

Test	Cables	Fire Door	Fire Damper	Renewal Rate [h^{-1}]	Objectives
CFS-5	H cable	yes	no	15 (3600 m^3/h)	– Effect of high renewal rate (15 h^{-1}) on fire spreading from cabinet to overhead trays filled with H cables – Investigation of smoke propagation through fire door – Malfunction of electrical / electronic components
CFS-6	NH cable	yes	no	15 (3600 m^3/h)	– Effect of high renewal rate (15 h^{-1}) on fire spreading from cabinet to overhead trays filled with NH cables – Investigation of smoke propagation through fire door – Malfunction of electrical / electronic components

Test	Cables	Fire Door	Fire Damper	Renewal Rate [h^{-1}]	Objectives
CFS-7	NH cable	yes	yes	RR = 15 h^{-1} for t < 150 s, then RR ~ 4 h^{-1} (due to leakages)	– Effect of closure of fire dampers (150 s after start of fire) – Investigation of smoke propagation through fire door – Effect of peak of pressure on fire door behavior – Malfunction of electrical / electronic components

Campaign 3: Fire Extinguishing System (FES)

The objective of this third campaign is to assess the performance of fire extinguishing systems (FES) based on water sprinkler system (e.g., Figure 8). Indeed, this topic is of great interest because water systems are often used to extinguish fire or decrease the thermal effects in switchgear rooms and cable rooms in nuclear power plants [10].

The two main parameters that characterize the efficiency of water sprinkler system are the droplet size distribution and the water flow rate. The decrease of the droplet size, for a given mass flow rate, promotes the cooling effect. The increase of water flow rate improves the process of extinction. The tests will investigate these effects by testing two types of industrial sprinkler nozzles (for 2 droplet size distributions) with two water flow rates. A set of four fire tests is foreseen (FES_1 to FES_4, see Figure 9).

The fire source should be a liquid pool fire. The fuel type and the pool area will be defined in agreement with the partners taking into account some pre calculations results. The number of rooms to be considered for the tests (one or two rooms connected by an open door, see Figure 8) is underway and today remains to be defined with the partners.

Figure 8 Sprinkler used in PRISME Integral tests (PRISME 1 Project)

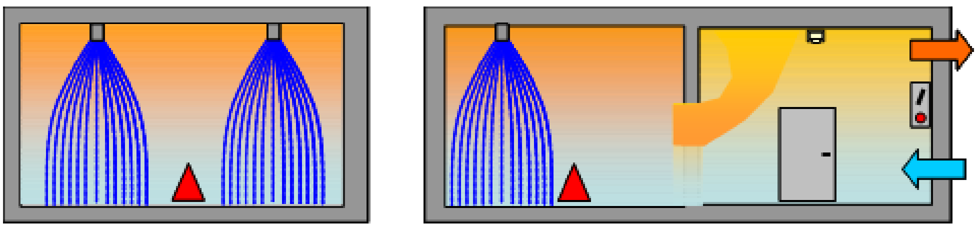
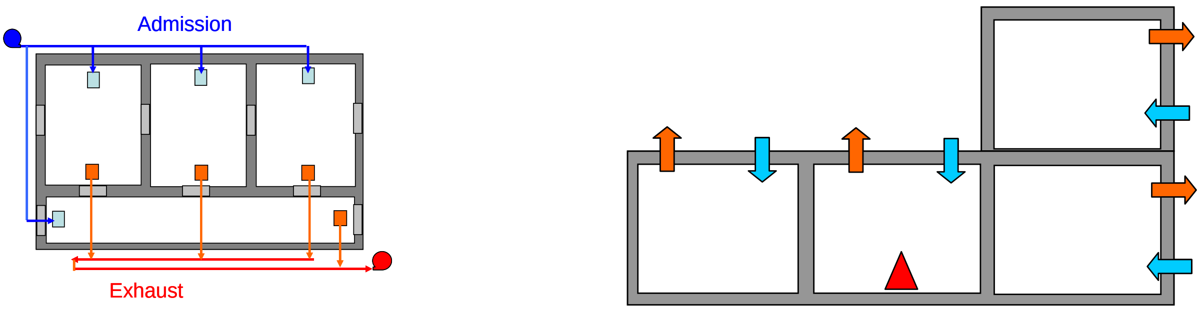


Figure 9 Schematic view concerning FES experimental tests

Campaign 4: Provisional Fire Tests

The last campaign concerns five provisional fire tests is not yet fixed and thus the technical objectives are kept open. The final definition will be fixed with partners on the basis of the results of the previous campaigns, the evolution of fire safety priorities, the interest in carrying out some fire tests for repeatability and the special wishes (as interaction of two fires, water mist and gas systems, functional performance of safety systems, fire spreading from vertical cable fire along a wall to an upper room, dampers, smoke and/or soot effect on relay contacts, etc.) from the project partners. These five full-scale fire tests could involve the whole DIVA facility, including up to five compartments (four rooms and the corridor, see Figure 10).

The fire source could be selected as a liquid pool fire and/or as a real fire (cables, cabinet). The only technical limitations for the scenarios proposed by the partners will concern the technical capability of DIVA facility to carry out the fire tests under safe conditions.



Bird's eye view of DIVA facility

Side view of DIVA facility

Figure 10 Full views of DIVA facility usable for the five provisional fire tests

Additional Tests (Support Tests)

Additionally, support tests can be lead to bring complementary input data for code simulations and experimental analysis. These support tests consist mainly in determining the fire source properties in open atmosphere (heat release rate, combustion products, radiative fraction, soot emission factor …) and/or material properties (nature, density, heat capacity, conductivity …). These tests will be defined more precisely during the experimental programme and, in the whole, a set of 16 to 20 support tests are foreseen during PRISME 2 Project.

Moreover, for FES campaign, some experiments will be carried out to provide the water flow parameters (droplet distribution and velocity) for the water suppression system (water mist, sprinkler). These input data will be used to predict the effects of water spray on fire source.

FIRST EXPERIMENTAL OUTCOMES OF THE PRISME 2 PROJECT

Experimental Results from VSP_1 to VSP_4 Fire Tests in the DIVA Facility

This first campaign concerns smoke propagation through a horizontal opening (as hopper) between two superposed compartments. After a first step consisting of fire characterization of heptane pool fire under SATURNE calorimeter (i.e. in free atmosphere), four fire tests were carried out in room 3 and 4 in DIVA facility (cf. Figure 1 and Figure 2). The fire scenarios of interest in this experimental campaign were described in detail previously (cf. Figure 5).

The thorough and full analysis of these fire tests is currently underway and a brief overview of the first experimental results is now proposed:

- Heptane fuel under vitiated conditions due to under-ventilated regime (i.e. low ventilation rate in fire compartment compared with heat release rate from fire source) showed a behavior concerning the mass loss rate (MLR) in accordance with the Peatross and Beyler correlation [8], [14].
- Both steady and unsteady regimes were observed for the heptane MLR (and consequently heat release rate) showing even an outbreak of mass loss rate oscillation during the fire tests (for instance, see Figure 11 for VSP_1). An additional study showed that this MLR's oscillation is not due to the experimental facility but rather due to fire behavior in under-ventilated regime (see also [16]). This point is currently investigated especially.

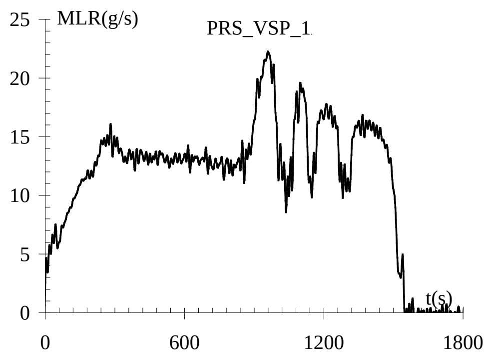


Figure 11 Time evolution of mass loss rate for VSP_1 fire test

Mono and bi-directional flows (measured by a set of McCaffrey-type pilot tubes located at the hopper, see Figure 12) are observed through the hopper during fire tests depending on the experimental conditions (forced flows, gas temperatures, location of pool fire) inside both fire room and superposed room. The thorough understanding of such flows is an important challenge of this study.

Figure 12 Set of 13 bi-directional McCaffrey-type pilot tubes at horizontal opening

- For VSP_2 fire test, the pool fire is located just below the hopper (see Figure 13 (a)). So, smoke and hot gases from fire plume (Figure 13 (b)) flowed directly from fire room to upper compartment. Later, a significant part of the flame coming from heptane pool fire appeared above the horizontal opening as shown in Figure 13 (c). This point can be a great interest to assess the fire propagation from lower room to a superposed compartment.

a) Flame above heptane pool fire in lower room

b) Smoke flow coming from fire room to upper room above the hopper

c) Flame above heptane pool fire in lower room above the hopper

Figure 13 Smoke flow then flame observed just above the horizontal opening for VSP_2 fire test

These experimental results presented in this paper are just a brief overview of VSP campaign and the full analysis of these fire tests will be done by the end of 2013.

Experimental Results from CFS Support Tests (or CFSS Tests) in SATURNE Calorimeter

First of all, the fire properties of complex source as five cable trays were determined in open atmosphere by means of the SATURNE large scale calorimeter (see Figure 1 and Figure 2) before carrying out fire in DIVA facility.

The fire source consisted of five horizontal ladder trays of 2.4 m length, 0.45 m width and 0.3 m spacing, as shown in Figure 14. This experimental configuration of tray width and tray spacing were chosen because, on one hand, they are commonly met in NPP, on the other hand, they were similar to some fire tests in the CHRISTIFIRE program carried out by NIST (*N*ational *I*nstitute of *S*tandards and *T*echnology, USA) [17]. The fire source configuration also included an insulated side wall against the five trays in order to get the cable trays in similar conditions (i.e. close wall) as encountered in confined and ventilated multi-rooms (DIVA facility). A square sand burner (400 x 400 mm^2 side by side) was used to ignite the cable trays during the fire tests and was supplied with commercial propane gas of fire power about 80 kW. It was stopped for all fire tests as soon as HRR of cable tray fires exceeded 400 kW (measured by calorimeter system). The instrumentation used during these tests has been defined previously (see paragraph entitled “The SATURNE facility”.

Figure 14 Cable trays device for CFSS fire tests (right: five trays with cables; left: cable trays under calorimeter)

Provided by PRISME partners, four types of electrical cables were tested in this study. They could be classified as: Halogenated/Power (HP), Halogenated/Control (HC), Non-Halogenated/Power (NHP) and Non-Halogenated/Control (NHC). The main characteristics of cables (dimension, number of conductors, nature and so on) are described hereafter.

Table 3 Main characteristics of cables (cf. [15])

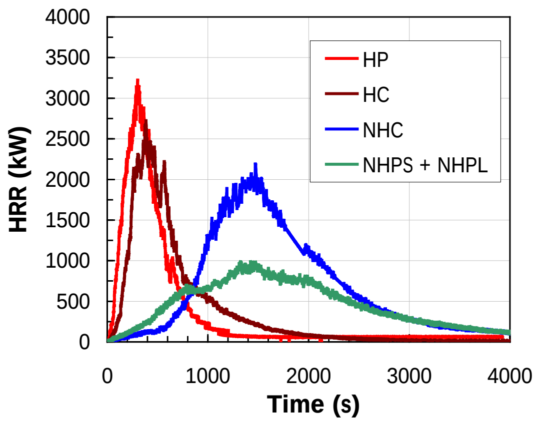
Cable Type	Power / Control	Reference*	Conductors	Diameter [mm]	Cable nature (fire retardant)	Cable construction
HP	Power	MCMK	3 x 2.5 mm^2	13	Halogenated	Sheath-filler insulation
HC	Control	SHCVV	8 x 2 mm^2	14.5	Halogenated	Sheath-insulation
NHC	Control	NU-SHX(ST)HX	12 x 1.5 mm^2	20	Non-halogenated	Sheath-filler insulation
NHPS	Power	Cu CST 74 C 068 00 K2 SH	3 x 2.5 mm^2	12	Non-halogenated	Sheath-filler insulation
NHPL	Power	Cu CST 74 C 068 00 K2 SH	3 x 95 mm^2	37	Non-halogenated	Sheath-filler insulation
* given by cable manufacturer						

Concerning cable arrangements on trays, all the cables were packed loosely over all trays in a similar way than CHRISTIFIRE fire tests. This arrangement seems to promote the fire spreading. Tray loading on the five cable trays is detailed just below.

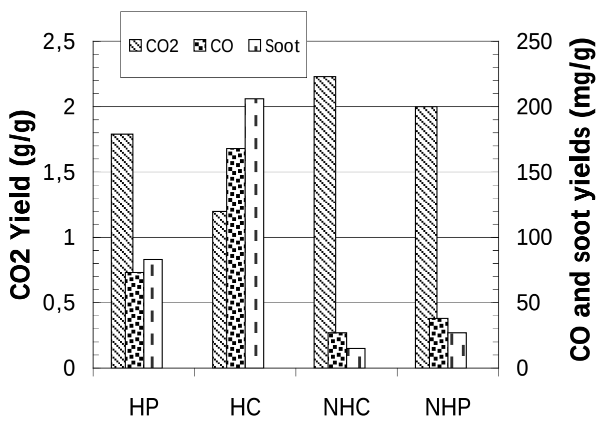
Table 4 Tray loading with cables (cf. [15])

CFSS Fire Test	Cable	Outer diameter [mm]	Number of Cables per Tray	Tray Loading Parameter [% of NEC_{max}]
CFSS-1	HP	13	49	48
CFSS-2	NHC	20	32	74
CFSS-3	Trays 1 and 2 : NHPS	12	53	44 for trays 1 and 2
	Trays 3, 4 and 5 : NHPL	37	12	96 for trays 3, 4 and 5
CFSS-4	HC	14.5	44	54

The outcomes of CFSS fire tests (see Figure 15 (a)) highlighted two fire categories: fast growth fires for fire sources with the Halogenated cables and slow growth fires for the ones with the Non Halogenated cables. The peaks of HRR are higher for the fire sources with Halogenated Cables (about 3 MW) than for these with Non Halogenated cables (HRR varied from 1 to 2 MW). Fire growth acceleration and higher peaks of HRR due to halogenated nature of cable were enhanced by the smaller cable mass (or diameter) of Halogenated cables. Concerning the release of combustion products, CO and soot yields are much more significant for fire tests with cables having halogenated fire retardant (H) than those having non-halogenated fire retardant (NH).



(a) Heat release rate



(b) Combustion products

Figure 15 Heat release rates and combustion products during CFSS fire tests

All the experimental outcomes coming from CFSS fire tests can be found in more details in [15].

ONGOING AND FUTURE WORK

This paper presents the current status of the international fire research project (2011-2016), named PRISME 2, which is carried out by The French Institut de Radioprotection et de Sûreté Nucléaire (IRSN) under auspices of OECD Nuclear Energy Agency. The whole project is devoted to deal with nuclear fire safety issues coming from PRISME partners' concerns. After recalling the three topics of interest addressed in the project (i.e. propagation of smoke and hot gases through an horizontal opening, fire spreading on cable trays and from cabinet to cable trays and water extinguishing system) and the design of large-scale facilities (calorimeter, multi-compartment facility with ventilation network) used to investigate the fire scenarios defined by partners, this paper reviews the current state of PRISME 2 program. Indeed, the work carried out by IRSN up to now is as:

- The first VSP campaign (four fire tests in DIVA facility) was fully done including the fire characterization of heptane fuel under large-scale calorimeter. Now, the analysis in-depth of experimental database is in progress and will be provided to partners by the end of 2013.
- The second CFS campaign (seven fire tests in DIVA facility) is on-going on the year 2013 and the last test is foreseen in January 2014. Nevertheless, determining fire properties of five cable trays under SATURNE calorimeter has already been done in 2012.

The third FES campaign (four fire tests in DIVA facility) is today in discussion in order to fully design the test matrix following partners' wishes. The definition of FES test series will be done before the end of 2013. The fire tests in DIVA and SATURNE facilities are planned to start already in 2014.

The fourth and last campaign (five fire tests in DIVA facility) will be discussed in shortly time with PRISME partners in order to define the fire scenarios of interest following partners' wishes based on previous fire tests and their special requests (safety research priorities, repeatability, …). These fire tests are foreseen from 2015.

ACKNOWLEDGEMENTS

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RECENT FIRE RESEARCH RELATED TO SWEDISH NUCLEAR POWER PLANTS AND EUROPEAN SPALLATION SOURCE

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ABSTRACT

This paper gives an overview of recent activities in fire research related to Swedish nuclear power plants and also the European Spallation Source. It focuses mainly on pool fires and prediction of ventilation flows between rooms. For pool fires there are two aspects discussed in this paper. The first topic is with respect to the mass loss rate of pool fires in enclosed compartments. In this paper, a first attempt is given to develop an engineering model to predict the pool fire development in under ventilated fires as a complement/alternative to more advanced pyrolysis models. The second aspect is the fire behavior of different insulation transformer oils. They comprise not only as a serious fire hazard for nuclear power plants, but also for the new large facility European Spallation Source (ESS) in Lund. ESS is one of the largest science and technology infrastructure projects being built today using large amounts of transformer oils inside the facility. The facility design and construction includes a linear proton accelerator, a heavy-metal target station, a large array of state-of-the-art neutron instruments, a suite of laboratories, and a supercomputing data management and software development center. Results on the heat release rate of different transformer oils will be reported from tests done with the cone calorimeter (ISO 5660). The work was done within a master thesis project by one of the Erasmus mundus students of the International Master of Science in Fire Safety Engineering program. Finally, the article will report and summarize on the validation of the models in FDS6 for prediction of ventilation flow between mechanically ventilated compartments.

SIMPLIFIED POOL FIRE MODEL WITH ENVIRONMENTAL FEEDBACK

The mass loss rate, and the resulting heat release rate, is one of the key elements in predicting the behavior of a compartment fire. Computational simulations using a prescribed fuel mass loss rate, so called a posteriori simulations, have often been shown to give a good agreement with experimental results, but the burning rate in an enclosed space with or without technical installations is often not easy prescribed without experiments of the exact same configuration. This work focuses on predicting the mass loss rate of enclosed fires using data collected in a free burning environment or data derived from correlations (for example the Babrauskas rate [1]) by taking the environment feedback and environment interaction into account. This will hopefully increase the understanding of phenomena such as oscillating burning behavior where the natural or the mechanical ventilation and fire source interacts coupled to each other. This model is intended to be a simplified “engineering model” in the sense that the actual liquid phase will not be taken into account, only the incoming radiation to the surface and the surrounding oxygen fraction will be considered.

Regarding the influence of the oxygen fraction on the burning rate, an empirical correlation has been obtained from a steady-state combustion regime by Peatross and Beyler [2]. This correlation provides fuel mass loss rate against oxygen concentration measured at the flame base for large-scale fire compartments:

$$\dot{m}''_{fuel,O_2} = \dot{m}''_{\infty,21\%} \cdot (0.1 \cdot O_2[\%] - 1.1) \qquad \text{Eq. 1}$$

One of the main drawbacks of this empirical relationship lies in that it was obtained in conditions for which external heat fluxes were negligible. This limits its relevance to situations where high gas and wall temperatures, affecting incoming heat fluxes, are present. The effect of the external radiation can be taken into account in a simplified matter where the extra fuel mass loss rate is proportional to the external radiation and the heat of vaporization:

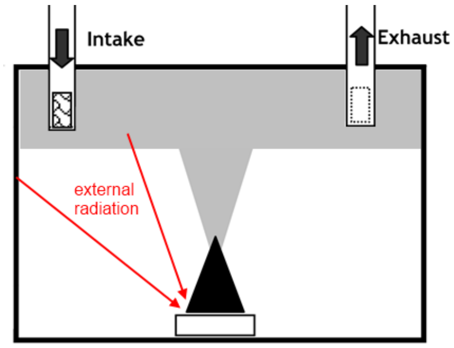


Figure 1 Descriptive figure of external radiation sources in a compartment fire

$$\dot{m}''_{external} = \frac{\dot{q}''_{rad,in\ walls} + \dot{q}''_{rad,in\ sootlayer} - \dot{q}''_{rad,out\ fuel\ surface}}{\Delta H_{vap,fuel}} \qquad \text{Eq. 2}$$

When combining these to expressions the total fuel mass loss dependent on both local oxygen concentration and external radiation can be expressed as:

$$\dot{m}''_{fuel,tot} = \dot{m}''_{fuel,O_2} + \dot{m}''_{external} \qquad \text{Eq. 3}$$

If the initial phase of the fuel mass loss is of less importance, the term $\dot{q}''_{rad,out\ fuel\ surface}$ can be approximated using the fuel emissivity and boiling temperature to calculate the outgoing radiation. However, this will result in an over estimation of the initial fuel mass loss rate.

If the initial phase is of importance more mechanics has to be added. According to Hayasaka [3] the total heat needed for vaporization during the growth phase is expressed by the equation:

$$Q_{growth\ phase} = \dot{m}''_{growth\ phase} \cdot (c_p \cdot (T_{boil,fuel} - T_{fuel,surface}) + \Delta H_{vap,fuel}) \qquad \text{Eq. 4}$$

When the temperature in the pre-heating layer has reached the boiling temperature of the fuel the equation reduces to:

$$Q_{steady\ state} = \dot{m}''_{growth\ phase} \cdot \Delta H_{vap,fuel} \qquad \text{Eq. 5}$$

Hayasaka also concludes that the total heat balance of the pool fire during all phases was approximately the same, as in $Q_{growth\ phase} = Q_{steady\ state}$. Combing the equations for the growth phase and steady state phase an expression for the fuel mass loss rate during the preheating process can be formed:

$$\dot{m}''_{growth\ phase} = \dot{m}''_{\infty,21\%} \cdot \frac{1}{\left(\frac{c_p \cdot (T_{boil,fuel} - T_{fuel,surface})}{\Delta H_{vap,fuel}} + 1\right)} \qquad \text{Eq. 6}$$

This equation gives a reasonable fit to experiments conducted by Hayasaka [3] during the pre-heating process:

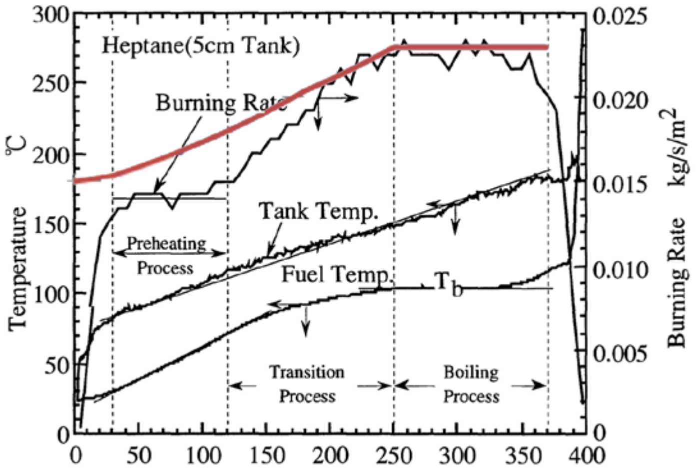


Figure 2 Comparison between experiments performed by Hayasaka [3] and the simple model (red line) to describe the initial phase of the pool fire

To increase the accuracy a more refined heat transfer model including heat exchange with and through the fuel vessel, especially during the very initial phase of the process since the heat loss to the vessel seems dominant during this period.

The initial work with this model will focus on validating the post-ignition phase, as in the pre-heating process will not be included. If the validation is successful, further work to include the pre-heating process will be initiated.

FIRE BEHAVIOR OF INSULATION TRANSFORMER OILS

One of the major key components of today's power grids is the transformer [4]. Transformers are traditionally filled with mineral oil, to serve as a coolant and dielectric insulator [5]. However a number of accidents have shown the fire risk of this type of liquid [6]. Therefore a rising trend is observed towards the adoption of less flammable, biodegradable transformer liquids.

Testing procedure standards that give a reliable assessment of the fire behavior of electro technical insulating liquids based on relevant physical characteristics of the fluids are currently under development, such as IEC 60695-8-3 [7]. However more effort is required in order to provide meaningful information concerning the relation between small-scale tests and large-scale tests and that between the tests and failure scenarios in real life applications. For this reason a master thesis was initiated within the international master program for fire safety engineering (IMFSE), a program organized by University of Gent, Lund and Edinburgh. The thesis deals in detail with the fire safety of transformers [5] but in this article only the cone calorimeter results will be reported.

Test Methodology

The experimental focus of the study, small-scale comparative tests in the Cone Calorimeter and other settings, is limited to pool fires and heat release rate in small-scale tests. Spray and vapor/gas cloud fires and explosions, even though of great importance, were not considered. In total five liquids were tested: mineral oil, silicone liquid, synthetic ester and two natural esters.

The starting point of the thesis was the procedure outlined in IEC 60695-8-3 [7] which is based on the cone calorimeter instrumentation firstly developed in ISO 5660-1 [8]. But other procedures were also investigated.

For the purpose of the test, the test apparatus specified in this standard and additional equipment was used.

Test specimen tray

The test specimen tray in the traditional procedure shall be located so that the surface of the liquid test specimen is 25 mm ± 1 mm below the lower edge of the conical heater.

Figure 3 Test specimen recipients (photo Denis Hellebuyck)

For the actual experiments a shallow square tray (dimensions 10 cm x 10 cm x 2 cm) and a deeper round cup, diameter 10 cm, depth 5 cm, were used. Both can be seen in Figure 3 (left and right holder) and are made of stainless steel. The circular holder had even an arrangement to introduce thermocouples at different heights in the holder. The square tray is the one according to ISO 5660-1 [8].

Procedure

The Sample liquid was placed in a sample holder on a load-cell, a short distance beneath a conical radiant heater. This heater subjects the exposed face of the sample to a nominally constant (in time) and uniform (across the surface) heat flux.

Provided the external flux is large enough, the sample will eventually begin to pyrolyse and release flammable gases. Once sufficient gases have been released to produce a flammable gas/air mixture in the volume above the surface, the gas is ignited by means of an electrical spark, positioned slightly above the sample surface.

The time between the initial exposure of the sample to the external heat flux and the establishment of a persistent flame at the surface is taken to be the 'ignition delay time' or 'time to ignition', (t_{ig}).

Air, pyrolysis and combustion gases are drawn away from the cone through a hood and duct positioned above it. Various sensors in the duct record temperature, pressure, velocity, opacity and gas concentrations (oxygen, carbon monoxide and carbon dioxide). From these, the heat release rate (HRR; Q) can be calculated.

The test procedure used was based on standard IEC 60695-8-3 [7] and consists of the following steps cited below:

- Place the liquid in the test specimen holder (1cm for the shallow square tray, 4.5 cm for the deep round cup).

- Place the test specimen screen in position.
- Place the test specimen holder under the cone heater set at zero irradiance.
- Start logging and remove the screen after 1 min. Simultaneously activate the spark igniter.
- When the liquid ignites shut off the cone heater.

Alterations were made to the procedure in the IEC standard. More liquid was put in the sample holders to diminish the influences from the boundaries of the cup. This was investigated even more by using a deeper cup. The radiation element was shut off after ignition. However it took a while for this element to cool down, especially when big flames kept on heating it.

Calibration

The rate of heat release in full-scale fire tests was determined based on the O_2 consumption principle described by Janssens [9]. Janssens discusses the fact that a more or less constant net amount of heat is released per unit mass of oxygen consumed for complete combustion. This is found to be also true for organic substances and an average value is obtained for this constant of 13.1 MJ/kg of O_2. This method was used for all five liquids; however it should be noted that this is incorrect for the combustion of silicon liquid as it is not mainly based on the reaction of carbon with oxygen.

Results

Extinction of Flame

In the square shallow cup all samples burnt out except for the silicone oil where the formation of a white crust on the surface impeded the combustion process.

In the deep cup the liquid bulk acting as a heat sink resulted in the extinguishment of both natural esters. The other liquids were manually put out after 30 - 40 minutes burning.

HRR

Results of the HRR are given in Figure 4 for a heat flux level of 30 kW/m^2. The mineral oil clearly shows the highest heat release rate. The peak just before burn out in the square shallow pan is to be explained by increased pyrolysis due to various changing boundary conditions, such as re-radiation from the bottom of the tray. The other liquids do not display this behavior in a similar way.

Apart from this peak the heat release rates displayed in are correlated to the heat of combustion of the respective liquids (see Table 1 and Figure 4). However for the silicon liquid the combustion process was impeded by the formation of a white crust on the surface resulting in very low values.

Table 1 Heat of combustion for dielectric liquids

	Mineral Oil	Synthetic Ester	Natural Ester 1	Natural Ester 2	Silicon Liquid
Heat of combustion [J/g]	46050	31600	37500	-	32100

A steady state regime was reached after a while, in particular in the shallow square pan. Heat losses to the cold bulk liquid in the deep cup resulted in the fire extinguishing after a while for the natural esters.

Times to ignition are not reported here. However for different experiments the same ranking was observed: Mineral oil ignited almost right away, next to ignite were the synthetic esters and the silicone liquids. The natural esters took a long time to ignite.

As prescribed in the IEC standard [7] the applied heat flux was chosen to 30 kW/m² so that the times to ignition were below 10 min. Thermal losses to the sample holder boundaries become too large after that.

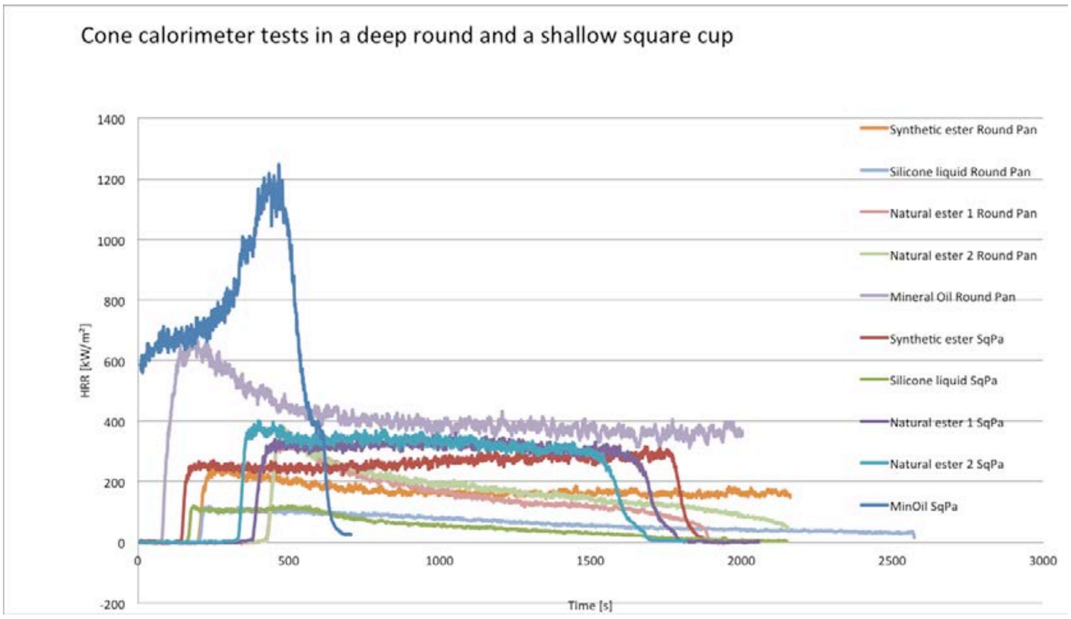


Figure 4 HRR for the different liquids in different holder at a heat flux level of 30 kW/m^2

Conclusions

It is clear that less flammable liquids (K class, FM approved) exhibit a fire risk far less than mineral oil. However, quantifying how much less it is, is not an easy task. The experiments in this study give an idea of how much the heat release rate is less, but bear in mind that this was for very specific laboratory conditions. Relating laboratory findings back to the actual failure conditions requires in depth knowledge of transformer failures scenarios as well as a great deal of fire science. When a mineral oil filled transformer failure results in a fire the transformer will often be damaged to a degree where repair is not economic. Traditionally the aim is therefore not to save the transformer if a transformer fire occurs but rather to limit damage to the surrounding equipment and the environment. However for these less flammable liquids the fire will be less fierce, less likely and shorter in duration so a revision of the 'traditional' protection goals is in place.

The experimental scope of this study was limited to pool fires due to the complex nature of the problem and the lab setting: transformer failures resulting in fire. The comparative tests display a wide range of fire properties for the respective liquids. The higher the fire point the longer it takes for a liquid to ignite. The heat release rate calculated from the cone experiments show analogies with the heat of combustion values tabled, except for the silicone liquid where a crust formation on the liquid's surface impeded combustion. Great care should however be taken when scaling this small scale burning behavior to use in fire safety applications.

Following IEC 61039-8-3 (draft), slightly altered though, a somewhat steady state heat release rate was reached for most of these liquids. These values can be used for extrapolating to real size pool fires. An important difference with the standardized procedure was the fact that the external heat flux from the Cone was shut off after ignition and more liquid was put in the sample. Heat losses from the burning surface to cooler liquid below or boundaries greatly affect the burning behavior. Providing a large enough heat sink in the form of bulk liquid, the fires extinguished whenever the liquid surface cooled below its flame point. There is no simple way to quantify this heat sink effect for different dielectric liquids. This was investigated further with a deeper cup and two thermocouples in the fluid. The extra fluid acted as a heat sink clearly visible on the graphs. Heat was conducted away from the liquid surface restricting the burning.

Future research would have to include pool fire experiments over a range of pool sizes and external heat fluxes. Another aspect is more research into heat losses from the burning liquid surface. Equipping the Cone Calorimeter with a removable Cone would be useful to not have the effect of a slow cooling Cone element when shutting it down after ignition.

VALIDATION OF FDS6 FOR PREDICTION OF MECHANICALLY VENTILATED COMPARTMENTS

Fires in enclosures equipped with forced (or mechanical) interconnecting ventilation remain one of the key issues for fire safety assessment in the nuclear industry since substantial smoke spread can occur through these systems. Yet there is very little validation work done in this specific area. One reason is due to the lack of well-defined experiments, even fewer so in full scale. Another reason is that few CFD models have had the capability to handle such scenarios without resolving the ventilation system within the CFD domain itself. Recently a one dimensional HVAC model was coupled [10] to the CFD software Fire Dynamics Simulator (FDS) [11]. A simple and a complex validation exercise showed that the combined solvers could accurately predict HVAC flows for a duct network in a complex geometry with fire effect [10], but there is still need for validating the model with more complex and detailed experimental scenarios. The tests performed within the PRISME project was a perfect candidate for this task, since it is a multi-room setup with an elaborate mechanical HVAC system and very tightly sealed compartments. The objective of this part of the work done was to perform a validation study of FDS for the proposed scenarios to be able to evaluate the accuracy, and thereby suitability, for future applications. This work is a part of a larger effort ([12] to [22]) to quantify comparisons between several computational results and measurements performed during a pool fire scenario in a well-confined compartment with forced ventilation.

Fire experiments

Description of the experimental facility

The experimental scenarios were conducted at the French “Institut de Radioprotection et de Sûreté Nucléaire” (IRSN) between 2007 and 2011. The DIVA installation (see Figure 5) is located in the IRSN laboratories within a large-scale compartment (3600 m^3 in volume) known as JUPITER [13]. It offers a large-scale multi-room set-up comprising four rooms (labeled from 1 to 4) with individual volume of 120 m^3. A corridor is connecting the three rooms at the bottom level and the whole construction is made out of 0.3 m thick concrete. All rooms are equipped with an interconnected mechanical ventilation system. The facility can be used both with a single room-setup as well as combinations of connected rooms and a connecting corridor. Inlet and exhaust ducts are normally situated in the upper part of each room, near the ceiling, unless changed for specific tests. The complete ventilation system is very complex installation with extensive use of valves, bends and changes in duct dimensions to be able to control the flow and air resistance to each branch and room.

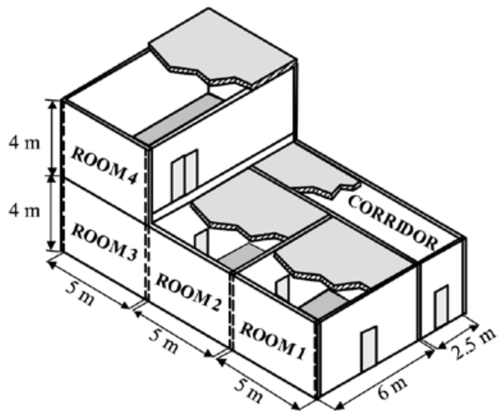


Figure 5 Scheme of the DIVA facility; figure courtesy of IRSN

Overview of the simulated test series

- ***PRISME SOURCE*** tests containing pool fires in a ventilated enclosure. Open calorimeter tests were not considered in this work since the ventilation system behavior was the main focus. Since some tests were similar with only minor changes (height placement of inlet branch) only four tests in total were compared to simulations performed with FDS 6 [11]. Some previous work has been published using tests from this series [12].
- ***PRISME DOOR*** tests with a pool fire in one mechanically ventilated room connected to one or more than one mechanically ventilated room. Some tests in this series included evaluation of the functional performance of cables when exposed to hot and sooty gasses. Simulations including the cable response were not performed in this work since it was not required to predict the ventilation system behavior. Some data from this test series has previously been published [21].
- ***PRISME LEAK*** tests with a pool fire in one room connected to other rooms by means of several types of leakages. Two tests from this series were chosen since they were the most suitable for the application. More detailed work done on the experimental and theoretical aspect of parts of this tests series has been published previously [16]. Some tests in this series included evaluation of the functional performance of cables when exposed to hot and sooty gasses, a detailed study on the cable response has been published elsewhere [22].

Modeling with FDS

Previous versions of Fire Dynamics Simulator (FDS) only had the ability to specify either fixed flow boundary conditions (velocity or mass flux) or a simple pressure boundary condition. While these inputs could adequately represent very simple HVAC features, they could not model an entire multi-room system with interconnected boundary conditions. There was no coupling of the mass, momentum, and energy solutions amongst the multiple inlets and outlets comprising the HVAC network [11]. To address this limitation, an HVAC network solver was added to FDS [10]. The solver computes the flows through a duct network described as a mapping of duct segments and nodes where a node is either the joining of two or more ducts (a tee for example) or where a duct segment connects to the FDS computational domain. The current HVAC solver does not allow for mass storage in the duct network (i.e. what goes in during a time step, goes out during a time step) [23]. HVAC components such as fans and binary dampers (fully open or fully closed) can be included in the HVAC network and are coupled to the FDS control function capability. There is also an option to select from three fan models [11]. A series of verification exercises has demonstrated that the network model correctly models HVAC flows and that it's coupling with FDS maintains mass conservation [10]. A simple and a complex validation exercise show that the combined solvers can accurately predict HVAC flows for a duct network in a complex geometry with fire effects [10], but there is still need for validating the model with more complex and detailed experimental scenarios. The tests performed in the DIVA facility was a perfect candidate for this task with its multi-room setup and elaborate mechanical HVAC system.

The thermal properties of the materials used in the DIVA facility were experimentally determined by IRSN and the following properties were used for the concrete: specific heat 0.736 kJ/(kg·K), conductivity 1.5 W/(m·K), density 2430 kg/m^3 and an emissivity of 0.7. The thermal properties of the insulation (Thermipan) that was used to protect the concrete in some scenarios were the following: specific heat 0.84 kJ/(kg·K), conductivity 0.102 W/(m·K), density 140 kg/m^3 and an emissivity of 0.95.

All simulations were performed using FDS 6 (SVN 11220) since the latest officially released version (FDS 5, SVN 7031) did not have the full functionality for simulating the HVAC network. A uniform mesh was used in all cases with cubic cells of 10 cm x 10 cm x 10 cm. The default LES-mode (as opposed to DNS) in FDS was used in all simulations.

Results

This section presents the comparison between experimental data and simulations performed using FDS 6 (SVN 11220). Since the objective of the paper was to characterize and simulate the ventilation system and its behavior, most results presented concern pressure and flows at inlets and exhausts. Only some tests which are thought of as being representative are being displayed to give a quick overview.

Initial conditions

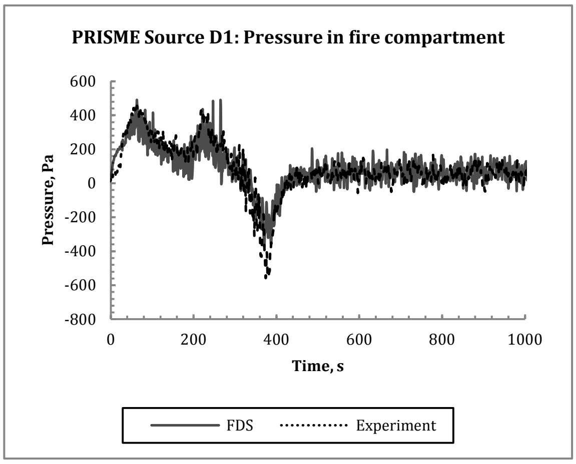
To be able to predict the ventilation behavior in fire conditions it would be crucial to also be able to model the non-fire situation. Table 2 summarizes the difference in node pressure between the experimental data and simulations at the inlets and exhausts for all tests. The pressures at these nodes were the most critical ones since they govern the flow behavior to a large extent. All results were within 5 % difference margin and most cases even less (see Table 2). This was an important step for giving confidence in the model to continue with the fire scenarios and try to model more advanced HVAC system behavior.

Table 2 Comparison of the pressure at critical nodes in the HVAC system prior to ignition

	Difference between experiment and simulation [%]										
Node	SI-D1	SI-D2	SI-D3	SI-D6a	D2	D3	D4	D5	D6	LK1	LK3
N6 (R1 in.)	-	-	-	-	-0.84	0.29	-2.37	-1.22	-1.13	-	-
N7 (R2 in.)	-4.87	0.50	0.14	-0.37	-0.83	0.30	-2.52	-1.21	-0.88	0.15	0.05
N8 (R3 in.)	-	-	-	-	-	-	-	-	-0.87	-3.46	0.05
N14 (R3 ex.)	-	-	-	-	-	-	-	-	-3.42	0.20	-0.04
N15 (R2 ex.)	0.15	-2.57	-0.03	-0.25	0.17	0.29	-1.37	-0.90	-3.41	0.20	-0.05
N16 (R1 ex.)	-	-	-	-	0.23	0.32	-1.39	-0.88	-4.45	-	-

Fire conditions and ventilation system response

The following results with respect to pressure in the fire compartment and ventilation system response (in particular room 2) have been obtained (see Figure 6 to Figure 7):



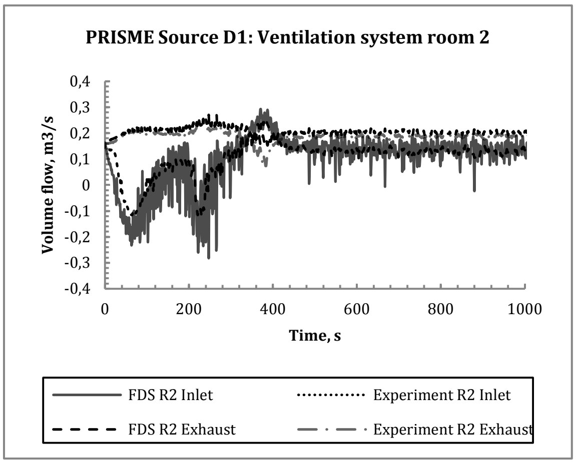
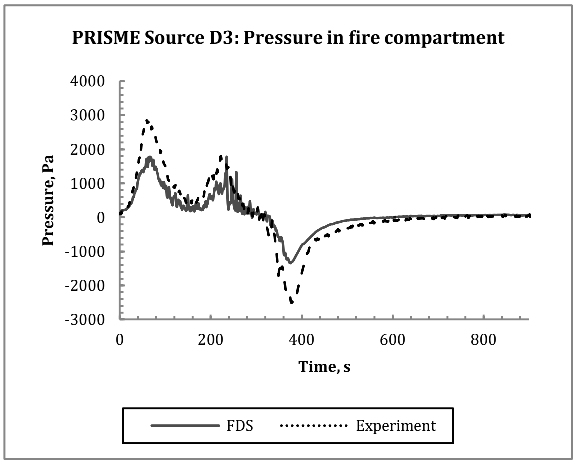


Figure 6 Predicted vs. experimental data from PRISME SOURCE Test D1 (SI-D1)
a: pressure inside the fire compartment (left),
b: flow rates at inlet and exhaust (right)



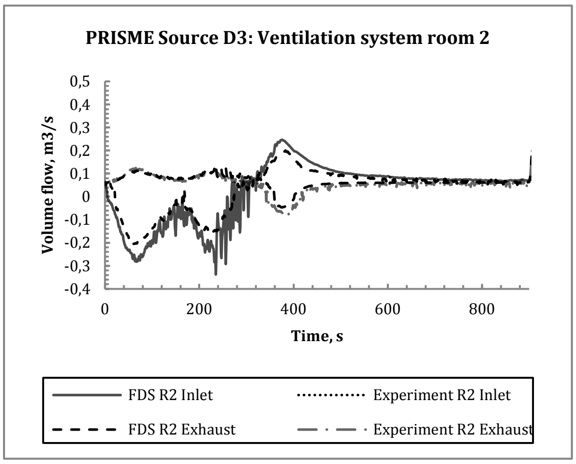


Figure 7 Predicted vs. experimental data from PRISME SOURCE Test D3 (SI-D3)
a: pressure inside the fire compartment (left),
b: flow rates at inlet and exhaust (right)

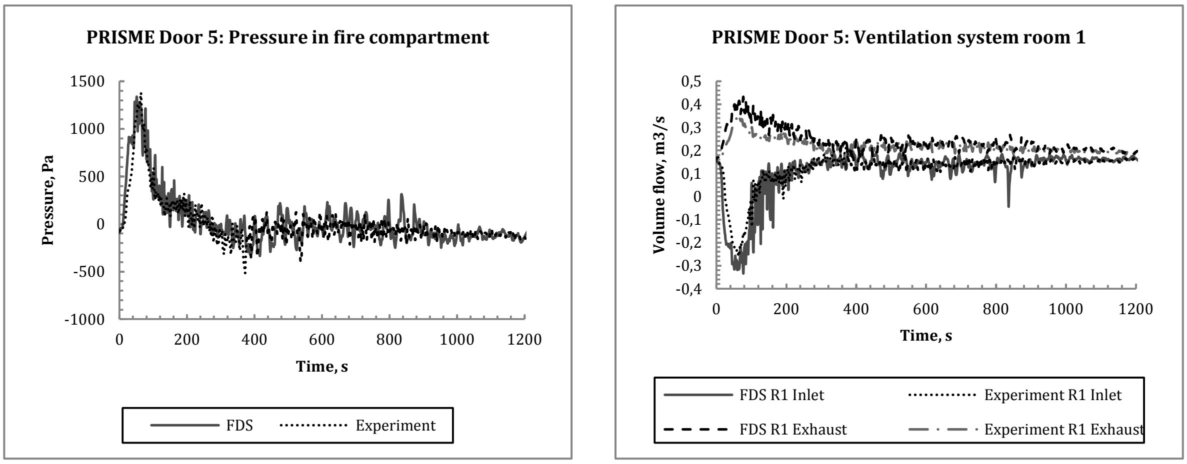


Figure 8 Predicted vs. experimental data from PRISME DOOR Test D5
a: pressure inside the fire compartment (left),
b: flow rates at inlet and exhaust (right)

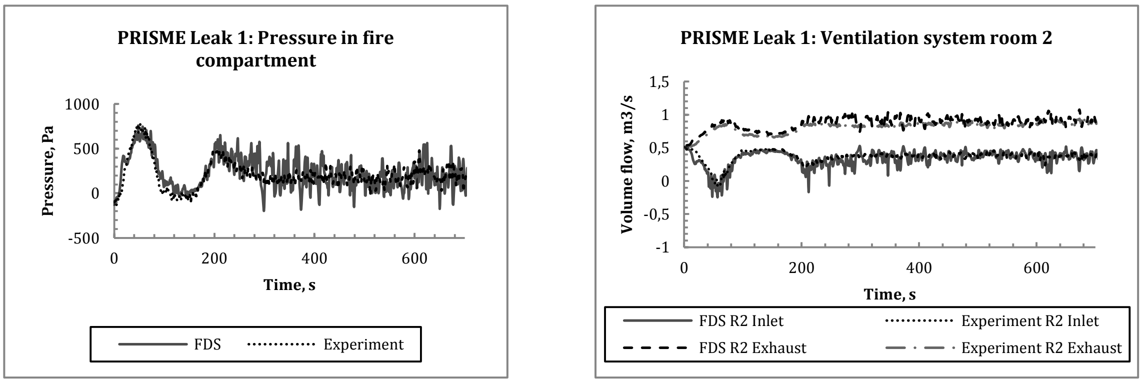


Figure 9 Predicted vs. experimental data from PRISME LEAK Test L1
a: pressure inside the fire compartment (left),
b: flow rates at inlet and exhaust (right)

Conclusions

The possibility of simulating a tightly sealed fire compartment connected to a mechanical ventilation network using FDS has been demonstrated with success. Using only data collected before the fire was ignited (with the exception of mass loss rate from the pool fire), FDS manages to correctly predict the pressure inside the fire compartment and consequently the effects on the ventilation system, for example backflow in the inlet branch in the early stages of the fire.

Although it must be noted that the ventilation system can be quite sensitive, this could especially be seen in PRISME SOURCE D3 shown in this article, and also SOURCE D6a (not shown due to space constraints) which behaved similarly. When the loss coefficients of the inlet and exhaust branches were not correctly characterized, FDS failed to predict the magnitude of the pressure peak and subsequently the magnitude of the response of the ventilation system. The error does not seem to be introduced by FDS and the coupled HVAC solver, and as a first stage to understand this discrepancy, it is necessary to check the accuracy of some experimental parameters influencing the pressure peaks magnitude.

CONCLUDING REMARKS

The mass loss rate and the resulting heat release rate is one of the most important elements in predicting the behavior of a compartment fire. Being able to use non-prescribed mass loss rates will hopefully increase the understanding of phenomena such as oscillating burning behavior where the natural or the mechanical ventilation and fire source interacts are coupled to each other. The model described in this paper is intended to be a simplified "engineering model" for possible future use in performance based design, which is of interest to the Swedish nuclear power plants.

Regarding transformer oils, it is clear that less flammable liquids (K class, FM approved) exhibit a fire risk far less than mineral oil. However, quantifying how much less it is, is not an easy task. The experiments presented give an idea of how much the heat release rate is less, but bear in mind that this was for very specific laboratory conditions. Relating laboratory findings back to the actual failure conditions requires in-depth knowledge of transformer failures scenarios as well as a great deal of fire science.

Being able to predict the fire behavior in interconnected enclosed spaces is of key interest to the nuclear power plant industry in Sweden and the new ESS facility. It has been shown that predicting the ventilation system behavior using FDS can be done with acceptable precision, which could make it possible to estimate secondary damage in non-fire rooms, for example smoke spreading through the ventilation system causing thermal and/or corrosive stress. However, there is a need for more experimental validation to ensure the quality of any of the proposed applications. But the results of experimental validation done so far show great potential for future use in performance based design.

ACKNOWLEDGMENTS

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VALIDATION OF CFD CODE ISIS FOR COMPARTMENT FIRES WITH LEAKAGE

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ABSTRACT

The CFD code ISIS has been used to simulate four experiments conducted during the LEAK campaign of the OECD PRISME-project, which aims to study the leakage during fires in a nuclear power plant (NPP). The experimental setup is described. Further, the model is validated and evaluated regarding the ability to simulate leakage scenarios. Several measured and predicted values are compared in terms of combined uncertainty. Therefore, data is carefully selected to be representative for the considered fire related attribute. Besides fire code validation, a series of discussions regarding uncertainties and the validation method are presented.

INTRODUCTION

The objective of this work is to establish confidence for the application of the CFD code ISIS to model nuclear power plant (NPP) fire scenarios. Validation of the fire code for some particular scenarios is conducted in this study in order to achieve the objective. Test data used for the validation process are obtained from the OECD PRISME Project [1].

The use of fire models to support fire protection decision making requires a good understanding of their limitations and predictive capabilities. NFPA 805 [2] states that fire models shall only be applied within the limitations of the given model and shall be verified and validated. ASTM E 1355 [3] provides definitions of the terms model verification and model validation.

Model verification is the process of determining that the implementation of a calculation method accurately represents the developer’s conceptual description of the calculation method and the solution to the calculation method. The fundamental strategy of verification of computational models is the identification and quantification of error in the computational model and its solution.

Model validation is the process of determining the degree to which a calculation method is an accurate representation of the real world from the perspective of the intended uses of the calculation method. The fundamental strategy of validation is the identification and quantification of error and uncertainty in the conceptual and computational models with respect to intended users.

ASTM E 1355 [3] and ISO 16730 [4] establish a process for conducting a V&V (verification and validation) study of a fire model. The methodology for the assessment of fire models proposed in this work is as follows:

(1) Define a list of typical NPP fire scenarios.

(2) Select and describe the fire models for which an evaluation can be conducted.

(3) Assess the documentation of the calculation method.

(4) Technical documentation that explains the scientific basis of the calculation method.

(5) Assess the experimental data.

(6) Define fire modeling parameters.
(7) Conduct the verification study for each fire modeling tool.
(8) Conduct the quantitative validation study for each fire modeling tool.
(9) Report validation results.

Figure 1 graphically represents this approach. This approach stands for a throughout process for both verification and validation. In this paper, however, only the validation process is analyzed as the verification is done by the developer of the code.

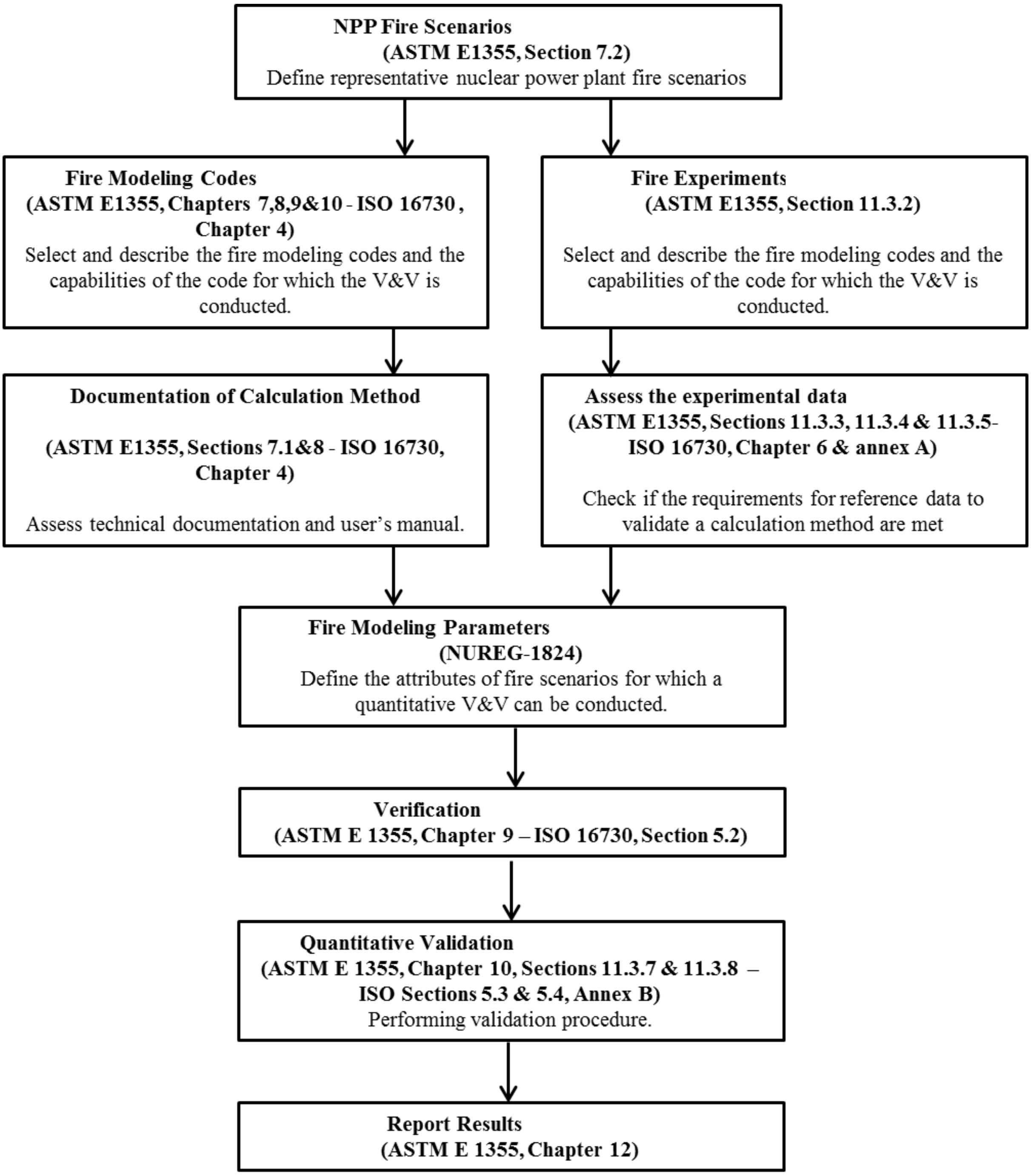

Figure 1 Overview of the approach for V&V study of selected fire models for nuclear power plant applications

EXPERIMENTAL SETUP

The PRISME LEAK fire experiments were carried out in the DIVA facility. DIVA (the name DIVA is the French acronym for "experimental facility for the study of fires, ventilation and airborne contamination") was built by Institut de Radioprotection et de Sûreté Nucléaire (IRSN) in order to study fires in multiple room configurations [1]. DIVA is located in Cadarache (France). Two rooms (see Figure 2) are involved: Room 2 (also called fire compartment) which holds the pool fire located in its center and Room 3 (also called target room), the adjacent room, for which the impact of smoke and hot gases propagation will be analyzed. These two rooms have identical size (length x width x height = 6 x 5 x 4 m^3). They are connected to the ventilation network to manage accurately the air renewal rates in both the fire compartment itself and the adjacent room.

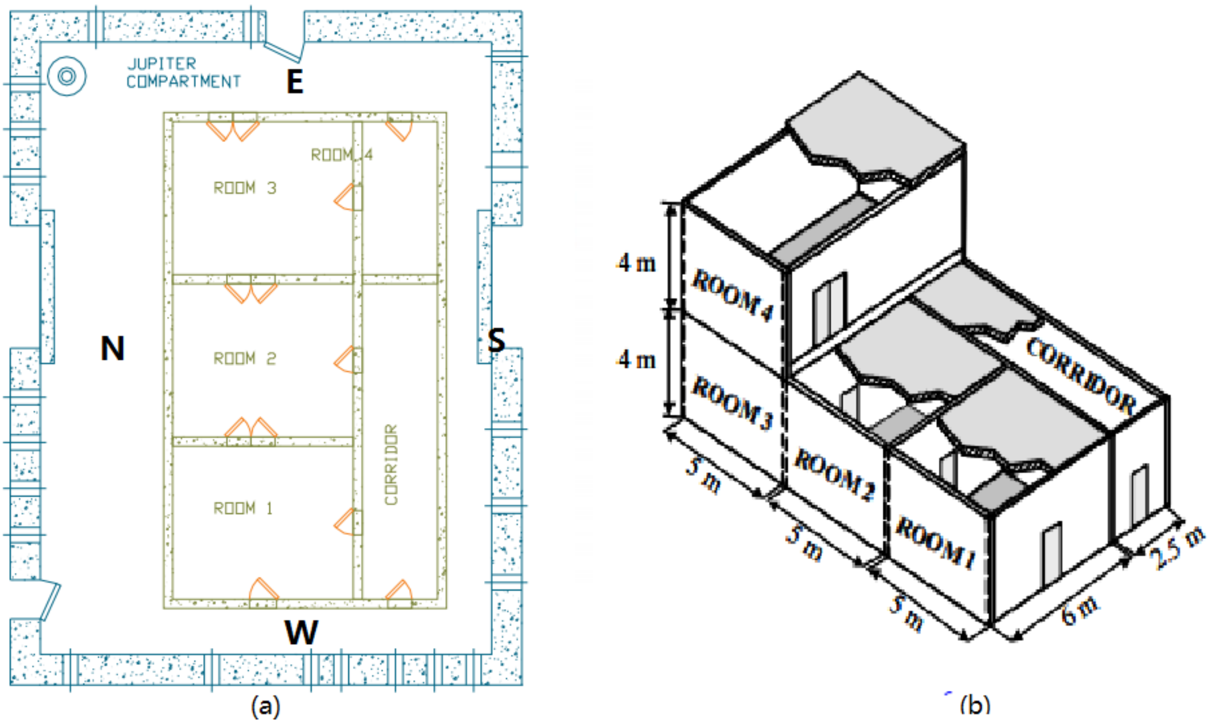

Figure 2 Design of the DIVA facility

The four side walls and the ceiling of the fire compartment are insulated with rock wool panels fixed on metallic frames screwed on the concrete. The ceiling of the target room is also insulated by rock wool. The thickness of the insulation for ceiling and side walls is 5 cm and 3 cm respectively.

The experiments include a total of four different scenarios. The four scenarios are LEAK1, LEAK2, LEAK3 and LEAK4. Each scenario represents a different kind of leakage mechanism.

LEAK1 scenario aims to simulate the leakage between two rooms. This scenario could concern, for example, a cable penetration through the wall between fire compartment and adjacent room. The connection between these two rooms consists of two circular ducts of 210 mm inner diameter (A = 314 cm^2) located in the upper part and lower part on the wall between rooms 2 and 3. The pipe is 1.5 m long and it is welded on the rectangular steel plate used as crossing plate between the two rooms.

LEAK2 scenario involves a vertical slot between two rooms. It consists of a vertical slot (1730 mm*16 mm = 279 cm^2) located at the center of the wall separating the two rooms. The depth of the slot is about 60 mm. The bottom of the slot is located at 17 cm from the ground level.

LEAK3 case aims to simulate the effect of a defective fire door. Fire and target room are connected by a failed fire door. The fire door was closed during the test. However the fire door itself is leaky. This represents the situation where the fire duration exceeds the fire rating of the fire door. The one-wing fire door has a height of 2.054 m and a width of 0.948 m.

LEAK4 resembles the configuration of LEAK3, which means that a leaky fire door also is put in place. However, in LEAK4 there is one additional internal duct going through the fire compartment which ventilates the target room. The air gets heated up while passing by the fire compartment. The internal duct is a rectangular steel duct of 0.4 * 0.4 m^2 in area. The height of the duct is 3.5 m.

The fire source is a pan which contains tetra-propylene. The surface area of the pan is 0.6 m^2, the inner diameter 0.874 m. Some key test parameters are listed in Table 1.

Table 1 Test parameters

Item	Value
Mass of fuel	17.5 kg
Heat of combustion of fuel	4.55 x 10^7 J/kg
Fire duration	20 min
Air renewal rate fire compartment	15 h^{-1}
Air renewal rate target room	3 h^{-1}
Average heat release rate during stable stage	800 kW

SIMULATION DESCRIPTION

The ISIS CFD code is studied in this paper. ISIS (French for: *I*ncendie *Si*mulé pour la *S*ûreté) is a CFD code developed by IRSN that can cope with a wide range of applications, including laminar or turbulent flows, possibly reactive, governed by incompressible or low-Mach number Navier-Stokes equations.

An extensive description of the physical modeling of the ISIS code is provided in [5].

The first public release of the software was April 4, 2008. Since then, several verification and validation studies have been performed by the developer [6], [7]. Because the code is relatively new, external verification and validation work is scarce.

Version 3.0.1 of ISIS is used. Openmpi 1.4.4 is installed as external library for parallel execution. Metis 4.0.3 is installed as external mesh splitter.

The information for the server on which the simulations are running is as follows:

Server type: Dell PowerEdge 1950

Processor (CPU): 2x Intel Xeon X5355 Quad-core 2.67GHz

Memory: 32GB (8x 4GB) DDR2 FB 667MHz

Operating system: Scientific Linux 4.5 64-bit

METHODOLOGY

Analysis of Uncertainties

Uncertainties must be investigated within the validation process. Uncertainties come from different sources.

The measurement uncertainty is the one associated with the measurement devices in the different experiments. Each device or method has its accuracy level. For the PRISME Project, the measurement uncertainty is provided in the deliverables of the Project.

The model uses the heat release rate (HRR) or mass loss rate (MLR) data as an input for simulation. The MLR data are also an experimental measurement, which inevitable includes certain amount of uncertainty. The uncertainty associated with this input value will result in uncertainty of the output data. The degree of uncertainty of the output data caused by the input uncertainty can be calculated by analytic analysis. Chapter 4 of NUREG 1934 [8] provides detailed information about calculation of the model uncertainty.

Typically, it is possible to provide rational estimates of the experimental measurement uncertainty and the experimental model input uncertainty. Both are related to measurements. Another type of uncertainty, the model intrinsic uncertainty, is far more difficult to quantify.

The measurement uncertainty and model input uncertainty can be treated together as combined uncertainty. The combined uncertainty is then used as criterion to judge the performance of fire codes. The method to calculate the combined uncertainty is described in Chapter 1 of Volume 2 of NUREG-1824 [9]. The same method will be followed in this study.

U_E, the measurement uncertainty, is given in several PRISME Project deliverables.

U_M, the model input uncertainty, is associated with parameters derived from experimental measurements that are used as model input. The most influential input is the HRR for most of the outputs. The uncertainty for the HRR measurement is estimated at 15 %. With a 15 % uncertainty in the HRR, expanded uncertainties for each parameter can be calculated by the way stated in NUREG-1824[9].

With the information on measurement uncertainty and model input uncertainty, the combined uncertainty (U_ε) can be calculated by the formula:

$$U_\varepsilon \approx (U_M + U_E)^{1/2}$$

The result is shown in Table 2.

Table 2 Combined uncertainty

Quality	Measurement uncertainty U_E	Model input uncertainty U_M	Combined uncertainty
Radiative heat flux	30 %	22 %	37 %
Wall temperature	3 %	10 %	11 %
Floor temperature of fire compartment	15 %	10 %	18 %
Soot concentration	30 %	18 %	35 %
CO_2 concentration	2 %	8 %	8 %
O_2 concentration	1 %	8 %	8 %
Pressure	1 %	75 %	75 %
Flow rate	10 %	10 %	14 %
Gas temperature in the fire compartment	8 %	10 %	13 %
Gas temperature in the target room	3 %	10 %	11 %

Validation Criteria

The measured and predicted values are compared in terms of combined uncertainty. Figure 3 shows this strategy. If the model and experiments are in perfect agreement, the data points fall along the 45 degree line indicated in the graph. The data in the left picture are such that the models are in agreement with the experiments within the bounds of the combined uncertainties. In contrary, the right picture shows data where the models and experiments are not in agreement within the bound of the combined uncertainties.

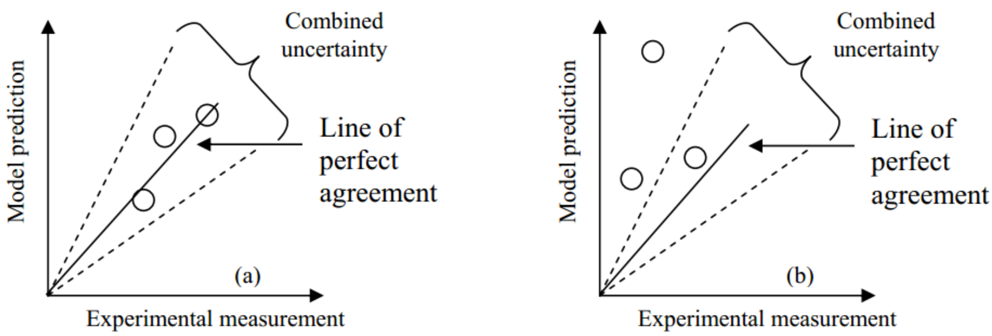

Figure 3 Scatter plots depicting validation results in and out of the range of combined uncertainty

This approach does in fact compare the "relative difference" between the measured and predicted values with the combined uncertainty. The relative difference is defined as follows:

$$\varepsilon = \frac{\Delta M - \Delta E}{\Delta E} = \frac{(M_p - M_o) - (E_p - E_o)}{(E_p - E_o)},$$

where ΔM is the difference between peak value of the model prediction and the ambient value, and ΔE is the difference between the experimental observation and the ambient value.

It has been demonstrated [9] that, if |ε| < Uε, the variation between simulation and test results can be explained by the uncertainties. In other word, the simulation tool is reliable within the uncertainty level. In this work, this criterion is used to determine the capability of fire models in predicting the fire attributes.

SIMULATION RESULTS

Radiative Heat Flux

Radiative heat flux measurements are available from the PRISME LEAK scenarios. Between the ISIS simulation results and the experimental data, a great discrepancy was observed (cf. Figure 4). The much lower value predicted by ISIS can be explained by the fact that the surface temperature of the radiometer sensor is much lower than the wall temperature. The surface temperature of the radiometer sensor is kept around 298 K by the cooling water. The wall surface temperature during the test is much higher compared to 298 K. The radiation heat fluxes compared above are the net radiation heat fluxes between target and the whole environment.

The wall surface temperature at those measurement points is also available from ISIS. The radiation heat flux is adjusted taking into account the wall surface temperature by:

$$R_{adj} = R_{ISIS} + \theta(\epsilon\sigma T_{wall}^4 - \epsilon\sigma 298^4),$$

where R_{adj} is the adjusted radiative heat flux, R_{ISIS} the radiative heat flux calculated by the model, ϵ the emissivity of the wall, which is 0.95 in this case, T_{wall} the wall surface temperature at the same position and θ the factor taking into account the view factor and gas absorptivity.

The θ value is difficult to determine by hand calculation. A value of 0.4 is chosen so that the result would show the best match with the experimental data.

The relative differences for the adjusted radiative heat flux are presented in Figure 5. The entire relative differences fall within combined uncertainty. With proper adjustment, ISIS can predict the radiative heat flux satisfactory.

In real applications, the heat flux to a target is the most significant value. In that sense, ISIS can provide predictions directly.

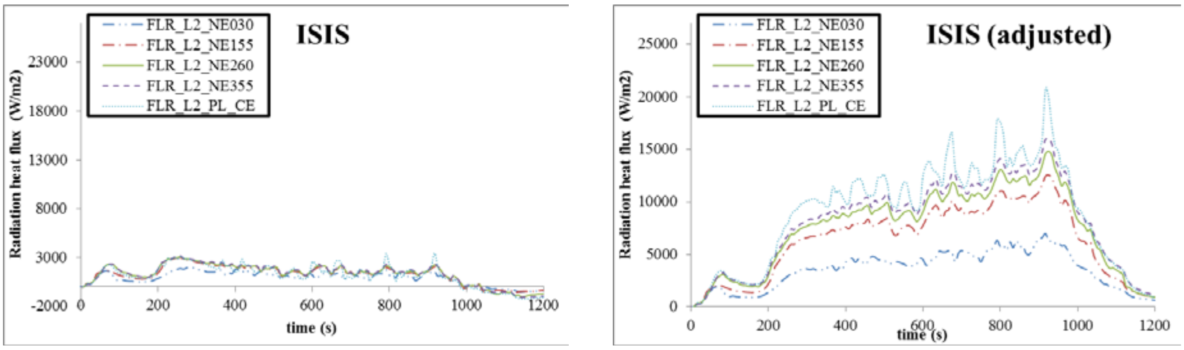

Figure 4 Summary of prediction of radiative heat flux

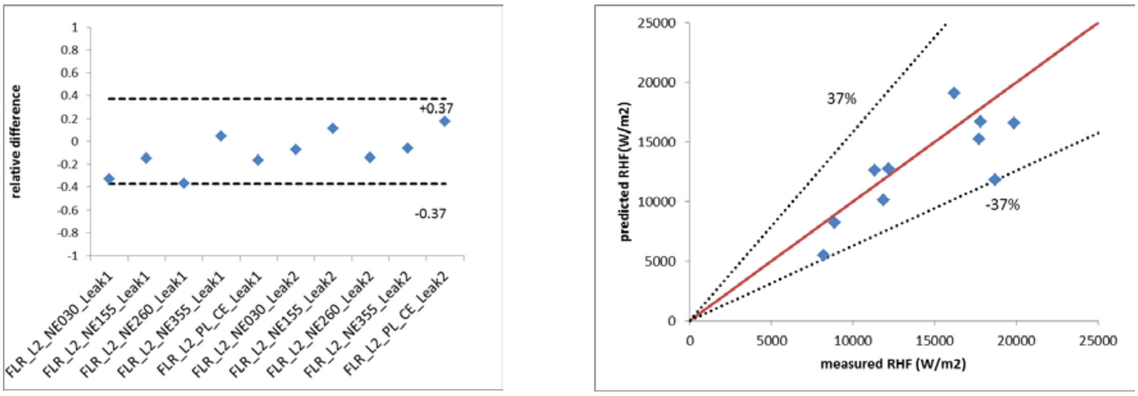

Figure 5 Summary of prediction of radiative heat flux (adjusted value)

Wall Temperature

Wall surface temperature measurements are available from PRISME LEAK scenarios for several points in the north wall and also one point on the floor.

The walls and ceiling of experimental rooms were insulated with rock wool to create higher temperature inside the fire compartment. Also with insulation, there could be more intensive heat attack on the target room. There are two layers of two different materials for the boundary condition. The duration for the fires is around 1200 s for PRISME LEAK tests. The thermal penetration depth in the rock wool during the test is:

$$2\sqrt{\alpha t} = 2\sqrt{8.67 * 10^{-7} * 1200} = 0.065m,$$

where α is the thermal diffusivity of the rock wool [m^2/s], t the time.

The thickness of the rock wool is 0.03 m for the wall and 0.05 m for the ceiling. Both are less than the thermal penetration depth, which means that the insulation layer is thermally thin during the later period of the fire. It is thus necessary to specify a multi-layer boundary condition, which was considered beyond the capability of ISIS version 3.0.1. In fact, definition of a multi-layer boundary condition was possible as from version 3.0.0, but became available in the GUI in the later version 3.1.0.

Figure 6 below shows the relative differences of the wall and floor temperature in the target room, where there is no insulation on the walls. In this situation, the ISIS prediction of the wall temperature is quite satisfactory. As the temperature rise in the target room is relatively small, the relative difference becomes quite large, even with a small amount of deviation. Besides, the figure shows a trend of over-prediction of the wall temperature. However, the wall boundary conditions specified in ISIS would in fact reduce the heat loss through walls, and thus enhance both the wall temperature and gas temperature.

The wall temperature prediction from ISIS can be utilized in real applications even though some of the relative differences are beyond combined uncertainty.

The wall temperature prediction, however, is not reliable while the boundary is multi-layered.

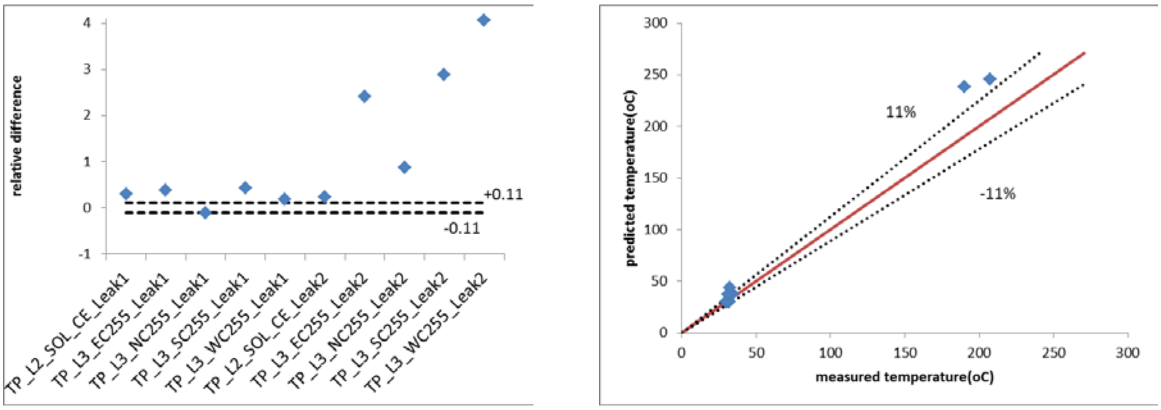

Figure 6 Wall temperature in the target room and floor temperature

Soot Concentration

Soot concentration of the exhausted gas from both rooms is available from PRISME LEAK scenarios. The most important input parameter for the soot concentration is 'soot yield fraction'. The soot yield fraction input for ISIS is calculated based on the test data. Tewarson also provides soot yield fraction data for hydrocarbon, which is 0.059 [10]. Sensitivity analysis shows that the soot yield fraction influences the soot concentration result greatly. For real applications of ISIS there is no test data for soot yield fraction. Thus although ISIS provides good prediction of soot concentration in this study, it does not guarantee as good predictions in real applications where there is no test data to determine the soot yield fraction.

One possible way to solve the problem with soot yield fraction is using the Moss model [11], [12] for soot production. The Moss model is a two equations model which takes into account the processes of nucleation, surface growth and coagulation. The soot yield fraction can be calculated by this model.

However, the soot concentration prediction in the target room is much higher than that from experimental data. ISIS is principally able to predict the soot concentration in the fire compartment correctly but not in the target room.

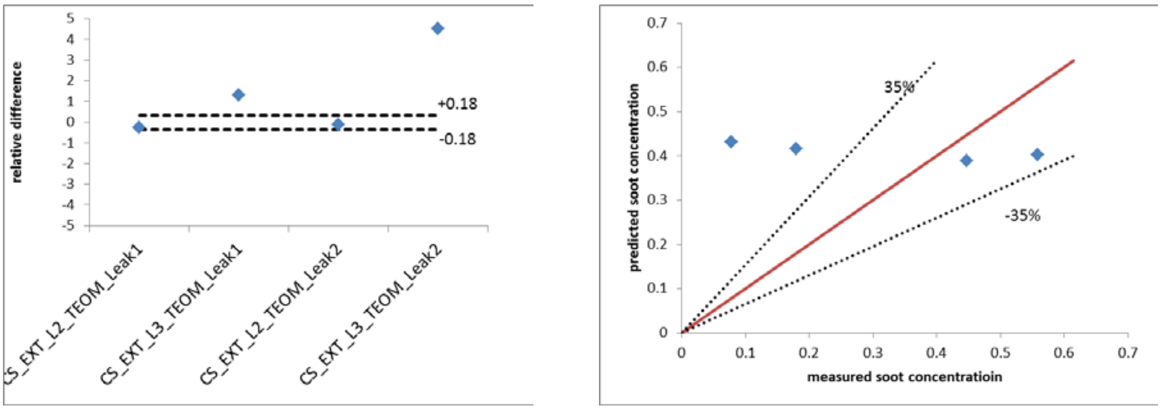

Figure 7 Soot concentration

Oxygen Concentration and Carbon Dioxide Concentration

ISIS uses a mixture fraction combustion model, meaning that the concentrations of all of the major gas species are related to a single scalar variable for which a single transport equation is solved. Assuming that the basic stoichiometry of the combustion process is known, predicting oxygen and carbon dioxide concentrations is similar, mathematically, to predicting temperatures. Gas sampling data is available from PRISME LEAK scenarios.

The figures below show the relative differences for oxygen and carbon dioxide concentration. These two gas species show similar behavior. In general, the gas concentration predictions in the fire compartment by ISIS are satisfactory. However, for both gases the concentration in the target room is over-predicted. The accurate prediction in the fire compartment shows that ISIS is reliable in calculating the combustion products. The over-predictions in the target room, however, show that the simulation of leakages is not perfect.

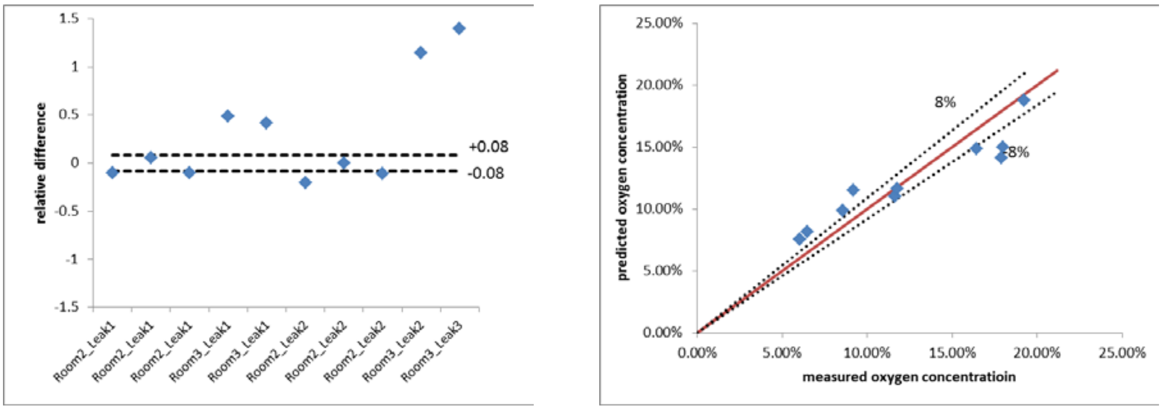

Figure 8 Oxygen concentration

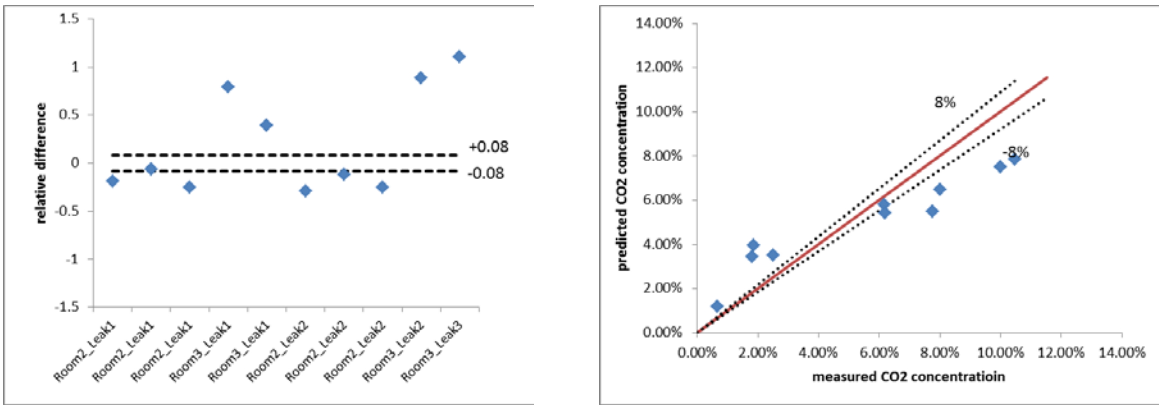

Figure 9 CO_2 concentration

Leakage Flow Rate

The flow rate from the fire compartment to the target room by leakage is a key attribute for PRISME LEAK scenarios. However, the leakage flow rate measurement is only available for the LEAK1 scenario, where two circular pipes were used as leak route. Although it is the total flow from the fire compartment to the target room that determines the thermal response in the target room, here the local maximum flow rate is compared for consistence of the methodology.

Figure 10 below shows the relative differences of the leak flow rate. ISIS predicts the leak flow rate quite well. The relative differences fall within the combined uncertainty.

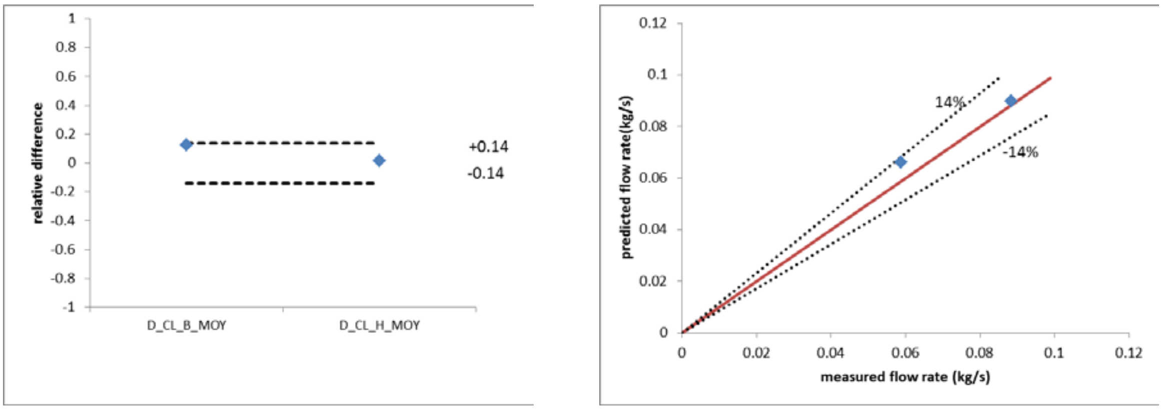

Figure 10 Flow rate through leakage pipes

Gas Temperature

The gas temperature measurements are available from PRISME LEAK scenarios. Several thermocouple trees were put in different positions of both rooms. Vertical temperature distribution can be obtained from the measurements. The thermocouple couple tree located in the center of the fire compartment is indeed providing the information for fire plume temperature. As there are plenty of gas temperature data from PRISME and the gas temperature predictions of LEAK1 and LEAK2 scenarios are almost the same, here only the relative differences for the LEAK1 scenario is presented.

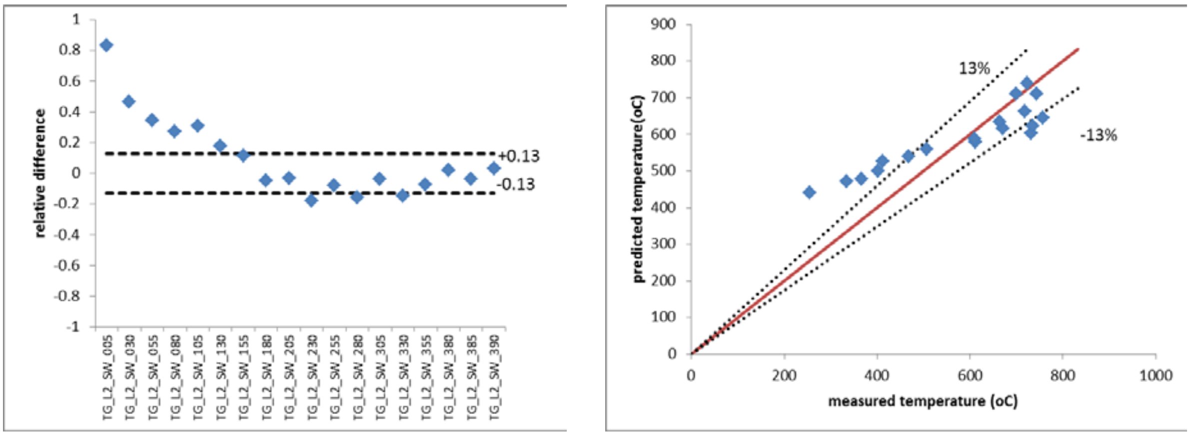

Figure 11 Gas temperature in the SW axis of fire compartment

The gas temperature in the SW and NE axis shows similar trend. This is not surprising since the positions of these two axes are symmetric. ISIS over-predicts the gas temperature in the lower part of the room. For the higher part of the room, the gas temperature is predicted quite accurately by ISIS. One common problem with the gas temperature measurement is the influence of radiation from fire plumes. The temperature of the bare thermocouple beat is in fact not the real gas temperature. A common approach is to correct the measured temperature for radiation in order to determine actual gas temperature. This however is burdensome, because the radiative exchange correction may depend on the characteristics of the thermocouple. The experimental data from the PRISME data is not adjusted for radiation. In the upper part of the room the thermocouples are immersed in thick smoke and thus they are less influenced by the flame radiation. Also, as the gas temperature in the higher altitude is high by itself, which means the thermocouple there would also emit radiation compensating the radiation from the fire source. That is why the prediction for the upper part gas temperature is more accurate. However, in the lower part of the room the thermocouples are more susceptible to the fire radiation.

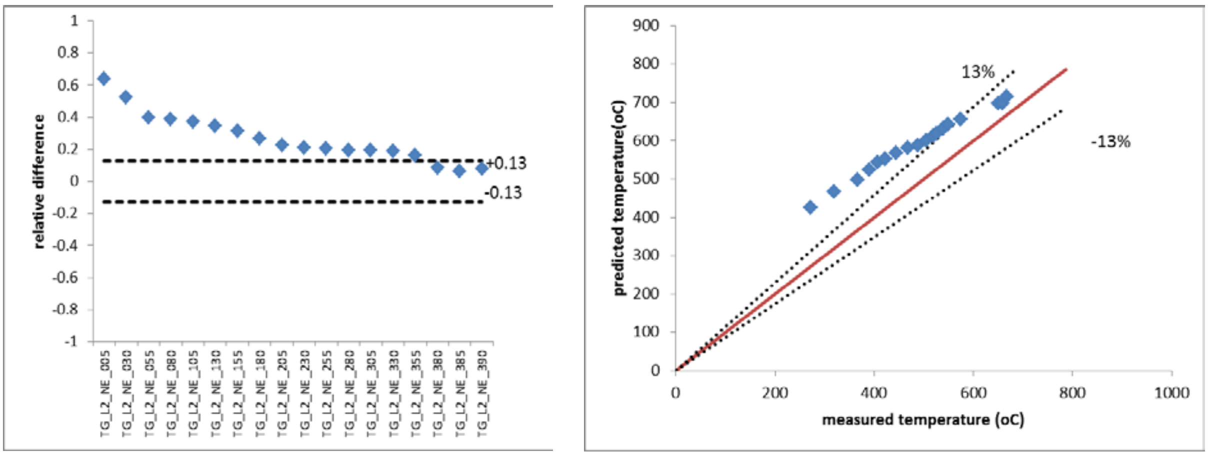

Figure 12 Gas temperature in the NE axis of fire compartment

The figure below shows the gas temperature in the fire plume. ISIS over-predicts the fire plume temperature at each point. This again can be explained by the radiation exchange between the thermocouple and the environment. In the experiments, the thermocouples in the fire plume are at very high temperature. The wall temperature of the room, on the other hand, is much lower. The thermocouple bead would lose heat by radiation to the wall surface and thus give a lower value for the plume temperature. Another explanation could be the under-estimation of turbulences by ISIS. The difficulties to measure plume temperatures makes comparison difficult and it might be that predicted gas temperatures by ISIS are more realistic than the measured gas temperatures.

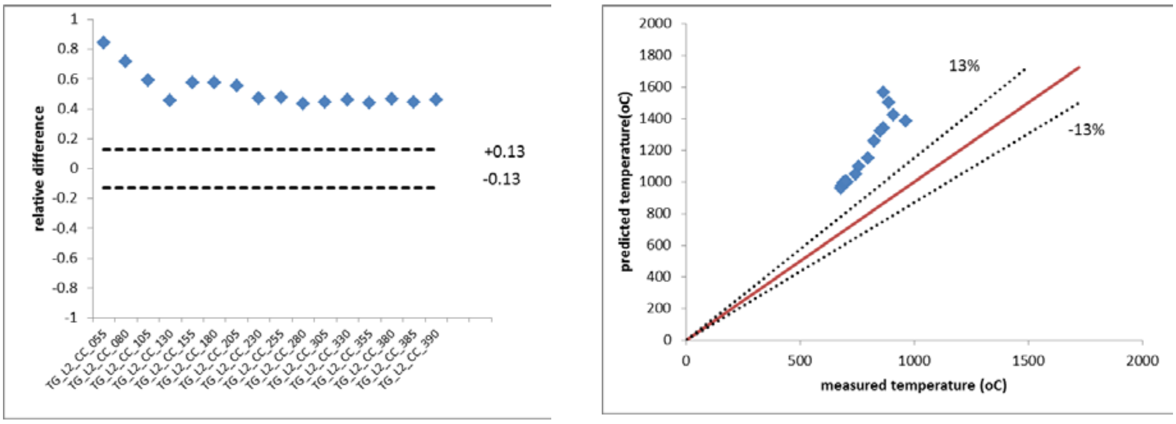

Figure 13 Gas temperature in the central axis of fire compartment

The figures below present the relative differences for the gas temperature in the target room. ISIS generally predicts the gas temperature in the target room well. However, the temperature rise in the target room is relatively small. As a result, the relative difference is large even with small amount of deviation. The walls are modeled as a single-layer of rock wool with an adiabatic backing. This insulation layer is thermally thin during the later period of the fire. This boundary condition at the walls in the fire room reduces the heat loss through the walls and thus enhances the gas temperature inside the fire compartment. Consequently, gas with higher temperature spreads to the target room through leakage. The gas temperature in the target room is consequently higher.

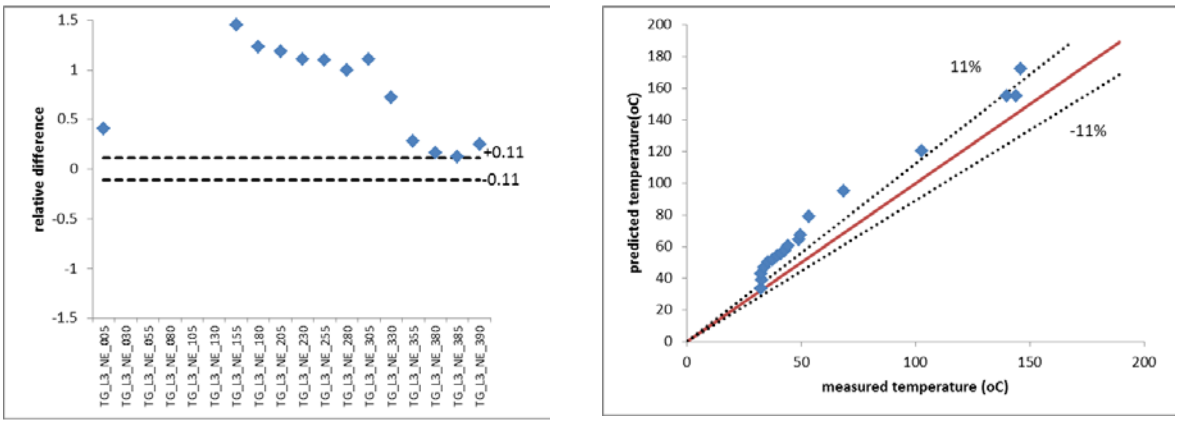

Figure 14 Gas temperature in the NE axis of target room

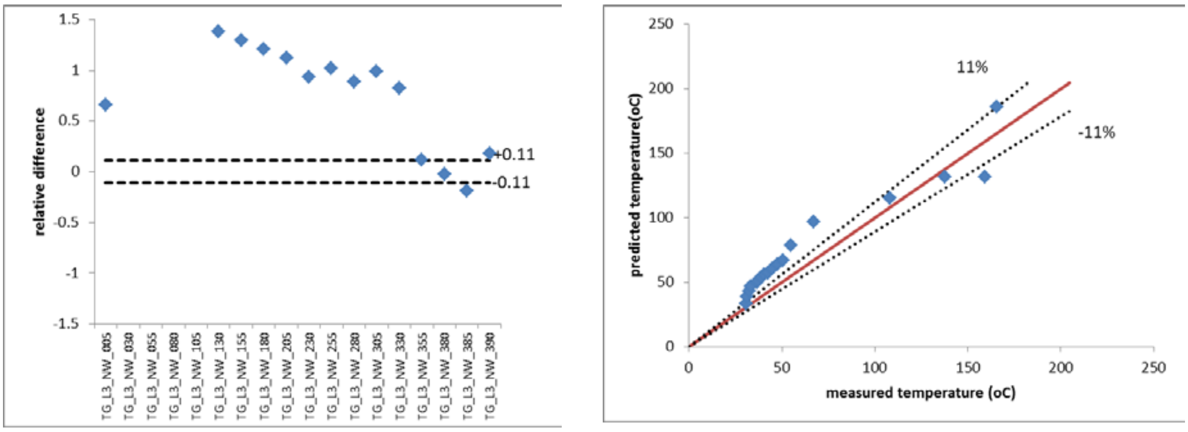

Figure 15 Gas temperature in the NW axis of target room

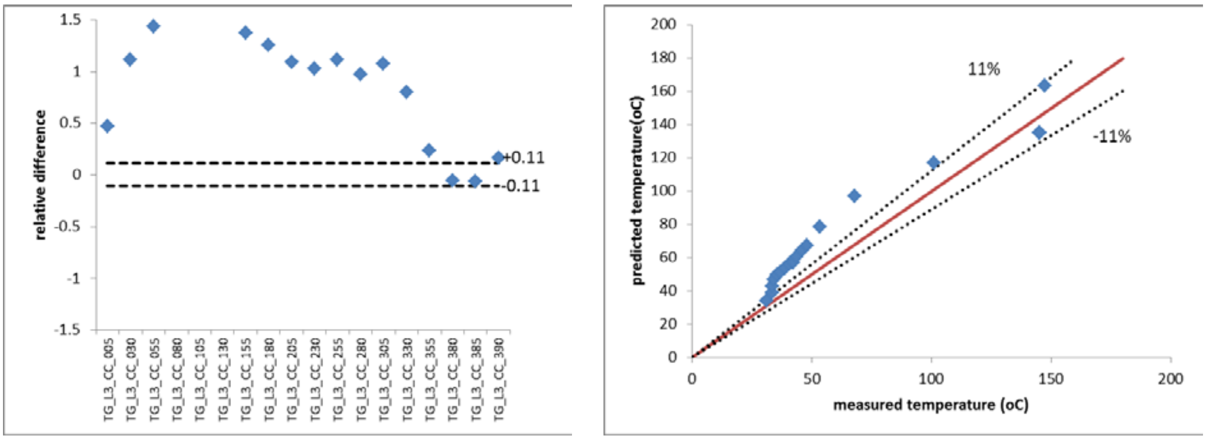

Figure 16 Gas temperature in the central axis of target room

DISCUSSION

Further Uncertainties for Real Applications

Experimental uncertainty and model input uncertainty have been identified in current V&V studies. The model input uncertainty originates from the uncertainties of the input parameters such as HRR, material properties and dimension of configurations.

In this study, the model input uncertainty is reduced drastically because most of the input comes from experimental measurements.

The HRR is the most significant model input for simulation [8], [13]. In most V&V studies, the HRR data are obtained from instrumentation measurements. The uncertainty of the input for HRR is thus the same as the measurement uncertainty of the HRR, which varies between 7.1 % and 13.5 % with the oxygen depletion method [14]. However, in real applications, there is no experimental data for the HRR, thus modelers need to estimate the HRR of the design fire scenario. In this case, the uncertainty of the input HRR is much higher. Sometimes it is easy to estimate the HRR as in case of the PRISME LEAK tests, where the fire source is a liquid fuel pool. The mass loss rate of the fuel pool can be calculated by the method of Babrauskas [15]. The figure below shows the HRR input for the LEAK4 scenario. The red curve stands for the HRR in the V&V study, where the measurement value is used.

The blue curve stands for the HRR calculated by the method of Babrauskas. The zone model SYLVIA by IRSN [16] is used to produce the estimated HRR with lower oxygen limit. The difference of these two HRR curves reveals the further uncertainty for real application of fire model. Moreover, the Babrauskas calculation method is valid for open air environment. Fire in a compartment would further influence the HRR [15].

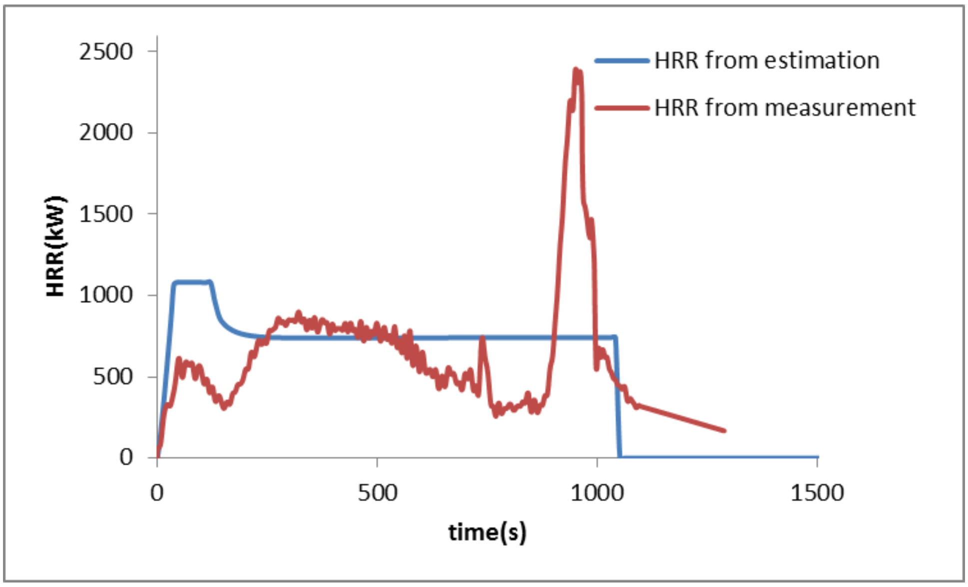

Figure 17 HRR input for the PRISME LEAK4 scenario

Soot yield fraction is another input that could cause large uncertainty. The input of soot yield fraction in this V&V study is calculated from experimental data, while in the real application, the soot yield fraction could be obtained from the SFPE handbook [10]. For the PRISME LEAK scenarios, the value from experimental data is 0.023; however, the recommended value from the SFPE handbook is 0.056. This would lead to further uncertainty because the radiation is very sensitive to soot yield fraction.

A verified and validated fire model does not guarantee good predictions in real applications. The quality of the design fire scenario, where the HRR-curve and other key parameters are determined, is as important as the quality of the fire model. It is possible that a model which gives good predictions in a V&V study might provide wrong predictions in real applications. That is why a sensitivity analysis is always an important procedure in applying fire models to real scenarios.

Time Aspects in the Validation Process

Metrics are used in this work for quantitative validation. Single point comparison is used as criterion for the validation of fire models. For some scenarios, the timing of the fire is also an important attribute. The single criterion of using local single point value comparison can be misleading in some circumstances. Figure 18 shows an example of model predictions for gas temperature with two different fire models.

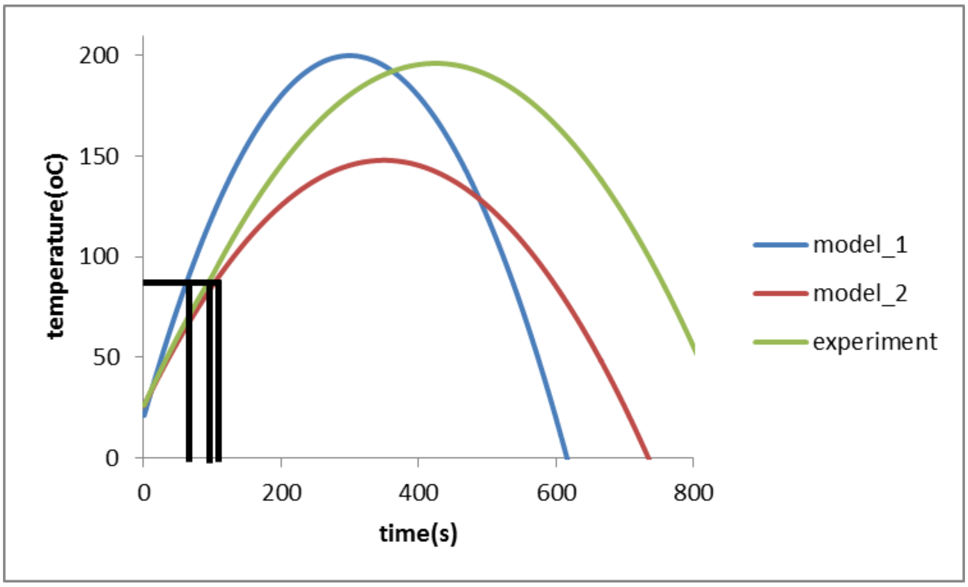

Figure 18 Gas temperature prediction by two models

The relative differences for the maximum gas temperature are indicated in Table 3.

Table 3 Relative differences for maximum value

	Maximum temperature [°C]	Relative difference
Experimental data	196	N/A
Model 1	200	2 %
Model 2	148	24 %

Model 1 is by far better than model 2, if we only compare the maximum value. However, in some situations it can be the other way around. Now consider situation where the gas temperature prediction is used to determine the time for the actuation of sprinkler (actuation temperature of 85 °C). Table 4 gives the time to for the gas temperature to reach 85 °C.

Table 4 **Prediction of activation time**

	Actuation time [s]	Relative difference
Experimental data	91	N/A
Model 1	61	33 %
Model 2	100	10 %

In this case, model 2 provides a better gas temperature prediction for the sprinkler activation. This simple example illustrates the fact that the maximum value alone cannot be the perfect criterion for a fire model V&V study. The time aspects should also be integrated into the V&V study. However, currently there is no established way to incorporate time aspects into the V&V study in a quantitative way.

Table 4 also indicates that the relative difference methodology can also be applied to time-related values.

The table below gives an overview of the capabilities of fire models in predicting fire modeling attributes. The conclusions are based on the results given in chapter 4.

CONCLUSIONS

Table 5 gives a qualitative overview for the capability of the CFD code ISIS in simulating the LEAK fire scenarios, based on the relative difference and scatter plots. In general, it can be concluded that ISIS is a satisfactory tool for fire simulation for the considered scenario.

Table 5 Overview of models' capability for the considered scenario

	ISIS
Radiative heat flux	Good prediction[1]
Wall temperature	General good prediction for single layer wall Unable to predict temperature for multilayer wall.
Soot concentration	Good prediction in the fire compartment Large relative difference in the target room
Oxygen concentration	Good prediction
Carbon dioxide	Good prediction
Leakage flow rate	Good prediction
Gas temperature	Good prediction of hot gas layer temperature Over-prediction of lower layer temperature More accurate temperature than experimental data for fire plume

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DETERMINING THE COMPLIANCE OF EXPERIMENTAL DATA AND NUMERICAL RESULTS USING FDS

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ABSTRACT

In this paper, a methodology for quantifying the compliance of experimental and numerical data in the field of fire protection is presented. For this goal, large scale experiments have been conducted in a four room facility. The four rooms are connected via three doors. The whole facility is mechanically ventilated via air inlets and exhausts which can be installed in every room.

Considering the focus of the experiments, liquid carbon hydride pools or solid electrical installations ignited by a gas burner were used as fire source. The quantities assessed in detail are the gas temperature, the velocity, mass and volume flow through the doors and the pressure development in the fire compartment. In case that the results of the ventilation of the fire compartment and the adjacent rooms and the heat release rate are known and imposed as boundary conditions of the numerical simulation, the simulation is referred to as open simulation. This fact has to be considered in the review of the data.

INTRODUCTION

The experiments analyzed in this paper have been conducted by the French IRSN (Institut de Radioprotection et de Sûreté Nucléaire) in the frame of the international OECD (Organization for Economic Co-operation and Development) / NEA (Nuclear Energy Agency) / CSNI (Committee on the Safety of Nuclear Installations) project research project PRISME (French acronym for "Fire Propagation in Elementary Multi-room Scenarios") as last campaign, named PRISME INTEGRAL, of several test series INTEGRAL. Both experiments analyzed in the following were conducted with comprehend focus on gas temperatures and gas concentrations, mass and volume flows as well as the pressure development in a multi-compartment and mechanically ventilated 4-room configuration. Two of the INTEGRAL test campaign were selected as experimental data base for a validation analysis of the fire simulation tool FDS.

INTEGRAL 4 focuses on the propagation of hot gases and toxic concentrations through the doorways from the fire compartment into the adjacent rooms under the conditions of forced ventilation. As fire source, a fuel pool fire was used. The second test, INTEGRAL 6, had the same major goals with additional evaluation of a realistic fire source for industrial buildings, an electrical installation which was ignited by a gas burner. Additionally, the closure of the dampers of the mechanical ventilation system was introduced to identify the related effects on hot gas and toxic propagation through the doorways as well as the pressure development.

Considering the goals of both tests, they are appropriate as basis for validating the widely used CFD code FDS. The methodology and criteria used for the validation are explained in the following sections without going into much detail of the actual simulation or experimental setting. The focus of this paper is on the general evaluation of the compliance considering experimental and model uncertainties derived in the literature (see [1]). Furthermore, it is shown that these values shave to be derived for the second validation criterion used in this paper, the L2-Norm or so-called PEACOCK criterion.

EXPERIMENTAL SETUP

The experiments were conducted in the diva testing facility at IRSN which is overall located in the Jupiter compartment (seeFigure 1). The diva test facility contains three rooms L1, L2 representing the fire compartment and L3 which are connected via a corridor L0. On the top of room L3, another room L4 is located. In the assessed experimental setup, this room was not connected to the considered test volume and is therefore omitted. The rooms L1, L2 and L3 consist of a volume of 5 x 6 x 4 m³ each, the attached corridor has the dimensions 15.6 m x 2.5 m x 4 m. Every room is connected by means of a door with 0.95 m width and a height of 2.1 m. An overview of the whole research facility is given in Figure 1.

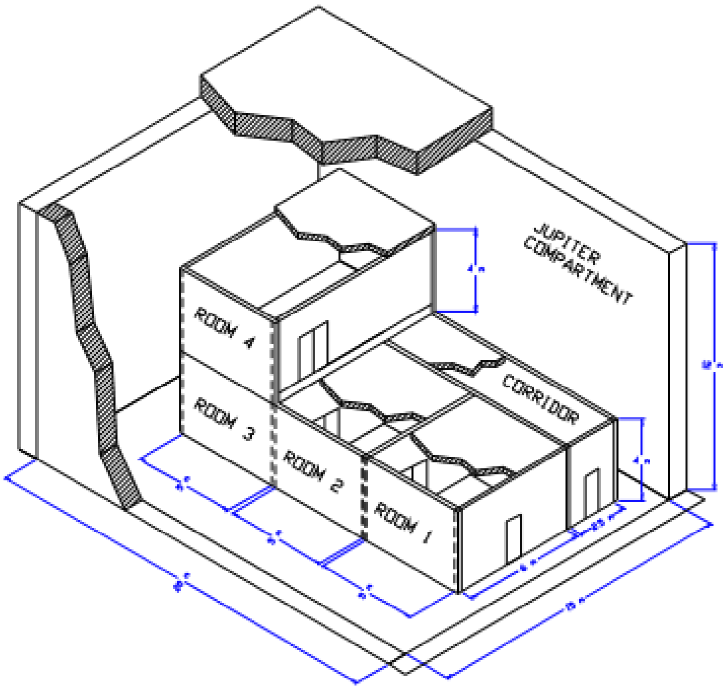

Figure 1 Overview of the research compartment Jupiter and the diva facility

The walls of the diva facility are made of concrete walls with a thickness of 30 cm. Where it was necessary, the walls are protected with Rockwool thermal insulation layers with different thickness ranging from 3 to 6 cm. The ceiling of the diva facility is protected with an insulation layer of 5 cm thickness. For all materials of the test facility, detailed information concerning the heat conductivity λ, the specific heat capacity c_p and the density ρ are available and were considered in the following numerical assessment.

The testing facility contains of a ventilation network made with three separate ventilation circuits. For the presented paper, the experimental setup contains of an inlets located in the south-west edge of the room L0 and an inlet located centrally at the northern wall of the room L1. One exhaust, located in front of the door L0/L3 was utilized. As depicted in Figure 2, the doorways L1/L2, L3/L2 and L0/L2 are opened. The other doors were closed throughout the whole test. All inlets and exhausts are fixed at a height of 7.5 cm lower than the ceiling of the compartment. The direction of the in- and outflow is depicted with arrows in Figure 2.

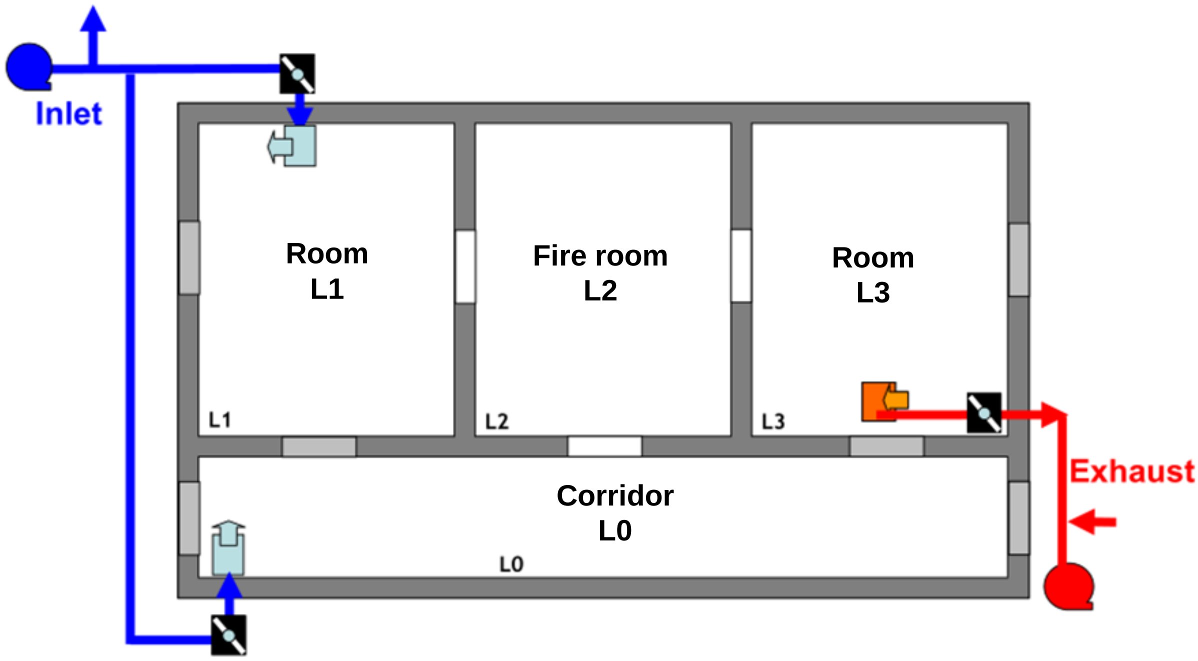

Figure 2 Overview of the rooms and the mechanical admission and extraction system of the diva facility

The volume flow imposed by the mechanical ventilation system depends on the experiment. For both tests evaluated in this paper, an air renewal rate of 6 compartment volume units per hour was imposed as steady-state initial condition. For the INTEGRAL 6 test, the dampers of the mechanical ventilation were closed after a defined duration (800 s) to analyze the impact on pressure development and the other quantities of interest in under-ventilated conditions. For the whole duration of the fire test, the volume flow is logged and written down. The experimental results are then used for comparison with the numerical data or imposed as boundary conditions.

DESCRIPTION OF THE FIRE SOURCES

The evaluation and comparison of experimental and numerical data is presented analyzing INTEGRAL 4 and INTEGRAL 6 tests conducted in the diva facility in 2010. Besides the ventilation conditions mentioned in the section above, two different fire loads were considered. The first one was a pool fire with a surface area of 1 m², the second one an electrical cabinet, emulating an electrical installation in a nuclear power plant which catches fire. The second fire source and the consideration of the electrical installations in FDS are shown in Figure 3.

In both experiments, the heat release rate (HRR) was determined from the experiment and delivered for numerical analysis. In this paper, this data was imposed as boundary condition in FDS which makes this evaluation a so-called open simulation. Furthermore, a detailed summary of polymer fractions of the electrical cabinet was known. These data were used to derive a mixture fuel concerning the FDS mixture fraction model [2]. The soot and carbon monoxide yield data were taken from the SFPE handbook [3].

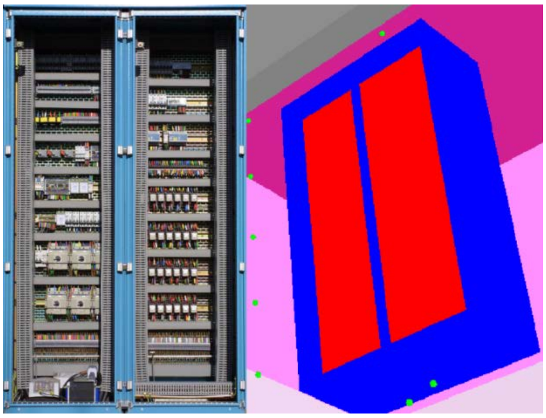

Figure 3 Electrical cabinet, original front view and FDS model

The maximum heat release rate measured in INTEGRAL 4 was about 2500 kW and 1000 kW for INTEGRAL 6.

FDS MODEL AND SETUP

FDS has been developed for numerically solving the Navier-Stokes equation for low-speed, thermally-driven flows. The conservation equations of mass, momentum and energy are solved using a finite difference algorithm on a three-dimensional grid. The species are calculated using a mixture fraction model. Details of the mathematical model are documented in [4]. As turbulence model for the following simulation, standard LES was used. If not specified in the text, solver parameters were set as default values.

The FDS version used for calculation was the current stable release FDS 5.5.3, compiled at 29.10.2010. The computational domain was discretized in 85 cells in X direction, 150 cells in Y direction and 40 cells in Z direction, leading to 10 cm x 10 cm x 10 cm cell volumes and a total amount of 510,000 cells.

An overview of the DIVA facility modeled in FDS is depicted in Figure 4. Here, the inlets and exhausts are visible as blue boxes with dimensions, location and direction of the opening considering the conditions available in the tests. The same applies for the thermal parameters heat conductivity, heat capacity, emissivity and density which were chosen as shown in accordance to the tests.

The inlets located in the rooms L0, L1 and L3 are modeled as discrete obstacles. The volume flux boundary conditions were applied onto the upper surfaces as depicted in Figure 4 as green surface. The direction of the opening was defined as depicted in Figure 2 and the test report. This approach was considered in previous validation simulations for several Benchmark Exercises in the PRISME Project.

To check whether the boundary conditions are applied correctly, a recording device was defined in front of the surface at which the volume flow was attached. The material data for the steel sheets was considered concerning the test report.

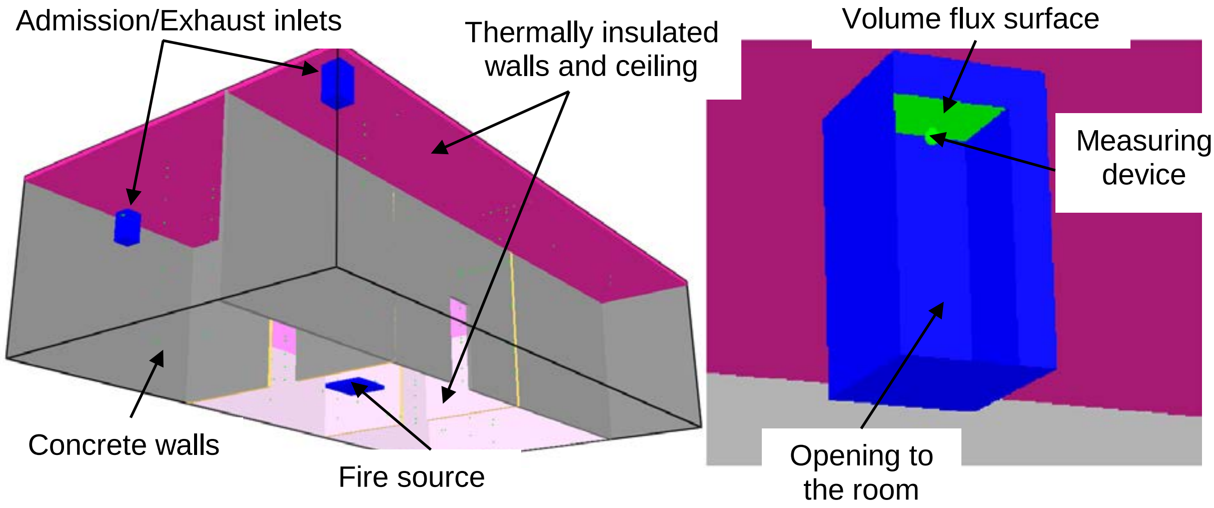

Figure 4 Overview of the FDS model of the analyzed compartment and the detail of the inlet/exhaust

In total, the evaluated simulations needed between 58 to 78 hours to finish on a standard Workstation (Intel Core i7-3770, 12 GB RAM), depending on the imposed heat release rate and additional simulations run on other cores of the CPU.

DEFINITION OF PRESSURE ZONES

In FDS, any region within the computational domain can be defined as pressure zone which is separated from the rest of the domain by solid building components, modeled as obstructions in FDS. To adequately model the leakage of the DIVA facility as well as model the volume flow boundary conditions, at least two pressure zones have to be defined. Here, zone 1 is the diva facility and zone 0 the environment. Both zones are connected via inlet L0, inlet L1 and exhaust L3 and a leakage area of $A_{Leak} = 0.001$ m² for INTEGRAL 4 and $A_{Leak} = 0.002$ m² for INTEGRAL 6, which was imposed at the ceiling of the diva model. Figure 5 gives an overview of the used pressure zones.

Detailed information on the pressure zone model of FDS can be found in [2].

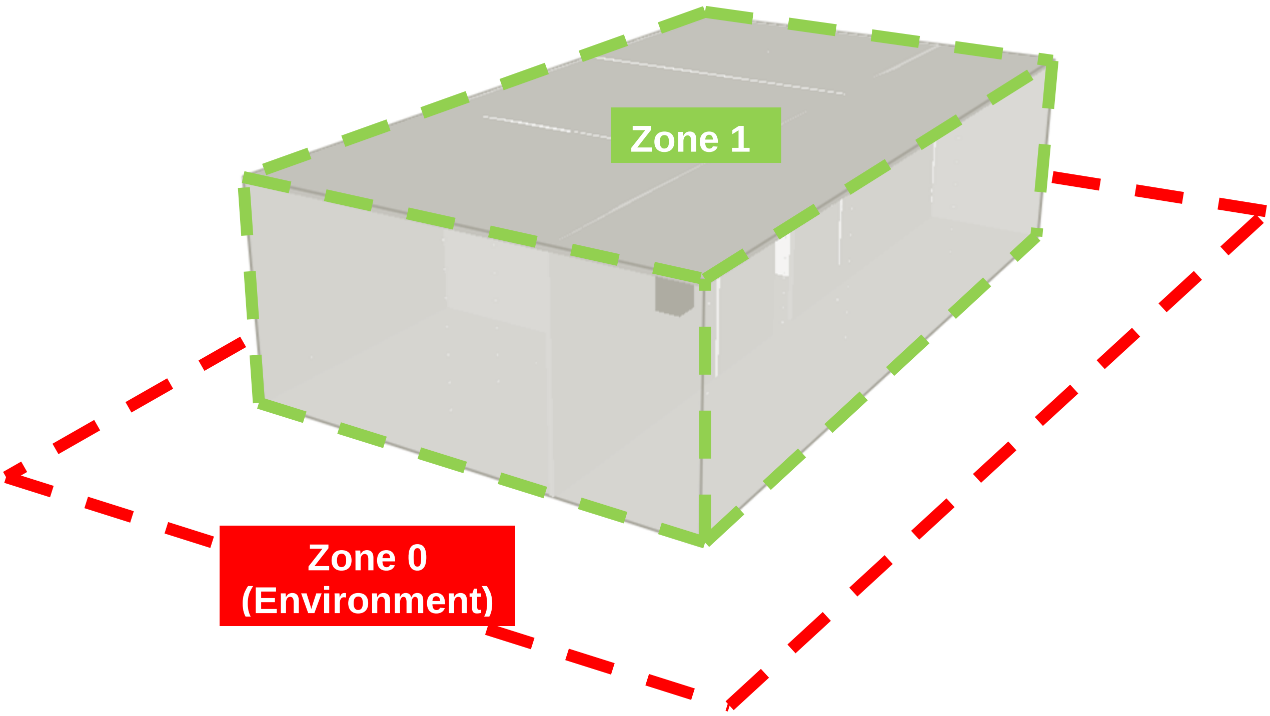

Figure 5 Pressure zones as used in the diva FDS model

INITIAL AND BOUNDARY CONDITIONS

For all FDS simulations, the initial pressure was assumed to be $p_{init} = 0$ Pa, i.e. the ambient pressure. The experimental and numerical results are compared considering the overpressure $\Delta p = p - p_{init}$. The volume flow boundaries were imposed as a VENT in FDS, with a horizontal surface SURF located at the upper part of the inlets/exhausts (see Figure 4). As initial values, the targeted values for the inlet located in the rooms L0 and L1 and for the exhaust located in L3 were imposed. To consider the change in the volume flow due to pressure changes, the relation depicted in Equation Eq. 1 was defined for all three ventilation boundary surfaces.

$$\dot{V} = \dot{V}_{init} \, sign\left(\Delta p_{max} - \Delta p\right) \sqrt{\frac{|\Delta p - \Delta p_{max}|}{\Delta p_{max}}} \quad (1)$$

The volume flux is calculated using the initial volume flux $\dot{V}_{init}$ and a maximum pressure value Δp_{max} which is defined as flow inversion point. The value Δp_{max} was set as 1000 Pa for both inlets and the exhaust fan.

The imposed boundary conditions as a result of the aforementioned input values and Eq. 1 are depicted in Figure 6.

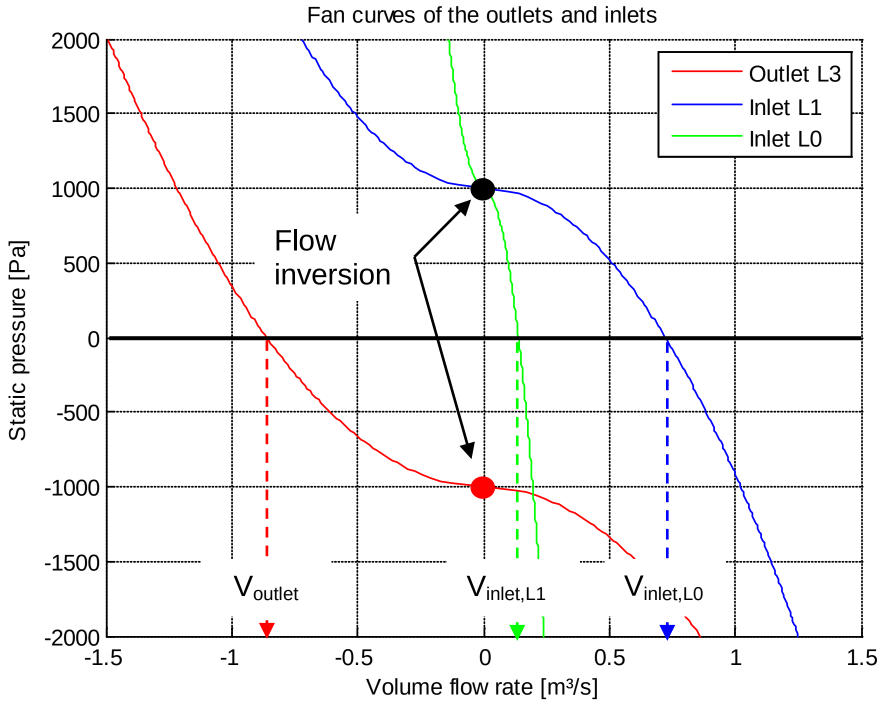

Figure 6 Volume flow boundary conditions, compared to the measured data

Here, a detailed modeling of the connected HVAC system was omitted to reduce the complexity of the simulation. All initial temperature values considering the volume flux boundaries and the computational domain were set to the ambient temperature measured at the day of the experiment.

Beside this approach, the volume flows of the mechanical ventilation system were taken of the experimental recordings and imposed as boundary conditions in an additional simulation to check which approach leads to better results.

VALIDATION METHODOLOGY

The mostly analyzed quantities described in the aforementioned section are recorded as time series, e.g. the temperature of a spatially defined point is written down every recording step. The validation of fire models is therefore done using techniques described in ASTM E1355 [5] and [1]. The methodology utilized in this paper was used in previous cases by Hosser et al. [6] and Hohm and Klinzmann [7] and compares a reference time series to a comparison time series using local and global parameters. Depending on the task of the analysis, the reference time series consisting experimental data which has to be compared to numerical results (comparison time series) or numerical data which has to be compared to data of a different model or version are typical cases for this kind of analysis.

One comparison criterion is the so-called PEAK value which relates the difference of the maximum (or minimum for specific quantities) values of the reference and comparison time series to the maximum (minimum) value of the reference time series (see Eq. 2).

$$Peak = \frac{\max/\min\left(Y_{comp}\right) - \max/\min\left(Y_{ref}\right)}{\max/\min\left(Y_{ref}\right)} \quad (2)$$

The PEAK value is only capable of comparing local (in temporal and spatial domain) values of a quantity. Any further information of the temporal curse of the data is not given. To assess the compliance over the whole duration, the L2-Norm criterion described by Peacock in

[8] is utilized (see Eq. 3). This criterion is cumulating the difference of the assessed data for every time step, squaring the difference of the reference and the comparison time series to avoid neutralization of positive and negative differences.

$$L2 - Norm = \sqrt{\frac{\sum_{i=1}^{n}\left(Y_{ref,i} - Y_{comp,i}\right)^2}{Y_{ref,i}}}. \quad (3)$$

For both evaluation criteria, the raw data has to be conditioned for further analysis. As exemplarily depicted in Figure 7, the data can show scattering effects due to special local conditions in the experiment or numerical solver characteristics. Utilizing this data for the Peak or L2-Norm criterion, temporal peaks would yield to a distortion of the outcome where only the evaluation of real physical effects is aspired. This is done using a finite impulse response filter (moving average) with a definable subset size.

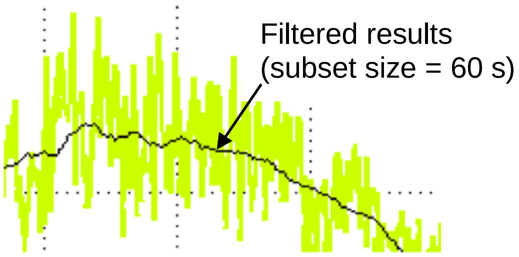

Figure 7 Original (green) and smoothened data (black) as an example of the data conditioning used

The subset size has to be chosen adequately to filter out the unwanted distortion and leaving the real physical effects in the data. As it can be difficult to determine whether a detected extreme value is valid for more than 300 analyzed quantities, the subset size was set to 60 s. For the data analyzed with an overall duration of 2000 s, this approach turned out to be appropriate concerning the aforementioned requirements.

Additionally, the existing data can be consisting of different time steps where the L2-Norm needs to refer on the same time step (index i in Eq. 3). Figure 8 shows the validation methodology exemplarily for the development of the pressure in the corridor L0. The experimental as well as the numerical results were smoothened with a moving average filter with 60 s subset size, which is depicted as black curve in Figure 8.

This example shows the benefit of evaluating both criteria, PEAK and the L2-Norm (PEACOCK) as the peak value yield to a good compliance, whereas the PEACOCK criterion gives a statement of the cumulated differences for each (averaged) time step. Due to the fact that a larger PEAK value automatically increases the surface area between both data sets for constantly increasing and decreasing quantities, both values are positively correlated. This is e. g. valid for the gas temperature. In other cases like presented in Figure 8 for the pressure, the PEAK value might be small and only representative for a short period. In this example, the damper closure in the experiment led to a pressure peak between 800 s to 1100 s. The behavior after this peak is not assessed by a single evaluation of the PEAK criterion.

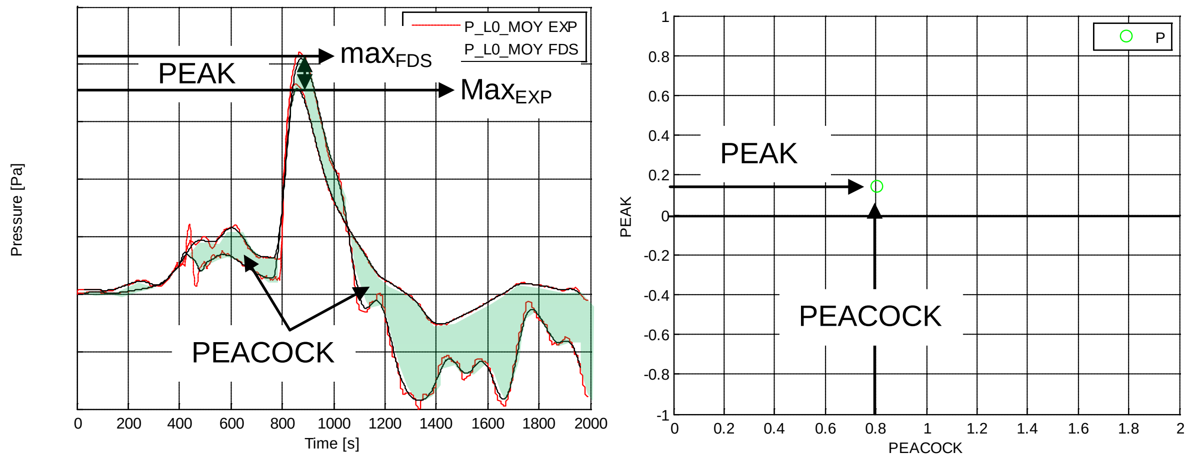

Figure 8 Pressure development (left) and resulting PEAK-PEACOCK plot for a single pressure sensor (right)

Interpretation of the Data

For both criteria, a value of 0 describes perfect compliance of the compared time series. For the Peak criterion, the result can be interpreted as the time independent percentage difference. Values violating the range of [-1,1], i.e. a difference between both evaluated peak values of more than 100 % have to be considered as problematic and checked against numerical or experimental plausibility.

The L2-Norm criterion leads to values ranging between [0,+∞], but two characteristic points can be determined. A value of 1 occurs, when the comparison curve is coincident to the x-axis, where a value of 2 states a similar comparison and reference curve, mirrored at the x-axis. Keeping those test cases in mind, a value of the L2-Norm higher than 1 has to be checked for plausibility or errors.

A second approach is a statistical analysis of the output sample assuming a normal distribution of the overall population. Here, nearby methodology is the utilization of boxplots. Boxplots consist of a rectangular, displaying the section of data lying between the 25th and 75th percentile (q_1 and q_3 in Eq. 4, Eq. 5 and Figure 9). The threshold determines whether a sample is called an 'outlier' or lies in the range of the whiskers which are defined using the following equations Eq. 4 and Eq. 5.

$$w_{\min} = q_1 - 1.5 \cdot (q_3 - q_1) \tag{4}$$

$$w_{\max} = q_3 + 1.5 \cdot (q_3 - q_1) \tag{5}$$

The factor 1.5 in both equations leads to a total of 99.3 % coverage of a normally distributed data sample or about 2.7 standard deviations between the mean values.

The advantage of the depiction of the median instead of the mean value lies in the robustness against outliers, reducing the influence of extreme values.

For both criteria Peak and L2-Norm, a median at 0 would state perfect compliance. In combination with a small variance of the samples, e.g. a narrow blue rectangular (cf. Figure 9), a good compliance of the comparison and the reference time series can be shown. A bad Peak or L2-Norm median, with a negligible variance usually shows faults in the basic data, e.g. the comparison of concentrations with different units (ppm with percent).

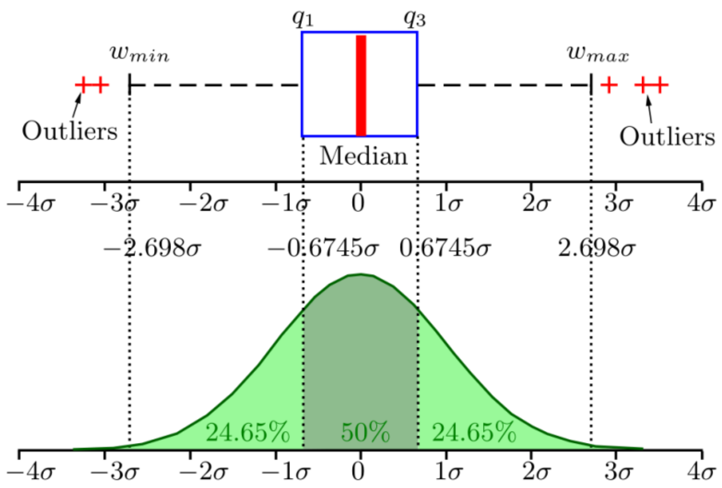

Figure 9 Boxplots utilizing interquartile range statistics for the PEAK criterion

The PEAK as well as the PEACOCK value do not include a concluding statement of the quality, they represent just a quantified “difference” between experimental and simulation data. Depending on the physical nature of the actual quantity and the known uncertainties of the measurement process, so-called weighted uncertainties U_{cw} are listed in [1], ranging from 9 % (CO, CO_2, O_2) up to 80 % for pressure (forced ventilation). They are listed in Table 1.

Table 1 Weighted Combined Expanded Uncertainty (taken from [1])

Quantity	Number of Tests	Weighted Combined Expanded Uncertainty U_{cw} [%]
HGL Temperature Rise	26	14
HGL Depth	26	13
Ceiling Jet Temperature	18	16
Plume Temperature	6	14
Gas Concentrations	16	9
Smoke Concentrations	15	33
Pressure	15	40 (no forced ventilation); 80 (forced ventilation)
Heat flux	17	20
Surface / Target Temperature	17	14

The values were derived concerning the experimental as well as the simulation uncertainty.

EVALUATION OF INTEGRAL 4 AND INTEGRAL 6 TEST DATA

The results of the FDS simulations are analyzed and compared to the experimental data with focus on the quantities gas temperature, doorway flow velocities and flow volumes, admission and exhaust volume flows and the pressure development in the compartment. The focus on this quantity is based on the fact that the gas temperature is highly influenced by the heat release rate imposed as boundary conditions whereas the volume flows and the pressure development is also highly sensitive to the modeling of the mechanical ventilation system.

For this paper, a large number of sensors were evaluated, mostly gas temperature data. The amounts are depicted in Figure 10.

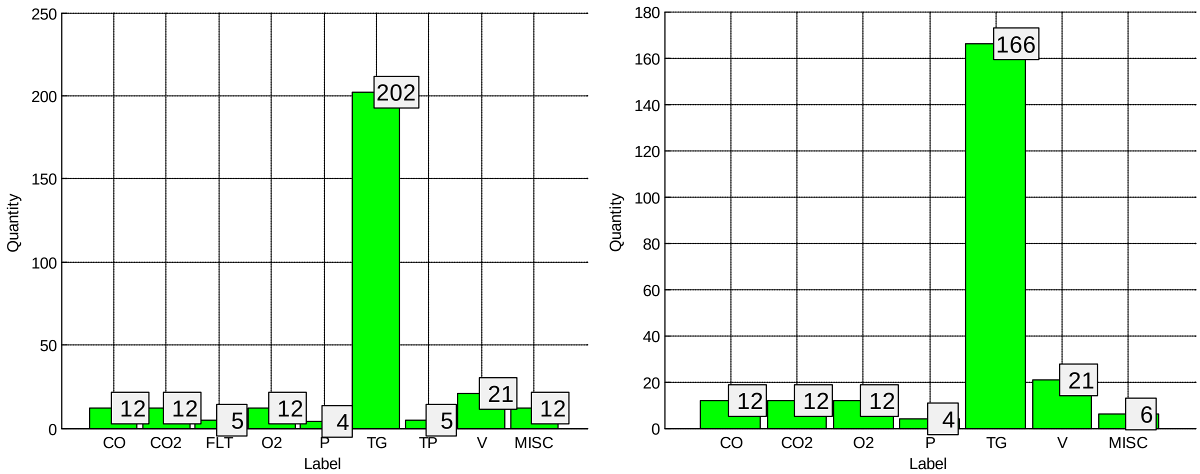

Figure 10 Amount of the assessed sensors for main quantities of the test INTEGRAL 4 (left) and INTEGRAL 6 (right)

As shown in Figure 10, a large amount of the total evaluated sensors are gas temperature sensors. When assessing the data using box plots, this has to be considered when looking at the resulting variance of the results of each quantity.

COMPLIANCE BETWEEN EXPERIMENT AND FDS SIMULATION

Gas Temperatures

The PEAK-PEACOCK plot of all gas temperature data is shown in Figure 11 with the U_{cw} value for the PEAK criterion depicted as a shaded surface. This plot gives a good overview of the quality of compliance for all gas temperature sensors. Additionally, the already mentioned correlation between high PEAK and PEACOCK values is visible.

Particularly valid for the right picture of Figure 11, showing the test INTEGRAL 6, a lot of values lie in the region around a PEAK value of zero and a PEACOCK value of 0.15 which shows the good compliance between experimental and numerical data. As an example, Figure 12 shows the associated time series for a vertical sensor tree located in central west position of the fire room L2 (cf. Figure 2).

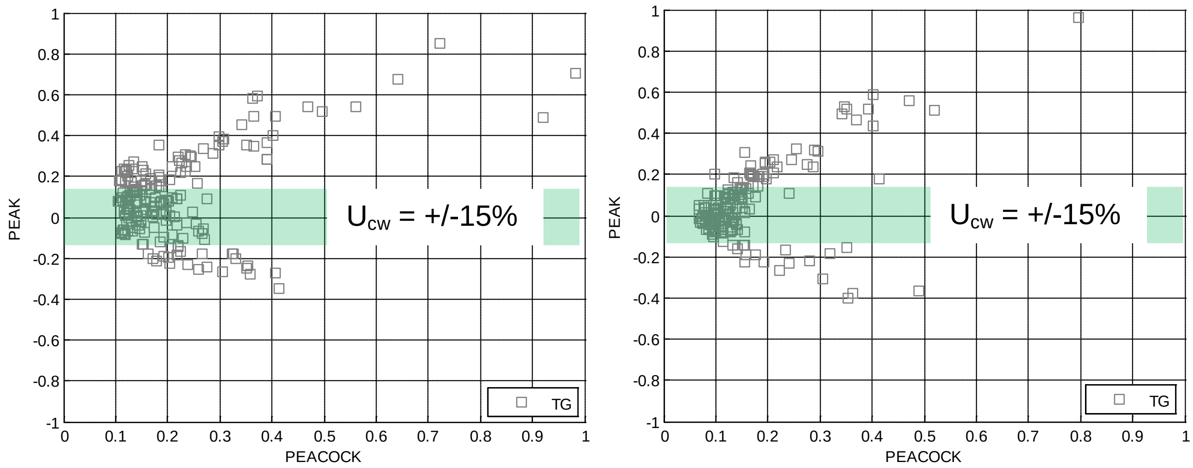

Figure 11 PEAK-PEACOCK plots of the INTEGRAL 4 test series (left) and INTEGRAL 6 test series (right) for the quantity gas temperature

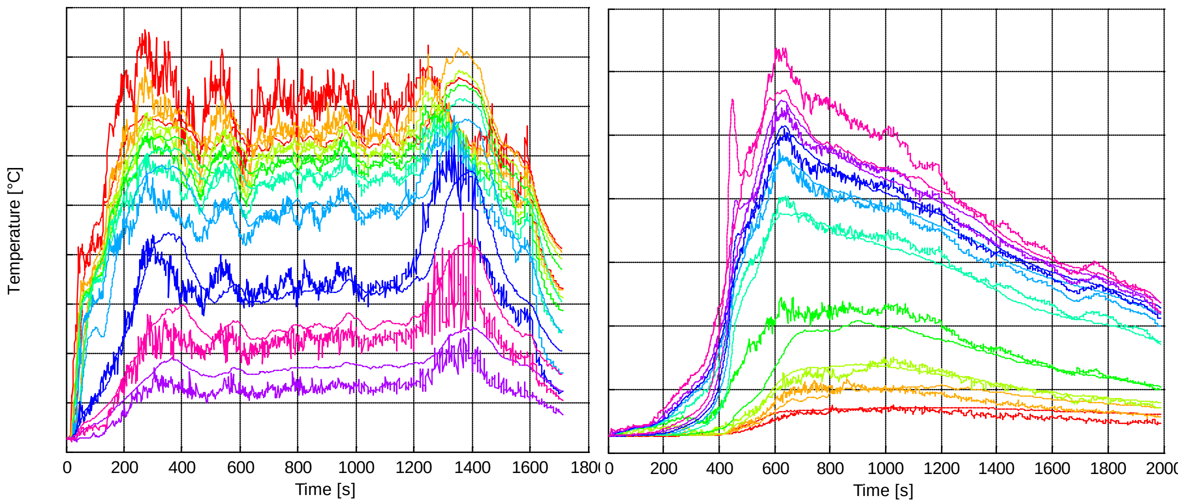

Figure 12 Experimental and numerical data of the gas temperatures in the fire room L2, measured from 5 cm to 390 cm height for test INTEGRAL 4 (left) and INTEGRAL 6 (right)

It can be noted that FDS is capable of calculating gas temperatures in open simulation runs in a good accuracy.

Admission and Doorway Flows and Pressure Development

Compared to the gas temperature, the results of the admission and doorway flows, flow velocities and pressure development provide more confusing results with different quality of compliance for each value as they differ in modeling and experimental uncertainty. Figure 13 gives an overview of the results.

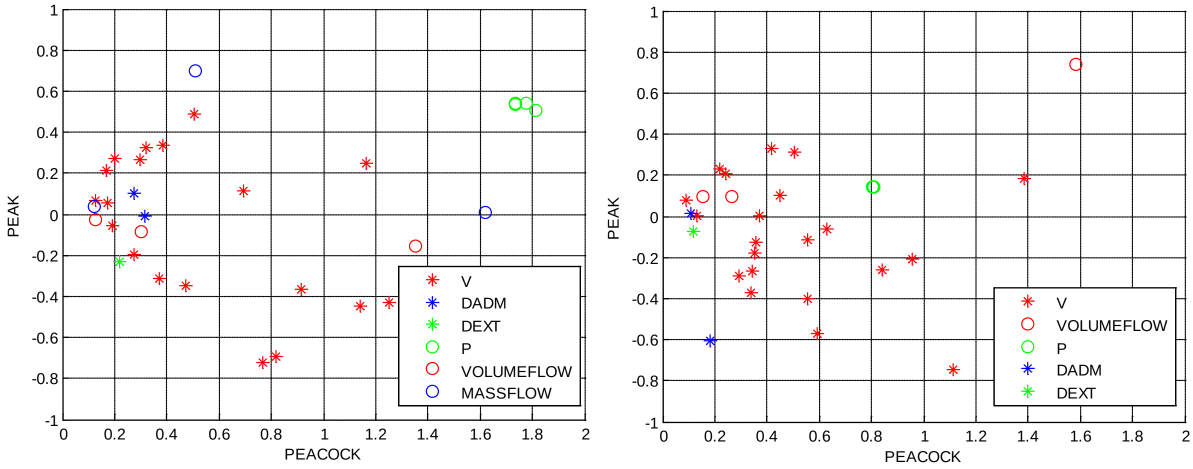

Figure 13 PEAK-PEACOCK plots of the INTEGRAL 4 test series (left) and INTEGRAL 6 test series (right) for the quantities doorway flow velocities, volume and mass flows and pressure

The volume flows calculated in the admission and exhaust line were modeled with the boundary conditions explained in the section above and show a good compliance to the experimental results. The time series are depicted in Figure 14.

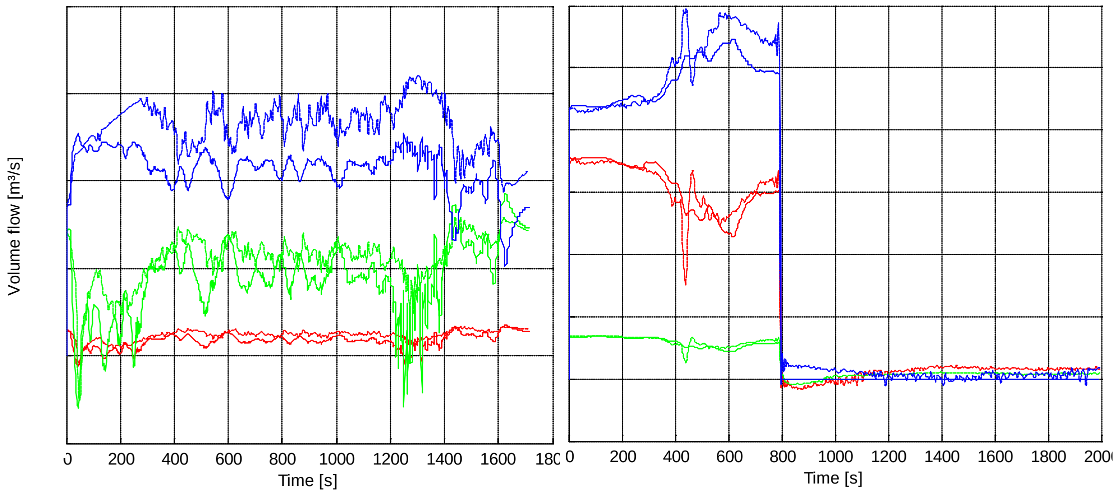

Figure 14 Experimental and numerical data of the volume flow out of the admission inlets (green and red curve) and the exhaust (blue curve) for test INTEGRAL 4 (left) and INTEGRAL 6 (right)

Whereas the data in Figure 14 shows a good compliance, the pressure development has to be assessed by both, PEAK and PEACOCK criteria to deliver an estimation of compliance. This is visible in Figure 15 where a separated look only on the PEAK value does not account for the difference between experimental data and simulation which occurs at most of the time.

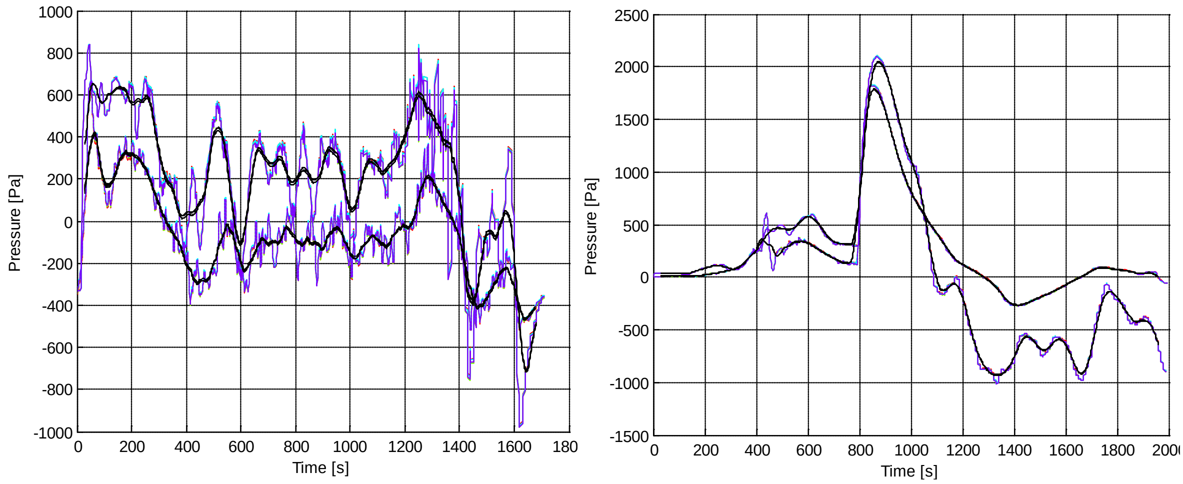

Figure 15 Experimental and numerical data of the pressure development in the diva facility for test INTEGRAL 4 (left) and INTEGRAL 6 (right)

Box Plots of the PEAK Criterion

A global evaluation of the PEAK criterion using box plots was done for the gas concentration quantities (carbon monoxide and dioxide, oxygen concentration), the pressure, gas temperatures (measured using vertical and horizontal sensor trees) and the flow velocities in the doorways. The result is depicted in Figure 16.

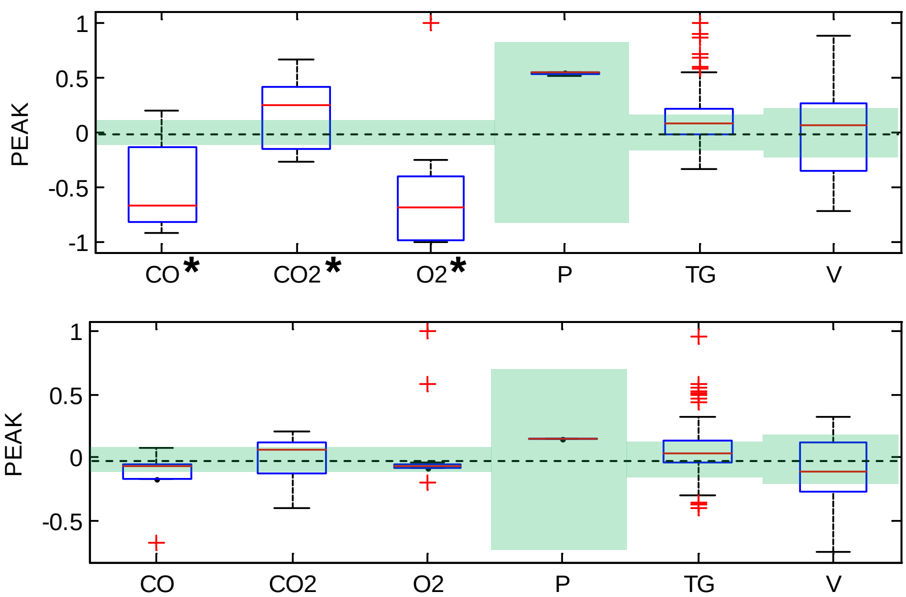

Figure 16 Boxplots of the distribution of the PEAK values of the INTEGRAL 4 test series (upper picture) and INTEGRAL 6 test series (lower picture)

The green layer marks the area of the U_{cw} value for each quantity corresponding to Table 1. For the doorway velocities, a value of 20 % was used. The gas temperatures which are detailed in Table 1 were evaluated with an U_{cw} value of 15 %.

Here, we can see that the results of the gas concentration of the test INTEGRAL 4 (marked with a star in Figure 16) seem to comply bad with the experimental results. The reason for this is a large maximum value in carbon monoxide, carbon dioxide and oxygen consumption for both upper and lower layer sensors which is not recorded in the simulation and was measured in a short time step in the extinction phase of the fire. By just evaluating the PEAK criterion, this yields to this seemingly bad compliance for the test INTEGRAL 4.

The analysis of the INTEGRAL 6 test shows that, besides the carbon monoxide quantity, about 50 % of all evaluated time series (blue rectangle of the box plots) agree with the weighted expanded combined uncertainty, stating that FDS is sufficiently capable of calculating the gas temperatures, gas concentrations, volume and mass flows in the admission and exhaust system as well as in the doorways and the pressure development in the compartment. Considering the mentioned conditions for the gas concentrations in test INTEGRAL 4, the compliance of the numerical simulation and the test results is good.

The acceptable uncertainties between the test and the numerical data were taken from [1]. Each U_{cw} value was derived from a number of tests of 6 to 26 which can be compared to the ones evaluated in this paper. The derivation of U_{cw} values was done on the basis of the error propagation law, considering the experimental and model uncertainties as normally distributed and as a result, the PEAK value distribution as normally distributed. When using distribution fitting techniques, it can be seen that this is a valid assumption for the PEAK criterion and allowing the usage of box plots like shown in Figure 16. When looking at a typical distribution of PEACOCK values, e.g. in Figure 11 for the gas temperatures, a normal distribution cannot be used when using confidence intervals as threshold quantities for the definition of the quality of compliance. In a first analysis, a lognormal distribution fits the distribution of PEACOCK values evaluating the PRISME INTEGRAL test series quite well. Additionally, the lognormal probability density function is only defined in the positive domain as also true for the PEACOCK values.

CONCLUSIONS

The evaluation and quantification of the compliance between experimental and numerical data for validation purpose is an important factor in the confidence of performance-based engineering methods in the field of fire protection. In this paper, two tests of the INTEGRAL test series of the international PRISME Project were considered using FDS in Version 5 for the numerical assessment. Using PEAK and PEACOCK validation criteria and considering weighted combined expanded uncertainties derived from [1] as confidence intervals, it can be shown that the results of FDS comply with the experimental data in the range of the U_{cw} values. The discrepancy (large PEAK values) for the gas concentrations for INTEGRAL 4 can be explained with temporal effects measured over a short duration in the extinction phase.

As shown for the gas temperature, volume flows and pressure development, a single comparison criterion such as the PEAK value is not capable of explaining temporal differences. These differences are important in evaluating data with steep peaks and areas of discrepancy after duration of good compliance. A practical example is the data of INTEGRAL 6 where the dampers of the mechanical ventilation system were closed after 800 s. To considerer those effects in an appropriate manner, the model and experimental uncertainty have to be evaluated for the INTEGRAL test series considering the non-normal distribution of the PEACOCK criterion.

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COMPUTATIONAL APPROACH FOR SODIUM FIRE PHENOMENON IN SODIUM COOLED FAST REACTOR

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ABSTRACT

In sodium cooled fast reactor, a safety assessment for sodium fire is one of most important issues. Two types of computational approaches, which have been developed by Japan Atomic Energy Agency, are summarized in this paper. One is a multi-zone model in which each room or compartment of the plant is treated based on one point approximation. A computational code, SPHINCS, has been developed. The other is a field model where a sodium combustion model is coupled with a multi-dimensional thermal hydraulics analysis in order to investigate a local effect such as distributions of temperature, oxygen concentration and aerosol concentration caused by fire (AQUA-SF code).

In the paper, numerical models of, sodium combustion models (pool combustion and spray combustion), the aerosol behavior, a radiation model and a fluid dynamics model are summarized. Benchmark analyses of both computational codes are also discussed in the paper.

INTRODUCTION

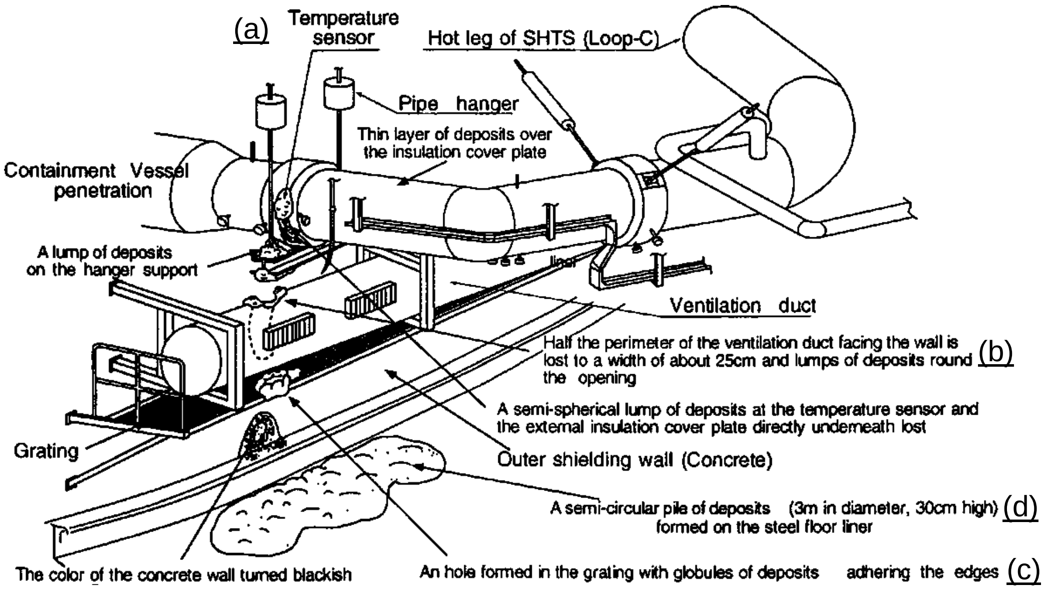
In a liquid metal fast reactor (LMFR), sodium is used as the heat transfer fluid to remove the heat from the reactor core. The liquid sodium has excellent heat transport capability and large margins to the boiling point (880 °C) at ambient pressure. However, its high chemical reactivity in contact with air and/or water is to be overcome from a viewpoint of safety.

When liquid sodium leaks out of a heat transport system, it may break up into small droplets with various diameters. In the air atmosphere, the droplets burn as they fall down. This is designated as spray combustion. The unburnt sodium will pile up on the floor resulting in pool combustion. The reaction products, such as sodium oxide (Na_2O), peroxide (Na_2O_2) and hydroxide (NaOH), aerosolize and then the heat of reaction is transferred by the conduction, convection and gas radiation.

Since the saturated vapor pressure of sodium is not high because of its high boiling temperature, it is commonly said that sodium fire is mild rather than that of petrol [1]. Therefore, both the spray and pool combustion will appear when liquid sodium is leaked out.

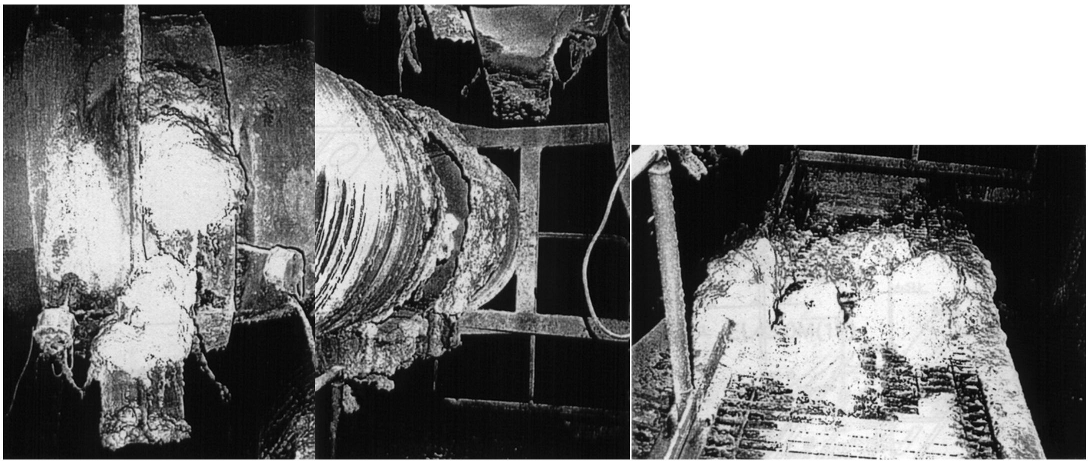
In 1995, a sodium fire incident was taken place at a secondary heat transport system (SHTS) loop C in Japanese prototype LMFR Monju. Figure 1 shows the state of sodium compounds after the incident [2], [3]. In the incident, it was reported that liquid sodium was leaked out through the thermocouple temperature sensor. The leakage rate and duration was estimated to approximately 50 g/s and 220 min respectively and the total amount was approximately 640 kg.

With regard to the spray combustion, a major incident has not been taken place in LMFR plant. However, it is noted that it happened at Almeria solar plant in Spain, 1986 [4] and one has been paying much attention to spray combustion after the incident.

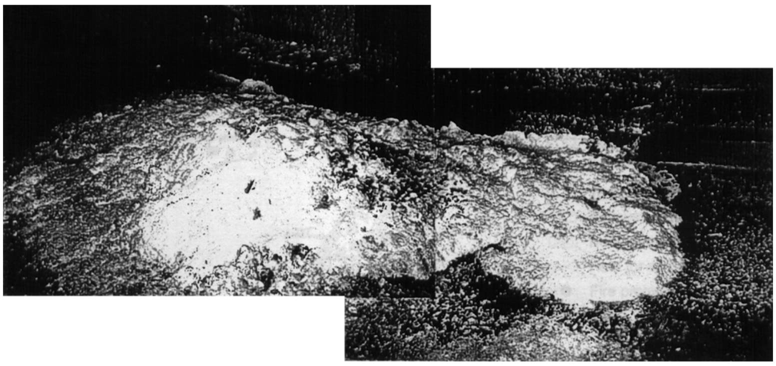


(a) - (d) correspond to the following photographs:

State of sodium compounds



(a) Thermocouple box (b) Ventilation duct (c) Walkway grating



(d) Floor liner

Photographs of sodium compounds

Figure 1 State of sodium compounds after sodium fire incident in Monju [2], [3]

Figure 2 summarizes key phenomena in sodium fire incident. Firstly, an intensity and duration of sodium fire is much affected by feeding of oxygen and/or water vapor to the combustion area. Hence, a fluid dynamics effect, which includes ventilation between rooms caused by both forced and natural convections, is one of the key issues.

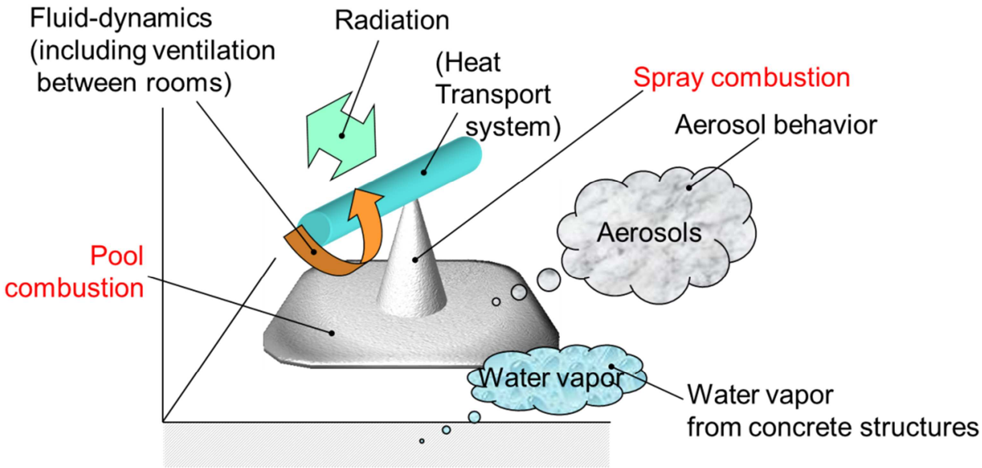


Figure 2 Key phenomena in sodium fire

In general, a visibility is quite poor caused by the reaction product (aerosols). Hence, heat transfer due to radiation from the combustion area to surrounding walls and gas region is also of importance. Furthermore, the aerosols are harmful to both human and electrical devices due to its strong alkaline. Thus, a transportation of the aerosols (aerosols behavior) to surrounding rooms is also a key issue from the viewpoint of safety. Since concrete structures are used in the plant and include bonging moisture, water vapor will be released and react with sodium when they are heated up due to sodium fire.

After the sodium fire incident in Monju, experimental and numerical researches on sodium combustion have been extensively performed to develop or improve computer codes for safety evaluation and to obtain better understanding on the combustion phenomena. New numerical tools for sodium fire evaluation have been developed in Japan Atomic Energy Agency (JAEA) based on a multi-zone model (SPHINCS code [5]) and a field model (AQUA-SF code [6]).

In the present paper, numerical models of, sodium combustion models (pool combustion and spray combustion), the aerosol behavior, a radiation model and a fluid dynamics model are summarized. Then benchmark analyses for airflow due to temperature difference and a small pool combustion experiment are also discussed.

NUMERICAL MODELS

Spray Combustion Model

In the spray combustion, mass, momentum and energy balances of sodium liquid droplets are taken into consideration. The following assumptions are introduced to the model.

- Droplets are sphere-shaped.
- Different combustion rate are considered for pre-ignition and post-ignition phases depending on the droplet temperature.
- After a droplet temperature reaches its boiling point, the temperature is kept unchanged during the droplet was ran out. All reaction heat is transferred to ambient gas except for the latent heat for vaporization of liquid sodium.

The governing equations of a droplet are expressed as:

$$-\frac{d}{dt}(\frac{\pi}{6}d_p^3\rho_p)=\dot{m}_{burn}\,, \tag{1}$$

$$m_p\frac{d\mathbf{u}_p}{dt}=m_p\mathbf{g}-\mathbf{f}\,, \tag{2}$$

$$\frac{\pi d_p^3}{6}\rho_p Cp\frac{dT_p}{dt}=Q_{burn}-Q_g\,. \tag{3}$$

where, t, d and ρ mean the time, the diameter and the density respectively. The subscripts p denotes the droplet. *u, g* and *f* represent the vector form of the velocity, the gravity constant and the drag force respectively. Q is the heat generation (source). Q_{burn} means the combustion heat generation due to the spray combustion and Q_g indicates the heat source transferred to atmospheric gas.

Combustion Rate of Droplet in Pre-ignition Phase

Before a droplet ignites, it is considered that the surface reaction due to oxygen and/or water vapor transferred to the surface is dominant. When one assumes that oxygen and/or water vapor vanishes at the surface due to combustion and takes an analogy between heat and mass transfers into account, the mass flow rate of oxygen and/or water vapor at the droplet surface is obtained as:

$$\dot{m}_j=\pi d_p^2\rho_g(Y_{m\,j}-0)\frac{D_j}{d_p}Sh_j=\pi d_p\rho_g Y_{m\,j}D_j Sh_j\,, \tag{4}$$

Here, Y_m is the mass fraction of oxygen and/or water vapor. *D* and *Sh* mean the diffusion coefficient and the Sherwood number respectively. As all of oxygen and/or water vapor reacts with sodium, the total combustion rate is shown as follows using a model proposed by Tsai [7].

$$\dot{m}_{burn}=\sum_j\frac{\dot{m}_j}{i_{m\,j}}=\sum_j\frac{\pi d_p\rho_g Y_{m\,j}D_j}{i_{m\,j}}(2+0.6Re^{*1/2}Sc_j^{1/3})\,. \tag{5}$$

Where, i_m is the stoichiometric coefficient per unit kg of sodium. Re^* and *Sc* mean the droplet Reynolds number, which is calculated using the droplet diameter and the relative velocity of the droplet to atmospheric gas, and the Schmidt number respectively. The stoichiometric coefficient is estimated based on the Gibbs free energy minimization method [8].

Combustion Rate of Droplet in Post-ignition Phase

After a droplet ignites, the combustion rate is evaluated according to the quasi-state droplet combustion theory. A well-known d_p^2-law, which describes a square of droplet diameter decreases linearly with time, is applied. Developing Eq. (1) by d_p^2 and assuming that the density change will be negligible in a short period of time, one obtains as:

$$\dot{m}_{burn}=-\frac{\pi}{4}\rho_p d_p\frac{\partial d_p^2}{\partial t}=\frac{\pi\rho_p K}{4}d_p\,, \quad \left(K=-\frac{\partial d_p^2}{\partial t}\right). \tag{6}$$

According to Spalding [9], the quasi-steady sate combustion rate of sodium against oxygen and/or water vapor, $\dot{m}'_{b\,j}$, is given from Eq. (6) as:

$$\dot{m}'_{b\,j}=\frac{\pi\rho_p K_j}{4}d_p\,, \tag{7}$$

$$K_j = \frac{8\lambda_g}{Cp_g \rho_g} \ln(1 + B_j),$$
$$B_j = \frac{1}{\Delta H_m^{eva}} \left\{ Cp_g (T_g - T_p) + \frac{\Delta H_{m\,j}^{c} Y_{m\,j}}{i_{m\,j}} \right\}. \qquad (8)$$

where the prime means a quasi-steady state. ΔH_m^{eva} and ΔH_m^{c} indicate the latent heat for evaporation per unit kg sodium and the total combustion (reaction) heat per unit kg sodium.

In general, the combustion rate of a falling droplet is affected by forced convection. Under the forced convection condition, flame of a droplet is no longer sphere shape and the combustion rate increases. The combustion rate of sodium is evaluated from Eq. (7), considering the effect of forced convection by Ranz and Marshal [10].

$$\dot{m}_{burn} = \sum_j \dot{m}'_{b\,j} (1 + C_0 Re^{*1/2} Pr^{1/3}),$$
$$C_0 = 0.24 \sim 0.31. \qquad (9)$$

Here, *Pr* is the Prandtl number.

Heat Generation and Heat Transfer of Droplet

Heat generation due to the combustion Q_{burn} is obtained by subtracting latent heat for vaporization from reaction heat, shown as:

$$Q_{burn} = \sum_j \dot{m}'_{b\,j} (\Delta H_{m\,j}^{c} - \Delta H_{m\,j}^{eva}). \qquad (10)$$

When a droplet temperature reaches the boiling point, it is assumed that the temperature is constant until sodium runs out and all of the combustion heat Q_{burn} is transferred to the gas phase. The heat transferred to gas phase Q_{gas} is equal to Q_{burn}. On the other hand, the combustion heat is transferred to both gas and droplet, if the temperature is under the boiling point. The forced convection heat transfer from the droplet to the gas is calculated as follows:

$$Q_{gas} = \pi d_p \lambda_g (2 + 0.6 Re^{*\frac{1}{2}} Pr^{\frac{1}{3}})(T_p - T_g). \qquad (11)$$

Drag Force of Droplet

When a droplet is assumed to be sphere, the drag force (**f**) is shown by the following equation.

$$\mathbf{f} = m_p \frac{3\rho_g U^* (\mathbf{u} - \mathbf{u_g})}{4\rho_p d_p} Cd^*, \qquad (12)$$

where U^* and Cd^* are the velocity magnitude and the drag coefficient based on the velocity relative to gas phase respectively. The drag coefficient (Cd^*) is estimated as follows [11]:

$$Cd^* = \begin{cases} 24/\mathrm{Re}^* & ,\mathrm{Re}^* < 0.1 \\ 2.6 + 23.71/\mathrm{Re}^* & ,0.1 \le \mathrm{Re}^* < 6 \\ 18.5/\mathrm{Re}^{*0.6} & ,6 \le \mathrm{Re}^* < 500 \\ 4/9 & ,\mathrm{Re}^* \ge 500 \end{cases}. \qquad (13)$$

With regard to the distribution of droplet size, the Nukiyama-Tanasawa distribution is used to represent the statistical characteristics of the liquid droplet size as recommended by Tsai [12]. The droplet size is discretized into over ten groups. Since the spray region is segmented into computational cells in AQUA-SF code, a number of droplets in each group are randomly generated and Eqs. (1) - (3) are solved for each droplet using the Lagrangian coordinate system. A momentum exchange between particles and gas phase is also taken into account.

Pool Combustion Model

The flame sheet concept is applied for the pool combustion in which mass and energy conservation equations are solved regarding as an infinitely thin flame. Figure 3 shows a schematic of the flame sheet concept. Local equilibrium is assumed in the flame. Namely, all reactants such as sodium, oxygen and water vapor are consumed in the flame. Reaction heat is partitioned between atmospheric gas and pool surface. The mass and energy conservation equations are obtained by:

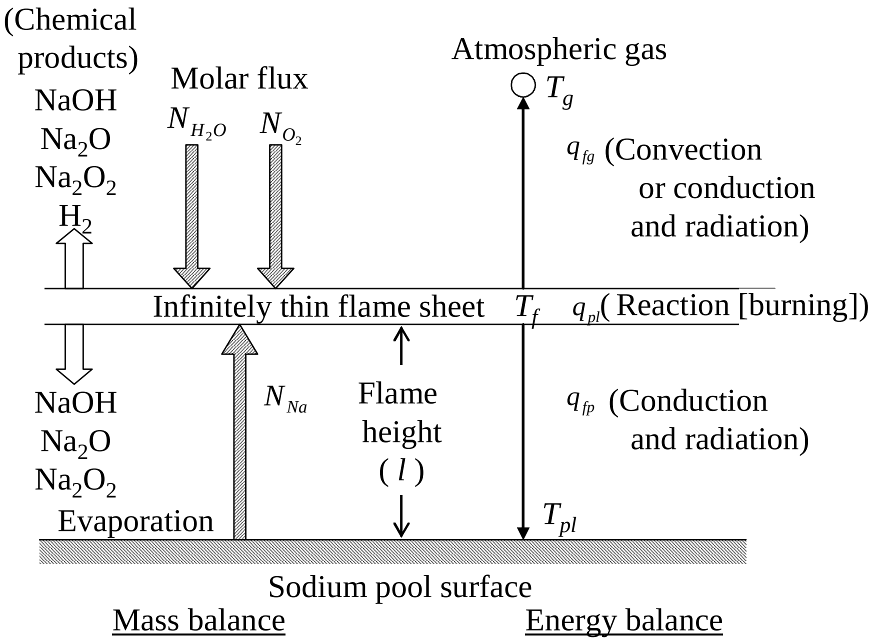


Figure 3 Flame sheet concept in pool combustion

$$N_{Na} = \sum_j \frac{N_j}{i_{N\,j}}, \tag{14}$$

$$q_{burn} = q_{fg} + q_{fp}. \tag{15}$$

where N is the molar flux and i_N is the stoichiometric coefficient per unit mole of sodium. q represents the heat flux. Subscript j, $burn$, fg and fp denote the oxygen (O_2) and/or water vapor (H_2O), the combustion (reaction), between flame and atmospheric gas and between flame and sodium pool surface respectively.

Molar Flux of Sodium Vapor to Flame

Since the flame is close to sodium pool surface, it is enough to assume that the molar flux of sodium vapor can be estimated based on one-dimensional steady state diffusion in the following:

$$N_{Na} = Y_{Na}(N_{Na} + N_{N_2}) - C_{fp} D_{Na} \frac{dY_{Na}}{dx}, \tag{16}$$

where Y_{Na}, C and D_{Na} mean the molar fraction of sodium vapor, the molar concentration and the diffusive coefficient of sodium on inert gas (N_2) respectively. Solving Eq. (16) with condition of $Y_{Na,\,x=0}$, $Y_{Na,\,x=l}$ and no inert gas flux ($N_{N_2} = 0$), one obtains the following equation.

$$N_{Na} = \frac{C_{fp} D_{Na}}{l} \ln\left(\frac{1 - Y_{Na,x=l}}{1 - Y_{Na,x=0}} \right), \tag{17}$$

Here, l represents the flame sheet height from the pool surface. In the flame sheet concept, sodium vapor vanishes at the flame due to combustion ($Y_{Na,\,x=l} = 0$) and the molar fraction of sodium on the pool surface ($x = 0$) can be expressed using the saturation vapor pressure (P^{sat}) and the ambient pressure (P) as:

$$Y_{Na,x=0} = \frac{P_{Na}^{sat}}{P}. \tag{18}$$

Finally, Eq. (17) is rewritten in the following.

$$N_{Na} = \frac{C_{fp} D_{Na}}{l} \ln\left(\frac{P}{P - P_{Na}^{sat}} \right). \tag{19}$$

Molar Flux of Oxygen and Water Vapor to Flame

Applying the same assumption with the sodium vapor flux estimation but adding an effect of convectional mass transfer, one obtains the following equation.

$$N_j = \frac{C_j D_j}{l} \ln\left(\frac{Y_j}{1 - Y_j} \right) \times Sh_j. \tag{20}$$

Sh_j in Eq. (20) is evaluated from the analogy of heat and mass transfers. The natural convection mass transfer coefficient for flat plate is given by Fishenden and Saunders [13] using Grashof number Gr and Schmidt number Sc as:

$$Sh_j = 0.14 (Gr \cdot Sc_j)^{1/3}. \tag{21}$$

When a computational cell size is small enough with flame sheet height (l) in case of the field model (AQUA-SF code), the molar flux is evaluated only by diffusion and the following equation is applied instead of Eq. (20) as:

$$N_j = \frac{C_j D_j}{z} \ln\left(\frac{1}{1 - Y_j} \right). \tag{22}$$

Here, z is the distance between the flame and the center of the computational cell.

Burning Heat Flux

When one determines a local stoichiometric coefficient $i_{N\,j,k}$, the burning heat flux q_{pl} is obtained as:

$$q_{pl} = \sum_{k1} \frac{N_{O_2}}{i_{N O_2,k1}} \Delta H_{298_{k1}} + \sum_{k2} \frac{N_{H_2O}}{i_{N H_2O,k2}} \Delta H_{298_{k2}} - N_{Na} \Delta H^{eva}, \tag{23}$$

Here, ΔH^{eva} means the latent heat of sodium for evaporation. Subscripts $k1$ and $k2$ mean the chemical reaction process (ex. $2Na + 1/2O_2 \rightarrow Na_2O$,$\Delta H_{298} = -415\text{kJ/mol}$). As shown in Eq.(23), the latent heat of sodium is subtracted from the reaction heat. As concerns with the local stoichiometric coefficient, the Gibbs free energy minimization method is applied same as the spray combustion model.

Heat Flux to Pool Surface

Heat transfer between the pool surface and flame is caused by thermal conduction and radiation. Furthermore, convection of gases and aerosols carries combustion energy as well. The heat flux to the pool surface q_{fp} is obtained in the following.

$$q_{fp} = \lambda_{fp} \left.\frac{dT}{dx}\right|_{x=l} + F_{fp}\sigma(T_f^4 - T_{pl}^4), \tag{24}$$

here, λ and T mean the thermal conductivity and the temperature respectively. F is the fraction of radiant energy leaving from the flame (multiplier for the view factor and emissivity between flame and gas) and σ is the Stefan-Boltzmann constant. The subscript pl represents the pool surface. dT/dx is deduced from one-dimensional steady state equation as:

$$\begin{aligned} &\alpha \frac{dT}{dx} = \lambda_{fp} \frac{d^2T}{dx^2}, \\ &\alpha = (\dot{m}Cp)_{Na} - (\dot{m}Cp)_{Na_2O} - (\dot{m}Cp)_{Na_2O_2} - (\dot{m}Cp)_{NaOH}. \end{aligned} \tag{25}$$

where $\dot{m}$ and Cp devote the mass flux of species and the specific heat. Solving Eq. (25) with boundary conditions of $T = T_{pl}$ at $x = 0$ and $T = T_f$ at $x = l$, one obtains the following equation.

$$\left.\frac{dT}{dx}\right|_{x=l} = \left\{ \frac{T_f - T_{pl}}{\exp(\frac{a}{\lambda_{fp}} l) - l} \right\} \exp\left(\frac{a}{\lambda_{fp}} l \right). \tag{26}$$

Heat Flux to Atmospheric Gas

The heat flux from the flame to atmospheric gas, q_{fg}, is estimated by similar idea used in the molar flux of oxygen and/or water vapor as mentioned above. If the computational cell size is sufficiently large, the heat flux is evaluated considering radiation and convection in the following.

$$q_{fg} = 0.14(Gr \cdot Pr)^{1/3}(T_f - T_g)\frac{\lambda_g}{l} + F_{fg}\sigma(T_f^4 - T_g^4). \tag{27}$$

In case of the small computational cell in AQUA-SF code, the following equation is used by considering the thermal conductivity and radiation same as the manner applied in Eq. (22).

$$\begin{aligned} &q_{fg} = \lambda_g \left.\frac{dT}{dx}\right|_{x=z} + F_{fg}\sigma(T_f^4 - T_g^4), \\ &\left.\frac{dT}{dx}\right|_{x=z} = \left\{ \frac{T_f - T_g}{\exp\left(\frac{\beta}{\lambda_g} z \right)} - z \right\} \exp\left(\frac{\beta}{\lambda_g} z \right), \\ &\beta = (\dot{m}Cp)_{Na_2O} + (\dot{m}Cp)_{Na_2O_2} + (\dot{m}Cp)_{NaOH} + (\dot{m}Cp)_{H_2} - (\dot{m}Cp)_{O_2} - (\dot{m}Cp)_{H_2O}. \end{aligned} \tag{28}$$

Substituting Eqs. (16) - (28) into Eqs. (14) and (15), they become functions of the flame height (l) and the flame temperature (T_f). The Newton-Raphson method is used to solve the equations.

In LMFR, a steel liner is expected to bear sodium and reaction products on the floor in case of sodium leakage. When a leakage of sodium continues, the pool combustion area will also be enlarged. From the viewpoint of structural integrity of the steel liner, the temperature distributions of the pool and liner are important. Hence, a multi-dimensional treatment is applied to the multi-zone model (SPHINCS code) although one point approximation is used for each room. A schematic of the treatment is shown in Figure 4. The pool is divided into a number of axisymmetric rings and the following equation of mass conservation is solved.

$$\rho_{Na}\frac{\partial \delta A}{\partial t}=W_{in}-W_{out}+W_{spray}-W_{burn}. \tag{29}$$

where A is the pool area. W_{in}, W_{out}, W_{spray} and W_{burn} are the inflow rate, outflow rate, spraying mass rate and combustion rate, respectively. δ is the pool liquid level (thickness) and is evaluated by taking into account the surface tension (σ) and the gravity (g) forces as:

$$\delta=\sqrt{\frac{2\sigma}{\rho_{Na}g}(1-\cos\varphi)}, \tag{30}$$

here, φ is the contact angle. The pool combustion model is also applied to each ring. In case of the field model (AQUA-SF code), the floor (steel liner) is divided in accordance with a computational cell and mass conservation of the pool is calculated based on the same manner with Eq. (29).

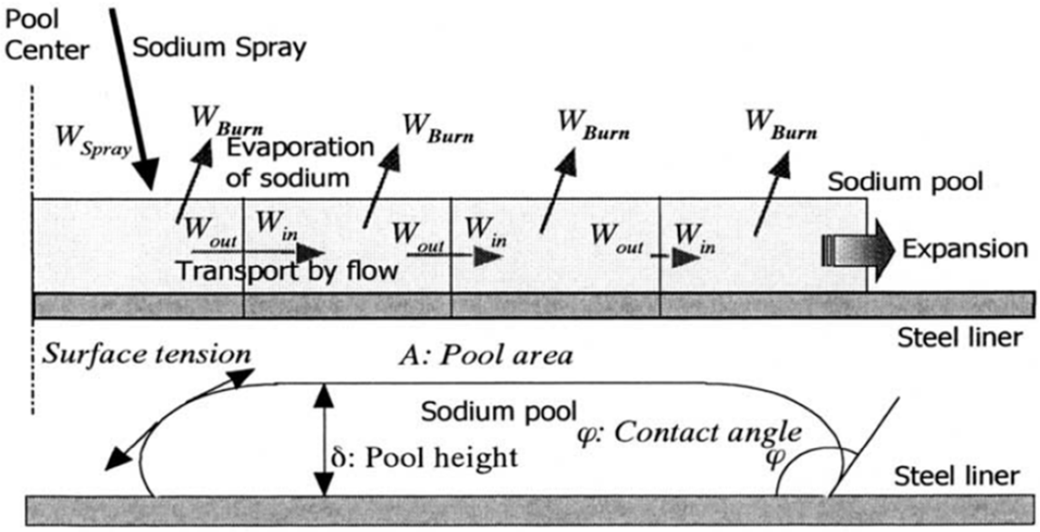


Figure 4 Multi-dimensional pool treatment in the SPHINCS code

Aerosol Behavior

The governing equation of aerosol dynamics is shown in the following [14]:

$$\begin{aligned}&\frac{\partial n(v)}{\partial t}+\frac{1}{Cu(v)}\nabla\cdot n(v)\mathbf{u_g}+\frac{1}{Cu(v)}\nabla\cdot n(v)\mathbf{U^{dif}}\\&=\frac{1}{2}\int_0^v n(v')n(v-v')\beta(v',v-v')dv'-n(v)\int_0^\infty n(v')\beta(v,v')dv'+S(v),\end{aligned} \tag{31}$$

Here, $n(v)$ represents the number density of the aerosol with its volume v. v' is a dummy variable that goes from 0 to ∞. Cu is the Cunningham correction factor. $\mathbf{u_g}$ and $\mathbf{U^{dif}}$ mean the velocity vector of gas phase and the terminal velocity vector of aerosol respectively. β and $S(v)$ are the coagulation rate and source term respectively.

Equation (31) is divided into the governing equations of flow dynamics and aerosol dynamics terms as:

$$\frac{\partial n(v)}{\partial t}+\frac{1}{Cu(v)}\nabla\cdot n(v)\mathbf{u_g}+\frac{1}{Cu(v)}\nabla\cdot D_B(v)\nabla n(v)=S(v), \tag{32}$$

$$\frac{\partial n(v)}{\partial t}+\frac{1}{Cu(v)}\nabla\cdot n(v)\mathbf{U}^{\mathbf{dif}\prime}$$
$$=\frac{1}{2}\int_0^v n(v')n(v-v')\beta(v',v-v')dv'-n(v)\int_0^\infty n(v')\beta(v,v')dv'. \tag{33}$$

Here, $D_B(v)$ is the diffusion coefficient due to In the SPHINCS code, The governing equation of the flow dynamics term (Eq. (32)) is taken into account in a flow network among rooms, while it is modified to a mass transfer model in a multi-dimensional thermal hydraulics computation in AQUA-SF code.

Radiation Heat transfer

In the SPHINCS code, the following simple radiation heat transfer model between structures and atmosphere, flame on the sodium pool and atmosphere, and the flame and structures.

$$q_r=\sigma\varepsilon_s(\varepsilon_m T_a^4-\alpha_m T_t^4), \tag{34}$$

where ε_m and α_m are the total gas mixture emissivity and absorptivity, respectively. T_i is a flame or structure temperature. T_a is the estimate of post-radiation atmosphere temperature. For a gray enclosure, some of the incident radiation striking its wall is reflected back to the gas and the other parts of the structure. Using the emissivity ε_i of surface i, ε_s accounts for this reflection and is evaluated as:

$$\varepsilon_s=\frac{\varepsilon_t+1}{2}, \tag{35}$$

The total gas mixture emissivity and absorptivity are evaluated in the following equations [15]:

$$\varepsilon_m=\varepsilon_a+\varepsilon_{gas}-\varepsilon_a\varepsilon_{gas},$$
$$\alpha_m=\alpha_a+\alpha_{gas}-\alpha_a\alpha_{gas}. \tag{36}$$

where ε_a and ε_a are, respectively, the aerosol emissivity and absorptivity. α_{gas} and α_{gas} are, respectively, the gas emissivity and absorptivity.

In the AQUA-SF code, the following gas flux model [16] is applied.

$$\nabla\cdot\Gamma\nabla\mathbf{R}+\mathbf{S_{rad}}=0. \tag{37}$$

Where, □, R and S_{rad} are the diffusivity, the radiant flux and the source term respectively. The diffusivity and the source term are defined as:

$$\Gamma=\frac{1}{\alpha+s},$$
$$S_{rad\,i}=\alpha E+\frac{s}{n}\sum_i R_i-(\alpha+s)R_i, \tag{38}$$

Here, s is the scattering coefficient. n indicates the number of dimension. R_i is the radiant flux of i-th coordinate. E is the emissive power for black body defined by σT^4.

The absorption and scattering coefficients of the aerosol are evaluated in proportion to its concentration that is calculated in the codes.

Flow Dynamics

In the multi-zone model (SPHINCS code), the mass conservation equations for every chemical species and mixture gas are solved for rooms in a reactor building. The energy equation of the mixture of gases and aerosols in terms of enthalpy is also solved to obtain mass-averaged temperature in each room. Since the rooms are connected by doorways and penetrations, the transport of chemical species and energy is calculated with a flow network model.

In the flow network, airflow due to temperature difference (buoyancy-driven natural ventilation) among rooms is taken into account in the momentum equation as well as a pressure-driven airflow. When no net flow rate across an opening and the Bernoulli equation at the opening are assumed, the flow rate due to temperature difference is evaluated semi-empirically [17] as:

$$Nu / Pr = \frac{G}{\mu H} = \frac{C}{3} Gr^{1/2}, \qquad (39)$$

Here, μ, G and H are the molecular viscosity of gas, the flow rate and the height of the opening, respectively. C is the shape factor that varies from 0.6 to 1.0 depending on the opening shape. In the semi-empirical theory [17], an integration of multi openings into one opening is also calculated considering a neutral elevation that means a stagnant elevation at the opening. An applicability of the model is discussed later.

In the field model (AQUA-SF code), the combustion, the aerosol behavior and the radiation models are coupled with a multi-dimensional thermal hydraulics analysis tool, the AQUA code [18].

In both codes, temperatures of surrounding concrete structures are also calculated so as to evaluate an emitting of bonding moisture from the concrete structures.

NUMERICAL INVESTIGATION

Two benchmark analyses have been carried out to investigate the applicability of the present methods. One is the airflow analysis due to temperature difference and the other is a small pool combustion experiment [19].

Airflow Analysis due to Temperature Difference

A benchmark analysis of the airflow due to temperature difference is carried out to validate the applicability of the field model (AQUA-SF code) and the compatibility between the multi-zone model (SPHINCS code) and the field model.

Figure 5 shows the computational geometry of the analysis used in AQUA-SF code. With regard to the opening, the same geometry as the Brown's experiment [17] is applied. On the other hand, a longer width (11.218 m) is used in order to keep the average temperature of each room constant regardless of the ventilation.

In the analyses, the temperature difference (Gr number, Gr = 1×10^7, 5×10^7) and the mesh arrangement in the opening region are selected as an analytical parameter.

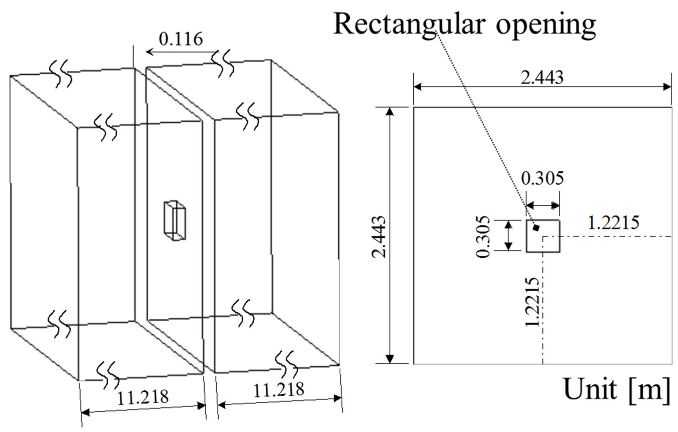


Figure 5 Computational geometry in airflow analysis

The comparison of the airflow rate between the computational and experimental results is shown in Figure 6. The empirical correlation (Eq. (39)) is also depicted in Figure 5. The computational results agree with the empirical correlation with sharp-edged opening and are in the range of the experiments. Consequently, it is concluded that the airflow due to temperature difference can be represented in the present tool.

Figure 7 shows the influence of the mesh arrangement in the opening on the airflow rate. Since the neutral elevation will appear at the center of the opening in the analysis, the flow rate is underestimated in case of odd mesh arrangement in the vertical direction (blue circles in Figure 7). It may suggest that one has to determine the mesh arrangement considering a location of neutral elevation. With regard to the mesh arrangement in the horizontal direction, the flow rate increase as the number of the nodding decrease (red allows in Figure 7).

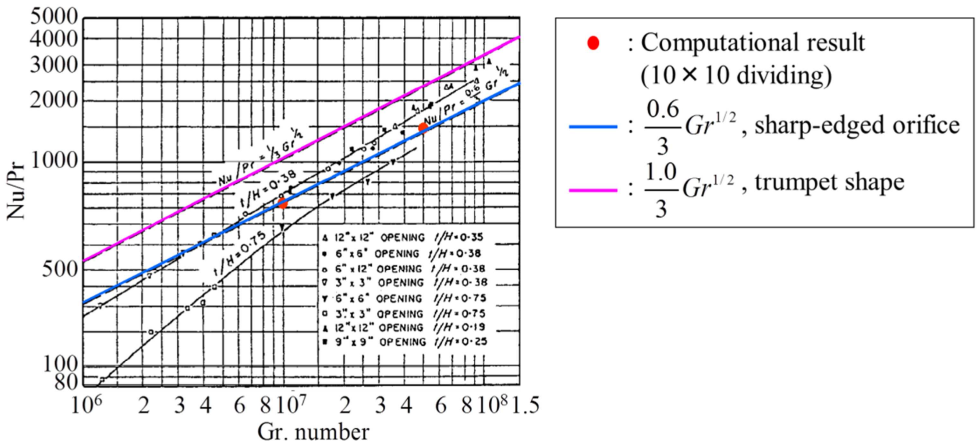


Figure 6 Comparison of airflow rate

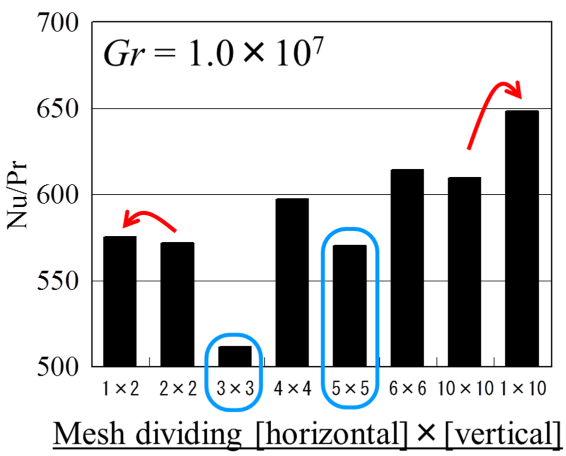
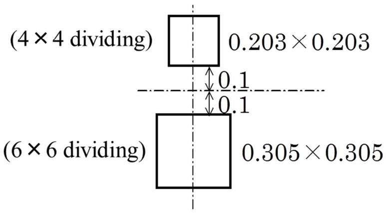


Figure 7 Influence of mesh in opening

The numerical analysis of the airflow in case of two opening is also carried out. In the analysis, two openings shown in the left side of Figure 8 is applied to the geometry (Figure 5). The comparison between the numerical analysis and empirical correlation is also summarized in Figure 8.

As shown in Figure 8, a good agreement is achieved although a comparative small mesh arrangement is used in the openings. It is concluded that the compatibility of the airflow rate due to temperature difference is validated in SPHINCS and AQUA-SF codes.



	Location of Neutral elevation (Δh) [m]	Airflow rate [kg/s]
Present computing	5.45×10^{-2}	2.02×10^{-3}
Empirical correlation	4.83×10^{-2}	2.23×10^{-3}

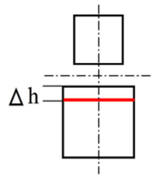


Figure 8 Influence of multi-openings

Benchmark Analysis of a Small Pool Combustion Experiment

A series of experiments was performed for understanding sodium pool combustion phenomena [19]. Three of them are designated as runs F7-1, F7-2 and F7-3 in which the leakage nozzle elevation and the forced ventilation rate are set as an input parameter. In this analysis, the benchmark analysis of run F7-1 is carried out.

The test section consists of a cylindrical vessel made of stainless-steel as shown in Figure 9. The measurement location of thermocouples, oximeters, hygrometers and aerosol concentration (inlet of gas sampling line) are also summarized in Figure 9. The floor of the vessel is covered with a steel liner. The leakage nozzle of 6.35×10^{-3} m in diameter is located at the height of 0.1 m from the liner in order not to enhance the influence of the spray combustion. The leak rate is 3.278×10^{-3} kg/s (11.8 kg/hr) and the duration of leakage is 1505 s. The sodium temperature at the leakage is 505 ºC. With regard to the ventilation of the test vessel, a pump is attached at the outlet of the vessel and suctions the gas in the vessel at a rate of 3.0 Nm^3/s.

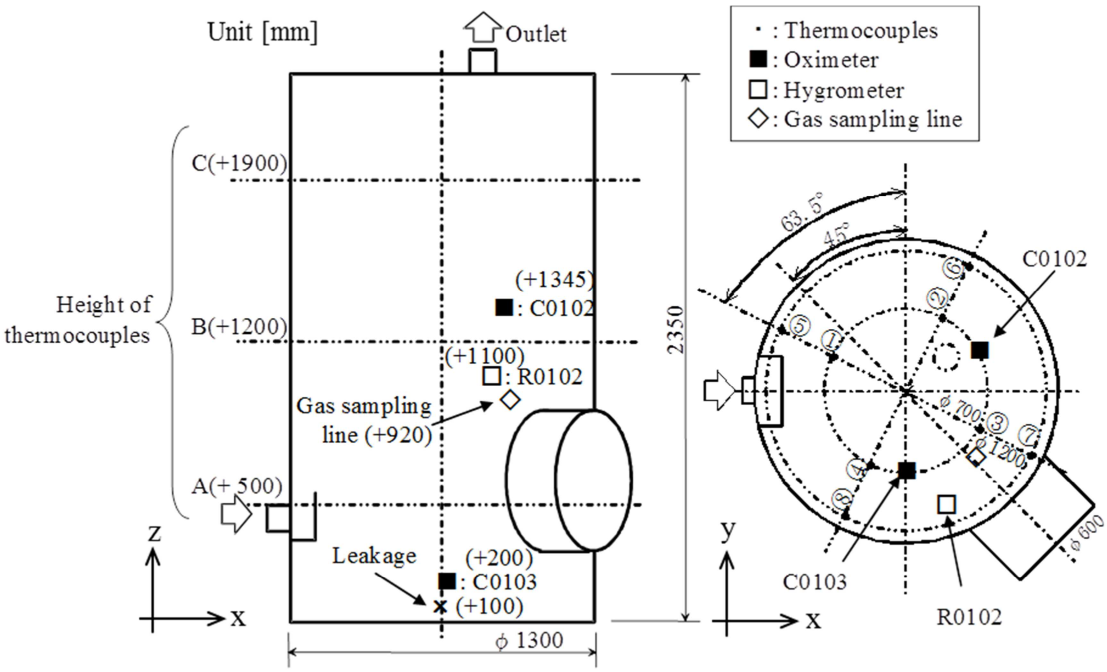
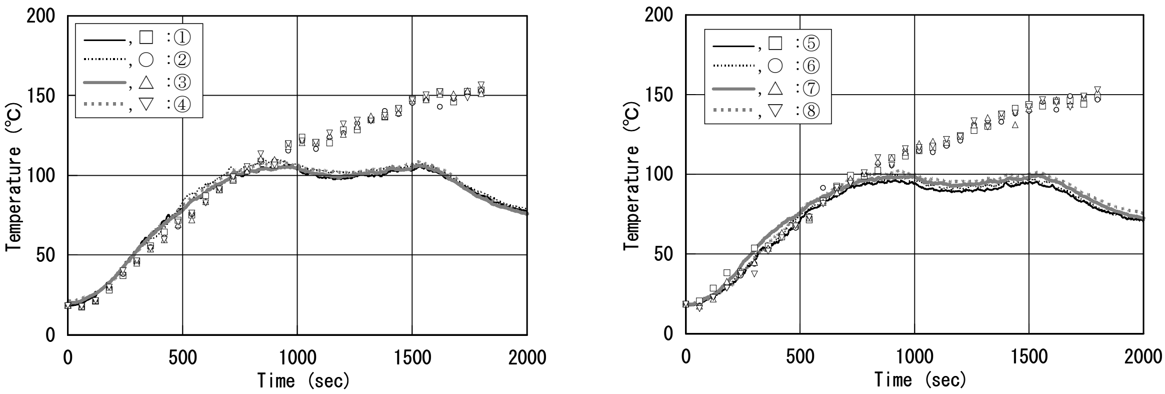


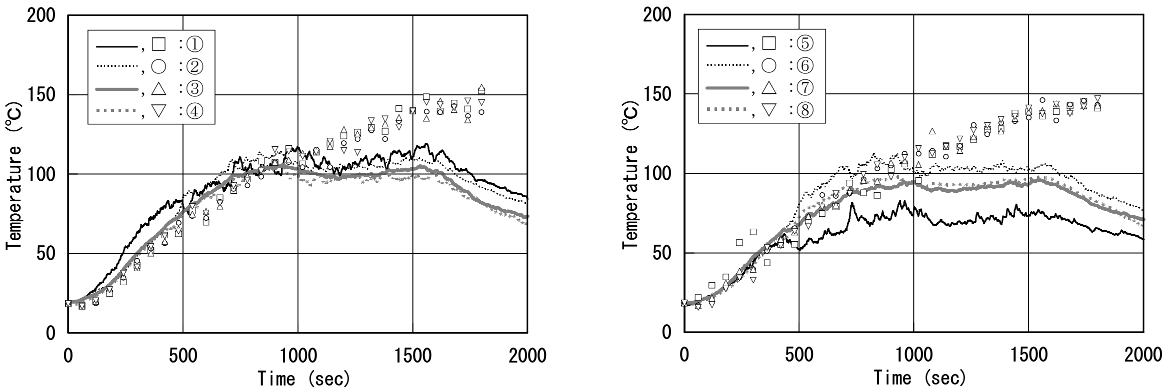
Figure 9 Test vessel and measurement locations of run F7

In the analysis, one still has to determine the condition for spray combustion (droplet diameter and nozzle angle). The average diameter is calculated based on the average velocity of sodium at the leakage and the surface tension and is set to 4.5×10^{-3} m considering a columnar mode. In the SPHINCS code, one point approximation is applied to the test vessel, while the inside of the test vessel is segmented into 29(x) × 29(y) × 25(z) cells in AQUA-SF code. The computational duration is set to 3600 s in the SPHINCS code and 1800 s in the AQUA-SF code.

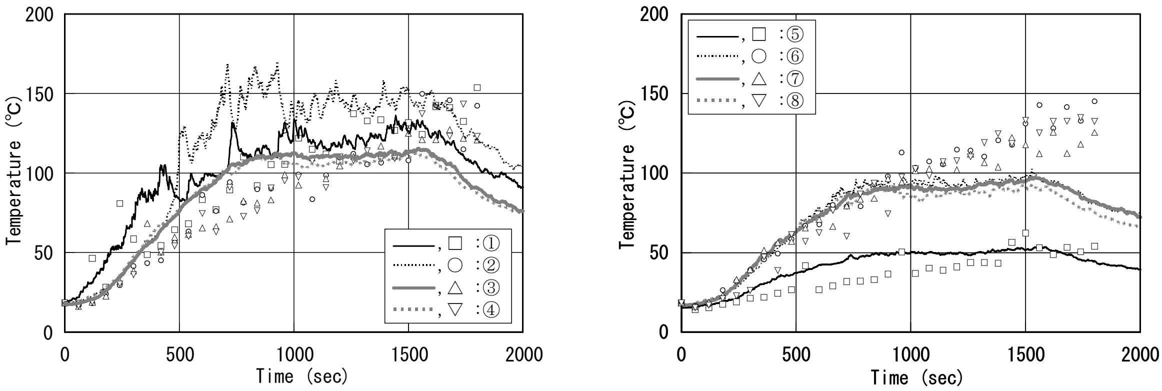
Figure 10 shows the comparison of the gas temperature between analytical and experimental results. The symbols indicate the analytical results in Figure 10. In the AQUA-SF code, a good agreement is obtained first 1000 s as shown in Figure 10. 1000 s after the leakage, the gas temperature still continue to increase resulting in overestimation of the gas temperature in the analysis, while almost the gas temperature is observed from 1000 s to 1500 s (end of the leakage) in the experiment. A similar behavior of the gas temperature is investigated in the SPHINCS code. However, the gas temperature is almost in range of the measured data as in Figure 10.



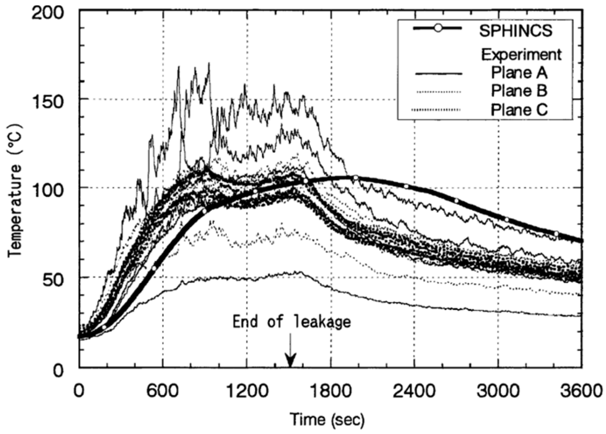
Top side (level C, + 1900 mm, AQUA-SF)



Center side (level B, + 1200 mm, AQUA-SF)



Bottom side (level A, + 500 mm, AQUA-SF)

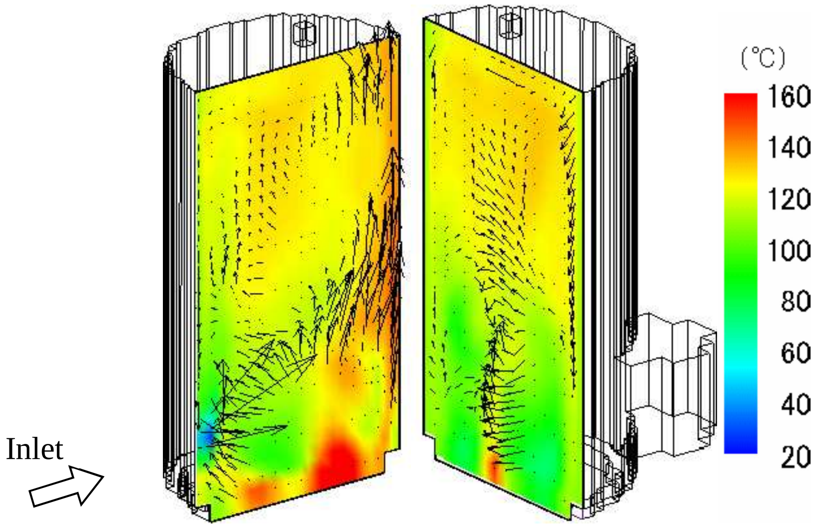


SPHINCS

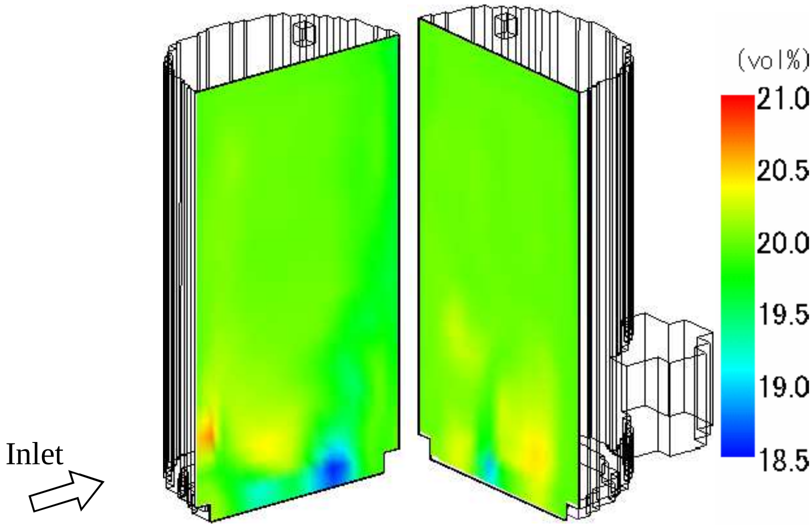
Figure 10 Gas temperature in the test vessel

The distribution of temperature, velocity field and oxygen concentration at 1200s in test vessel is pictured in Figure 11. As shown in Figure 9, an obstacle is implemented in order not to feed the fresh air directly to the pool surface in the experiment. Therefore, no direct flow path to the pool surface is investigated in the analysis and the high temperature region appears at the opposite side from the inlet. As a result, a local minimum of oxygen concentration also appears at the opposite side. However, local maximum of oxygen concentration also appears near the pool surface because of the fresh air feeding at the same time. Therefore, the higher pool combustion is achieved in the AQUA-SF code resulting in the higher gas temperature than that in the SPHINCS code. The overestimation of the gas temperature comparing with the experimental result will be discussed later.

Figure 12 show the comparison of oxygen concentration. In the AQUA-SF code, the same tendency with the gas temperature is obtained. Since the average oxygen concentration in the vessel is calculated in the SPHINCS code, the oxygen concentration increase gradually after 1200 s as in Figure 12. This is attributed to the fact that the average oxygen concentration is evaluated based on the mass balance among inlet feeding, outflow from the outlet and consumption at the pool. Although the recovery of oxygen concentration after approximately 1200 s differs from the measured data, the range of the concentration investigated in the analyses agrees with the experimental result.

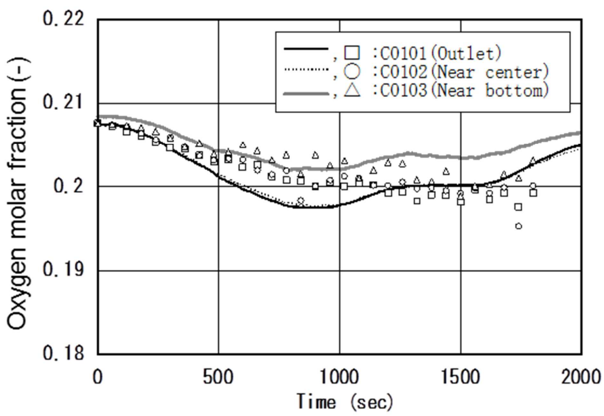


(a) Temperature and velocity distribution

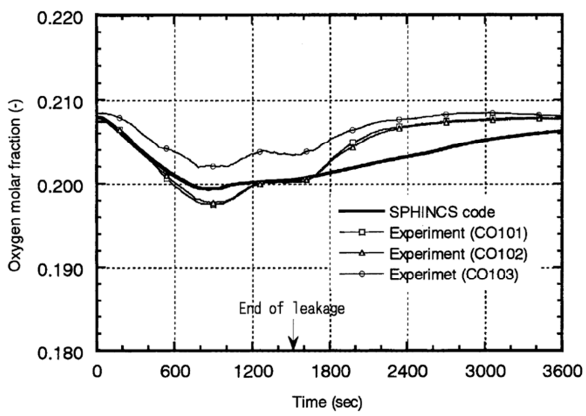


(b) Distribution of oxygen concentration

Figure 11 Gas temperature and oxygen concentration in the test vessel at 1200 s (AQUA-SF)



AQUA-SF



SPHINCS

Figure 12 Oxygen concentration in the test vessel

The aerosol concentration investigate in the AQUA-SF code is shown in Figure 13 (solid symbol indicates the measured data). As seen in Figure 13, the aerosol concentration is kept almost constant after 1000 s and agrees well with the measured data except the outlet concentration at 700 s. As mentioned in Eq. (31), the aerosol behavior is affected by not only fluid dynamics of circumference gas but also thermal diffusion, coagulation and a gravity effect. Therefore, the different transient from the gas temperature is investigated in the present study.

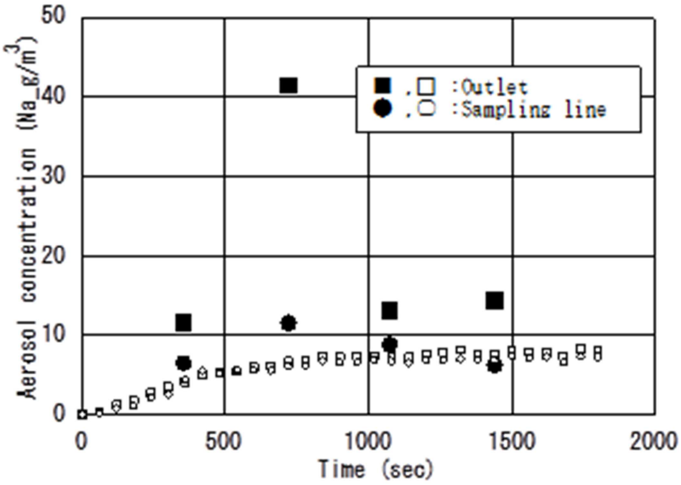
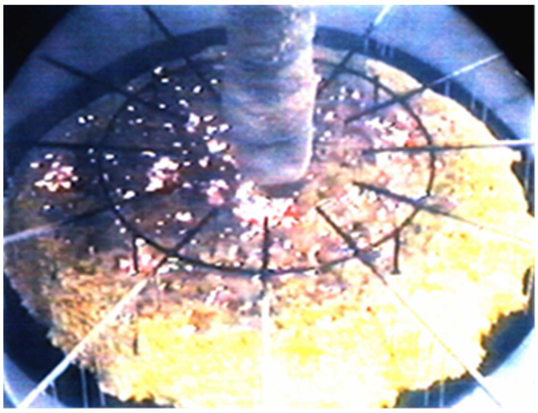
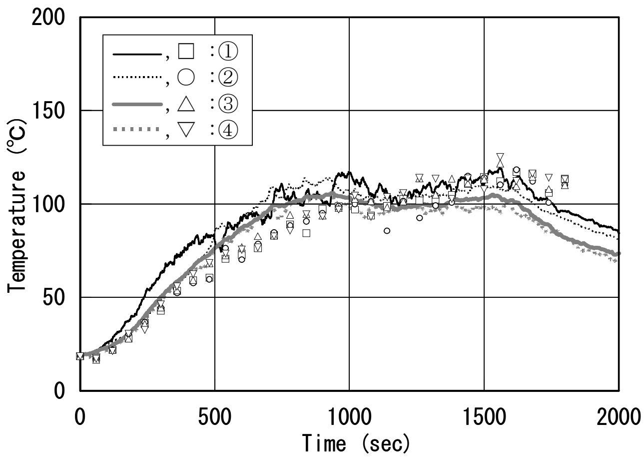


Figure 13 Aerosol concentration in the test vessel (AQUS-SF)

Let us discuss the different time history of the gas temperature between the analysis and the experiment. The photograph of the pool after the experiment is shown in the left side of Figure 14. As seen in the photograph, the pool surface was covered up by the reaction products with a pancake-like shape. It is reported that the aerosol release fraction at the pool combustion decreases in accordance with a decrease of pool temperature [20]. In run F7-1 experiment, a comparative small pool area was set (approximately 0.28 m^2). It is noted that almost the same pool area is investigated in the analyses. In general, a small pool combustion test leads to a low pool temperature comparing with that in a large scale pool combustion test.





Surface adhesion of reaction products Modification of pure sodium pool surface area

Figure 14 Influence of surface adhesion of reaction products

Hence, the surface adhesion due to the reaction products was observed in the experiment.

On the other hand, it is assumed that pure liquid sodium exists in the pool surface in the model. In order to investigate the influence of the surface adhesion on the combustion, the following simple model, where the pure liquid sodium surface decreases in proportion to the total amount of the reaction product in the pool, is introduced in Eqs. (17) and (19) as:

$$N'_{Na} = \omega_{ad} N_{Na}, \ \omega_{ad} = \frac{m^{pl}_{Na}}{\sum_k m^{pl}_k}. \quad (40)$$

Here, ω_{ad} and m^{pl}_k mean the damping factor due to surface adhesion and the mass of species such as Na, NaOH, Na_2O and Na_2O in each computational cell of pool. The gas temperature using the modified model is shown in the right side of Figure 14.

As seen in Figure 14, a good agreement is investigated when the influence of the surface adhesion is taken into consideration. However, it is noted that the surface adhesion will be a particular phenomenon especially in case of small pool combustion where the pool temperature does no increase so much. Hence, the surface adhesion model may not be necessary from the LMFR plant safety's viewpoint.

As a result of the benchmark analysis, it is concluded that a good agreement with the experimental result is achieved both in the SPHINCS and the AQUA-SF codes, even if the pool combustion is overestimated later in the experiment because the pure liquid sodium is assumed at the pool surface in the model.

CONCLUSIONS

In a liquid metal fast reactor (LMFR), sodium fire incident is one of the key issues from the viewpoint of plant safety. After the sodium fire incident in Monju, New numerical tools for sodium fire evaluation have been developed in Japan Atomic Energy Agency (JAEA) based on a multi-zone model (SPHINCS code) and a filed model (AQUA-SF code). Sodium combustion models (pool combustion and spray combustion), an aerosol behavior model and a radiation model are coupled with a flow network in the SPHINCS code and a multi-dimensional thermal hydraulics analysis in the AQUA-SF code.

Two benchmark analyses have been carried out to investigate the applicability of the present methods. In the benchmark analysis of airflow due to temperature difference (buoyancy-driven natural ventilation), it is concluded that the airflow can be investigate using the present field model (AQUA-SF code). It is also demonstrated that the mesh arrangement taking into account a neutral elevation will be useful to achieve good prediction accuracy with a small number of computational cells. The airflow with multi-openings is also investigated in the analysis and it is demonstrated that the numerical analysis agrees with the empirical correlation to integrate into one opening, which is applied in the SPHINCS code.

As a result of the benchmark analysis of small pool combustion experiment, a good agreement with the experiment is investigated during the early part of the experiment (- 1000 s) in both the SPHINCS and the AQUA-SF codes.

On the other hand, it is also found in the analyses that the pool combustion is overestimated later in the experiment. In the experiment, it was observed that the pool surface was covered up by the reaction products. Hence, the surface adhesion due to reaction products, which is not taken into account in the combustion model, affects the pool combustion. Since this phenomenon is particular especially for small pool combustion, it may not be necessary from the viewpoint of LMFR plant safety assessment.

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APPLICATION OF FIRE MODELING AND SIMULATION FOR FIRE HAZARD ANALYSIS

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ABSTRACT

Fire is one of the severest threats to any industry /dwelling units /commercial establishments needing proper attention for evaluation of the possible fire events and their outcomes so as to suitably design the structural members and fire barriers to limit the losses to lives, equipment and environment. It is mandatory in some countries and in nuclear industry, in particular, to carry out Fire Hazard Analysis (FHA) during the various phases of plant life cycle. For FHA it is required to estimate the variation of heat flux, temperature and smoke density of postulated fires in the plant. This paper deals with the application of fire modeling and simulation techniques in FHA along with case study as well. Post-Fukushima and other earthquake induced incidents of fire are very common, which require to be investigated using FHA for possible damages that can occur in case of fire. This paper is meant for the general awareness on fire modeling and simulation for the purpose of FHA and not really intended for the experts in FHA.

INTRODUCTION

In a nuclear power plant (NPP) a FHA should be performed to assess the fire hazard and demonstrate that the plant will maintain its ability to perform safe shutdown functions and minimize radioactive material releases to the environment in the event of a fire. The objectives of FHA are the following [1]:

- Consider potential in situ and transient fire hazards:
- Determine the consequences of fire in any location in the plant, paying particular attention to the impact on the ability to safely shut down the nuclear reactor or the ability to minimize and control the release of radioactivity to the environment;
- Specify measures for fire prevention, fire detection, fire suppression, and fire containment, as well as alternative shutdown capability for each fire area containing structures, systems and components (SSCs) that are important to safety;
- Basic goal of FHA: Whether a particular combination of fire hazard and fire protection results in an acceptable level of safety.

The goal of an FHA is to determine the expected outcome of a specific set of conditions called a fire scenario. The scenario includes details of the fire sources and combustibles present in the area of concern, area/room dimensions; contents and materials of construction; arrangement of rooms in the building; sources of combustion air; position of doors /windows: numbers, locations; ventilation flows and opening areas with height of location; characteristics of occupants; and any other details that have an effect on the outcome of interest.

FIRE MODELS

There are different fire models adapted to postulated fire scenarios based on the fire load of combustibles and inflammables, their quantity, type of combustibles, ventilation parameters such as air or oxygen flow, ventilation openings, etc. in the area under consideration.

Fire models are simulated and results are analyzed within FHA for the possible hazards in terms of damage to lives, property and environment caused by thermal degradation of materials and structures, burning/charring, smoke generation, soot formation.

Typical types of fire models are zone models, field models or computational fluid dynamics (CFD) codes, network models, algebraic / empirical models.

A zone model divides the entire hot gas layer resulted from fire into various temperature zones like upper layer and lower layer in a two-zone model and multiple layers in case of multi-zone models. Zone models use mathematical and empirical fire equations applying conservation of mass and energy to estimate the temperature, heat flux, smoke density and their variation with time. Zone sizes change during the course of the fire. The upper zone can expand and occupy virtually the entire room volume. By definition, zone models will always be approximate. Zone models are relatively simple and give less accurate results, but are faster to calculate than field models which are much more detailed and more accurate but slower.

A field model divides the entire fire compartment or space into small control volumes applying conservation of mass, momentum and energy using (CFD) so as to estimate the temporal variation of temperature, heat flux, smoke density etc. A typical CFD model consists of a pre-processor (preparing the input file based on geometry of the fire compartment, dimensions, ventilation flows and opening areas and the properties of combustibles), a solver solving Navier-Stokes equations for conservation of mass, momentum, energy and species, and a post-processor (preparing the output files to provide variation of temperature, heat flux, smoke density, velocity, pressure etc. parameters over time). It is a low-speed, thermally-driven flow, with an emphasis on smoke and heat transport from fires.

Various computational models are used for modeling fires and carrying out FHA. In the following, various models (as mentioned in [1]) are listed, some of them typically applied for nuclear installations fire simulation:

- Zone models (e.g. COMPBRN-III, CFAST, FIREWIND, BRANZFIRE, MAGIC;
- Field or CFD based models (e.g. FDS, FLUENT, JASMINE, PHOENICS, SMARTFIRE, SOFIE, STAR-CD).

Among these models, CFAST [2] as well as MAGIC (see [3] and [4]) as zone models and FDS [5] and JASMINE as field models are commonly used for fire simulation and modeling for nuclear installations. Figure 1 presents the accuracy versus simplicity and/or speed of computation for the various fire models aiming on tomorrow when compared today.

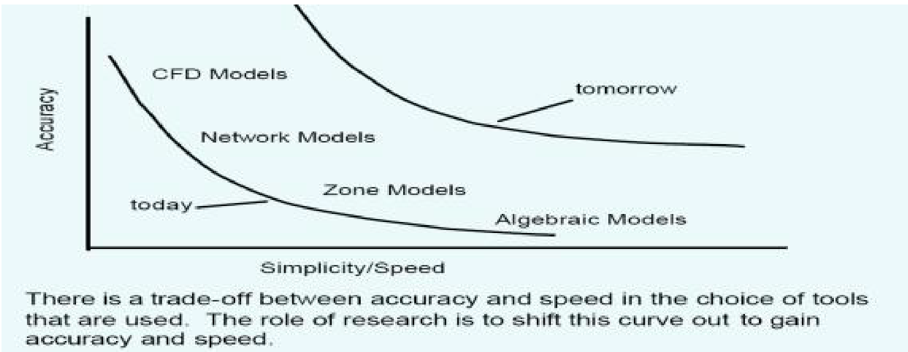

Figure 1 Performing comparison of fire models [4]

The recommended fire modeling methodology comprises in total six steps:

(1) Define fire modeling goals,
(2) Characterize the fire scenarios,
(3) Select fire models,
(4) Calculate fire generated conditions,
(5) Conduct sensitivity and uncertainty analyses, and
(6) Document the analysis.

The corresponding fire modeling process is depicted in Figure 2.

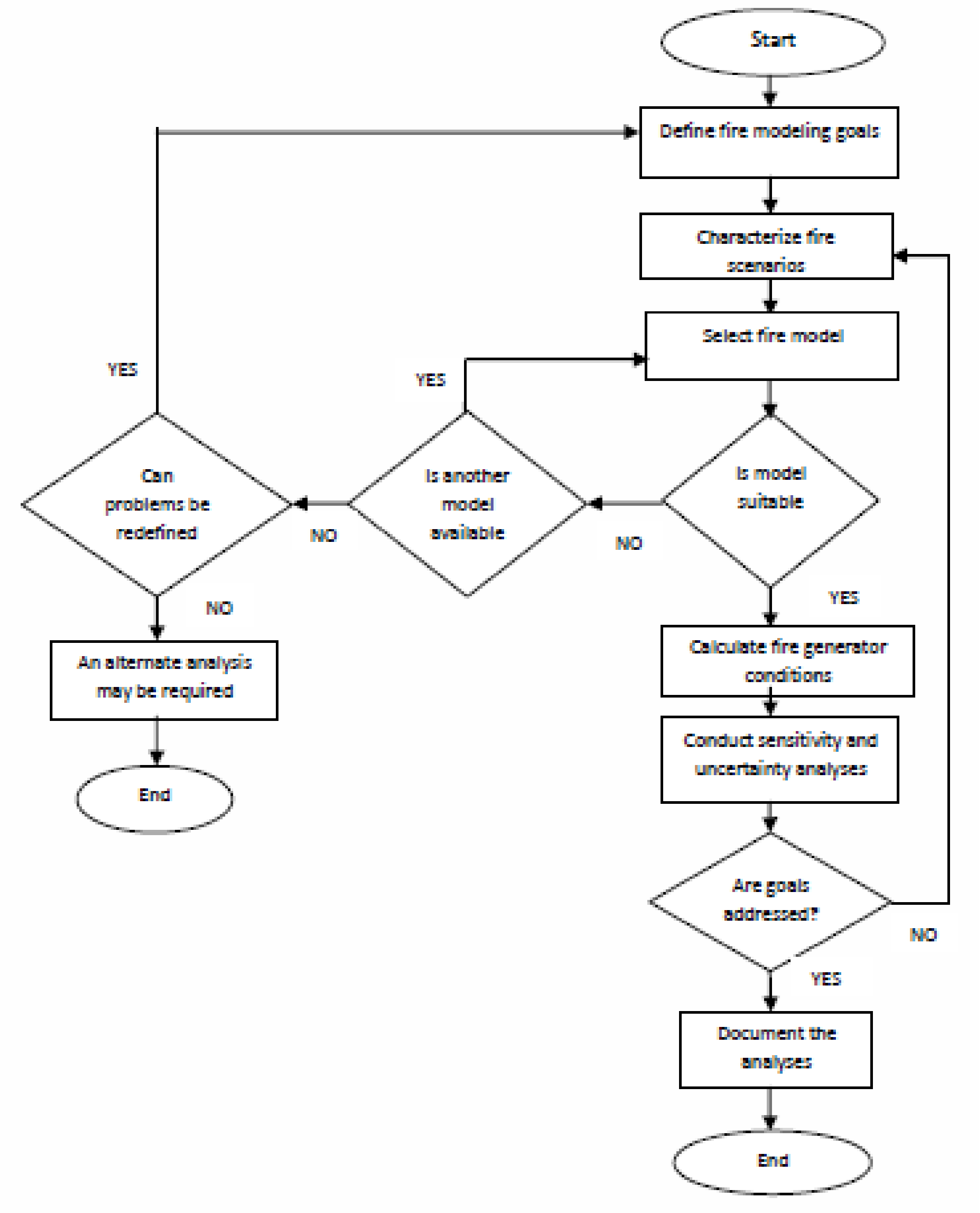

Figure 2 Fire modeling process [4]

Fire models are verified and validated ('V&V') by experiments under various collaborative projects such as ICFMP (*I*nternational *C*ollaborative *F*ire *M*odeling *P*roject) [7] involving various institutions from all over the world such as BRE, Fauske & Associates, GRS, iBMB, IRSN, NIST, U.S. NRC, SNL, etc.

Depending on the type of fire, there are different approaches for V&V of fire models have been applied, e.g. in the United States, such as THIEF (*T*hermally *I*nduced *E*lectrical *F*ires) as outlined in [8], the CAROLFIRE (Cable Response to Live Fire) cable fire experiments [9] and their resulting data [10], or the CHRISTIFIRE experiments [11] (*C*able *H*eat *R*elease, *I*gnition, and *S*pread in *T*ray *I*nstallations during *Fire*) which deal mainly with electrical and cable fires. As most of the fires in nuclear power plants in the world are due to cables or electrical equipment, cable fires are given special treatment – this is beside the point that the cables undergo smoldering or slow fires.

The first step in selecting a fire model is to determine whether the scenario can be analyzed using algebraic models, zone models, or CFD models. Some models are worth to be mentioned in this context: FDT^s [1], FIVE [6], CFAST [2], MAGIC [3], [4] and FDS [5]. FDT^s and FIVE represent a set of relatively simple algebraic models codified in the form of electronic spread sheets. CFAST and MAGIC represent the class of fire models commonly referred to as zone models, which divide a compartment of interest into two zones, an elevated temperature upper layer and a cool lower layer. FDS is an example of a CFD model, which divides each compartment into thousands or millions of cells. Temperatures and other quantities of interest are calculated for each cell.

In this paper, discussion is restricted to the application of the CFD based Fire Dynamics Simulator (FDS) [5] for estimating the variation of temperature, heat flux, smoke density, etc. over time for analyzing the fire hazards.

FDS AS FIRE MODEL

Due to space constraints (i.e. limit on the number of pages) in this publication only FDS is chosen as the fire model and simulation tool which is emphasized more in this paper on account of its widespread acceptability and benchmarking by experiments [7].

Why FDS?

1. FDS is an internationally bench-marked open source software developed by National Institute of Standards and Technology (NIST), USA and has been validated by multiple reputed expert organizations.
2. It is one of the two software tools to be used for FHA as recommended by Atomic Energy Regulatory Board (AERB) of India [12]. It is also one of the five analytical tools recommended by U.S. NRC for FHA [3], [4].
3. It is a Low Mach number (less than or equal to 0.3) CFD based code specific to fire-related gas flows and hence simulates the fire hazards in a better way. It is more suited for confined fires, as the heat release rate (HRR) in case of confined fires is much higher (5 - 6 times) than that in case of unconfined fires (fires open to atmosphere).
4. Fire protection engineers often need to estimate the location of the interface between the hot, smoke-laden upper layer and the cooler lower layer in a burning compartment. Relatively simple fire models, often referred to as two-zone models, compute this quantity directly, along with the average temperature of the upper and lower layers. In a CFD model like FDS, there are not two distinct zones, but rather a continuous profile of temperature.
5. FDS is an already verified and validated software by the FHA community and recommended by organizations such as NIST (as developer), SFPE, NFPA, etc., which are apex bodies in the area of fire research.

6. It has much better spatial fidelity than zone models, being able to distinguish conditions in one part of the volume from another.
7. It is more accurate than algebraic / empirical models like Fire Dynamic Tools (FDT^s) by U.S. NRC or Fire Induced Vulnerability Evaluation (FIVE) – Rev.1 by Electric Power Research Institute (EPRI) or zone models such as Consolidated Fire and Smoke Transport (CFAST) by NIST, MAGIC by EdF, France, etc.
8. Smokeview [13] is the visualization software, which FDS uses as supplementary software that helps in visualization of fire simulation and graphic output with animation of fire and smoke scenarios with contour diagrams and Microsoft EXCEL® sheets for temperature, heat flux, mass burning rate and smoke density as well.
9. The FDS simulation is able to describe the changing behavior of the fire as it interacts with its surroundings.
10. FDS is having many inbuilt models such as for liquid fires and cable fires with the properties of fire barrier structural materials and combustibles as well, which can be invoked directly by calling the names of these materials.

There are many FDS input parameters each of these can affect the simulation differently. In response to the inputs like geometry, fire models, materials, etc., FDS as a simulation tool processes the inputs and produces outputs in animated, graphical and spreadsheet formats which, in turn, need to be analyzed for fire hazards based on the simulation and experimental results.

A CFD model (e.g. FDS) has three basic parts:

- an interface to allow the user to input parameters,
- the flow solver which models the fire using the input,
- a graphical program to display results of the fire modeled.

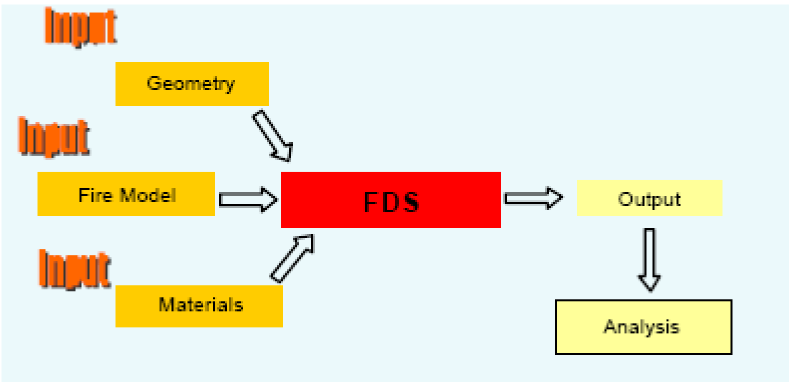

Figure 3 FDS as a fire dynamics simulation tool [6]

Where to Apply FDS?

While FDS provides a detailed analysis of a 3-D volume, it is effort wise costly to create, simulate and maintain. The input files created in the pre-processing stage require a significant effort to create. The user must understand the code syntax and the implications and assumptions embedded in the model. A firm understanding of fire dynamics is important in providing input data relevant to the application. Most FDS models have default values that must be recognized and adjusted as necessary, if the simulation is going to be accurate. The relevance of the default values needs to be confirmed for any application. User manuals [5] and technical references for each CFD model outline such values and may provide recommended ranges for the parameters.

FDS models are generally applied if according to [3] and [4],

- if spatial resolution is important, either relative to the locations of fuel packages or targets,
- if large compartments relative to the fire size are involved,
- if compartments have complex geometries, flow connections, or numerous obstructions in the upper part of the compartment, or
- if large numbers of compartments are within the area of interest and the presence of each compartment is expected to affect the fire environment in the area of interest.

Depending on the complexity of the scenario and the computer computational power, the solver within the model can take a few hours to weeks to complete all the calculations. Computation time cost depends on the measured parameters, the size of the geometry, and the mesh size of the calculations. Outputs of field models are visualized through a post-processing program. The CFD model developed at NIST, the Fire Dynamics Simulator (FDS) [5], employs the program “Smokeview” [13] to represent distributions of temperature, mass, heat flux, burning rate, etc. throughout the geometry. These parameters can be described through point locations, iso-contours or vector diagrams.

How to Apply FDS - A Case Study

FHA has been carried out for a large industrial facility in India, wherein FDS was used extensively for fire modeling and simulation and fire barrier ratings were calculated based on the fire curves [14], [15], [16] achieved by fire simulation using FDS. A sample FDS output for solid combustible like PVC cable catching fire is illustrated in Figure 4 and Figure 5 respectively.

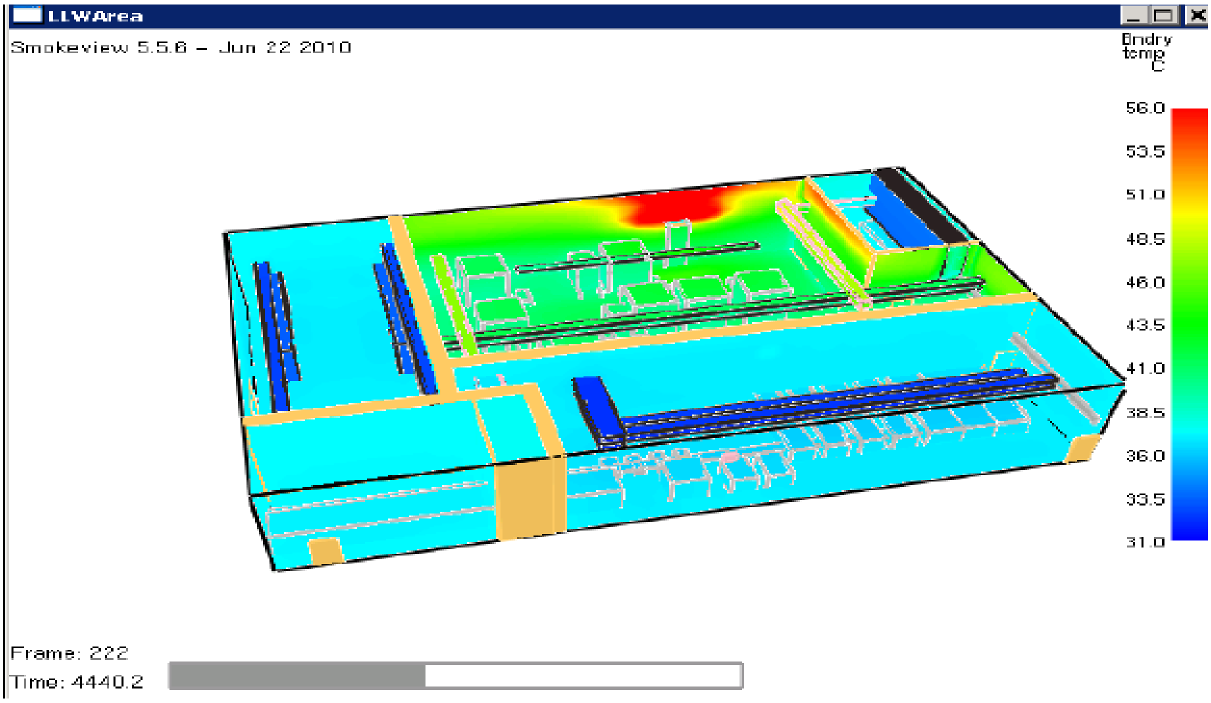

Figure 4 FDS – Smokeview output for temperature Profile for solid combustibles such as a PVC cable on fire

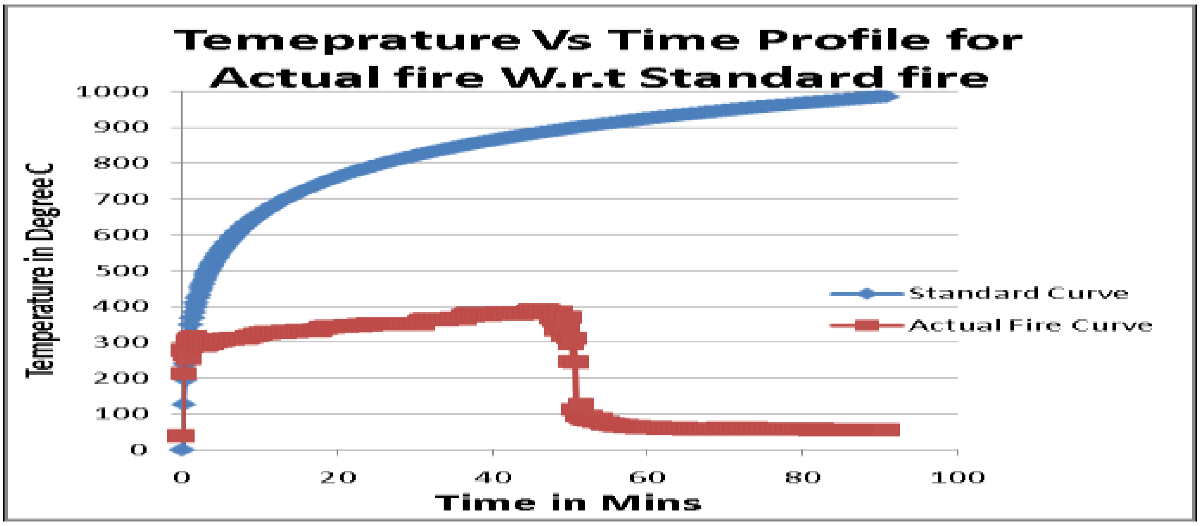

Figure 5 Temperature vs. time profile for a PVC cable fire based on FDS output

Using the Equal Area Criterion* much in line with NUREG-1547 [14], the fire resistance rating of the fire barrier was derived to be 21 min 12 sec based on the FDS results for solid fuels such as a PVC insulated cable on fire. Based on this value of fire rating a fire retardant paint of 30 min is suggested for the structural members and other non-structural members.

However, in this case no credit is given towards ventilation, fire loading etc. as Indian Standards insist on using worst-case fire scenario i.e. neither ventilation cut-off nor any automatic/manual intervention on detecting the fire.

Determination of fire rating for fire barriers in some countries (e.g. India) is governed by ISO 834 curve as the indigenous fire barrier manufacturers/suppliers of such countries follow the ISO 834 standard fire curve.

Fire curves using parametric models should be ideal for fire rating determination. Even German nuclear safety standards [17] can be used easily without going through the relatively complex procedure of fire rating determination using the comparatively complex FDS code.

**Note:*
The 'Equal Area Criterion' is basically equating the energy under the actual fire temperature-time curve and the standard fire temperature-time curve so as to get the fire barrier rating in terms of the equivalent fire temperature-time curve.

CONCLUSIONS

Application of fire dynamics modeling and simulation software tool FDS [5] within FHA with other variations of models have been discussed. Due to limitations on the number of pages for publication only some of the models could be discussed. One of the most widely recommended important fire models, FDS [5], is discussed with a sample case presented with FDS screen snapshots.

FDS is computationally quite expensive and time consuming taking hours to several days to receive the results. This should be improved by having better algorithms and a faster solver, which the researchers with high skills in computational mathematics and software should be able to easily develop. The author takes this opportunity to use the forum of the "SMiRT-22 Post-conference Seminar on Fire safety in Nuclear Power Plants and Installations" to appeal to all researchers for resolving this problem. The author regrets his inability to cite the exact applications based on his work in Indian nuclear industry associated with the application of fire modeling and simulation within FHA due to constraints of confidentiality agreements with the clients.

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FIRE PRA: DETAILED FIRE MODELING OF MAIN CONTROL BOARD

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ABSTRACT

In the absence of an existing verified and validated computational tool to determine the probability of damage to a target set of components due to a Main Control Board (MCB) fire, a method was proposed in NUREG/CR 6850 [1], Appendix L. This method has the advantage that it reduces analysis of a potentially large number of MCB fire scenarios to consideration of a limited number of individual target sets of critical MCB components/cables with each target set being defined only by a single parameter, the maximum separation distance (d) between them.

This paper describes the use of Monte-Carlo simulation to evaluate the probability of component failure due to Main Control Board fires. The method is applied to the specific scenario considered in NUREG 6850 [1], Appendix L using the same physical model and data and the results are compared with those derived analytically. The flexibility of the simulation technique is then demonstrated by applying it to different scenarios without the constraints of the simplifying assumptions necessary for the analytical method.

INTRODUCTION

NUREG/CR 6850 [1], Appendix L (hereafter referred to as "Appendix L") presents an analytical method for estimating the probability of fire damage to a target set of components on the front panel of a vertical Main Control Board. Results are presented in Appendix L for the specific case of a panel 60 ft. wide and 10 ft. high. For panels with different dimensions it would be necessary to repeat the analysis making the appropriate changes to the limits of integration. Moreover, to simplify the analysis, a number of assumptions and approximations were made that limit the applicability of the analytical method to practical situations. These assumptions are highlighted in a review of the Appendix L methodology, summarized below.

The limitations of the Appendix L methodology can be surmounted by using the Monte-Carlo simulation technique, which provides a powerful and flexible tool for solving a wide range of practical problems. The application of this technique and results using the physical model described in [1], Appendix L is described.

APPENDIX L FORMULATION

Physical Model

Appendix L considers a target set of two components mounted on the front panel of a vertical main control board a distance (d) apart (see Figure 1). The mid-point between the two targets has coordinates (w, h) and the fire is assumed to be fixed at the origin (0,0).

Assuming that the two targets are on the line joining the mid-point between them with the origin, the distance between the origin of the fire and the farthest target is given by:

$$r(d, w, h) = \frac{d}{2} + \sqrt{w^2 + h^2} \qquad (1)$$

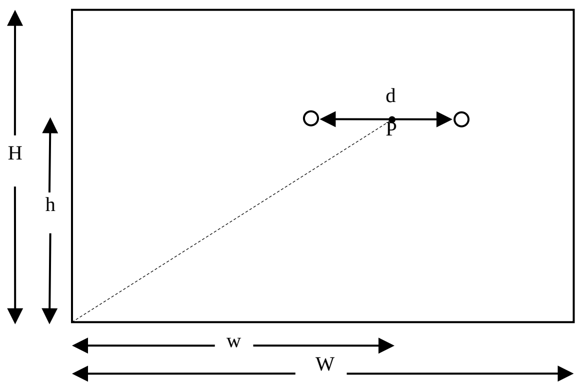

Figure 1 Diagram of control panel with two target elements

The maximum temperature rise above ambient (ΔT) at this distance from the fire is calculated from Alpert's correlation for fire plume temperature:

$$\Delta T = 16.9 \left[\frac{(kQ)^{2/3}}{r^{5/3}} \right], \qquad (2)$$

Where:

k = location factor = 2 for a vertical wall

Q = heat release rate [kW]

r = vertical distance above origin of fire [m]

Applying the plume correlation is clearly pessimistic as, in general, the farthest target will not be in the fire plume, i.e. vertically above the origin of the fire.

The heat release rate (Q) is assumed to follow a t^2 growth rate, rising to its peak value $\hat{Q}$ in 12 minutes. Thus:

$$Q = \hat{Q} \left(\frac{t}{12} \right)^2 \text{, t 12} \qquad (3)$$

The rate of decay after reaching the peak heat release rate is immaterial in this methodology, since the temperature rise is assumed to be dependent only on the instantaneous value of the heat release rate (Q) and not on the cumulative quantity of heat released.

The time taken to suppress the fire ($\hat{t}$) is modeled as a random variable with an exponential distribution, i.e.

$$\hat{t} = \frac{1}{t_m} \exp\left(-\frac{t}{t_m} \right) , \quad (4)$$

where

t_m = mean suppression time (assumed equal to 3 minutes).

Monte-Carlo Simulation

A Microsoft EXCEL® worksheet has been created to calculate the temperature rise (ΔT) at a distance (r) from the origin of the fire for any values of d, w, h and Q using equations (1) and (2). Using the “Crystal Ball” software, a simulation is performed to model the variability of the target location, the peak heat release rate and the time to suppress the fire.

For each iteration the following steps are performed:

1. The location of the mid-point between the two targets is chosen at random assuming that w and h are uniformly distributed between 0 and 60 ft. and between 0 and 10 ft. respectively, assuming the same panel dimensions as Appendix L.
2. The value of (r) is calculated from Eqn. (1) for given value of (d).
3. The peak heat release rate is chosen at random from a Gamma distribution with shape and scale parameters (0.7, 216) for qualified cable and (0.46, 386) for unqualified cables. These parameters are derived from NUREG/CR 6850 [1], Appendix G as in Appendix L but with scale parameter in units of kW.
4. The suppression time is chosen at random from an exponential distribution with a mean value of 3 minutes.
5. The heat release rate immediately before the fire is suppressed is calculated from Eqn. (3) and the corresponding temperature rise at the farthest component from the fire in the target set is calculated from Eqn. (2). (If the suppression time is greater than 12 minutes, the HRR is set equal to the peak value.)
6. If the temperature rise is greater than the damage threshold temperature of 330 °C for qualified cable or 205 °C for unqualified cable, a failure is recorded.
7. The probability of cable failure is calculated as the mean number of failures, calculated as a fraction of the total number of iterations performed.

The calculations are repeated for a large number of iterations until the probability of failure converges to a steady value (typically after a few hundred thousand iterations).

Results

The results of using Monte-Carlo simulation for the analysis of the model described in Appendix L are presented in Figure 2.

Good agreement is obtained with the results in [1], Figure L-1 for qualified cables, which provides confidence in both methods of analysis. The agreement for unqualified cables is not as good with the probability of damage calculated by simulation being predicted to be higher than predicted by the analytical method of Appendix L. Subsequent comparisons are performed for qualified cable.

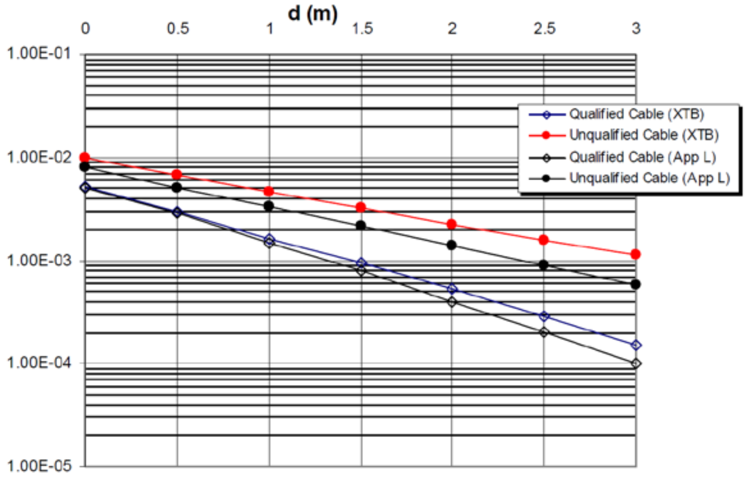

Figure 2 Probability of target damage vs distance d [m]; comparison of NUREG/CR 6850 [1], Appendix L vs Monte-Carlo model simulation (XTB)

EVALUATION OF APPENDIX L SIMPLIFYING ASSUMPTIONS

This section demonstrates how the Monte-Carlo simulation technique can be used to investigate the sensitivity of the results to the simplifying assumptions made in the analytical method presented in Appendix L and to provide results for a much wider range of situations encountered in practice. The simplifying assumptions made in the Appendix L methodology are identified in the review comments presented below.

Location of Targets

To simplify the mathematical analysis in Appendix L, the integration is carried out over all values of the coordinates (w, h) (the mid-point P between the two targets) within the panel boundary. This means that, for values of d greater than zero, the integration will include some positions of the mid-point, near the edges of the panel and remote from the origin, for which the farthest target lies outside the panel boundary. There will also be positions of the mid-point P near the origin (where the fire is assumed to be located) for which the nearest target lies outside the panel boundary allowing the farthest target to be impossibly close to the fire. The error introduced by this simplification is hereinafter termed the “edge effect”.

Another assumption made in Appendix L to simplify the analysis is that the targets are oriented such that they lie on the line joining the origin with the mid-point P (see Eqn. 1 and Figure 1).

To determine the significance of the above simplifications, the Monte-Carlo simulation model was modified to constrain both the targets to lie inside the panel boundary. In addition, the targets were oriented to lie on a horizontal line, considered to be the most likely orientation of targets of interest in practice. The results of the simulation using this model for a 60 ft. x 10 ft. panel with qualified cable are presented in Figure 2 and compared with the results from Appendix L. If d = 0 the edge effect disappears and, as expected, the probability of damage obtained from the Monte-Carlo simulation is the same as that predicted in Appendix L. However, as ‘d’ increases, the probability of damage from Appendix L is overestimated by an amount which increases up to a factor of about 30 when d = 3 m. It is concluded that the error introduced by the edge effect is dominated by inclusion of farthest target locations that are impossibly close to the fire at the origin thereby artificially increasing the probability of damage.

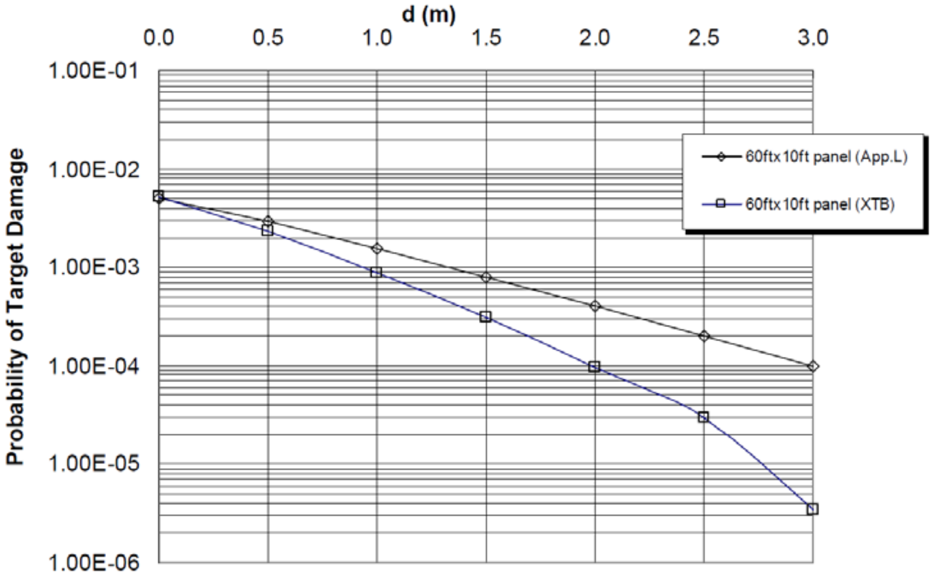

Figure 3 Investigation of "Edge Effect"

It is also worth noting here that, in the applications of the Appendix L method known to the author, the distance 'd' between the targets is taken to be the distance between the controls or instruments that are mounted on the panel regardless of the routing of cables inside the cabinet. In practice, the targets could be any points along the cables connected to the controls or instruments and the distance between them is therefore dependent on the cable routing inside the cabinet. Thus, bundling together of cables connected to panel-mounted targets of interest could significantly reduce the effective separation distance 'd' between them, thereby increasing the target failure probability.

Location of the Fire

Another of the most significant limitations of the method used in Appendix L is the assumption that the fire is fixed at the origin, i.e. at one corner of the control panel. This is non-conservative because the distance between the fire and farthest target component is on average greater than if the fire were considered to be anywhere on the panel.

Figure 4 shows the effect of allowing the fire to be located at random anywhere on a 60 ft. x 10 ft. panel with qualified cable, as compared with the results from Appendix L. These results were obtained using the simulation model described in Section 3.2 as the basis, i.e. with the edge effect eliminated and with targets aligned horizontally. This shows that the increase in probability of target damage that results from allowing the fire to be located anywhere on the panel outweighs the reduction achieved by eliminating the edge effect. The net effect is to increase the probability of target damage by a factor of a minimum of 3 when d = 0 increasing to a factor of 8 when d = 3 m.

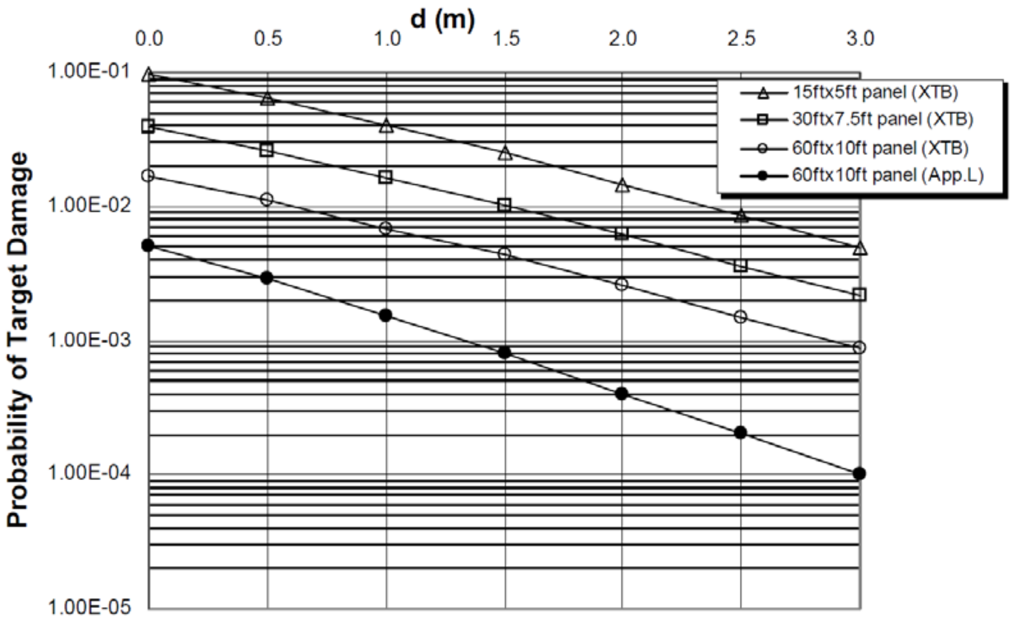

Figure 4 Effect of varying fire location

Figure 4 also shows the results for 30 ft. x 7.5 ft. and 15 ft. x 5 ft. panels using the same mathematical model, for which the restriction on panel size has been removed as well as removing the restriction on fire location, eliminating the “edge effect” and changing the assumption on target orientation.

Fire Modeling

The methodology in Appendix L of [1] is strictly only applicable to targets that are in the fire plume. This may be adequate for a vertical panel in which fire sources and targets are on the panel itself and there is sufficient ventilation to prevent build-up of a hot gas layer. However, in most practical applications, there will be target components (i.e. cables) and possibly some fire sources that are not mounted on a vertical surface but are inside the cabinet volume. In such situations, depending on the amount of ventilation to the outside of the cabinet, there will be a build-up of hot gas within the cabinet that could cause failure of more components than those located directly in the plume.

Furthermore, as in the case of components mounted on a near horizontal bench-board, failure could occur as a result of the effects of the ceiling jet spreading out beyond the area affected by an unconfined plume.

Although the Appendix L method is conservative to the extent that it assumes the plume extends equally in all directions, a more realistic model is required to correctly account for the effects of the hot gas layer and ceiling jet.

Summary of Issues Related to Simplifying Assumptions

Issue	Comments	Conservative	Non-conservative
Geometrical model	Assumes that both the fire and target components are on the front panel of vertical boards. Not applicable to bench board panels, which are almost horizontal.		✓
	Assumes both fire and targets are "points". Takes no account of cables routed inside the cabinet which may be closer together than the associated panel-mounted components.		✓
	Assumes that the fire is fixed at the origin (i.e. at one corner of the panel).		✓
	Assumes that targets are aligned with the origin of the fire, so that the furthest target from the fire is at its maximum distance away.		✓
	The model only limits the mid-point between the targets to lie within the panel boundary, so for values of 'd' greater than zero the most distant target could lie outside the boundary of the panel remote from the fire or impossibly close to the fire (termed the "edge effect").	✓	
Fire model	Assumes that targets are within a 2-D "axisymmetric" plume, in which the temperature is dependent only on the radial distance from the origin of the fire regardless of the targets' orientation relative to it. The justification is given that targets below the origin of the fire could be affected by molten material falling downwards.	✓	
	Neglects ceiling jet effects. This would be more significant for targets mounted on almost horizontal bench board panels.		✓
	Neglects the hot gas layer, which would build up inside a closed cabinet, engulfing targets within it and increasing the plume temperature by entrainment of hot gases by the plume.		✓
	Neglects direct radiant heat transfer from the fire.		✓
	The heat release rate curve (Figure L-3) includes the decay period, so that, if the suppression time is greater than 12 minutes, the plume temperature derived from it will be lower and could be below the damage threshold, even though the component could already have failed.		✓

APPLICATION OF MONTE-CARLO METHOD IN 3-D FIRE MODELING OF MCB

In the example MCB arrangement the cables enter the cabinets via conduits/sleeves passing through the main control room (MCR) floor into vertical cable risers located inside the back at both ends of each cabinet section (Figures 5 & 6). Cables are generally routed from these risers to the corresponding controls via two banks of four cable raceways, which run horizontally along the length of the cabinets aligned in the same vertical plane.

Cables connecting to controls and instruments on the MCB fascia emerge at intervals along the length of the horizontal cable raceways. The Appendix L methodology assumes that the distance between target components/ cables is determined by the location of the controls and instruments mounted on the front panel of the MCB. The method is not applicable to the cable raceways that run inside the MCB cabinets, since they are not mounted on the panel itself and moreover they are not point targets. An alternate model has thus been developed using MC simulation and applied to such cases. Fire scenarios are assumed to originate within an electrical component located on the control board front surface. As the fire grows, additional components located on the control board fall within the expanding zone of influence of the fire and become damaged. During this phase of the fire's growth the probability of damaging target sets is determined by the maximum separation distance (d) on the control board between any two components within the set according to the approach in Appendix L.

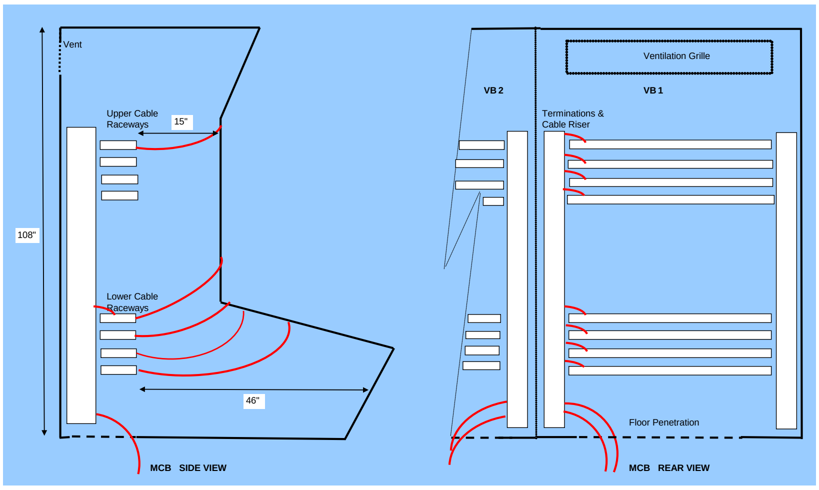

Figure 5 Example MCB arrangement

However, once the fire achieves a size where its zone of influence encompasses the upper or lower cable raceways located towards the rear of the panel, all components served by those raceways fail. In the case of the upper group of raceways, all components located on the upper section of the board are failed. In the case of the lower raceways, all components on the entire vertical section of the board are failed. This configuration serves to limit the distance over which fire spread on the control board surface is relevant. The MC model also encompasses the possibility of the fire being located in a position where it can impact the raceways of two adjacent sections of the vertical board.

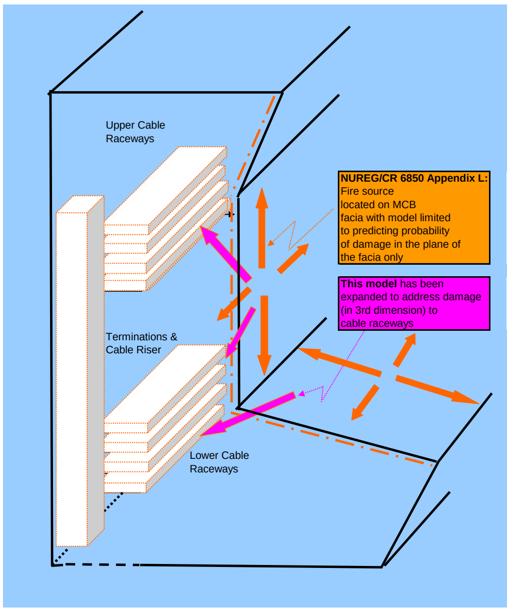

Figure 6 Example MCB arrangement – showing fire scenarios modeled

The fire source's heat release rate (Qs) is assumed to follow a t^2 growth rate, rising to its peak value $\hat{Q}_s$ in 12 minutes. Thus:

$$Q_s = Min\left[\hat{Q}_s\left(\frac{t}{12}\right)^2, \hat{Q}_s\right], \qquad (7)$$

where $\hat{Q}_s$ is modeled as a random variable with a gamma distribution having shape and scale parameters of 0.7 and 216kW respectively. These values are consistent with those used in Reference 1, Appendix L for a fire involving multiple bundles of qualified cable.

The time taken to suppress the fire ($\hat{t}$) is modeled as a random variable with an exponential probability distribution function, i.e.

$$F(\hat{t}) = 1 - \exp\left(-\frac{\hat{t}}{t_m}\right), \qquad (8)$$

Where t_m = mean suppression time (3 minutes).

Assuming a radiant heat fraction of 0.4, the heat flux at a distance r meters from the fire is then given by:

$$Q_r = \frac{0.4 Q_s}{4\pi r^2}, \qquad (9)$$

The distance r is calculated as the closest point to the fire on the section of the cable raceway being considered.

If the radiant heat flux exceeds the damage threshold level for a long enough time, cable failure could occur. The relationship between the incident heat flux and time to cable failure is given in Reference 1, Appendix H and is reproduced below in Table 1.

Table 1 Heat flux - failure time relationship for thermoset cables ([1], Table H-7)

Heat flux Q_r [kW/m^2]	Time to failure $t_{d\,[}$min]
< 11	No damage
11	19
14	12
16	6
18	1

The target is thus assumed to fail if the radiant heat flux exceeds the threshold level (i.e. Q_r > 11 kw/m^2) and the suppression time is greater than the time to failure (i.e. $\hat{t} > t_{d)}$. To calculate the time to failure it has conservatively been assumed that the cables are exposed to the maximum radiant heat flux throughout the fire growth phase.

The upper group of cable raceways were measured as 15" behind the upper, vertical panel of the MCB and, from the geometry of the MCB vertical cabinets, the mean distance between the lower cable raceways and the lower, sloping panel was calculated to be 26". Four separate cases were considered, one each for the upper group of cable raceways affected by a fire on either the upper or the lower panel and one each for the lower cable raceways affected by a fire on either the upper or the lower panel. In each model, the cable raceways were split into five separate sections, corresponding to the five sections of the vertical board (VB1 to VB5) and the probability of a fire anywhere along the whole length of the vertical board damaging any one or more of these sections of the cable raceways was calculated for each of the four cases.

The results are shown in Table 2 below, which gives the probability of damage to one section of either cable raceway, or to multiple sections, due to a fire anywhere along the upper or lower MCB panels.

It should be noted that the probability of damage to an individual raceway section given in 2 is inclusive of the probability of fires that also damage adjacent sections. Thus, for example, the cable raceway failure probability for VB2 includes the failure probabilities for combinations VB1, VB2 and VB2, VB3.

Table 2 **P**robability of damage to cable raceways

Vertical Board Section(s)	Upper Cable Raceways			Lower Cable Raceways		
	Fire on upper panel	Fire on lower panel	Fire on either panel	Fire on upper panel	Fire on lower panel	Fire on either panel
VB1	8.26E-03	3.26E-04	5.08E-03	1.15E-03	2.72E-03	1.78E-03
VB2	9.22E-03	4.24E-04	5.70E-03	1.41E-03	3.13E-03	2.10E-03
VB3	8.98E-03	4.34E-04	5.56E-03	1.29E-03	3.02E-03	1.98E-03
VB4	1.09E-02	4.40E-04	6.69E-03	1.54E-03	3.76E-03	2.43E-03
VB5	6.78E-03	2.76E-04	4.18E-03	8.85E-04	2.28E-03	1.44E-03
VB1,VB2	1.82E-03	9.00E-05	1.13E-03	3.05E-04	7.02E-04	4.64E-04
VB2,VB3	1.72E-03	1.18E-04	1.08E-03	3.40E-04	7.28E-04	4.95E-04
VB3,VB4	1.81E-03	1.06E-04	1.13E-03	3.10E-04	6.96E-04	4.64E-04
VB4,VB5	1.82E-03	1.02E-04	1.13E-03	2.65E-04	6.92E-04	4.36E-04
>2 VB sections negligible	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Using these values in the scenario frequency calculations for the probability of damage to the FTS comprising all the components associated with an individual section of the MCB is conservative. In the above the overall failure probability of the upper or lower cable raceway due to a fire on either the upper or lower panel of a given section of the MCB, was calculated as a mean value, weighted according to the relative frequency of a fire occurring on the upper or lower MCB panel. Assuming that the frequency of a fire on any panel is proportional to the panel area, the weighting factors are 0.6 and 0.4 respectively for the upper and lower panels, which are 48" and 32" in height respectively.

Damage probabilities associated with each fire scenario target set are based on [1], Appendix L (for scenarios involving component sets located on the MCB board face) and the method described in above for MCB cable raceway damage. In either case, the methods used imply the resulting probabilities are not mutually exclusive i.e. they include events involving more widespread damage.

Therefore, in order to avoid any double counting of the fire risk which may arise from the summation of the contribution from multiple fire scenarios, mutually exclusive damage probabilities for each fire scenario have been derived. The derivation of these probabilities is explained with the aid of the event trees provided in Figures 7 & 8, which illustrate the progressive development and relationship of each fire damage stage.

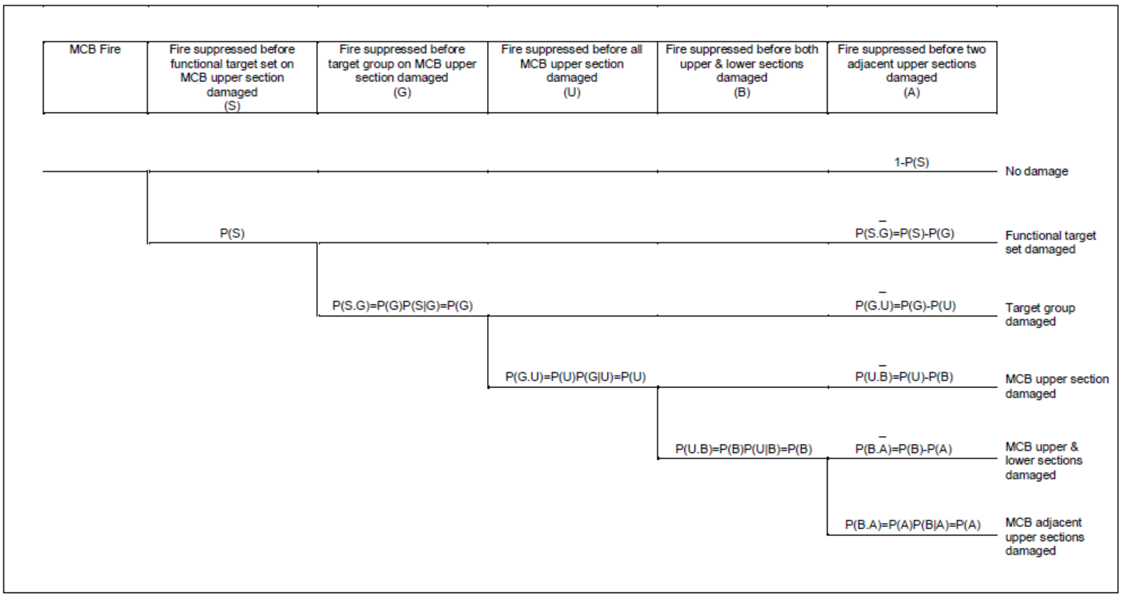

Figure 7 Fire scenario event tree for MCB upper section targets

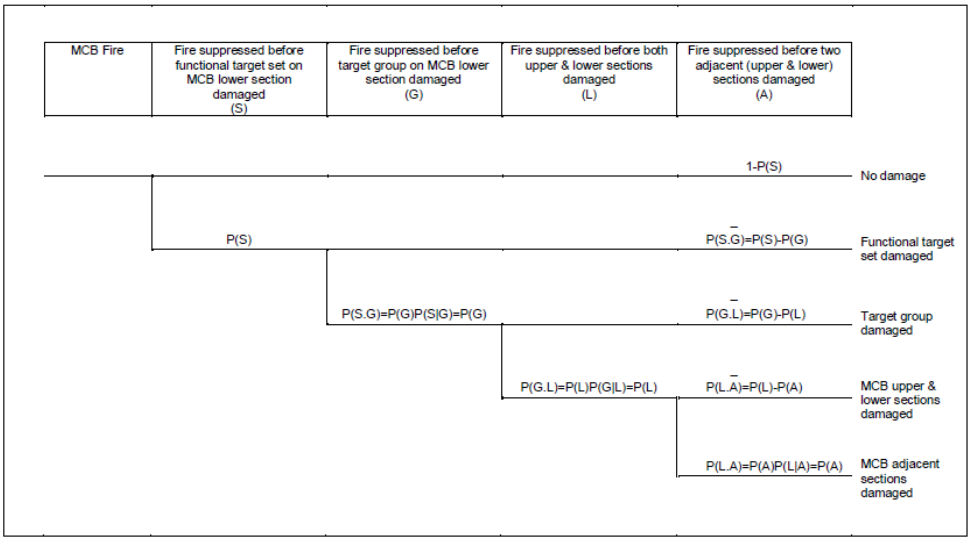

Figure 8 Fire scenario event tree for MCB lower section targets

CONCLUSIONS

In the absence of an existing verified and validated computational tool to determine the probability of damage to a target set of components due to a MCB fire, a method was proposed in NUREG 6850 Appendix L. However, to simplify the mathematical analysis, a number of assumptions and approximations were made that limit the applicability of the method in practice. A review of these assumptions has been carried out and presented above.

An alternative approach has been taken, using the Monte-Carlo simulation technique, and shown to give results in good agreement with those derived analytically in Appendix L when the same assumptions are made. The Monte-Carlo simulation model was then used to investigate the sensitivity of the results to a number of the most restrictive assumptions made in Appendix L, namely:

- Target location defined by mid-point lying within the panel boundary ("edge effect");
- Targets assumed to lie on the line joining the mid-point between targets to the origin;
- Fire location fixed at origin.

The sensitivity studies show that the overall effect of these assumptions is to potentially underestimate the probability of target damage (although conservative factors such as the use axi-symmetric plume model) may compensate.

The method has also been extended to consider three dimensional effects of fire that may result from damage to targets away from the control board fascia and to consider targets which are not necessarily located at single points.

The studies reported here demonstrate the flexibility of the Monte-Carlo simulation technique in its application to MCB fire analysis. The method can easily be extended to simulate complex 3-D geometries, including the location of sources anywhere in the MCB and the effect of cable routing inside the cabinet which may compromise the spatial separation of components observed on the MCB fascia. More realistic modeling of the effects of fire could also be incorporated to include ceiling jet effects and formation of a hot gas layer within an enclosed cabinet. The use of the MC technique also facilitates the propagation of modeling and parameter uncertainties through the fire modeling process.

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DEVELOPMENT OF THE METHODOLOGY FOR ANALYSIS OF CABLE FAILURE MODES AND EFFECTS (FMEA) FOR THE PURPOSE OF FIRE PSA

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ABSTRACT

Operational experience and analyses of fire events in nuclear installations have indicated that fire induced initiating events and component failures can contribute significantly to the safety of nuclear power plants. Meanwhile a state-of-the art Level 1 PSA includes Fire PSA as an integral part and supplement of the internal events PSA for all plant operational states. In the past it was assumed for Fire PSA that in case of fire in a compartment the entire components and cables in this fire compartment are damaged or in a "worst-case" state. However, this conservative assumption may lead to overestimation of the fire induced core damage frequencies.

In the last decade, GRS has developed a methodology to perform failure mode and effect analyses (FMEA) for electrical circuits of the cabling due to potential fire events in the compartments of a nuclear power plant. Main objective of this approach is to support analyses in the framework of Fire PSA. The FMEA approach helps to assess the effects of cable failures caused by fire in a more realistic manner. The computer aided analysis tool 'CaFEA' of GRS provides a basis for a comprehensive and systematic assessment of potential effects of cable failures caused by fire.

The FMEA method of GRS and the corresponding database have been recently enhanced to quantify different failure mode probabilities of the electrical circuits due to the cables affected by fire using the correlations given by NUREG/CR-6850. The enhanced methodology has been applied to cables within a reference fire compartment inside the reactor building of a German boiling water reactor.

INTRODUCTION

Meanwhile the fire risk assessment has become an integral part of a state-of-the art probabilistic safety assessment (PSA). Moreover, fires have been recognized as one major contributor to the risk of nuclear power plants depending on the plant specific fire protection concept and on the plant operational states.

One of the important parameters in a fire probabilistic risk assessment (PRA) is the conditional probability of a specific failure mode (e.g. loss of function, spurious actuation) of a selected component, given that a postulated fire has affected or damaged an electrical cable connected to that component.

In general, evaluation of this parameter can require the analysis of a number of cable failure scenarios, where each scenario involves a particular fire induced cable failure mode and the propagation of the effects of this failure through the associated electrical circuit. Analyzing the possible failure effects of cable failures in a nuclear power plant, a distinction has to be made between the functional types of cables: power supply cables, instrumentation cables, and control cables.

Failures of electrical circuits of these cables arise generally by the following conductor failure modes:

- Open circuit (loss of continuity),
- Short-to-ground, and
- Conductor to conductor short.

While short-to-ground or open circuit failure modes of a power supply cable may render a system unavailable, a hot short (a conductor to conductor short) failure mode might lead to other types of circuit faults with specific effects on the safety important components including spurious actuations, incorrect measurement signals, faulty alarm and monitoring functions.

In most of the Fire PSAs performed to date, circuit analysis has been performed in a simple manner. The analysis assumes a “worst case” scenario for all cables in a room affected by fire. These “worst case” failure modes have been deduced by expert judgment. This assumption does not generally apply to failures of instrumentation and control (I&C) cables. The circuit failures, taken individually or in combination with other failures, may have unique and not anticipated impacts on plant safety systems and on plant safe shutdown capability being not always reflected in current Fire PSA studies. Simplified assumptions on the failure modes could lead to overestimation of specific event sequences whereas other effects such as spurious actuation or blocking of not directly connected components were neglected.

During the last years an advanced computer aided methodology for analyzing potential impacts of cable failures has been developed by GRS for being applied within Fire PSA for nuclear power plants (NPP). The main purpose of the methodology and its supporting tools is to improve the comprehensibility and completeness of cable failure analysis within the context of Fire PSA.

This paper outlines an advanced approach for handling the effects on components attached to cables which fail in a specific failure mode due to fire in a compartment with cables routed through this compartment. The potential functional impacts on the operation of the NPP become accessible from the effects on the component. The fire in a compartment with cables or electrical components might lead to a fire induced initiating event and/or to the failure of a required safety function.

The computer aided methodology is supported by a plant specific database application named CaFEA (*Ca*ble *F*ailure *E*ffect *A*nalysis) developed by GRS. The database includes all relevant data of the cables, such as cable routing within the plant, cable type as well as data on the connected components. The determination of potential cable failure modes and their probabilities is based on results of fire tests performed for typical nuclear power plant cables in Germany [1], [2] and other countries [3], [4], and [5].

DESCRIPTION OF THE METHODOLOGY

A computer aided methodology based on the principles of FMEA provided in [6] has been developed by GRS to systematically assess the effects of the fire induced failure modes of complex cable connections in a nuclear power plant (see Figure 1) and is outlined in [7]. The main objective of the approach of the GRS is the generalization of the FMEA for similar electrical circuits in a nuclear power plant affected by a postulated fire event.

In the GRS approach, the traditional FMEA methodology is sub-divided into two phases of analysis. In the first phase, a generic FMEA is performed based on diagrams of representative circuits of the power supply of the instrumentation and control circuits. Based on the circuit type, the attached source and target component types and sub-types, the operating condition, and the transmitted signal the generic FMEA is performed under consideration of all potential failure modes of the representative circuits. The experiences gained while applying the computer aided cable FMEA to all cables within one fire compartment has demonstrated that about 100 representative (generic) circuit types have to be investigated for an entire nuclear power plant.

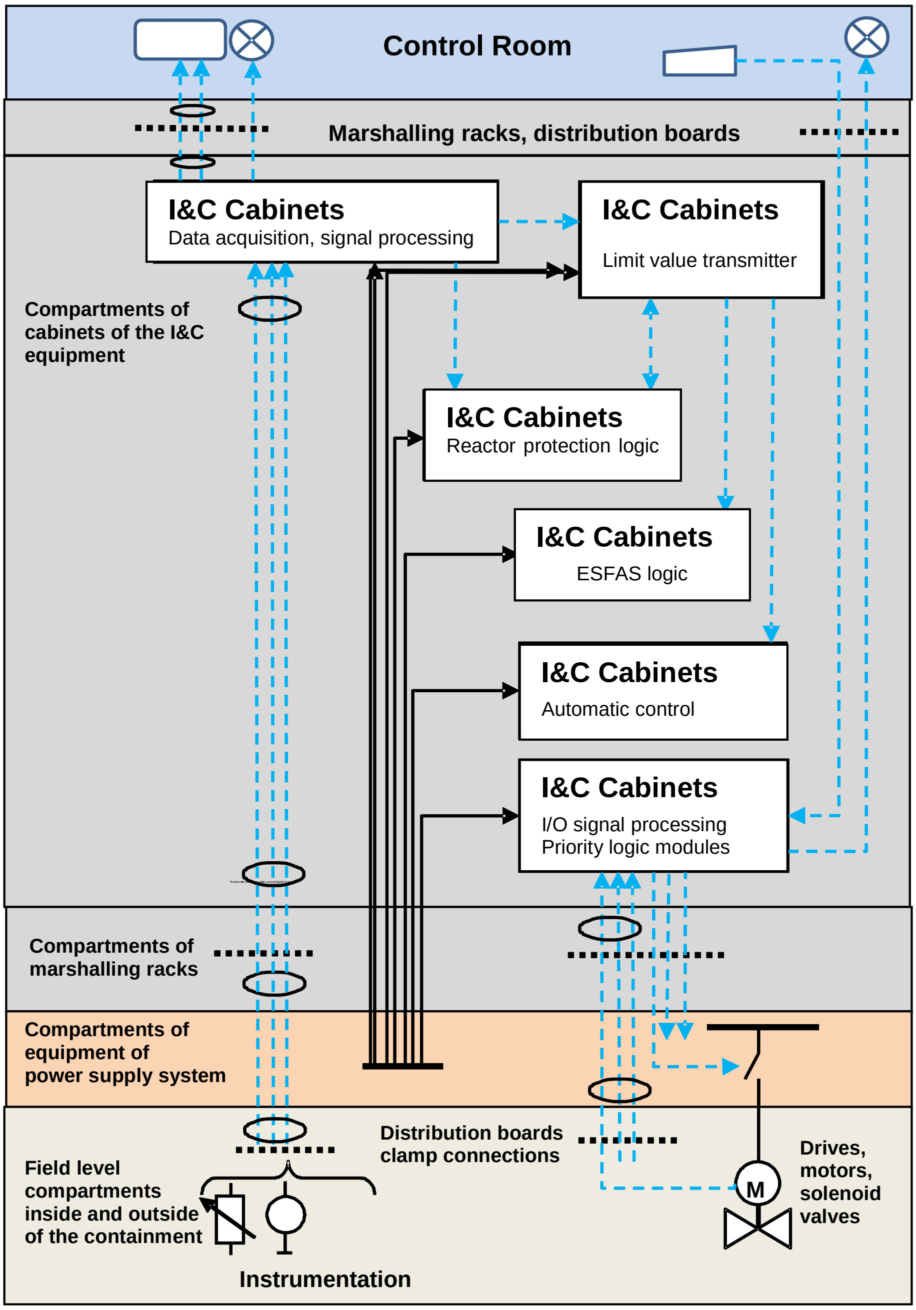

Figure 1 Schematic drawing of I&C (blue, dashed) and power cables (black, solid) [7]

In the second phase, a component specific FMEA is performed using generic results as well as component and cable specific information.

Generic Part of the FMEA

Due to the construction principle of redundancy in a nuclear power plant a large number of circuits can be grouped into generic circuit types. Therefore it is possible to reduce the amount of analytical work to be performed by the FMEA experts. The failure mode of the fire induced malfunctions of a cable (cable conductors) is analyzed depending on the failure conditions for specified cable types. The cable types are sub-divided into cable classes by means of the following cable parameters:

- Design and chemical composition of the insulating material,
- Number of cable conductors,
- Assembly of the individual conductors,
- Armoring of the cable,
- Shielding of individual/several conductors,
- Function of the cable (power supply, measurement, control).

The failure conditions for the cables were specified on the basis of the results of fire tests carried out at the Institute for Building Materials, Concrete Construction and Fire Protection (iBMB) of Braunschweig University of Technology. In these fire tests, among other things, the fire induced functional failures of the cables were examined for both energized as well as non-energized cables.

Based on the test results of the iBMB studies [1], [2], the following different types of cable failure modes have been specified and are used in the cable FMEA:

- Short-to-ground via cable jacket material or a grounded conductor inside or outside a cable or via grounded structures, e.g. a cable tray;
- Hot short to an energized conductor inside or outside a cable (e.g. high voltage propagation, impacts of electric arcs);
- Short circuit fault to a de-energized conductor inside or outside a cable (high or low impedance failure);
- Open circuit (e.g. loss of continuity as consequence of a damage of the cable conductors).

The analytical steps of the generic FMEA are provided in Figure 2.

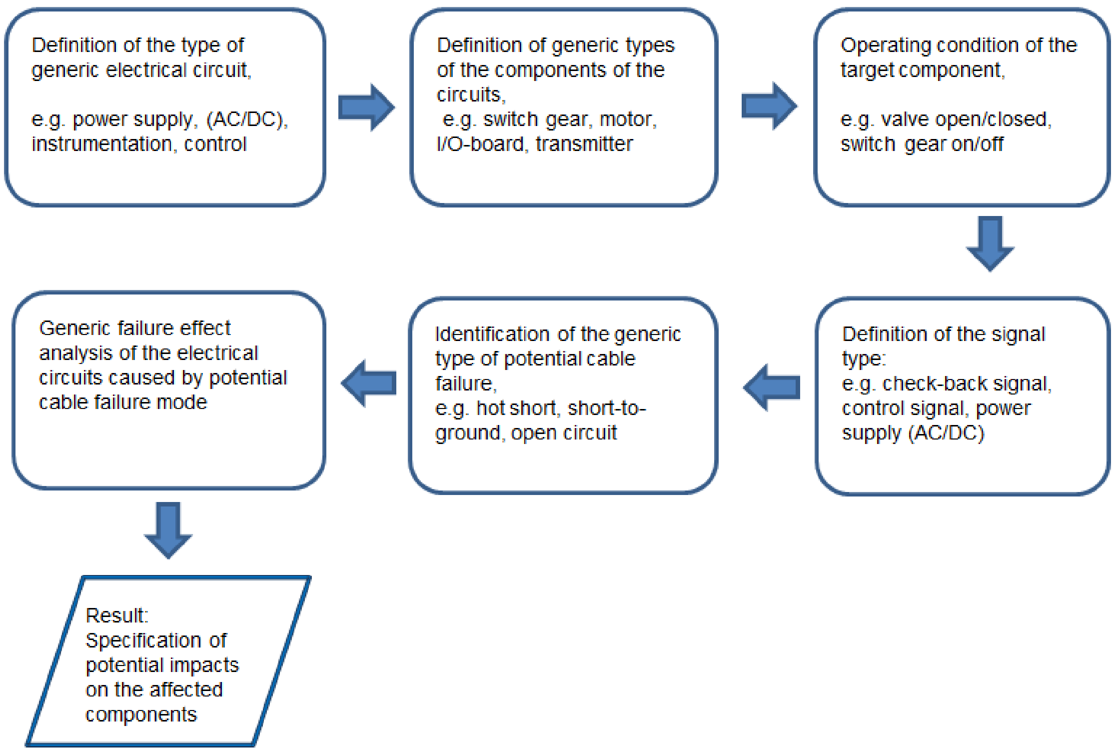

Figure 2 Generic phase of CaFEA [7]

In a first step, the FMEA expert has to screen the list of safety related components typically provided within a Level 1 PSA for full power operational plant states and define the representative circuit types to be investigated. Examples of circuit types may be circuits of the power supply systems (e.g. power supplies of I&C equipment, of the drives, of the solenoid valves) for the instrumentation (e.g. sensors, transmitters).

In the next steps, for each circuit type so-called “source” and “end” components have to be specified. These are the components physically connected to the cable. Additionally, a “target” component has to be specified, which is controlled by the cable or which provides data to be transmitted by the cable. The FMEA expert has to specify the component type and sub-types of the source component, the end component and the target component. The effects of the fire induced cable failure are analyzed for the target component. Typical source component types are switchgears or electronic boards. Examples of target component types are motor-driven pumps, solenoid valves and measurement transmitters.

When applying the CaFEA methodology it was found out that the component effect does not only has to be identified for the component directly connected to the ends of the primary circuits (source and end component) of the cable but for a (target) component connected via another cable with the end component.

Figure 3 shows two examples of cable routings. In the first example, the end component and the target component are the same; the source component is directly connected to the target component XXX via the cable XXX. In the second example, the source component is connected directly to the end component YYY via the cable YYY, which is further connected via another cable ZZZ to the target component ZZZ. For failures of the cable YYY the effects on the component ZZZ have to be identified and stored in the CaFEA database.

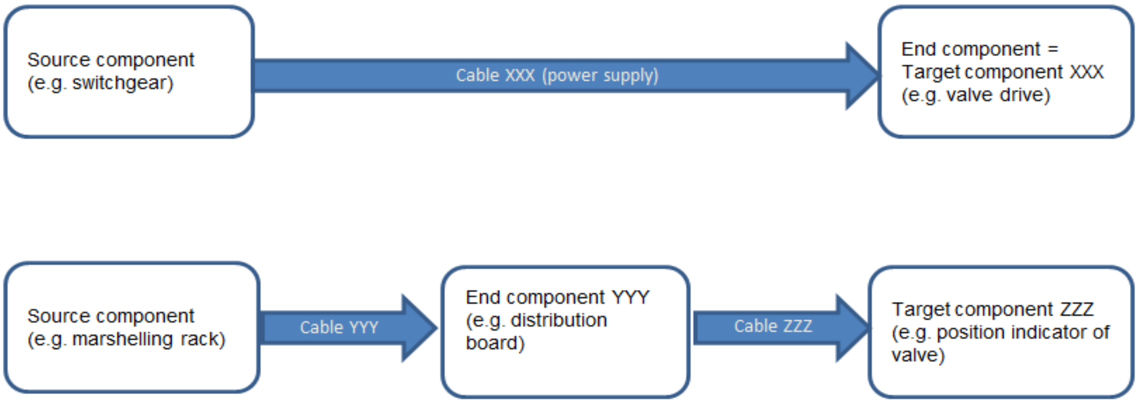

Figure 3 Different principles of cable routing: Direct connection between source and target component (top), indirect connection via distribution board (bottom) [7]

An example for the first type of cable routing is a power supply cable from a switch gear to a valve drive. In the example for the second type of cable routing a source component of type marshaling rack is connected to a position indicator of a valve (check-back signals) via a distribution board by an I&C cable (see also Figure 3).

Figure 4 presents an example of the generic analysis for a representative circuit considering the different cable failure modes. The 4-wire measurement transmitters transform a sensor signal (e.g. a pressure sensor) into an electrical current signal. This current signal is recorded in the analogous input module by measuring the voltage across a resistor. Important for the circuit analysis is the fact that all ground levels and also one of the signal wires (I1) are on the same electrical (ground) potential.

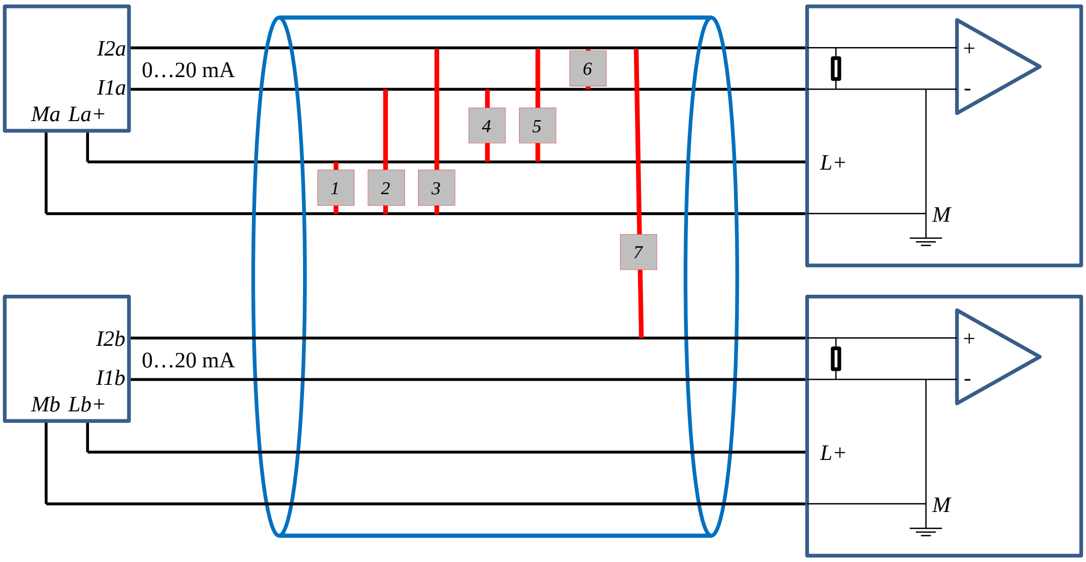

Figure 4 Example for a generic circuit FMEA: Two 4-wire measurement transmitters connected by a single cable and intra-cable shorts with different failure modes

In this example seven different failure modes of the cables can be identified (see Table 1). Due to the common ground potential, the wires I1 and M can be any (of both) possibilities in the given circuit, e.g. the cable failure short-to-ground between L+ and M can either be short to ground with Ma or Mb.

Table 1 Failure modes of the 4-wire measurement transmitter circuit as shown in Figure 4

Short No.	Failure Mode of the Instrumentation Cable	Generic Effect
1	Short-to-ground (*L+ - M*) (of power supply)	(Detected) failure of measurement
2	No failure, because both cables are on ground potential (*I1 – M*)	No failure
3	Short-to-ground (*I2 – M*)	Signal too low (possibly also detected failure)
4	Short-to-ground (*I1 – L+*) (of power supply)	(Detected) failure of measurement
5	Hot-short (*I2 – L+*)	Signal too high
6	Short-to-ground (*I2 – I1*)	Signal too low (possibly also detected failure)
7	Hot-short (*I2a – I2b*)	Signals undefined (one too high, the other too low)

This analysis has to be repeated for all representative circuit types.

Component and Compartment Specific FMEA

In the second phase, those generic failure modes should be identified for each cable, which might affect safety related components (see Figure 5). The probable cable failure modes are a sub-set of the failure modes evaluated in the generic FMEA. Based on the information on the cable type, the attached components and their types, as well as based on their operational mode, all the potential cable failure modes and probable effects should be identified by the FMEA expert. The conditions for the cable failures in the compartment affected by fire have been specified on the basis of the results of fire tests.

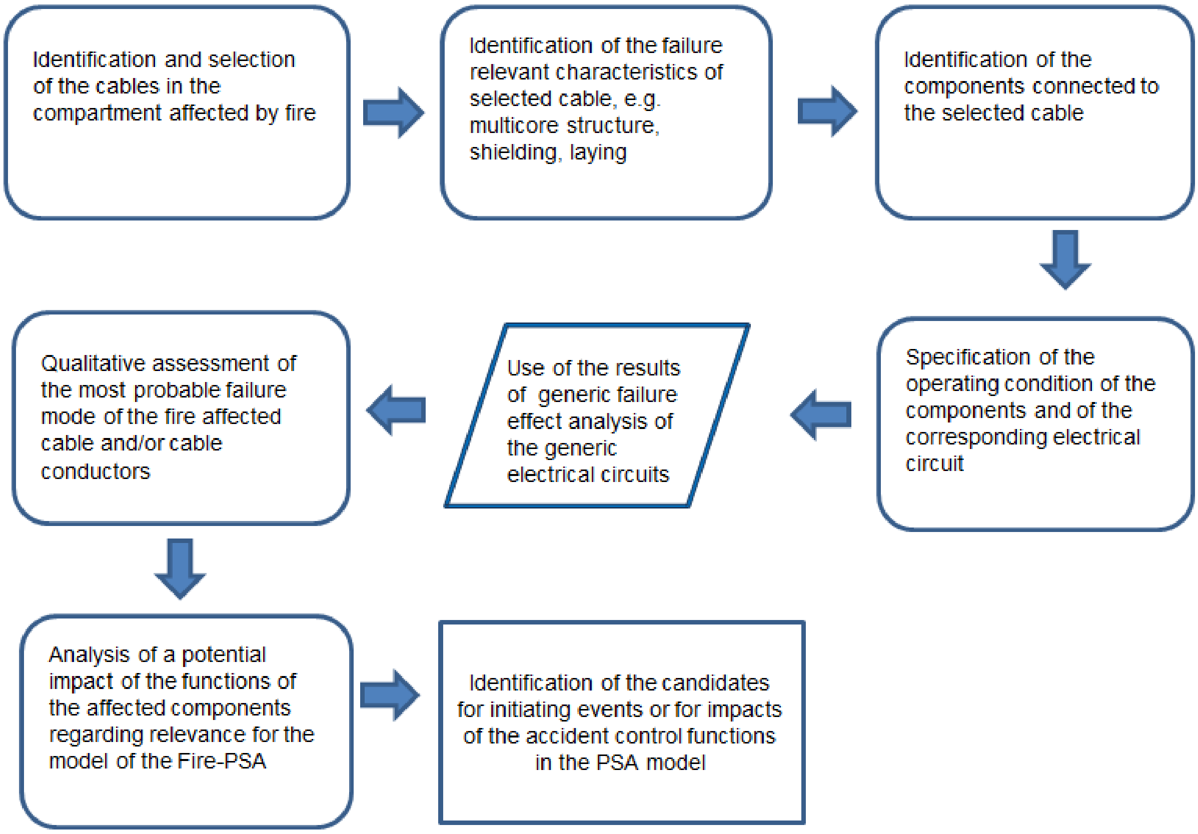

Figure 5 Room and component specific phase of CaFEA [7]

DESCRIPTION OF THE DATABASE APPLICATION CAFEA

Within the scope of PSA methodology development [**7**], the database CaFEA has been created. The database application consists of a database backend and a user interface frontend. By means of CaFEA, the data obtained in the FMEA for fire events can be systematically evaluated with respect to cable failures. The CaFEA database comprises the data from different sources, correlates them to each other and displays the correlation results to the FMEA expert, who carries out the actual failure mode and effect analysis (FMEA) and stores the results in the database.

The database frontend can be used for data sets of different nuclear power plants. The FMEA is specific for the plant operational state which is stored in the database.

Starting the database application the user can choose between the generic and the specific FMEA. For both tasks input forms are available.

For both generic and component specific FMEA results the database provides import and export functions to and from Microsoft EXCEL®.

The input form for the generic FMEA requires input of the following data:

- Type and sub-type of the source component,
- Type and sub-type of the target component,

- Operating condition of the target component,
- Identification of the signal type (circuit type),
- Failure of the cable occurring in the electrical circuit affected by the fire,
- Effect on the target component,
- Optional remarks on the determined component effect and its relevance for the PSA.

The user interface for the component specific FMEA in the CaFEA application sub-divides the different analytical steps into sub-tasks:

- After selecting a compartment and a cable function (corresponding to one signal transmitted via the cable) the first sub-task consists in providing information about the components connected to the cable (“start” and “end” component) and the target component. For the target component, the operating condition also has to be provided. The last step is supported by providing information from the plant operating manual and/or the safety specifications included in the database.
- In the second sub-task, the FMEA expert has to specify all potential cable failure modes for the selected cable function. The FMEA expert has to qualitatively assess the probability of each cable failure, too. Three different probability classes are used (high, medium, low probability). This qualitatively estimated probability can be assigned as conditional probability in case of fire to the corresponding effect on the component and the resulting PSA basic event or initiating event.
- The third sub-task consists of the determination of the effect on the component by the cable failure mode. By means of a query in the database it is checked if a generic FMEA result provided by the FMEA expert in the previous steps is applicable to the specific case. If this is the case, the FMEA expert has to decide how to apply it to the specific case.

EXEMPLARY APPLICATION OF THE CABLE FMEA AND FURTHER DEVELOPMENT

The analytical method and database tool CaFEA has been tested applying data of a reference nuclear power plant for a given compartment. 432 cables are routed through this compartment transmitting in total 932 signals due to the fact that some cables are I&C cables with multiple conductors.

Two of these 432 cables were found, for which different cable functions were mixed (temperature measurement and 4-wired pressure sensors). For the remaining 430 cables with 923 cable functions nine different generic circuit types were identified (see Table 2). The generic FMEA of these generic circuit types results in the component effects provided also in Table 2.

The GRS methodology for applying a FMEA to cables within a nuclear power plant for Fire PSA has been enhanced by a method to quantify the cable failure modes. The method proved to be applicable due to the reduction of the work load for the analyst. For the approx. 1000 cable functions in the reference compartment only nine generic circuit analyses had to be performed. By these nine analyses, all relevant circuit failures modes and the corresponding effects of the connected components could be identified.

Table 2 Generic circuit types, their components effects and their fraction of all cables functions in reference compartment

Generic Circuit Types	Effects on Component	Fraction
AC power supply (220 V, 400 V)	Detected failure	42,8 %
DC power supply (220 V, 24 V)	Detected failure	3,7 %
DC power supply for measurement transmitters (24 V)	Detected failure	0,9 %
4-wire measurement transmitter	Detected failure, signal too low, signal too high, undefined signal failure	5,3 %
3-wire measurement transmitter	Detected failure, signal too low, signal too high, undefined signal failure	0,7 %
Temperature measurement sensor	Signal too low	1,7 %
Common cable for temperature measurement sensors	Signal too low	6,7 %
Dual-position indicator of motor driven devices	Detected failure	20,6 %
Binary position indicator	Detected failure	17,7 %

The quantification is based on the correlations given in NUREG/CR-6850 [8] for cables typically used in U.S. nuclear power plants. The following assumptions were made:

- Hot-shorts between wires are only possibly inside a single cable and not between wires of neighbor cables.
- For the power supply cable function it was assumed that the only cable failure mode is a short-to-ground resulting in a (detected) failure of the attached component. This assumption is based on the protection concept of the electrical circuits of German nuclear power plants.
- For cable functions which are check-back signals or control signals an analysis is required based on the actual circuit layout.

The probabilities of each failure mode (see equations (1) and (2)) are given in [8] derived from experiments [9]. Then the probability of the different cable failure modes can be derived depending on type and number of the generic cable functions within each cable.

$$P_{FM} = CF \cdot P_{CC} \quad (1)$$

$$\mathrm{P_{CC}} = \frac{\mathrm{C_{Tot}} - \mathrm{C_G}}{(\mathrm{C_{Tot}} - \mathrm{C_G}) + 2\mathrm{C_G} + 3}, \ \mathrm{CF} = \frac{\mathrm{C_T}\left(\mathrm{C_S} + \left(\frac{1}{2\mathrm{C_{Tot}}}\right)\right)}{\mathrm{C_{Tot}}} \quad (2)$$

c_{Tot} is the total number of wires within a cable, c_G the number of ground wires, c_S the number of source wires, and c_T the number of target wires. P_{FM} is the failure mode probability, P_{CC} the probability that a conductor-to-conductor short occurs before a ground short and *CF* a configuration factor. The formulas are valid for shielded cables (such as all I&C cables).

CONCLUSIONS

This paper describes a methodology to assess effects of fire induced failure modes of electrical circuits of the cables in a nuclear power plant. The computer aided FMEA methodology provides a good basis for performing a systematic and traceable analysis of the effects of fire induced failures in the electrical and I&C systems in the frame of Fire PSA. The FMEA method has been tested using data of a reference plant for a given compartment.

In principle, the FMEA methodology developed may also be applied for the assessment of potential cable failures in the frame of analyzing the effects of other plant internal or external hazards such as flooding and/or structural damages by earthquakes.

The advantage of this approach developed by GRS is that the computer aided methodology CaFEA uses a combination of generic and specific tasks of the FMEA of the cable failures. This can help to reduce the large amount of analytical work of all circuits in the fire affected compartments of the nuclear power plant significantly.

Meanwhile the results of the FMEA can provide not only qualitative indications for the component effects resulting in the unavailability of system functions or new initiating events in the Fire PSA but also quantification of the failure mode probabilities and the corresponding effects on the affected components.

The quantification approach should be verified by fire experiments specific for the cables of the individual nuclear power plant for which the Fire PSA is to be performed.

Future challenges of the CaFEA development are the consideration of failure modes of new technologies of signal transmission, e.g. network architectures of I&C systems, fiber optical links, etc.

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NEED FOR PRUDENT USE OF RESOURCES FOR PASSIVE FIRE PROTECTION IN NUCLEAR POWER PLANTS AND INSTALLATIONS

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ABSTRACT

It has been observed that most conservative approaches adopted and measures are taken with respect to passive fire protection of nuclear facilities for the sake of fire safety. But we are aware of the fact that the costs of additional passive fire protective materials sometimes exceed 40 % of the finished construction costs of the structure itself. In view of environment and society we need to balance level of conservatism and resource utilization.

In order to comply with the national regulatory requirements and norms apart from the safety aspect, we follow the worst case approach without giving any credit to the probability of the occurrence of fire scenarios and the events which directly or indirectly cause fires to occur.

Even if the fire breaks out, no credit is given to the inherent fire ratings of the structures, i.e. without application of additional fire protective paints or other measures for fire protection.

Conservatism is good but needs to be judiciously applied when it comes to resources and environment.

On several occasions people do not carry out fire hazard analysis (FHA) by modeling fires, simulating the same and analyzing the fire dynamics simulation results effectively in many cases due to the effort needed or the ignorance of the subject of FHA and associated fire dynamics simulation (FDS). This results in compromises with safety and/or poor utilization of project resources (e.g. materials, time, costs, etc.) and thus is detrimental to safety and environment.

This paper deals with the prudent use of resources for passive fire protection in nuclear plants and installations in terms of cost, time, effort and materials. The author has expressed his opinion based on his personal experience, studies and analyzes of fire dynamics modeling, simulation and FHA experiences on the Indian Territory.

Due to clients’ confidentiality constraints the author’s full work experience could not be shared fully in this paper but he would try to capture the FHA issues and prudent use of resources for fire protection as applicable to nuclear facilities, in particular.

INTRODUCTION

Collapse of the Twin-tower, 110-storey World Trade Center (WTC) in New York, USA on September 11, 2001 due to terrorist attack by crashing two Boeing 767 aircrafts into the building and triggering explosions with fire ushered a new vista for research on fire hazards. The flame temperature of 1727 °C of avionic fuel melted and buckled the steel columns. This incident has renewed interest in fire resistant design of structures [1].

The approach of passive fire protection includes structural fire protection, the layout of escape routes, the fire brigade access routes and the control of combustible materials for construction [2], [3]. In a fully developed fire, the passive measures will provide sufficient fire resistance to prevent both the spread of fire and the structural collapse.

In Indian standards, only BIS-3614 (Part-2) [4] deals with the fire temperature-time curve ISO 834 specifying the fire resistance of doors. No other Indian standard specifically talks of the fire barrier rating based on the standard fire temperature-time curve. In view of the mandatory FHA for nuclear facilities and power plants it is now pertinent to specify the fire temperature-time curve based on hydrocarbon fires and other non-hydrocarbon fires. This proposed amendment will solve the problem of standardization of indigenous Indian fire barriers of suitable fire ratings arrived on the basis of FHA using the Fire Dynamics Simulator software [5] or alternative software such as the zone models MAGIC [6], CFAST [7], FIVE [8], etc.

Presently, none of the codes allow a total trade-off for sprinklers, but many national codes allow a 50 % reduction in the fire resistance of structural members, if the building under consideration is provided with sprinklers. However, in India no such codal provision exists up to the time being.

Even Eurocodes [9] suggest that for calculating the fire resistance rating, the full fire load in a building provided with sprinklers to be taken as 60 % of the design full load.

So far most of the fire protection measures specified in the standards are provided in view of the safe escape of the personnel and not in the interest of protecting the structure against the collapse.

Up to the time being, the Indian standards including nuclear ones do not specify the specific codes to carry out FHA nor do they specify requirements on any fire simulation to be carried out, without which the FHA is mostly prescriptive in nature.

Presently, there is no mention of the term FHA (*F*ire *H*azard *A*nalysis) in Indian standards used in the Indian industries and only Atomic Energy Regulatory Board (AERB) of India [10] specifies FHA to be carried out in Indian nuclear facilities.

Enough development needs to be done in Indian standards by adapting the lessons from WTC Collapse due to fire, from the ICFMP project [11] as well as from experimental and other research activities by NIST(*N*ational *I*nstitute of *S*tandards and *T*echnology, USA), GRS (Gesellschaft für Anlagen- und Reaktorsicherheit mbH, Germany), U.S. NRC (*N*uclear *R*egulatory *C*ommission, USA), iBMB (*I*nstitut für *B*austoffe, *M*assivbau und *B*randschutz, Germany), BRE (*B*uilding *R*esearch *E*stablishment, United Kingdom), Fauske & Associates (USA), and VTT (Technical Research Centre of Finland).

The fire resistance level (FRL) is specified in the Indian standards as per BIS: 1641-1988 [12], BIS: 1642-1989 [13] and BIS: 1643-1988 [14] varying between 30 minutes and 4 hours based on the following parameters:

1. The utility of the building/structure.
2. The time taken to evacuate the structure in case of a fire.

PRUDENT USE OF RESOURCES FOR PASSIVE FIRE PROTECTION

This paper emphasizes the prudent use of resources for fire protection (passive fire protection, in particular) based on various criteria as mentioned below:

Advantage of Steel over Concrete

Steel offers considerable advantages over concrete, making it the first choice material for large building construction in any location. Therefore, most of the conventional power plants have steel structures as compared to the nuclear power plants in India with the exception that the Turbine Generator (TG) Building of an under-construction twin-unit Indian nuclear power plant (2 x 700 MW_e) in Kakrapar, Gujarat, which has structural steel buildings.

If the fire protection measures are applied prudently based on FHA using simulation tools for modeling fire dynamics, steel structure of turbine building in a nuclear power plant can save lots of project costs, construction time and efforts along with material saving due to the following facts:

- The speed for construction of steel structures is much higher than that of concrete ones.
- All concrete frame structures need to begin later than the steel alternatives, since a ground-bearing slab must be constructed first.
- The long-span steel option is the fastest construction system, since there are fewer pieces to assemble, requiring less use of the crane. This type of long-span construction is quite common in a turbine building spread over multiple floors.
- Faster construction has additional benefits. It results in savings in the costs of site management and on-site activities. It reduces the costs of finance, since a shorter construction period reduces the time during which interest has to be paid. The rapid completion of a building also brings an earlier return on investment.
- Steel construction minimizes dust and noise, shortens the construction period and reduces the amount of waste generated.
- Small amounts of waste produced are generally recycled, and all steel is potentially reusable. Today, around 40 % of steel is produced from scrap. This is an environmentally friendly benefit.
- Whereas in concrete structures, the construction time is longer, more waste generation which cannot be recycled or re-used much and maintenance is also costly with the problem of water seepage/leakage, etc. being more difficult to be plugged.
- Deliveries can even be timed to suit local traffic conditions and keep disruption in the area to a minimum.
- Off-site fabrication improves the quality of the building frame, since the majority of work is carried out under closely controlled factory conditions – where it is not affected by on-site trades or the weather. All steel frames are pre-fabricated leading a right-first-time build and minimizing time and disruption on site.
- Steel does not suffer from creep or shrinkage and, if properly protected, does not rot or decay.
- Long-span steel construction reduces the number of vertical columns in a building and offers complete flexibility of internal layout. That means a building can be configured to incorporate any possible change in general arrangement or layout of the building.
- All internal walls can be re-positioned if needed and possible according to the use of the building and its inventory, allowing buildings to be adapted endlessly to suit the changing needs with respect to their use. Also, if in the construction the building use changes, steel frames are easier to alter than the concrete alternative.

In general, reinforced concrete systems are 3 % to 8 % more expensive than the steel options as per CORUS literature [15]. Whether to use steel or concrete for the structural frame is one of the most significant early decisions of any project. This has an impact on costs and value of the project and is fundamental to its overall success. Corus funded an independent cost comparison study. The study looks in detail at the costs of commercial buildings, built using a range of steel and concrete framing options. Corus employed the services of leading practitioners in the industry – including Arup, MACE, Davis Langdon and the Steel Construction Institute – to ensure the study drew on the most up-to-date knowledge and expertise.

Environmental Concern over the Use of Material of Construction: Steel over Concrete

The construction industry, in general, accounts for a vast majority of raw materials (wood, metals, minerals, water, agricultural products, construction materials etc.) consumed in USA and most of the developing countries. The enormous consumption rate poses a major challenge because of limited supply of natural resources on hand. The extraction and use of natural resources has significant potential impact on the environment [17].

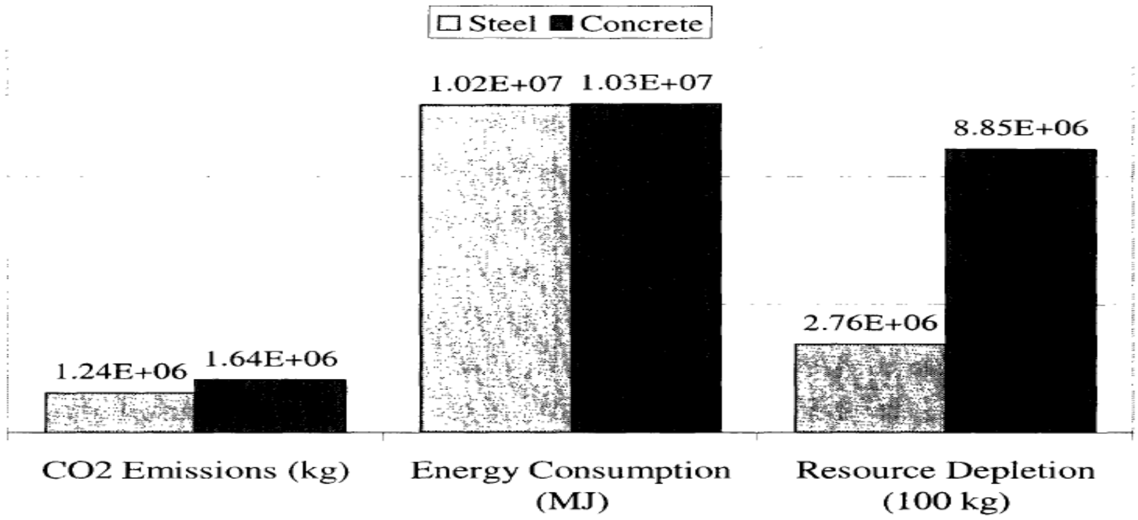

Figure 1 EIA parameters for steel and concrete for a 100,000 sq. ft. office building [16]

Note:
The unit for resource depletion is adjusted to 100 kg to make the result comparable on the same chart as in Figure 1. The results are tracked in kg.

The result of three targeted environmental impacts is presented in the following Table 1:

Table 1 EIA parameters for steel vs. concrete [17]

Material	CO_2 Emission [kg/ft^2]	Energy Consumption [MJ/ft^2]	Resource Depletion [10^3 kg/ft^2]
Steel	12.4	102.1	2.8
Concrete	16.4	102.5	8.8

The Environmental Impact Assessment (EIA) result [17] provided above concludes that steel is better than concrete with 25 % less CO_2 emission and 68 % less total natural resources used.

FHA: An Enabler for Prudent Use of Passive Fire Protection Measures

In a nuclear power plant (NPP), a FHA is performed to assess the fire hazard and demonstrate that the plant will maintain its ability to perform safe shutdown functions and minimize radioactive material releases to the environment in the event of fire. The objectives for a FHA are the following [18]:

- Consider potential in-situ and transient fire hazards;
- Determine the consequences of fire in any location in the plant, paying particular attention to the impact on the ability to safely shut down the nuclear reactor or the ability to minimize and control the release of radioactivity to the environment;
- Specify measures for fire prevention, fire detection, fire suppression and fire containment as well as alternative shutdown capability for each fire area containing structures, systems and components (SSCs) that are important to safety.

Basic goal of FHA is to verify whether a particular combination of fire hazard and fire protection results in an acceptable level of safety. This paper focuses on the aforesaid fact.

FHA is a comprehensive assessment approach of potential fires to ensure that preventive as well as mitigative measures are in place so as to limit the damage from fires to an acceptable level.

IAEA Safety Requirement # 74 out of 82 for FHA [19] states that fire protection systems, including fire detection systems and fire extinguishing systems, fire barriers (for fire containment) and smoke control systems shall be provided throughout the nuclear power plant, with due account taken of the results of the FHA.

But in many cases it is observed that some prescriptive rules and regulations are used for recommending the fire barrier ratings (e.g. three hour fire resistance rating without considering FHA, three hour fire resistance rating for a battery room, etc.) and protection which is not really helpful in project resource utilization nor offering “green” environmentally friendly measures.

The goal of FHA is to determine the expected outcome of a specific set of conditions called a fire scenario. The scenario includes details of the fire sources and combustibles present in the area of concern, area/room dimensions, contents and materials of construction, arrangement of rooms in the building, sources of combustion air, position of doors/windows: numbers, locations, ventilation flows and opening areas with height of location, characteristics of occupants, and any other details that have an effect on the outcome of interest.

Within fire areas containing components of a safety related system special attention should be paid to detecting and suppressing fires that may adversely affect the system. Measures that may be taken to reduce the effects of a postulated fire in a given fire area include limiting the amount of combustible materials, installing fire resistant construction, providing fire stops or fire retardant coatings in cable trays, installing fire detection systems and fixed fire suppression systems, or providing other protection means suitable to the installation.

FHA is the mechanism to determine that fire areas have been properly selected. Based on the FHA, screening of fire areas needs to be done for various approaches (e.g. containment approach, fire influence approach of a FHA), which helps reducing the effort and time needed to analyze along with materials needed for fire protection.

Suitable design of the ventilation systems can limit the consequences of a fire by preventing the spread of the products of combustion to other fire areas. It is important that means be provided to ventilate, exhaust or isolate the fire area as required and that consideration be given to the consequences of failure of ventilation systems due to fire causing loss of control for ventilating, exhausting, or isolating a given fire area. The capability to ventilate, exhaust, or isolate is particularly important to ensure the habitability of rooms or spaces that must be attended in the event of an emergency. In the design, provisions should be made for personnel access routes to and escape routes from each fire area.

When design provisions of fire protection, such as ventilation trips on sensing fire and/or smoke, do exist, credit should be given to reduce the additional passive fire protection mechanism in terms of the fire rating of the barriers as redundancies and diversity are already provided in the design provisions such as fire alarms to caution the plant personnel, multiple fire detectors at different locations, with different orientations and of different types. This is how the resources may be prudently used without underestimating safety against fire hazards.

Use of Fire Dynamics Simulation and Fire Hazard Analysis for Balance between Safety and Resource Utilization

Using fire dynamics simulation and FHA does not only enable to only assess the fire safety aspect but also helps in reducing the costly project resources (costs, time, material) in addition to protecting the environment as follows:

- Selection of appropriate fire curves: Use UL 1709 curve for hydrocarbon fires instead of ISO 834 curve as applicable.
- Take credit of Inherent structural member design strength provided. Fire barrier rating may be suitably reduced to that extent. For example, a fire barrier rating of 30 min derived by the FHA using FDS [5] for a structural member with an inherent fire rating of 10 min for the structural member may require call an additional fire protection of only 20 min which is less than 30 min.
- Use FHA based on fire dynamics modeling and simulation which provides temperature, heat flux, smoke density, etc. Parameters vary over time and thus can help in getting an actual fire curve that can be compared to the standard fire curve to receive the appropriate fire rating of the barrier based on the Ingberg equal area criterion [20].
- Credit to be given for ventilation cut-off, fire brigade intervention and fire detection / suppression measures for a longer duration of 10 min or more.
- It is proven that out of the two standard fire curves, one for hydrocarbon fuels (e.g., UL-1709) and the other for solid combustibles (e.g., ISO 834 fire curve) the overall fire rating is lower for the first ones than for the second ones. This is due to the earlier saturation of the hydrocarbon curve compared to the later saturation of ISO 834 curve.
- Unless fire dynamics simulation is carried out and various thermal effects of fire are well analyzed for variations in time and space, fire barrier ratings cannot be ascertained correctly and appropriately. Fire barrier rating can only be checked for adequacy by FDS, and the fire rating calculation is based on the fire simulation results.
- Some regulatory requirements e.g. Indian standards often prescribe the fire rating, e.g. one hour for non-safety related systems and three hours for safety related systems, if FHA is not carried out. Not carrying out FHA is not rational and neither justified from safety point of view nor from project resource saving point of view. Following some prescriptive standards referring to prescribed values (3 h, 1 h, etc.) rather than results from FHA based on fire modeling may sometimes prove to be unsafe.
- Typical examples of immature regulatory requirement [10] can be cited as follows:
  “Unless otherwise specified ‘adequate’ barrier rating means, rating as calculated as per fire hazard analysis (FHA), or a minimum of 1 hour rating, whichever is more.
  Wherever FHA is not performed, the specified barrier rating shall be installed, subject to approval of regulatory authority. In such cases where FHA is not performed the rating shall not be less than 3 hours for safety related items and 1 hour for non-safety related items.”
  In the above passage irrespective of the FHA result, the minimum fire resistance rating is prescribed to be one hour even, if the FHA shows a lower value of the fire resistance rating; in that case the motivation for FHA is lost.
  Such type of irrationality in regulatory requirement needs to be corrected and discussed for immediate modification.
- Prudent to use a risk-informed, performance-based approach:
  In the risk-informed approach the analyst factors not just the severity of a fire but also the likelihood of a fire to occur. For example, based on the knowledge and experience of the equipment operator, a fire in a given turbine generator is likely to occur 80 % of the time. Based on the knowledge and experience of the fire protection engineer, the sprinkler system protecting that generator is 90 % likely to contain and control that fire. Because the risk-informed, performance-based methodology quantifies the likelihood of a

fire hazard as well as the likelihood that the fire protection system will contain or control the fire, it provides a more realistic prediction of the actual risk.

- While many nuclear power plants, in particular in India, use mineral oil for lubrication, other plants may use synthetic fire retardant lubricants for both the turbine generator control and lubricating systems. The purpose of using this type of fluid is to increase fire safety and to decrease the need for fire suppression systems in the turbine building. Ignition temperature of fire retardant lubricants is reported to be as high as 720 °C. A decrease in the level of fire protection is only acceptable when the FHA can clearly demonstrate the relative safety of the fire retardant fluid. However, if the FHA clearly demonstrates the safety adequacy, even in case of a reduced level of fire protection, this should be acceptable for implementation.
- However, if the FHA clearly demonstrates the safety adequacy, even in case of a reduced level of fire protection, this ~~d~~ should be acceptable ~~to be~~ ~~implemented~~ for implementation.
- FHA can reduce the costs of fire protection by suitably analyzing the plant under consideration and the fire protection measures must be optimized and applied where it is really needed.
- In some regulatory standards and norms it is mentioned that the turbine building should be separated from adjacent structures containing safety related equipment by a fire barrier with a minimum rating of three hours. Openings and penetrations in the fire barrier should be minimized and should not be located where the turbine oil system or generator hydrogen cooling system creates a direct fire exposure hazard to the barrier. Considering the severity of the fire hazards, defense in depth may dictate additional protection to ensure barrier integrity. But it does not seem to be fair to have such prescriptive limits on fire barrier rating rather than analyzing using FDS and FHA and, based on the analytical results, suitable recommendations for fire barrier rating needs to be made.
- We cannot afford to carry out FHA which is quite effortful and time intensive unless the credit arrived at by FHA is given in terms of adequacy of fire protection and not by following the forceful imposition of fire resistance ratings of one or three hours without being justified by fire simulation and FHA exercises. Steel frames (e.g., in the turbine hall) should be protected to increase their fire resistance based on the FHA results and the fire resistance rating derived from it. It is relevant in this context to quote from [21]: "*Steel frames (e.g., the turbine hall) should be protected to increase their fire resistance. Where steel frames are not protected, the configuration should be justified by the Fire Hazards Analysis"*. Many regulatory bodies impose the compulsory application of stipulated fire resistance ratings even after it is proven that FHA using fire dynamics simulation shows lower fire resistance ratings which are already catered by the inherent fire resistance ratings of the structural members because every structural member has its own inherent fire resistance rating derivable on the basis of its parameters like weight-to-heated perimeter (W/D) ratio, where W is the weight [lbs./ft. of length] and D is the heated perimeter [inches] of the structural member with W/D ratio is the factor that allows the interpolation of fire protective coating thicknesses. This is as per SFPE Handbook on Fire Protection Engineering [22] and also NUREG-1805 by U.S. NRC [23]. With reference to [22] and [23], the following can be presented:

  Based on theoretical and experimental studies, the following formulae have been developed for calculating the fire resistance of unprotected steel columns [22], [23]:

$$R = 10.3\left(\frac{W}{D}\right)^{0.7} \text{ for } \frac{W}{D} < 10$$

and

$$R = 8.3\left(\frac{W}{D}\right)^{0.8} \text{ for } \frac{W}{D} \geq 10$$

where:
R = fire resistance time [minutes],
W = weight of steel column per linear foot [lb/ft],
D = heated perimeter [in].

There are actually analyses that need to be conducted in a numerical assessment of fire resistance:

- Model fire development: to model the heating exposure provided by the fire.
- Model thermal response of assemblies and structural members, typically performed using CFAST, MAGIC, FDS, etc. codes.
- Model structural response of assemblies: to determine the structural integrity or the load carrying capacity of the fire exposed structural members. This needs to account for thermally induced deformations and property changes. It is typically performed using SAFIR, TASEF or ANSYS software.

- It makes sense to make statements such as: "*Where fire barriers are used for separation, a three hour fire resistance rating should be provided unless the FHA can demonstrate something less is adequate*" rather than stating *"Unless otherwise specified 'adequate' barrier rating means, rating as calculated as per fire hazard analysis (FHA), or a minimum of a one hour rating, whichever is more"* as per [10].
- Unless the FHA can demonstrate that something less is adequate prescribed territorial regulatory requirement is to be followed. Hence, the FHA derived result justifies the basis of fire protection adequacy and nothing else.
- A rough estimate shows the following for a steel structure turbine building of a single 700 MW_e nuclear power plant unit: Saving in terms of additional fire protection paint is observed to be 1 Million USD.

FHA had been carried out for a large industrial facility turbine building in India where FDS [5] was used extensively for fire modeling and simulation. Fire barrier ratings based on the fire curves [20], [22] and [24] using fire simulation (e.g. applying FDS [5]) and giving credit to inherent fire resistance rating resulting in enough saving in terms of project resources.

FHA had been carried out for a large industrial facility turbine building in India wherein FDS

CONCLUSIONS

Application of fire dynamics modeling and simulation software such as FDS in the frame of FHA with other variations of models have been found to be quite prudent in economizing the additional passive fire protection costs in terms of materials, time of construction and effort.

Regulatory requirements and standards of some countries are backdated enough for not accommodating the smart way of performing the FHA and applying the additional fire protection measures appropriately resulting in rising project costs and construction duration for fulfilling the provision of additional fire protection measures.

In many cases it has been observed that the regulatory requirements of a country are conservatively posing some prescriptive values of fire barrier ratings without going through the actual fire simulations and analyses. These are prescriptive values without any justification given based on fire dynamics simulation and fire hazard analysis using the simulation results.

No credit is given to inherent passive fire protection capability of the structural elements and members resulting in unnecessary additional fire protection measures leading to wastage of project resources besides environmental abuse.

It may be possible that the fire barrier rating of some barriers derived based on the fire simulation results by FDS [5] or other fire simulation tools are lower than the inherent fire resistance ratings and hence no additional fire protection in terms of fire resistant spray paints, intumescents, encasing, etc. is required.

It can be demonstrated that huge saving in costs (to the tune of 1 Million USD, e.g. for a structural steel turbine generator building of a NPP unit in India), materials and construction time can be achieved if a turbine generator building like huge structure (e.g. 100 m x 80 m x 45 m) can be fire painted with lower ratings or no additional fire protection based on the Inherent fire resistance ratings of structural components and fire simulation results.

The author - based on his personal experience, observations, studies and findings - has expressed his opinions and does not provide any representation of Tata Consulting Engineers Limited or its clients. It may be treated as a humble submission to review such cases of regulatory requirements and practices in terms of standards, guidelines, etc., which needlessly consumes extra project resources on overdesign in the name of conservatism and safety.

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LOAD AND DEFORMATION REDISTRIBUTION FOLLOWING COLUMN REMOVAL

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ABSTRACT

Structural engineers are becoming ever more concerned with protecting building structures from progressive collapse. Severe loading of a structure can be initiated by terrorist acts or accidents. Regardless of the initiating event, the severe loading caused by an explosion and/or a fire has the ability to greatly reduce or even remove a load bearing structural column. In steel structures which lack adequate fire protection or which have fire protection that is damaged due to a blast load, the steel structure can reach critical temperatures very quickly.

The response of a 10-storey steel framed building subjected to a ground floor corner column removal scenario and a middle column removal scenario was investigated. For both column removal scenarios, different column cross-sections were analyzed to determine the load redistribution to adjacent columns as well as the overall structural stability. The results showed that in both column removal scenarios the maximum load increase was at the columns directly attached to the removed columns. The middle column removal scenario was most sensitive to different column cross section sizes.

INTRODUCTION

Steel framed structures can be used to house offices, turbine buildings, control centers as well as other ancillary use buildings in the nuclear industry. In addition to naturally occurring disasters and accidental fires, malevolent actions against critical buildings/infrastructure is a serious concern for engineers throughout the world. An explosion targeted at a building's steel columns could completely eliminate the column and remove it from the structural load carrying geometry. Similarly, a fire burning in a compartment within a steel structure could relatively quickly reach the steel's critical strength temperature, after which the strength of steel begins to degrade quickly, not allowing the column to carry its intended load. Fire protection provided to steel structures by lightweight materials is susceptible to degradation after long duration high intensity fires and also damage/removal caused by an explosion.

When a structure experiences the removal of a critical load bearing member, the loads being carried by the initially stable structure must be able to redistribute the load to members adjacent to the failed member. If redistribution of the loads and re-stabilization of the changed structural system do not occur then progressive collapse can be initiated. In order to safeguard structures and protect the safety of the occupants, engineers must understand how a building structure will behave when columns are severely damaged or removed.

The purpose of this investigation was to study a steel framed structure's response to different ground floor column removal scenarios. More specifically, this study analyzed the changes in the structure's load and deformation distribution following column removal. Progressive collapse of building structures has been defined differently by many authors but the fundamental concept remains the same. Progressive collapse is the spread of an initial localized failure of a primary structural member, caused by a triggering abnormal load, from element to element resulting in a collapse which is disproportionate to the original initiating event [1] to [7]. Column removal scenarios are based on the United Facilities Criteria (UFC) [**8**] alternate load path method, with some modifications. For this parametric study, only ground floor exterior columns are considered.

Research has shown that modern commercial multi-story buildings may be particularly more vulnerable to progressive collapse because of the desire for larger open spaces leading to larger column centerline spacing as well as less use of stiff masonry partitions [9]. The use of large column centerline spacing can limit the amount of load redistribution following a column loss [9]. Structural geometry of the building can affect column removal response of the structure. A key factor contributing to the progressive collapse of the Murrah Federal Building following the damage of three ground level columns by a blast illustrated this point [9]. The destructed columns supported large transfer beams which in turn supported columns above; therefore the original failure of the three ground floor columns affected a much larger portion of the structural system [9].

Researchers term a structures ability to resist progressive collapse, as a structure's 'robustness'. One way that is commonly used to evaluate a structure's robustness is the alternate load path method, which involves removing selected columns in representing different failure scenarios from a structure and analyzing the possibilities of the structure being able to provide alternate load paths to carry the loads shed from the failed column [**10**] to [14] and others. This type of analysis is used with both dynamic and static analyses while considering material and geometric non-linearities.

Izzuddin et al. [15] and Vlassis et al. [16] proposed a simplified framework for analyzing a buildings resistance to progressive collapse assuming sudden column loss scenarios. The procedure employed used a non-linear static approach with a simplified method for accounting for the dynamic effects. A main conclusion from the work of [15] and [16] was that steel framed composite buildings with typical structural configurations can be prone to progressive collapse initiated by the failure of a column [16]. A main factor influencing a structures response to a column loss scenario is the strength and span of the beams directly connected to the removed column being able to transfer the shed loads to the undamaged portions of the structure thereby allowing for effective load redistribution and structural re-stabilization [16].

Fu [**17**] constructed a 3-D finite element model of a typical 20-storey composite steel and concrete building structure. This model was used to conduct many studies on factors affecting progressive collapse of building structures using column removal scenarios. Fu [**17**] employed a non-linear dynamic simulation of different column removal scenarios to investigate the alternate load path method for load redistribution. Different column removal locations were investigated, namely the removal of two adjacent central columns on the ground floor, one corner column on the ground floor and a corner column on the 14th floor. In the dynamic analysis, Fu [**17**] studied the axial load redistribution in the adjacent columns and other nodes as a function of time to visualize the damping effects of the structure. The main conclusions of Fu [**17**] investigation were that the dynamic response of the structure was primarily influenced by the areas directly affected by the column removal scenarios. Furthermore, based on the load combination defined in the study in accordance with [**8**], it was recommended that all members and their associated connections at the possible column removal level be designed for twice the static axial force calculated during ambient (no removal) design.

FINITE ELEMENT MODEL

For this research a typical composite steel 10-storey building was modeled using ANSYS finite element software. The structure was modeled to be able to capture the primary steel structures' response. The simulations were run as non-linear static analyses with non-linear material properties.

The floor plan is constructed on a 6 m by 6 m grid spacing as seen in Figure 1. The floor to floor height is 3.2 m and the building has ten storeys as shown in Figure 2. The structure is constructed using a structural steel frame with yield strength of 345 MPa. The primary structural members are constructed of typical 'I' section shapes as detailed in the various scenarios. The characteristics of the primary steel beams and columns are shown in Table 1. The floor system is a composite system modeled as a layered floor construction consisting of a 1.50 mm thick steel deck and a 148.5 mm thick concrete slab. The slab and beams are assumed to have full composite action. Lateral stability is provided by a 200 mm thick reinforced concrete shear wall enclosing the core area of the building spanning from the tenth floor to the ground.

Table 1 Steel beam and column cross-section properties

Section Designation	Mass [kg/m]	Flange Width [mm]	Depth [mm]	Flange Thickness [mm]	Web Thick ness [mm]	Area [mm^2]	Moment of Inertia, I_x [10^6 mm^4]	Moment of Inertia, I_y [10^6 mm^4]
W360X237	236.3	395	380	30.2	18.9	30100	788	310
W360X179	179.2	373	368	23.9	15.0	22800	575	207
W310X129	129.6	308	318	20.6	13.1	16500	308	100
W360X122	121.7	257	363	21.7	13.0	16500	365	61.5
W310X118	117.5	307	314	18.7	11.9	15000	275	90.2
W530X66	65.7	165	525	11.4	8.9	8370	351	8.57

The beams and columns were modeled using standard ANSYS beam elements with six degrees of freedom at each node. All beam to column connections were modeled as fully fixed connections sharing a common node at the intersection. The beam elements were constructed with intersecting centroids. The composite floor slabs and shear walls were modeled using ANSYS shell elements. Layering was added to the composite floor shells to account for the steel decking and concrete with embedded reinforcing. The layered construction was modeled using common nodes across the topology thereby simulating a full composite action between the steel and the concrete. The bases of all the columns were assumed to be fixed. The ANSYS multi-linear isotropic hardening material model was used to capture the non-linear effects of the structural steel beam elements and the concrete slabs. The yield strength and ultimate strength of the steel were taken as 345 MPa and 700 MPa, respectively. The modulus of elasticity of the steel was 200 GPa and the ultimate strain was 0.157. The concrete material model had an ultimate compressive strength of 40 MPa and a maximum strain of 0.0035. The mesh was sufficiently fine so as to accurately capture the non-linear material and geometric effects. The main goal of the numerical model was to capture the overall global response of the structure to column removal scenarios.

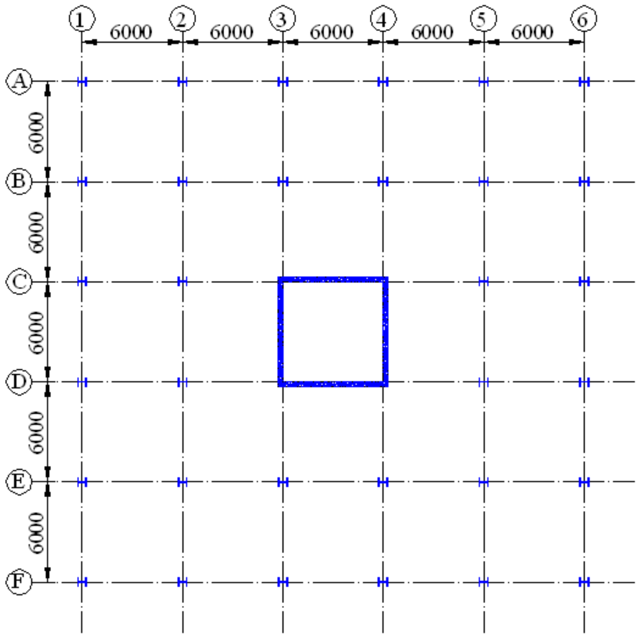

Figure 1 Typical floor plan grid layout

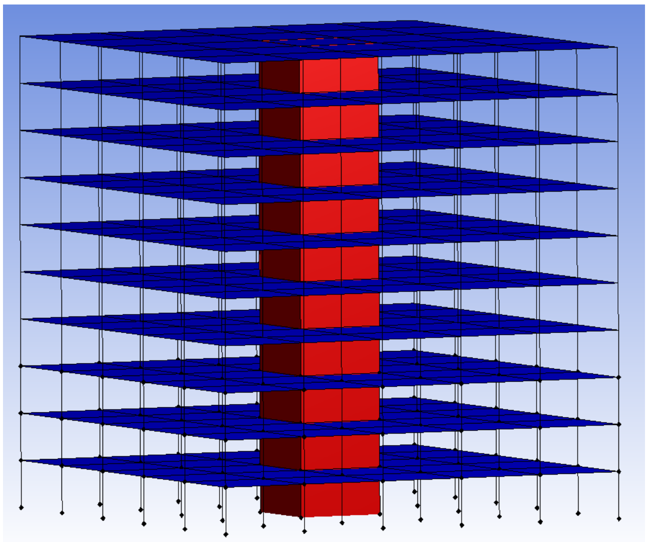

Figure 2 Isometric view of the ANSYS analysis model

The proposed structural model and modeling assumptions were validated against a full scale experiment conducted by Wang and Li [18]. The experimental program consisted of testing composite steel frames subjected to vertical loading. The details of the experimental program and specimen construction can be found in Wang and Li [18]. In order to compare the results of the experiment to the current proposed model, the experimental geometry and material properties were reconstructed in ANSYS. The model connections were assumed to be rigid and the composite concrete and steel floor slab was modeled as a layered shell element in ANSYS. A non-linear static analysis was carried out on the finite element model and compared to the experimental results obtained by Wang and Li [18].

To validate the model's stiffness and connection methods, a comparison with the moment-rotation of the Wang and Li [18] experiments was made. Results showed good agreement between the model and the Wang and Li [18] full scale tests. The initial stiffness and amount of rotation after yielding predicted by the model are very similar. The model does predict a more linear rate of change up to the yield capacity which is due to the abrupt change in the stress-strain curve for the idealized bilinear kinematic hardening material model used. This parametric study will focus on large deflection and large rotations for the global structural system; it is assumed that the proposed model will predict the results accurately.

The floor loading on the structure was chosen to replicate a commercial office type of occupancy. The live load and dead load pressures were taken as 2.4 kPa and 2.0 kPa respectively. For the purposes of conducting a parametric study, the applied floor loads were taken as 1.2 times the dead load and 0.5 times the live load. Therefore the total applied gravity load on the structure was 3.6 kPa. The loads in the non-linear static analysis in ANSYS were applied in increments over small time steps, to help achieve convergence. In addition, in accordance with UFC [8], a dynamic increase factor was included in the load distribution for the column removal scenarios. The factor accounts for the dynamic effects caused by the sudden removal of a column, so that a static analysis procedure may be used [8]. The dynamic increase factor was taken as 2 [4]. The dynamic increase factor is applied to the gravity load on every floor above the affected column, on every structural bay that is directly connected to the removed column.

Internal column removal scenarios and scenarios above the ground floor level were not considered. The column removal scenarios considered are; the removal of exterior corner column A1 at the ground floor level and middle column C1 at the ground floor level. Different column sizes are considered for each of the removal scenarios while the floor beam sizes remained constant for cases 1 thru 8 as summarized in Table 2. Ground floor level columns were denoted with the prefix, 'GF'.

Table 2 Parametric study cases

Case	Beam	Column	Column Removed
1	W530X66	W360X179	Ground Floor A1
2	W530X66	W310X129	Ground Floor A1
3	W530X66	W360X122	Ground Floor A1
4	W530X66	W310X118	Ground Floor A1
5	W530X66	W360X237	Ground Floor C1
6	W530X66	W310X129	Ground Floor C1
7	W530X66	W360X122	Ground Floor C1
8	W530X66	W310X118	Ground Floor C1

RESULTS

Axial Load Redistribution Following Corner Column Removal

Following removal of the corner column A1 on the ground floor (GFA1), the load previously carried by the column was shed to the adjacent columns. A review of the axial force distribution of the model indicated that the largest increase in axial load occurred in the ground floor columns A2 and B1. There was a slight increase in the axial load applied to column B2. The magnitude of the load increase in columns GFA2, GFB1 and GFB2 is shown in Figure 3 to Figure 5. The axial column loads are plotted against the ratio of the total applied structural load. The 'initial condition' represents the axial load in the column prior to any column removal.

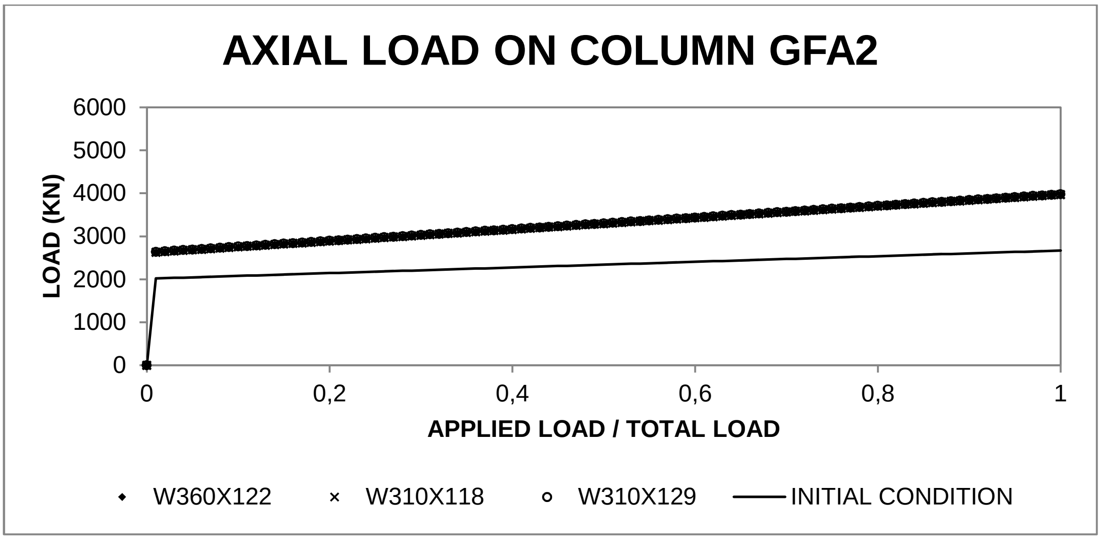

Figure 3 Increase in axial load at ground floor column A2

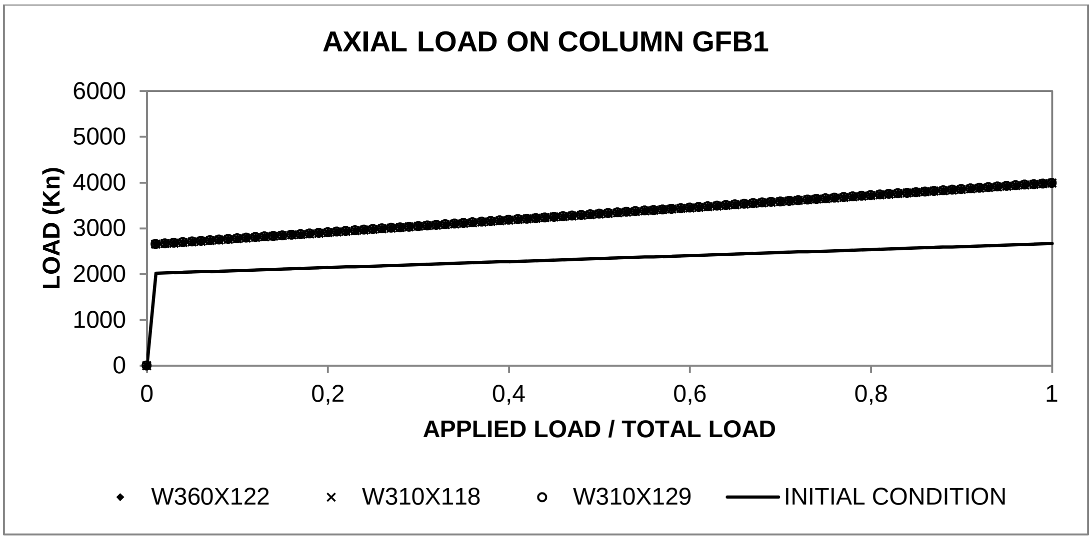

Figure 4 Increase in axial load at ground floor column B1

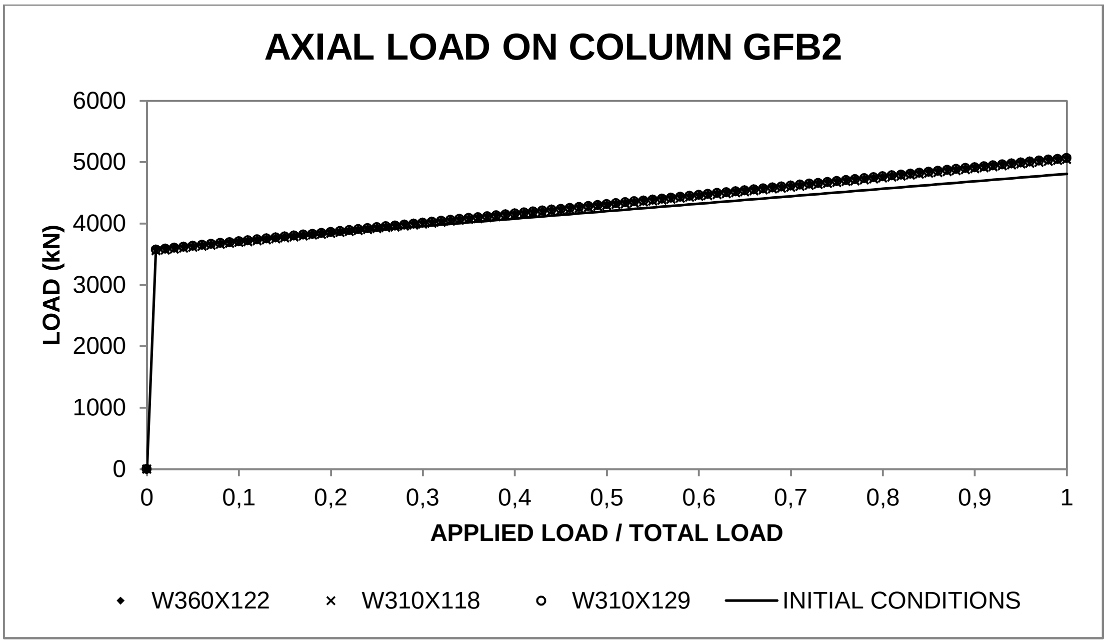

Figure 5 Increase in axial load at ground floor column B2

The load redistribution to the two periphery columns GFA2 and GFB1 was very similar. The maximum axial force in these columns at the full applied structural load was approximately 160 % of the value at the initial conditions. The loading was applied at the same rate for all the models, yet for the models with the corner column removed, the rate of increase in the column axial load was slightly higher. For the three columns studied, the cross sectional properties of the column did not affect the load redistribution, as long as the column remained stable at the increased load.

The increase in axial load in column GFB2 was not significant for the column and beam sizes tested. The increase in axial load between the initial condition and the corner column removal at the full applied load was approximately 107% of the initial conditions. The small increase in column GFB2 was attributed to the fact that load redistributed from the failed column GFA1 was transferred mainly through the beams directly framing into the failed column. Therefore, the adjacent columns directly framed into the cantilevered beam received the majority of the shed load from the failed column.

Beam Behavior Adjacent to Removed Corner Column

Following the removal of the corner column A1, the beams spanning column A1 and A2 as well as the beam between A1 and B1, transitioned to a cantilevered mechanism. The resulting downward deflection at the ends of both beams A1A2 and A1B1 for three column sections is shown in Figure 6. The cross sectional properties of the ground floor column did affect the maximum deflection attained at the junction of the cantilevered beam. The larger cross sectioned columns provided more resistance to out-of-plane deformation, thereby acting as stiffer beam-columns as the loads above the removed column applied a bending moment to the top of the columns directly adjacent to the removed column. For beams W360X122 and W310X118, the cross-section properties were very similar and so the deflection was not affected. The floors beams remained in the elastic range during loading. A review of the results indicated the largest out-of-plane deformation for the ground floor columns occurred at the top of column B2. Figure 7 is a plot of the maximum out-of-plane deformation at the top of column GFB2. The figure shows that the more slender W310X118 column had approximately a 57 % increase in out-of-plane deformation as compared to the stiffer W360X179 column.

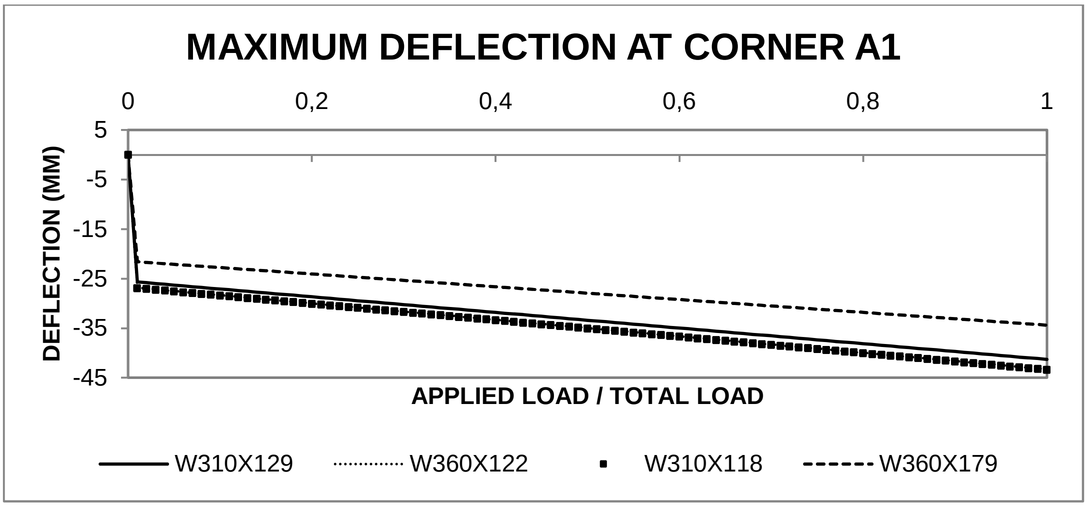

Figure 6 Maximum deflection of beams at removed column GFA1

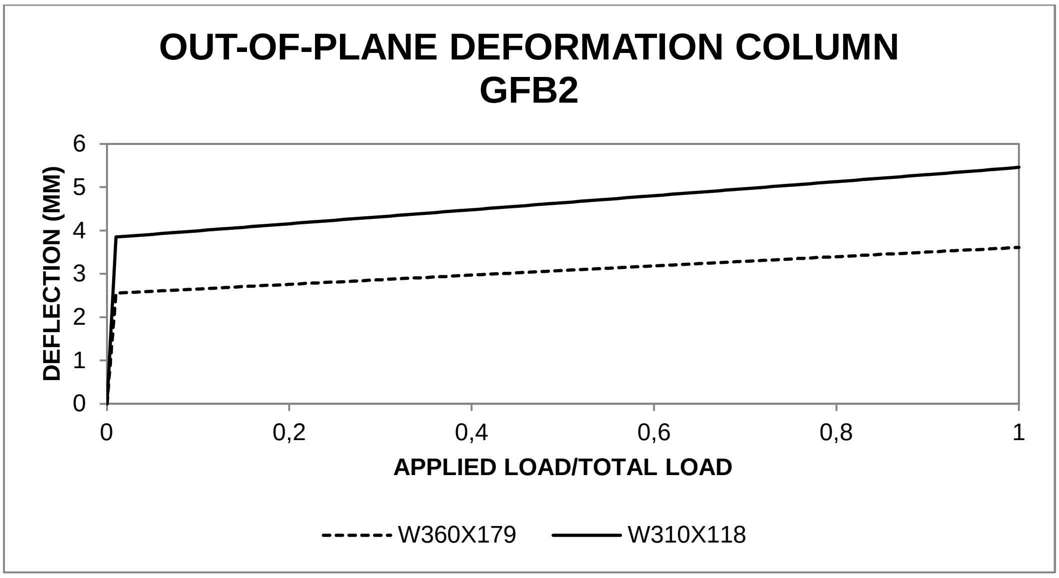

Figure 7 Out-of-plane deflection at top of column GFB2

Figure 8 and Figure 9 show the shear force and axial force diagrams, respectively, for the beam spanning the ground floor columns A1 and B1. Following the removal of column GFA1 the shear force in beam A1B1 increased drastically from ~ 7.5 kN to ~ 70 kN for the same W360X179 column. As the column cross-sectional properties decreased, the shear force in beam A1B1 also decreased. This was due to the reduced ability of the smaller cross-sectioned columns to redistribute the load. The maximum shear for all the columns occurred at the support nearest B1. The axial force in beam A1B1 nearly doubled once the W360X179 corner column GFA1 was removed. For columns with smaller cross sections, the axial force value present in beam A1B1 was less than larger cross sections.

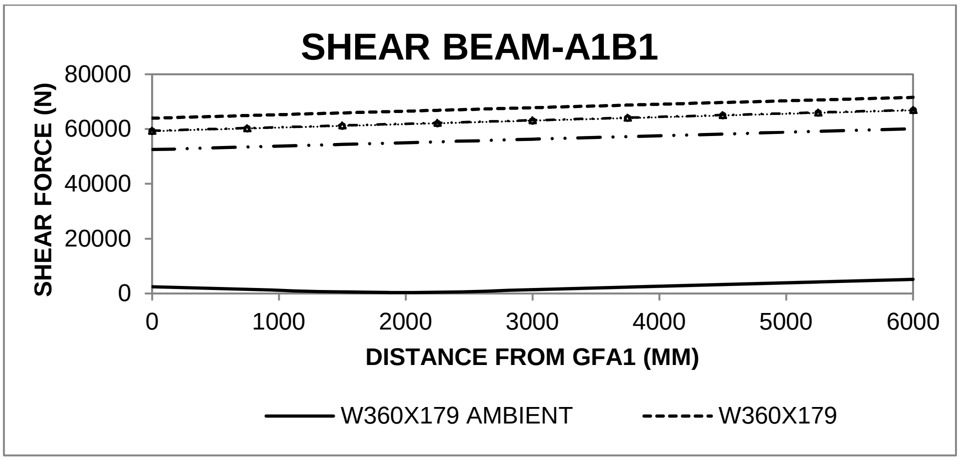

Figure 8 Shear force diagram for beam spanning between columns A1 and B1

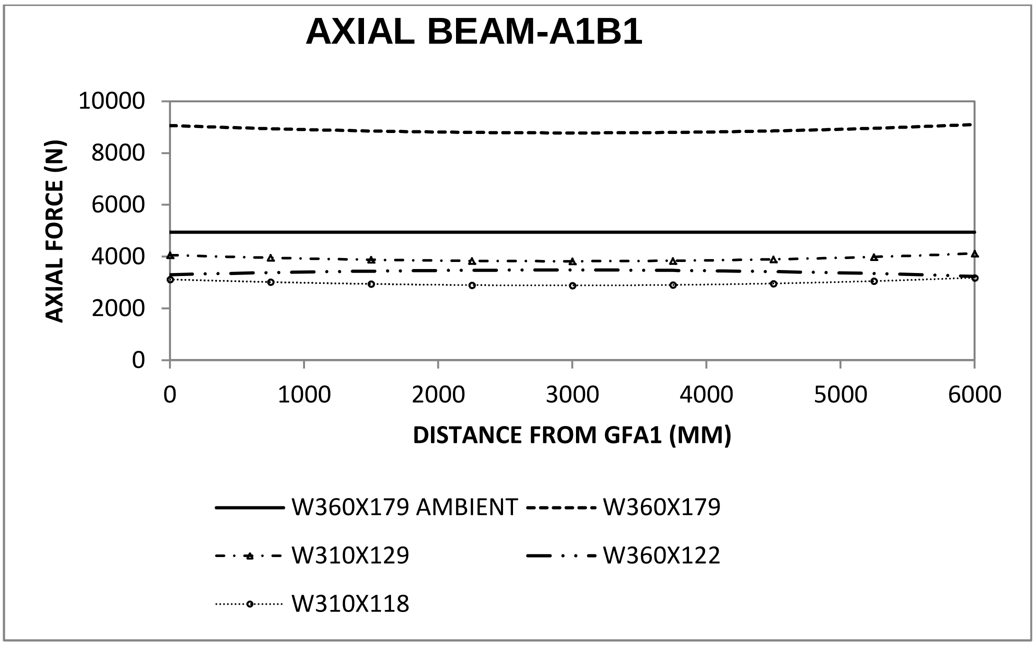

Figure 9 Axial force diagram for beam spanning between columns A1 and B1

The size of the column cross-section plays a role in force redistribution to the adjacent structural columns. This force must be transferred from column to column through the network of connected beams. As the force is passed through the beams, the forces within the transfer beam increase. In addition to ensuring that the beams and columns can sustain the increased loads, the design of the connections must take into account the increased forces if progressive collapse is to be avoided. The overall deflected shape of the building structure following removal of column GFA1 is shown in Figure 10.

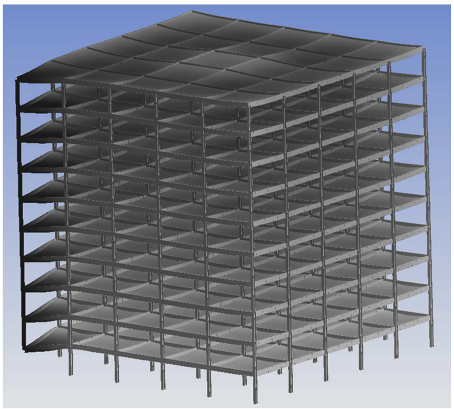

Figure 10 Overall deflected shape following removal of column GFA1

Axial Load Redistribution Following Middle Column Removal

Following the removal of ground floor column C1, the load was redistributed to the ground floor columns B1, B2, C2, D1 and D2. The axial force redistribution for these critical columns is shown in Figure 11 to Figure 15. A specific review of each graph follows; however it is important to note that the columns W360X122 and W360X118 were overloaded and the structure became unstable prior to the total structural load being applied. In order to verify that the smaller column sections did actually play a role in the overall building stability, a much larger W360X237 was added to the comparison scheme to verify that the larger column could remain stable at full applied load.

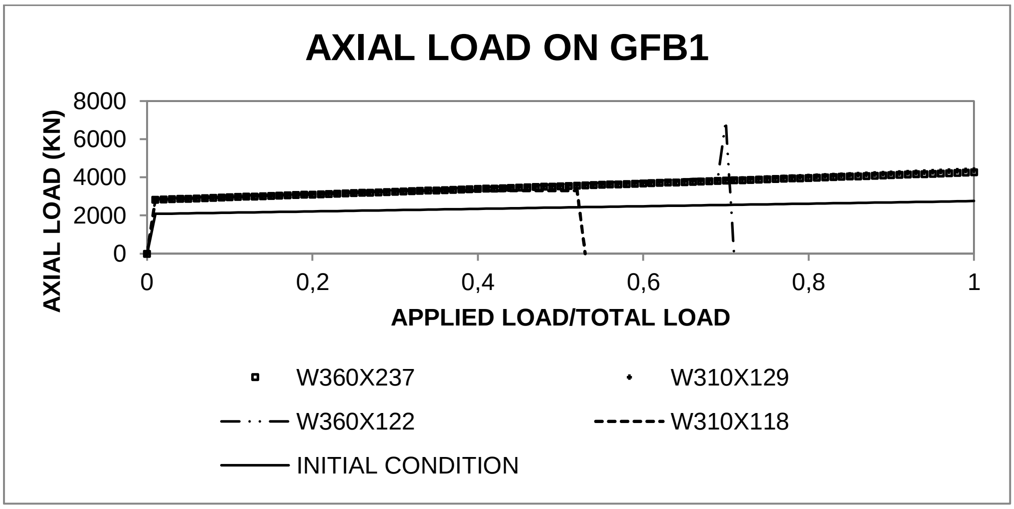

Figure 11 Increase in axial load at ground floor column B1

The load distributed to ground floor column B1 showed an approximately 60 % increase in the axial load applied to the column at full applied structural load as compared to the initial condition. Column section W360X122 failed to reach the fully applied structural load and the structure became unstable at approximately 72 % of the total load. The failure of column W360X122 was precipitated by a large spike in the axial load applied to the column. This load spike was attributed to an attempt of the structure to re-stabilize following an initial instability. However, column B1 was not able to resist the increase in load and the structure became unstable. This may have indicated a sudden failure of the column B1. Similarly, W360X118 failed at approximately 53 % of the total load. Column W360X118 did not show any load spike prior to failure, but rather exhibited a flattened portion of the axial load curve prior to failure, indicating a ductile failure.

Figure 12 shows a similar 60 % increase in axial load for ground floor column D1 at full load as compared to the initial condition. A sharp increase in axial load was seen when column W360X122 was used. The load spike on both columns B1 and D1 (perimeter columns) indicated that as the structure became unstable the floors above the ground floor began to lean towards the exterior perimeter thereby increasing the exterior columns' share of the gravity applied load as seen by the peaks. This is consistent with the overall deflected shape of the model just prior to failure.

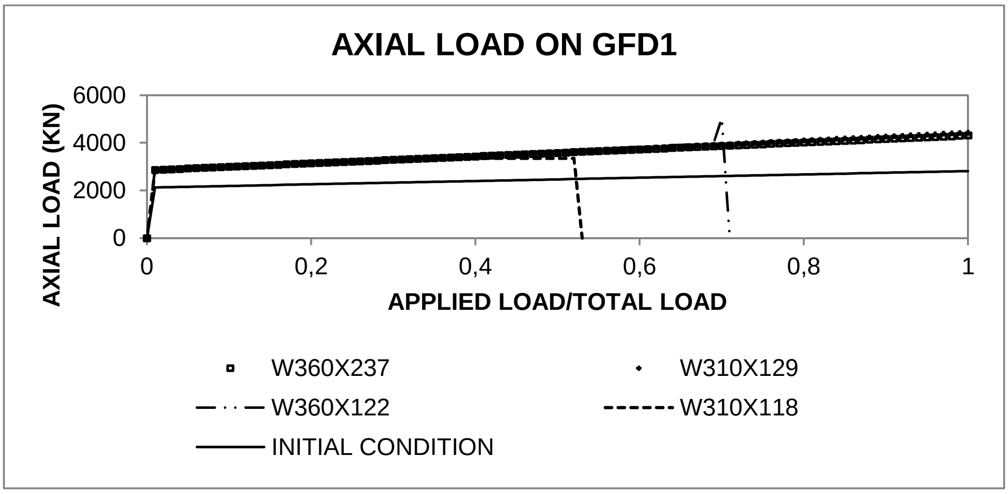

Figure 12 Increase in axial load at ground floor column D1

Interior ground floor columns B2 and D2 exhibited similar increases in axial force at full applied load of approximately 10 % (see Figure 13 and Figure 14). The smaller increase in axial load in columns D2 and B2 is consistent with the structural geometry, in which these two columns were not directly connected to the removed column by any beams and hence the load shed is less. A load spike on column D2 indicates that as the structure became unstable the gravity loads from the structure above were also slightly shifted towards column D2. This was due to the structural geometry. With the removal of column C1 the remaining structure was not symmetrical about column C1. There were two remaining intact perimeter structural bays adjacent to column D1 and one intact perimeter structural bay adjacent to column B1. The structure attempted to re-stabilize by transferring some load to the stiffer sections of the structural system.

Ground floor column C2 exhibited a similar change in behavior as the rest of the ground floor columns (see Figure 15). The load increased in columns W310X129 and W360X237 by 25 % and 45 % respectively, as compared to the initial condition. Column W360X122 had a sudden failure at approximately 72 % of the total load as seen in the other adjacent columns. Column W310X118 exhibited a ductile failure beginning at approximately 30 % of the total load and a total failure at 54 % of the total load.

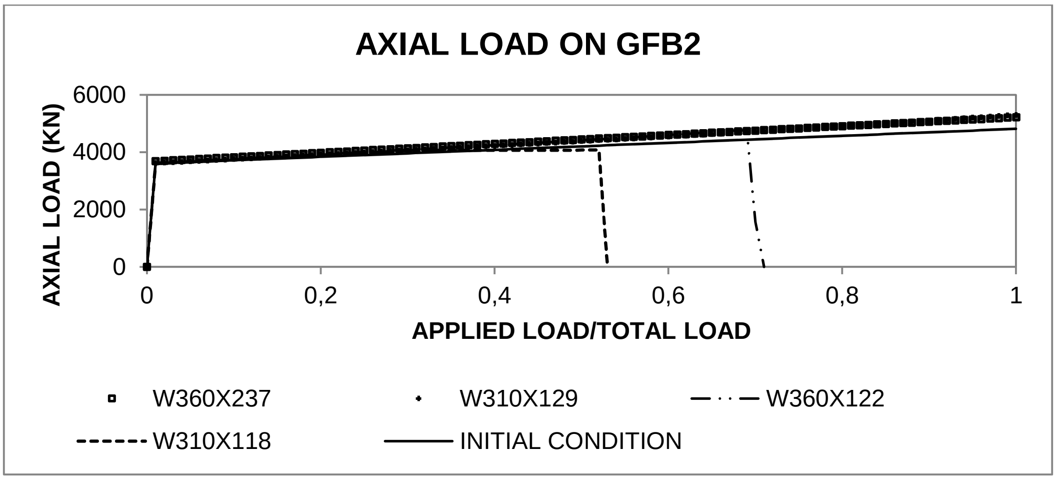

Figure 13 Increase in axial load at ground floor column B2

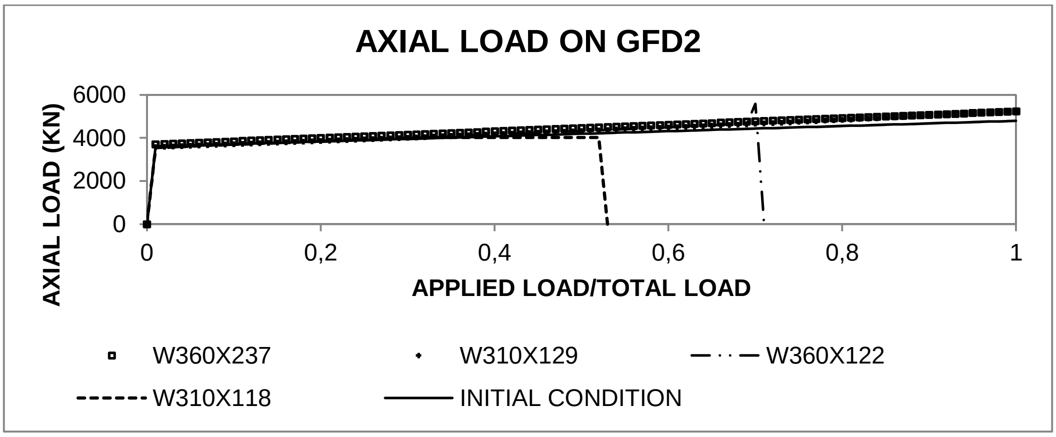

Figure 14 Increase in axial load at ground floor column D2

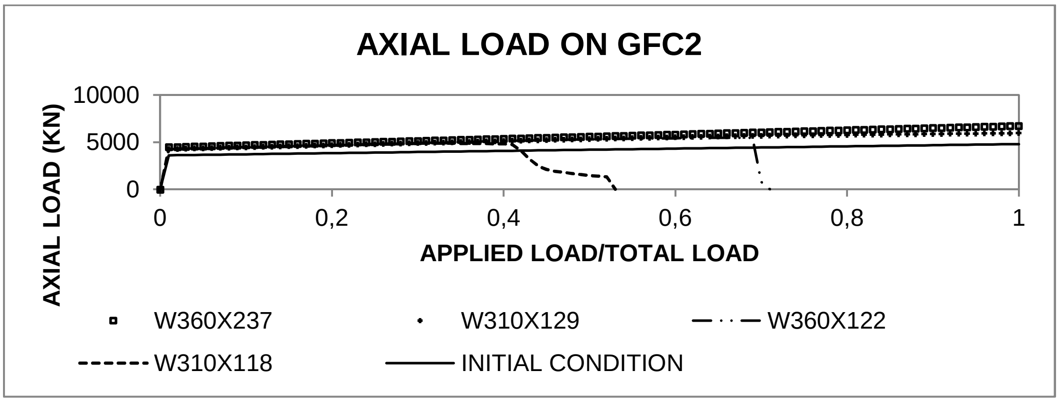

Figure 15 Increase in axial load at ground floor column C2

Beam Behavior Adjacent to Removed Center Column

Following removal of the ground floor column C1, the beams directly attached to the removed column along the structural perimeter begin to adopt a catenary action. The catenary action is centered around the top of the location where GFC1 was. The deflections developed at this critical location are shown in Figure 16. The larger cross section columns reached stable deflections at the total load whereas, the models constructed with the smaller cross section columns became unstable prior to attaining full load. This is witnessed on the deflection diagrams by the runaway deflection for columns W360X122 and W310X118.

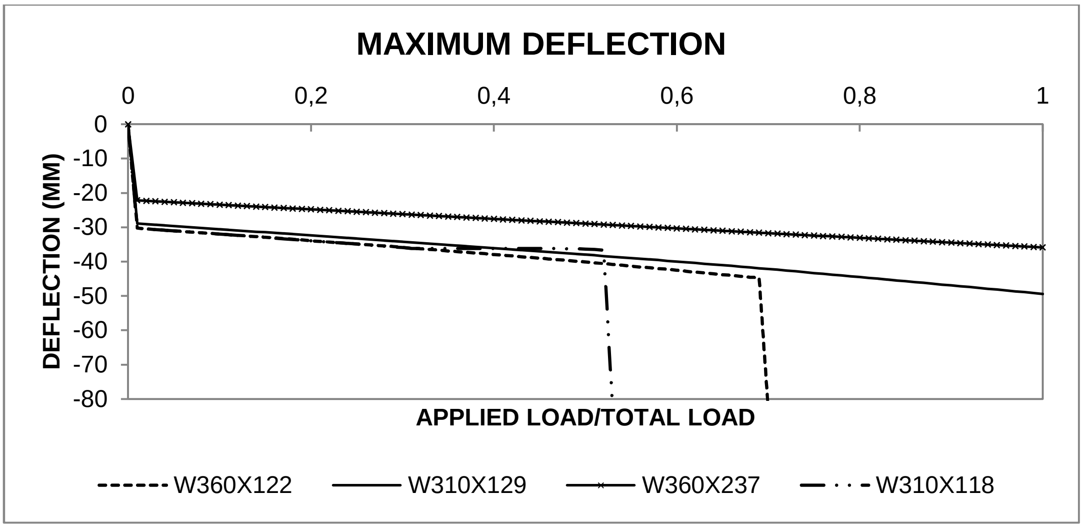

Figure 16 Maximum deflection at the top of the removed column GFC1

Figure 17 and Figure 18 show the shear force and axial force diagrams, respectively, for the beam spanning the ground floor columns B1 to D1. The shear force diagrams for beam B1D1 when the structure remained stable showed a flat profile on the shear force diagram. Once the structure became unstable with the use of smaller cross section columns, an increase in the shear force at the joint where GFC1 would have been was clearly visible, just prior to structural failure. Similarly, the axial force diagrams for beam B1D1 showed the same trend of large changes in axial force for the smaller, unstable column structure. For all beam diagrams, once the middle column GFC1 was removed, large forces developed in beam B1D1. As the column cross section reduced and the structure became unstable, the forces in beam B1D1 became larger.

The overall deflected shape of the structure prior to failure is shown in Figure 19. The global structural response induced large deflections at the beams above the removed columns. The catenary action of the beams directly adjoining where column C1 was is also visible in this figure. At the time of failure, plastic hinges formed in the beams at the two locations directly adjacent to columns B1 and D1 spanning to the location of C1. Large bending moments also developed at the joint between beams B1C1 and C1D1 where the removed column was. These large bending moments are the result of the greater beam span due to the removed column and the load from column C1 above the failed column.

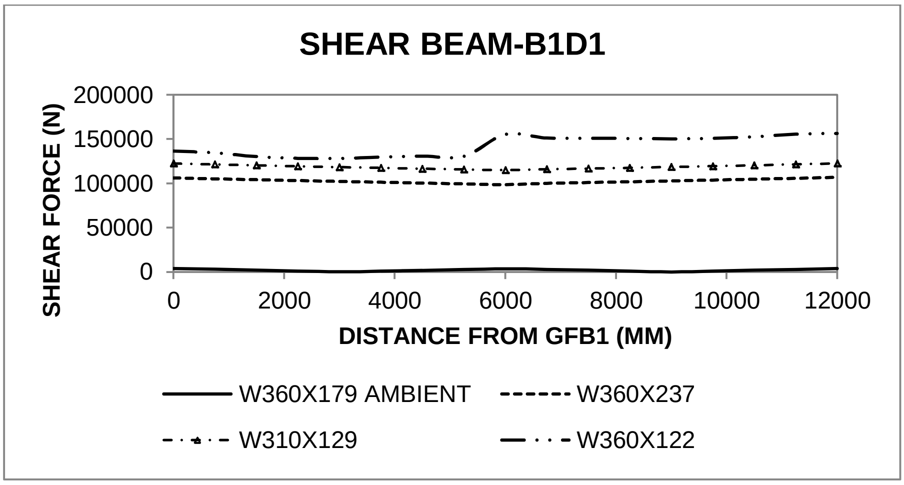

Figure 17 Shear force diagram for beam B1D1

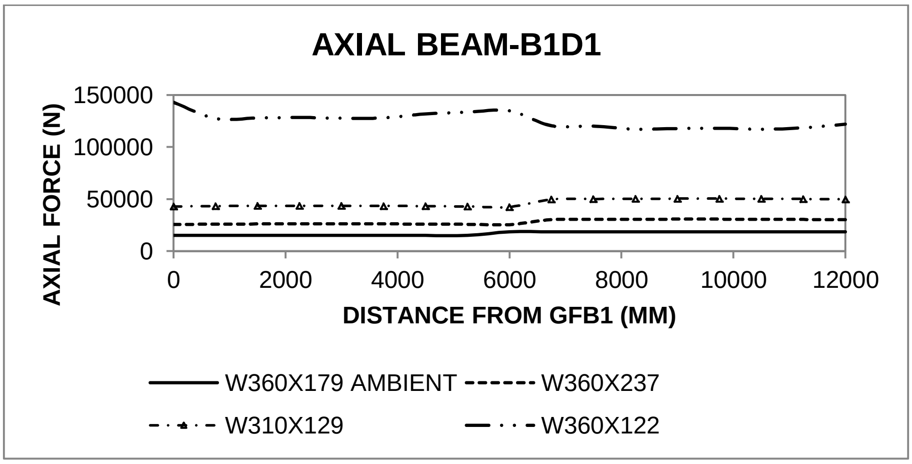

Figure 18 Axial force diagram for beam B1D1

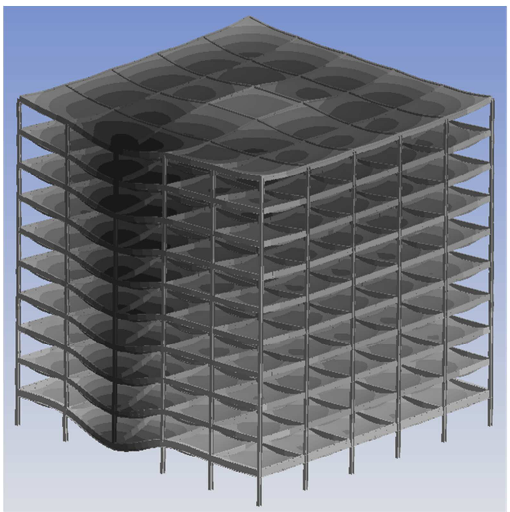

Figure 19 Overall deflected shape following removal of column GFC1

Discussion

The corner column removal scenario showed a 60 % increase in the axial load in the two columns directly adjacent to the removed corner column. The significant load redistribution in these two columns was attributed to the beams being directly framed into the failed column; as such the adjacent beam adopted a large cantilever mechanism. Large out of plane deflections were exhibited by the two columns with increased axial loading. This increased axial load needs to be considered when designing a building to remain stable following the removal of a corner column. Particular attention should be paid to the connection detail at the top of the two remaining adjacent columns as these connections will be required to transfer larger axial forces. When considering the corner column removal scenario for the sections tested the overall structure remained stable and the majority of the structure remained elastic, with only a few members becoming only slightly plastic.

The middle column removal scenario showed load redistribution to the five surrounding columns with the largest increase in axial load of 60 % at the two remaining perimeter columns directly adjacent to the failed column. Similarly to the corner column removal scenario, the redistribution pattern was strongly connected to the structural geometry, whereby the members directly connected by the floor beams to the failed column showed the highest increase in axial load. When considering the middle column removal scenario, the column section used had a strong influence on the overall stability of the model. The more robust cross sections became plastic but still remained stable, while the models constructed with slender cross sections became highly plastic and caused the model to become unstable.

Clearly, both column loss scenarios need to be considered when analyzing a steel structure's robustness and ability to transfer loads away from failed columns. By focusing efforts on increasing the resistance of the ground floor columns by increasing the cross-sectional properties to be able to withstand the load redistribution as shown in this study, will greatly improve the overall building's robustness which is critical in nuclear installations. Furthermore, increasing the cross-sectional area of the column could also increase the time required for the entire column to reach its critical temperature in a fire, thereby delaying the time to failure of the column.

CONCLUSIONS

Based on the results of this study the following conclusions can be stated:

- For both the corner column removal scenario and the middle column removal scenario, the majority of the load was shed to the columns directly adjacent to and directly connected by the floor beams to failed member. Therefore, when reviewing the design of a steel structure in a nuclear facility building to resist the column removal effects of an explosion or a severe fire, the columns directly adjacent to the column being considered must also be analyzed.
- For both the corner column removal scenario and the middle column removal scenario, the increase in axial load was approximately 60 %. Therefore, a passive strategy for the design of collapse resistant buildings in nuclear facilities should include for sufficient reserve capacity of the ground floor columns of at least 60 %. In accordance with other researchers, and to include a safety factor, ground floor exterior columns should be designed for twice the ambient condition load in order to resist progressive collapse from a single column removal scenario which could be induced by fire or explosion.
- The middle column removal scenario was more sensitive to the cross sectional properties of the ground floor columns as compared to the corner column removal scenario. This sensitivity resulted in greater instability for the middle column removal scenario as compared to the corner column removal scenario.
- Increasing the capacity and stiffness of the floor beams will also help to ensure that the building remains serviceable by avoiding excessive deflections during an extreme event

such as an explosion or fire. Steel structures used in control room buildings and turbine buildings contain equipment that must remain operational even during a severe loading event. Excessive deflections caused by inadequate beams could render parts of the building inoperable or inaccessible.

- The joints between the cantilevered beams and the remaining adjacent columns should be adequately designed to resist the additional loads; which can be significant. Joint behavior in steel structure fires is a widely researched important topic. Optimal joint configurations providing increased strength and ductility are required in all steel structures exposed to the possibility of a severe fire and can be found in the literature.

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QUALIFICATION OF FIRE BARRIERS IN U.S. NUCLEAR POWER PLANTS

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ABSTRACT

Qualification of fire barriers in nuclear power plants has a long and varied licensing history.

The basis of the qualification for all fire barriers from a regulatory standpoint is based on testing conducted in accordance with the time-temperature curve of ASTM E-119. The regulatory bases for fire testing include a diverse list of testing standards, depending on which type of barrier is under review (i.e. wall/floor, penetration seal, door, damper, raceway wrap, etc.). There are also several methods available for evaluating the qualification of barriers. Examples are presented in this paper for evaluation of a seal design in comparison to test reports, qualitative evaluation of an area for non-rated seals based on the hazard presented to safe shutdown circuits, evaluation of an as-installed configuration that is a variance from the design parameters and an evaluation for the required rating of a raceway fire wrap utilizing fire modeling.

INTRODUCTION

The importance of fire barriers was highlighted by the fire at the Browns Ferry nuclear power plant in 1975 **[1]**. A fire barrier penetration seal was ignited after being improperly repaired, resulting in loss of many safety related functions associated with two of the units at the site. Since that time, the Nuclear Regulatory Commission (NRC) has issued a number of regulations and guidance documents that address the qualification and evaluation of fire barrier components. These evaluations can involve anything from a relatively simple, qualitative evaluation to a complex fire model that establishes the rating a particular barrier is required to have.

HISTORY OF ASTM E-119 TIME-TEMPERATURE CURVE DEVELOPMENT

The basis for all testing standards used to qualify fire barriers follow the ASTM E-119 time-temperature curve [2]. The ASTM E-119 time-temperature curve was first published in 1918 as part of a standard titled "Method of Fire Tests of Materials and Construction", issued by the ASTM Committee C-5, (later changed to E-5) [3]. Although in use for such a long time, the following was noted related to the technical basis of the time-temperature curve:

> "*The historical evidence indicates that the ASTM E-119, standard, temperature-time curve was prescribed in 1917 with very little knowledge of the levels and the temporal development of temperatures in actual room fires. The standard curve was basically an idealization of temperature-time curves measured in furnaces at various laboratories, was deemed to represent a severe fire, and was intended only to provide a basis for comparing the fire endurance of building assemblies using a simple test. Full-scale room burnout tests conducted at the National Bureau of Standards in the 1920s established that the actual temperature histories of room fires differed significantly from the standard curve."* [3]

It is still widely used today in the United States, and in general is considered the basic start of any fire test used to qualify barriers for nuclear power plants. Methodologies that could be used to develop alternate time-temperature curves have been published [4], [5], and [6]. However, these methodologies have not been used widely, if at all, in the nuclear power industry. The ASTM E-119 time-temperature curve is shown in Figure 1.

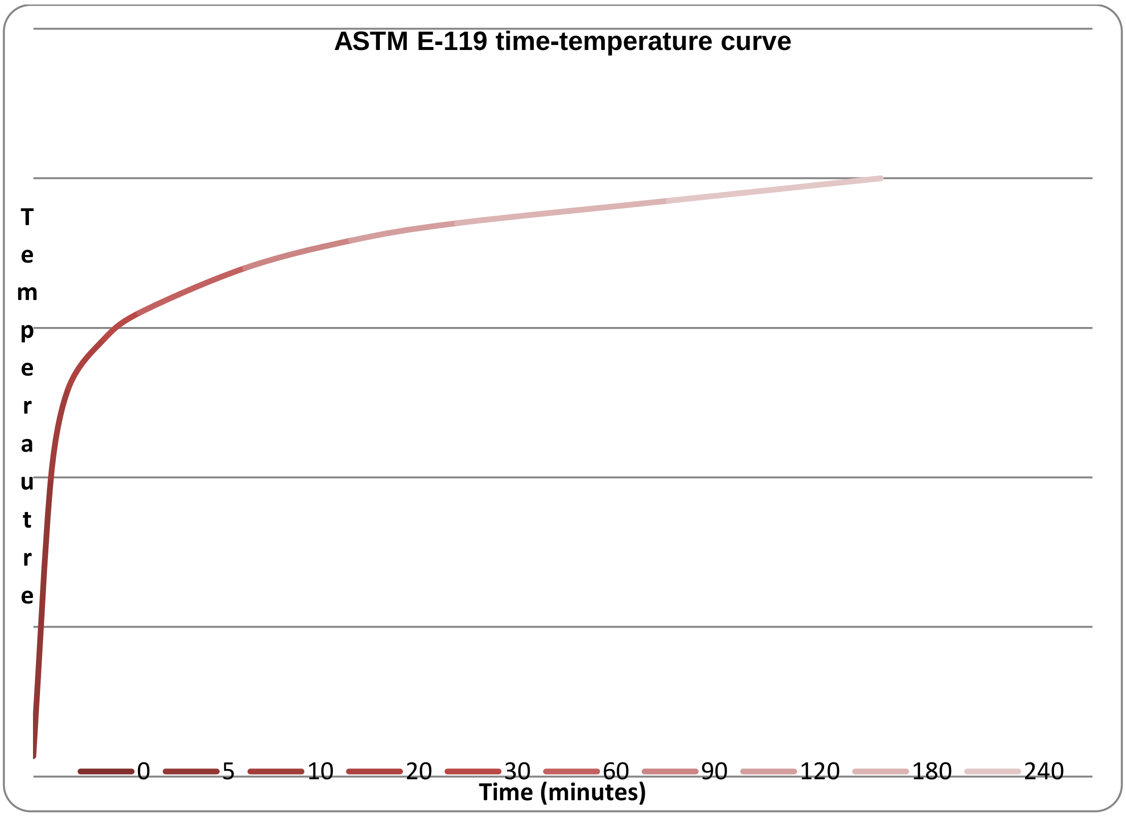

Figure 1 ASTM E-119 time-temperature curve

REGULATORY BASES FOR FIRE BARRIER QUALIFICATION

Testing Standards

At various times, the Nuclear Regulatory Commission has referenced certain testing standards used to qualify fire barriers:

Table 1 NRC referenced fire testing standards

Barrier Type	Testing Standard	Endorsing Document
Walls / Floors / Ceilings	ASTM E-119	Appendix A to BTP APCSB-9.5-1 [14] NUREG-1552 [15] GL 86-10 Supplement 1[16] NFPA 805 [17]
	NFPA 251 [7]	NUREG-1552

Barrier Type	Testing Standard	Endorsing Document
		GL 86-10 [18] GL 86-10 Supplement 1 NFPA 805
Doors	NFPA 80 [8]	Appendix A to BTP APCSB-9.5-1 NUREG-0800] Reg Guide 1.189 [20] NFPA 805
Dampers	NFPA 90A [9] UL 555[1] [10]	NUREG-0800 Reg Guide 1.189 NFPA 805 IN 89-52 Reg Guide 1.189
Penetration Seals	ASTM E-119 NFPA 251 ASTM E-814 [11] IEEE 634 [12] UL-1479 [13]	Appendix A to BTP APCSB-9.5-1 IN 88-04 [21] NUREG-0800 NUREG-1552 Reg Guide 1.189 NUREG-1552 Reg Guide 1.189 IN 88-04 NUREG-1552 Reg Guide 1.189 IN 88-04 NUREG-1552 Reg Guide 1.189 NUREG-1552
Electric Raceway Fire Barrier Systems (ERFBS)	ASTM E-119[2]	GL 86-10 Supplement 1

Acceptance Criteria

[1] The NRC noted that UL 555 did not test fire dampers under airflow conditions. Reg Guide 1.189 [20] and IN 89-52 [22] provide additional guidance for how to address damper closure under airflow conditions.

[2] GL 86-10 Supplement 1 [16] added additional criteria for qualification of ERFBS, including thermo-couple placement, and methods to evaluate cable damage when the temperature criteria are exceeded.

The one common feature of these testing standards is that the time-temperature profile of the furnace is the method from ASTM E-119. The acceptance criteria for passage of the test consist of the following:

1. The cable fire barrier penetration seal has to withstand the fire endurance test without passage of flame or hot gases that could cause ignition of secondary combustibles on the unexposed side for a period of time equivalent to the fire resistance rating required of the barrier. One example of secondary combustibles is cotton waste that is used during the test to test for smoke and gases leaking through the barrier. Other references use the ignition point of the cables that are used at the plant;
2. The temperature levels recorded for the unexposed side are analyzed and need to demonstrate that the maximum temperature does not exceed a maximum value. Many testing standards use the criteria of either 181 °C (325 °F) temperature rise above ambient conditions when measured by a single thermocouple or 139 °C (250 °F) temperature rise above ambient when averaging all thermocouples. Fire-stop systems tested to ASTM E-814 (UL 1479) [11], [13] can have two ratings, F and T. The F-rating is expressed in hours and indicates the length of time that a barrier can withstand fire before permitting the passage of flame through the opening. The F-rating is also subject to withstand the hose stream test. The T-rating is expressed in hours and indicates the length of time that the maximum single point temperature on the non-fire side of the penetration does not exceed 181 °C (325 °F) above ambient temperature. IEEE-634 [12] and 10CFR50 Appendix R [23] state that this value shall be below the cable insulation ignition temperature, and
3. The fire barrier penetration seal must remain intact and not allow projection of water beyond the unexposed surface during the hose stream test. There are three variations of this hose stream test that are allowed in the guidance documents [16], [19]:
   - The stream applied at random to all exposed surfaces of the test specimen through a 6.4 cm (2 in) national standard playpipe with a 2.9 cm (1 in) orifice at a pressure of 207 kPa (30 psi) at a distance of 6.1 m (20 ft) from the specimen, or
   - The stream applied at random to all exposed surfaces of the test specimen through a 3.8 cm (1 in) fog nozzle set at a discharge angle of 30 ° with a nozzle pressure of 517 kPa (75 psi) and a minimum discharge of 284 lpm (75 gpm) with the tip of the nozzle at a maximum of 1.5 m (5 ft) from the test specimen, or
   - The stream applied at random to all exposed surfaces of the test specimen through 3.8 cm (1 in) fog nozzle set at a discharge angle of 15 ° with a nozzle pressure of 517 kPa (75 psi)] and a minimum discharge of 284 lpm (75 gpm) with the tip of the nozzle at a maximum of 3 m (10 ft) from the test specimen.

   Duration of the hose stream testing varies based on the area of the specimen and the duration of the qualification test. GL 86-10 Supplement 1 [16] provided set durations of hose stream tests for ERFBS qualification testing.

METHODS OF DEMONSTRATING COMPLIANCE

Fire Barriers (Walls, Floors, and Ceilings)

In this context, fire barriers include walls, floors and ceilings, including the beams, joists, columns and other structural elements.

Published results demonstrate that 6¼” of normal weight concrete can be expected to provide a three hour fire resistance rating. These results are based on the most conservative values based on slab thickness and the type of aggregate used [24]. These results are shown in Figure 2.

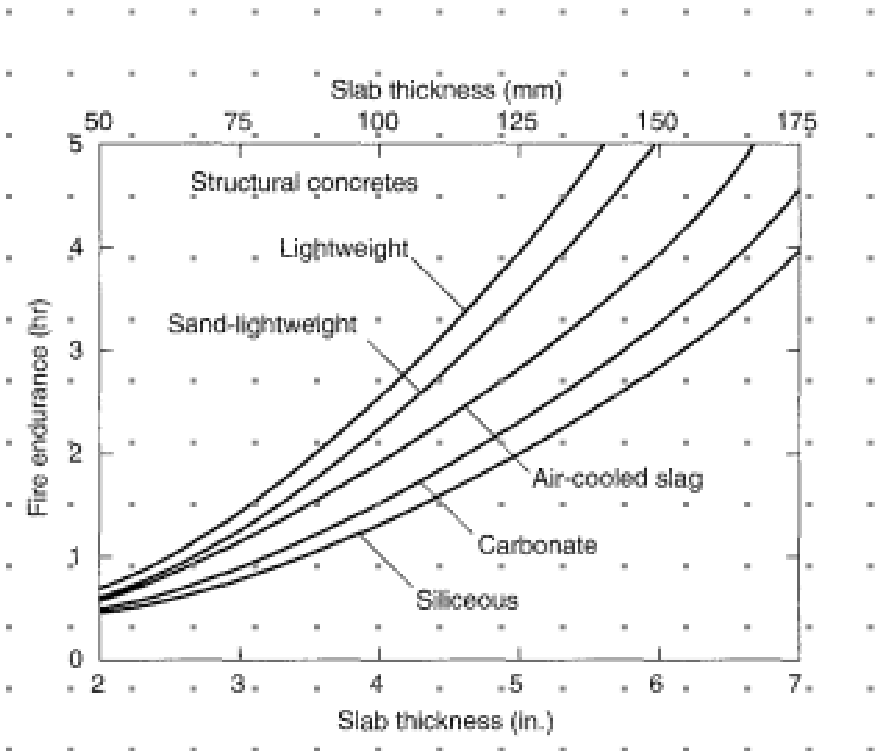

Figure 2 Fire resistance of concrete barriers

Walls constructed of materials other than normal weight concrete (e.g. gypsum board drywall), are typically compared to a qualification test published in a directory by an organization such as Underwriter's Laboratories (UL) or Factory Mutual (FM). UL and Factory Mutual (FM) [25], [26] both provide typical designs for other types of construction in fire barriers, including beam and joist construction, protection of columns, and built up roofing.

Penetration Seals

It is recognized not all configurations that are found in construction can be tested. In general the following criteria are applied when evaluating fire barrier penetration seals for compliance [20], [22]:

1. Size of sealed opening — In some cases, a successful fire endurance test of a particular fire barrier penetration seal configuration for a particular size opening may be used to justify the same configuration for smaller openings.
2. Penetrating items — A satisfactory test of a seal configuration that contains a particular pattern of penetrating items can be used to qualify variations on the tested pattern. Variations that are acceptable include eliminating or repositioning one or more of the penetrating items, reducing the size (cross-sectional area) of a particular penetrating item, or increasing the spacing between penetrating items. However, since penetrating items provide structural support to the seal, the free area of the seal material and the dimensions of the largest free span may also be factors that affect the fire-resistive performance of the seal assembly. The thickness of the seal material needed to obtain a particular fire rating may also be a function of the free area or the distance between the penetrating items and the outside edge of the seal assembly. In other cases, consideration of the penetrating items takes on special performance because of the heat sink they provide.
3. Cable type and fill — A satisfactory test of a seal configuration with certain electrical penetrations containing a specified fill ratio and cable type can be used to qualify similar

configurations containing the same or a smaller cable fill ratio and the same cable jacket material or a less combustible jacket material. The thermal conductivity of the penetrating cables is also important.

4. Damming materials — The fire resistive performance of a given seal configuration can be improved if a fire-resistant damming material covers one or both surfaces of the seal. A satisfactory test of a seal configuration without a permanent fire-resistant dam can be used to qualify the same configuration with a permanent fire-resistant dam, all other seal attributes being equal. The converse is not true.
5. Configuration orientation — A satisfactory test of a particular seal configuration in the horizontal orientation (with the test fire below the seal) can be used to qualify the same configuration in a vertical orientation if the symmetry of the design configurations are comparable. For example, if a non-symmetric penetration seal configuration (e.g., a seal with a damming board on the bottom, but not on the top) is qualified for a floor-ceiling orientation with the damming board on the fire side of the test specimen, the configuration could only be qualified for a wall orientation if a damming board was installed on both sides of the seal or if the potential fire hazard is limited to the side with the damming board.
6. Material type and thickness — Satisfactory testing of a particular seal configuration with a specific seal material thickness can be used to qualify the same configuration with a greater seal material thickness of the same type of seal material. The converse is not true.
7. Type testing — In cases in which a single test of a particular seal configuration is to serve as a qualification test for the same or similar design configurations with different design parameters, the tested configuration should be the worst-case design configuration with the worst-case combination of design parameters. This would test and qualify a condition that would fail first, if failure occurs at all. Successful testing of the worst-case condition can then serve to qualify the same or similar design configurations for design parameters within the test range. It would be appropriate to conduct multiple tests to assess a range of design parameters.

Special guidance has been provided for internal conduit seals. Openings inside conduit larger than 102 mm (4 in) in diameter should be sealed at the fire barrier penetration. Openings inside conduit 102 mm (4 in) or less in diameter should be sealed at the fire barrier unless the conduit extends at least 1.5 m (5 ft) on each side of the fire barrier and is sealed either at both ends or at the fire barrier with material to prevent the passage of smoke and hot gases [17], [19], and [20].

Fire Doors

Guidance that has been provided for fire doors [20], [23] stipulates that the construction and installation techniques for doors and door openings through fire barriers should be in accordance with the door manufacturer's recommendations and the tested configuration.

Modifications to fire doors should be evaluated. Where a door is part of a fire area boundary, and a modification does not affect the fire rating (for example, installation of security "contacts"), no further analysis need be performed. If the modifications could reduce the fire rating (for example, installation of a vision panel), the fire rating of the door should be reassessed to ensure that it continues to provide an equivalent level of protection to a rated fire door. Fire doors should be self-closing or provided with closing mechanisms and should be inspected semiannually to verify that automatic hold-open, release, and closing mechanisms and latches are operable. One of the following measures should be provided to ensure they will protect the opening as required in case of fire.

1. Fire doors should be kept closed and electrically supervised at a continuously manned location;

2. Fire doors should be locked closed and inspected weekly to verify that the doors are in the closed position. Fire brigade leaders should have ready access to keys for locked fire doors;
3. Fire doors should be provided with automatic hold-open and release mechanisms and inspected daily to verify that doorways are free of obstructions; or
4. Fire doors should be kept closed and inspected daily to verify that they are in the closed position.

Fire Dampers

Guidance provided for fire dampers [20], [22] states that openings should be protected with fire dampers that have been fire tested. In addition, the construction and installation techniques for ventilation openings through fire barriers should be qualified by fire endurance tests. For ventilation ducts that penetrate or terminate at a fire wall, guidance in NFPA 90A [9] indicates that ventilation fire dampers should be installed within the fire wall penetration for barriers with a fire rating greater than or equal to two hours. NFPA 90A requires that fire dampers be installed in all air transfer openings within a rated wall.

UL Standard 555, "Fire Dampers and Ceiling Dampers" [10] does not evaluate whether or not fire dampers will close under air flow conditions. Therefore, the UL fire damper rating only indicates whether a fire damper in the closed position will maintain its integrity under fire conditions for a specific time period.

Fire damper testing methods that do not simulate the actual total differential pressure at the damper (i.e., visual inspection or drop testing with duct access panels open) may not show operability under air flow conditions. Fire damper surveillance testing should model air flow to ensure that the dampers will close fully when called upon to do so. This can be addressed by (1) type testing "worst-case" air flow conditions of plant-specific fire damper configurations, (2) testing under air flow conditions all dampers installed in required fire barriers, or (3) administratively shutting down the ventilation systems to an area upon confirmation of a fire. The last approach should be incorporated into plant emergency procedures [20], [22].

Electric Raceway Fire Barrier Systems

The primary guidance for ERFBS is in GL 86-10 Supplement 1 [16], where the NRC provided the following criteria:

"The staff considers the fire endurance qualification test for fire barrier materials applied directly to a raceway or component to be successful if the following conditions are met:

- The average unexposed side temperature of the fire barrier system, as measured on the exterior surface of the raceway or component, did not exceed 139 °C (250 ° F) above its initial temperature; and
- Irrespective of the unexposed side temperature rise during the fire test, if cables or components are included in the fire barrier test specimen, a visual inspection should be performed. Cables should not show signs of degraded conditions resulting from the thermal effects of the fire exposure; and
- The cable tray, raceway, or component fire barrier system remained intact during the fire exposure and water hose stream test without developing any openings through which the cable tray, raceway, or component (e.g., cables) is visible."

EVALUATION TECHNIQUES FOR FIRE BARRIERS

One of the earliest instances of the NRC addressing fire barriers occurred in Interpretation 4 of GL 86-10 [18]. In this document, the NRC provided their definition of a fire area boundary as follows:

> "The term "fire area" as used in Appendix R means an area sufficiently bounded to withstand the hazards associated with the area and, as necessary, to protect important equipment within the area from a fire outside the area. In order to meet the regulation, fire area boundaries need not be completely sealed floor-to-ceiling, wall-to-wall boundaries. However, all unsealed openings should be identified and considered the evaluating the effectiveness of the overall barrier. Where fire area boundaries are not wall-to-wall, floor-to-ceiling boundaries with all penetrations sealed to the fire rating required of the boundaries, licensees must perform an evaluation to assess the adequacy of fire boundaries in their plants to determine if the boundaries will withstand the hazards associated with the area. This analysis must be performed by at least a fire protection engineer and, if required, a systems engineer."

Situations that are subject to evaluation include, but are not limited to the following:

- Evaluation of design details against qualification tests to ensure the design details are bounded by the tests.
- Evaluations of as-installed configurations that deviate from the design details.
- Evaluations of non-rated configurations in fire barriers.
- Evaluations of required barrier ratings based on the hazards that exist in the areas.

Evaluations tend to either demonstrate functionally equivalency (i.e., the barrier is fully qualified for a specific rating), or that the barrier in question can withstand the hazards associated with the area.

Example 1

This example involves evaluation of a typical seal detail against a qualification test. In this case, the typical detail is 9" of silicone foam with 1 " of ceramic fiber damming board on each side in a wall configuration. When reviewing the qualifying fire tests, the following deviations from the guidelines were noted:

- In one test, no discharge pressure was noted during the hose stream test,
- In a second test, no discharge pressure was noted during the hose stream test. In addition, the spray angle used (30 °) was supposed to be a maximum of 5 feet from the surface, as opposed to the 10 ' tested.

Based on these deviations, more testing was located that had a larger area than the original tests reviewed. This test had multiple hose stream tests conducted with all of the appropriate criteria identified. As a result the seal design was considered functionally equivalent to a three hour rated fire seal.

Example 2

This example involves the utilization of a seal design that specified 9 " of silicone foam with 1 " of ceramic fiber damming on both sides of a wall penetration. The maximum seal area tested was 1160 in^2. The as-installed configuration for the seal in question was a seal area of 2584 in^2. A walkdown of the seal found the free area of the seal was minimized based on the penetration configuration. Since the penetration was in a wall configuration, there was nothing in the area that would be able to fall on the penetration directly. Therefore, it was determined that the configuration as-installed was functionally equivalent to a three hour fire seal.

Example 3

This example involves the evaluation of non-fire rated penetration seal designs in a fire area boundary. One side of the barrier (in a Reactor Building) includes safety related equipment that is not required for safe shutdown. This area includes ionization detection and an automatic wet pipe suppression system. The combustibles in the area do not pose a significant hazard to the penetrations.

The other side of the wall is a covered pipe tunnel with negligible fixed combustibles or ignition sources. This portion of the tunnel communicates with an area that contains safe shutdown circuits. The lower elevation of the tunnels is generally infiltrated with ground water precluding any transient storage.

Based on the lack of exposure to the seal from a fire in the Reactor Building, and the absence of combustibles in the pipe tunnel that could present a propagation path to the safe shutdown circuits, the penetrations were considered as adequate for the hazards they were being presented.

Example 4

This example involves the determination of the required rating for a proposed ERFBS installation for a conduit containing circuits required for safe shutdown. The area does not contain fire suppression, and the deterministic requirement would be to protect the conduit with a three hour fire barrier. The room in question is approximately 7.3 m x 11.7 m (24 ft x 38 ft) with a ceiling height of approximately 3 m (10 ft). Boundaries are normal weight concrete between one and three feet thick. A ventilation system is provided. The overall area geometry is shown in Figure 3.

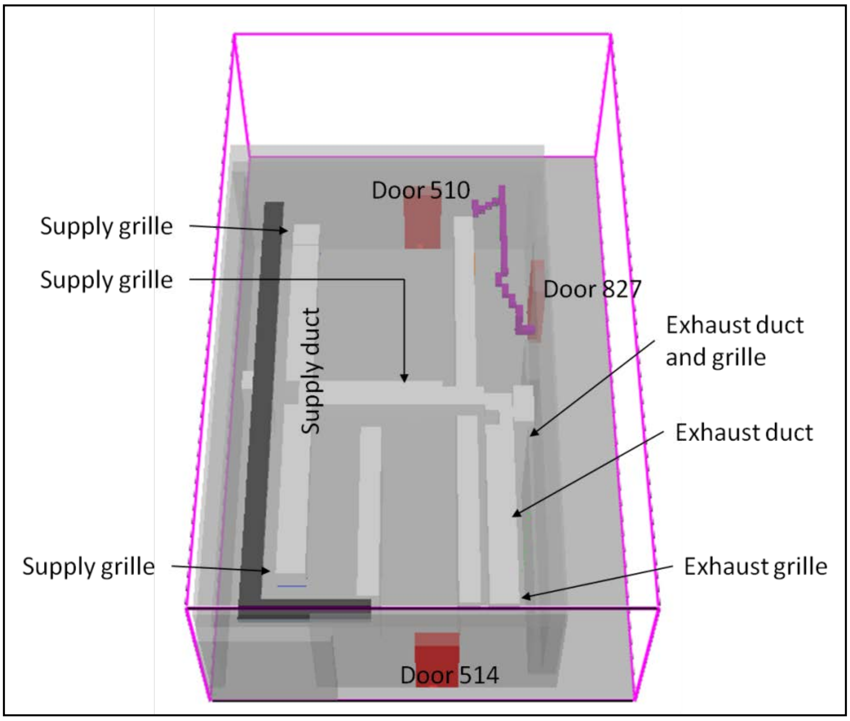

Figure 3 Fire area geometry for Example 4

The target in question is a conduit that is located in the northeast side of the room. It enters the room through the east wall, 0.8 m (32 in) below the ceiling, then runs along the ceiling, until it reaches the north wall. It drops down to 1.7 m (69 in) above the floor, then exits the room through the north wall.

Ignition sources are electrical cabinets. Heat release rates and fire growth is based on the guidance provided in NUREG-6850 [27]. This includes the growth from one cabinet to another. The combined heat release rate is shown in Figure 4.

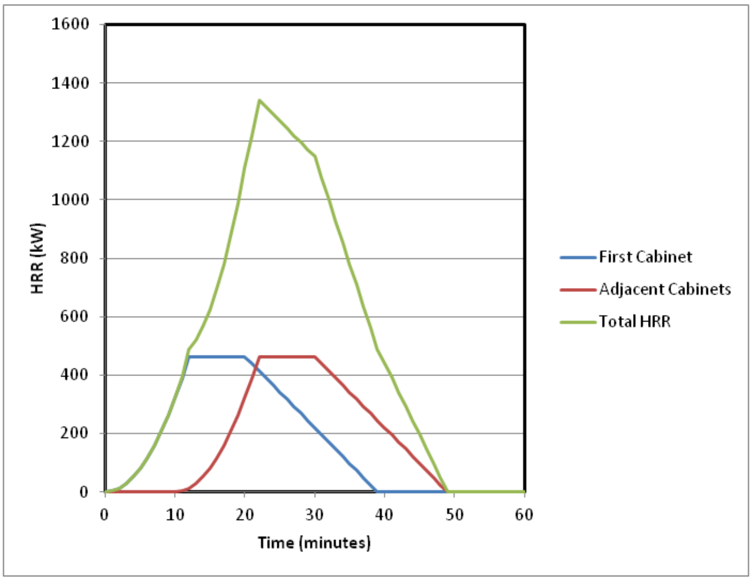

Figure 4 Combined HRR for three electrical cabinets

The model was conducted using Fire Dynamics Simulator (FDS) by NIST [28]. The overall results demonstrated that an unprotected cable in conduit would be damaged at the following timeframes:

Table 2 **Time to damage for fire scenarios**

Fire Scenario	Time [min]
Open doors	8.4
Closed doors	8.6
Doors open at 15 min	8.6

Therefore, an ERFBS is justified. Appendix C of NUREG-1934 [29] suggests two strategies for assessing the viability of the protected cables. One of them is to compare the predicted fire generated conditions near the target conduits (i.e., exposure temperature) to the standard fire endurance curve under which the ERFBS was tested to determine if the predicted thermal exposure is comparable to the qualification test. The second is to calculate the temperature of the cable directly, using the nominal thermal properties of the fiber insulating blanket. The first option was used in this scenario. A comparison of the most conservative scenario against the ASTM E-119 curve is shown in Figure 5.

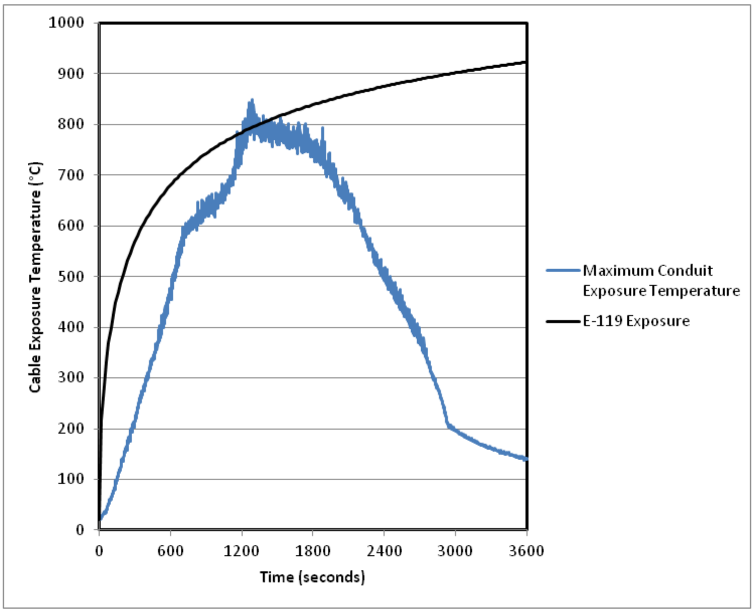

Figure 5 Conduit thermal exposure temperature compared to ASTM E-119 exposure

The comparison suggests the fire generated condition is under the endurance test exposure during the length of the fire event with the exception of a brief period of time. In order to compare the relative exposure of the ERFBS, it is necessary to consider the integrated incident heat flux corresponding to the model hot gas layer predictions and the ASTM E-119 time-temperature curve. The integrated heat flux is given by the following formula (see Appendix C of NUREG-1934 [29]):

$$q'' = \int_{t_n}^{t_1} \dot{q}''(t)\,dt = \int_{0}^{3600} \sigma(T^4 - T_0^4) + h(T - T_0)\,dt$$

Here, q" is the integrated heat flux received by the ERFBS, T is the hot gas layer (HGL) temperature, T_0 is the ambient temperature (20 °C), h is the convective heat transfer coefficient (assumed 0.025 $kW/m^2/K$), and σ is the Stefan-Boltzmann constant (5.67 x 10^{-11} $kW/m^2/K^4$). Note that the equation above is the total energy transferred from a thermally-thick (emissivity of 1) hot gas to a cold target. It is intended only to compare the different temperature curves. In reality, the net heat transferred to a target in the compartment decreases as the target heats up. The integral equation above applied to the ASTM E-119 test temperature curve yields values of 346 MJ/m^2. The same integration was conducted for the three FDS simulations discussed in this example. Table 3 summarizes the integrated thermal exposure and associated safety factor for each case.

Table 3 Integrated thermal exposure and associated safety factor

Fire Scenario	Thermal Exposure [MJ/m^2]	Equivalent Exposure Duration [min]	Approximate Factor of Safety
Open doors	139	31	2
Closed doors	142	31	2
Doors open at 15 min	139	31	2

The results of the analysis suggests that the fire exposure generated by the worst case scenario conditions are lower in terms of temperature and total thermal energy than those to which the barrier system is subjected during qualification testing. Consequently, an ERFBS rated for one hour will provide adequate protection for the fire hazards identified in the fire areas.

CONCLUSION

Since the Browns Ferry fire in 1975, multiple guidance documents have been issued that address the qualification and evaluation of fire barriers. Common features of qualification standards are:

- The time-temperature profile used to qualify barriers and their components is that provided in ASTM E-119.
- The barrier cannot allow the passage of flame or products of combustion of a nature that could cause secondary ignition on the unexposed side.
- The temperature rise on the unexposed side must be below a specified value or below the ignition point of cables that penetrating the seal.
- The barrier must demonstrate structural integrity by passing a hose stream test. NRC documents allow different applications depending on the time, pressure, nozzle types and distance.

Barriers may be evaluated for their ability to withstand fire. Evaluation methods vary from relatively simple, qualitative analyses performed by a qualified fire protection engineer to complex fire models, used to determine the minimum rating required for that barrier.

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RECENT CONSIDERATIONS ON THE FIRE BARRIER RESISTANCE RATING FOR GERMAN NUCLEAR POWER PLANTS

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ABSTRACT

The German standards on fire safety in nuclear power plants and, in particular the part on fire safety of structural elements includes a simplified method for the fire resistance rating of fire barrier elements. The method covers the specific features of compartments in nuclear power plant buildings in terms of the boundary conditions which have to be expected in the event of fire. The method has proven to be relatively simple and straightforward to apply.

The paper gives an overview of the method and two examples for application. Moreover, a recently conducted review of the method has provided first indications that for some parameters of the rating the method should be reconsidered. In case of specific fire scenarios in compartments of a nuclear power plant the values for an adequate fire resistance rating of structural elements by means of the simplified fire rating method may not be enough conservative. This paper contributes to the discussion on enhancing the rating method within the update of the KTA on fire protection.

INTRODUCTION

According to the German nuclear fire safety standards, in particular the standard KTA 2101, Part 2 on "Fire Protection of Structural Plant Components" [1], for nuclear powers plants (NPP) a simplified method is recommended to be applied in the design of fire barriers and other structural elements with respect to adequate fire resistance rating. The method for estimating the required rating as outlined in Appendix A of [1] considers typical boundary conditions in the buildings of a NPP, such as ventilation conditions, room heights, and available heat sinks in the fire area.

In the context of the actually ongoing update of the German nuclear fire safety standards, the existing methodology has been reviewed from a practical point of view in regard of potential improvements.

This paper presents the methodology, gives some practical advice and applications, and discusses recommendations for further considerations.

FIRE RESISTANCE RATING ACCORDING TO THE GERMAN SIMPLIFIED METHOD PROVIDED IN KTA 2101.2

In the following, the design approach for fire barriers and other structural elements as given in KTA 2101, Part 2 [1] is briefly outlined. The primarily required input parameters are the effective fire load density (fire load [MJ] per floor area of the compartment [m^2]) and its distribution over the fire compartment. As a first result, the equivalent fire duration [min] is given. In this context, the term "equivalent" means that the given fire load density in an exemplary compartment will heat up a sample structural element to the same temperature as is will be heated up by a fire according to the standard temperature time curve from ISO 834 [2] during an equivalent time period. The reference temperature is taken in 3.5 cm depth of a concrete ceiling slab which is heated in one dimension. The analytical step from the sample compartment to an actual compartment is done by consideration of the compartment height

[m], and the ventilation conditions from natural as well as mechanical ventilation. Heat sinks by steel or concrete constructions within the fire compartment, which will decrease the compartment temperature additional to the walls and ceiling, can be considered by reducing the fire load in the calculation. In the last step, the required fire resistance rating is calculated from the equivalent fire resistance by a so called "safety parameter" that depends on the fire extinguishing means provided in the given compartment (fixed systems as well as manual fire fighting), the relevance of the structural element to be rated and whether the ventilation conditions are as intended or not (unintended). The methodology is principally based on research activities by Hosser, Blume, et al. (cf. [3] to [5]). There are some similarities to the design method for structural fire protection in industrial buildings in Germany [6].

Effective Fire Load Density

The effective fire load density, q_R [kWh/m^2], of a given fire compartment is calculated from the individual masses of combustibles, M_i, the calorific value, H_{ui}, and the combustion efficiencies of the entire unprotected fire loads, χ_i, as well as from the corresponding values M_j, H_{uj} and χ_j for the "protected" fire loads.

In this context, fire loads are postulated to be protected ones,

a) if their ignition can be excluded in case of an impact of a fire from outside the protected fire load or
b) if it is demonstrated that any release of the combustible material from inside the protection can be excluded under consideration of the fire impact.

Typically, protected fire loads are encapsulated, e.g. by metal containers, or shielded against fire effects.

If energy losses come into effect (cf. [1], [3]), this has to be considered as ΔQ_W which is subtracted from the fire loads.

$$q_R = (Q_u + Q_g - \Delta Q_W) / A \qquad (1)$$

where A is the compartment floor area [m^2].

The calorific values, H_{ui}, and the combustion efficiencies, χ_j, are given in Table 1 for some fire loads typically present in nuclear power plants.

Table 1 Material related data for fire loads, from [1]

No.	Material	H_u [MJ/kg]	H_u [kWh/kg]	χ_i [-]
1	Oil	42.0	11.7	1.0
2	PVC cables (without inert parts)	18.0	5.0	0.50 2,5)
3	Wooden cribs	17.3	4.8	0.75 2)
4	Activated carbon (charcoal)	32.8	9.1	1.0 4)
5	Hydraulic oil, DTE	40.5	11.3	0.8 2)
6	Polypropylene	43.9	12.2	0.9 3)
7	Paper	13.7	3.8	0.75 3)
8	Cotton rags	31.7	8.8	0.75 3)
9	Polyethylene (granulate)	43.2	12.0	0.8 2)
10	Polyethylene with 25 % chlorine	31.6	8.8	0.7 3)
11	Rubber (caoutchouc)	42.1	11.7	1.0 4)

No.	Material	H_u [MJ/kg]	H_u [kWh/kg]	χ_j [-]
12	Cold cleaning fluid (gasoline)	42.8	11.9	≈ 1.0
13	Lubrication grease	41.4	11.5	1.0 [4)]
14	Glycol	16.6	4.6	0.8 [2)]
15	Polystyrene	39.2	10.9	0.65 [3)]
16	Methanol	20.0	5.6	0.95 [3)]
17	Heptane	44.6	12.4	0.95 [3)]

1) Data for further materials may be taken from the literature
2) Experimentally determined values from [5] with a 10 % variance.
3) Values from literature (cf. [5])
4) These are conservative estimations. Exact values are not available at the time being and can only be determined experimentally.
5) The value for PVC cables is currently under review

The consideration of energy losses due to heat sinks is an iterative procedure. Initially it is assumed that $\Delta Q_W = 0$; the procedure is presented in [1].

Equivalent Fire Duration

For a given compartment the equivalent fire duration, t_e [min], is calculated from a basic value, $t_{e,0}$ [min], and compartment specific correction factors for the actual compartment height, f_H [-], as well as the actual ventilation condition, f_{Av} [-]:

$$t_e = t_{e,0} * f_H * f_{Av} \quad (2)$$

The basic compartment has got a reference height of H_{ref} = 2.5 m and a reference opening ratio given by the effective vertical opening area, $A_{V,eff}$, divided by the compartment area, A, of 1.6 %.

The basic value $t_{e,0}$ is to be taken from Figure 1. The diagram is based on a series of fire simulations with the multi-room zone model code FIGARO (abbreviation for: *Fi*re and *Ga*s movements in *Ro*oms) [7]. Here, a distinction is made concerning the distribution of the fire load over the compartment by three cases, namely:

a) Uniformly distributed fire load:
In the fire simulations, the fire extended over about 2/3 of the compartment area,
b) Non-uniformly distributed fire load:
In the fire simulations, the fire extended over about 1/3 of the compartment area,
c) Point-source fire load:
In the fire simulations the fire was limited to less than 1/5 of the compartment area.

Figure 1 demonstrates that the more the fire load and the resulting fire is concentrated on a smaller floor area, the larger the local fire effects become.

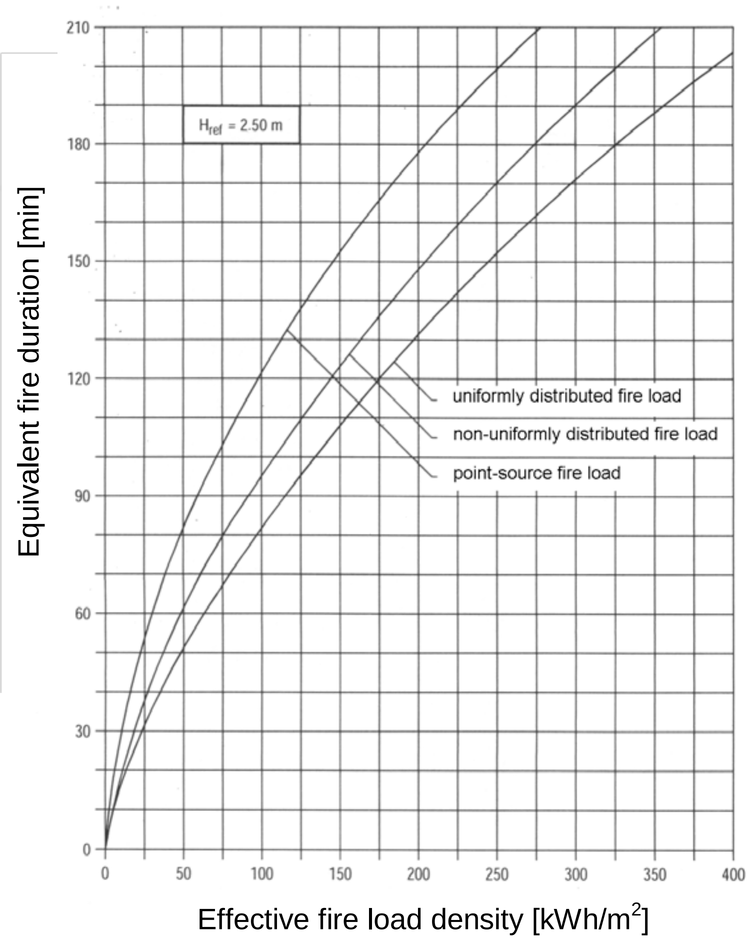

Figure 1 Basic equivalent fire duration, $t_{e,0}$, as a function the effective fire load density in [kWh/m^2] [1]

The correction factor for the actual compartment height is calculated by

$$f_H = (2.5 \text{ m} / H)^{0.3} \qquad (3)$$

This equation mainly attributes to the increased heat losses in compartments higher than 2.5 m. E.g., for a compartment height of H = 5.0 m, the factor f_H becomes 0.81.

The correction factor, f_{Av}, for the actual ventilation condition can be taken from Figure 2 as a function of the relative effective ventilation area, $A_{V,eff}/A$

$$f_{Av} = \text{f}(A_{V,eff} / A) \qquad (4)$$

with

$$A_{V,eff} = A_V + \dot{\boldsymbol{V}}_{zu} / 6000 \quad [\text{m}^2] \qquad (5)$$

where:

A_V: overall surface area of vertical vents in the enclosing walls [m^2],

$\dot{V}_{zu}$: volumetric air supply rate in the case of forced ventilation [m^3/h],

A: surface area of the compartment [m^2].

The correction factor, f_{Av}, needs to be calculated twice for different ventilation conditions, namely the intended ("planned") (p) and unintended (u) ventilation. In case of intended (p) ventilation conditions it is considered that

- all openings (including doors) which are intentionally open or which are open with a relatively large probability (e.g. blocked fire doors) in the event of fire,

- a forced ventilation, which is intended to work or not supposed to be switched off, according to operation procedures, during fire would continue to be in operation in the event of fire, and
- leakage openings in the enclosing structural elements

have to be considered.

In case of unintended (u) ventilation conditions, it is considered that

- doors stand open, which regularly would be closed in the event of fire, e.g. due to the failure of a self-closing device, or
- the forced ventilation that regularly would be switched off during fire would continue to operate, and additionally
- the leakage openings related to the intended ventilation

will contribute to ventilation.

Care should be taken when assessing the ventilation openings to calculate $A_{V,eff} / A$ and the resulting f_{Av}. On the one hand, a small value for $A_{V,eff}$ will significantly reduce the equivalent fire resistance rate, because the fire lacks of oxygen. However, the surface area of leakage openings in the enclosing structural elements is always difficult to assess. Therefore, a minimum leakage is assumed in Figure 2 for small opening ratios between 0 % < $A_{V,eff} / A$ < 1.6 %. Here the curve resulting from the fire simulations, which is leading through the origin (f_{Av} = 0 at $A_{V,eff} / A$ = 0 %) of the diagram, was lifted up to a factor of f_{Av} = 0.5 for no ventilation and drawn to the value f_{Av} = 1.0 for $A_{V,eff} / A$ = 1.6 %.

On the other hand, with a factor $A_{V,eff} / A$ larger than 1.6 % a cooling effect of the fire is assumed. Therefore, it must be scrutinized whether an opening vent is really operating. This matter is further discussed below.

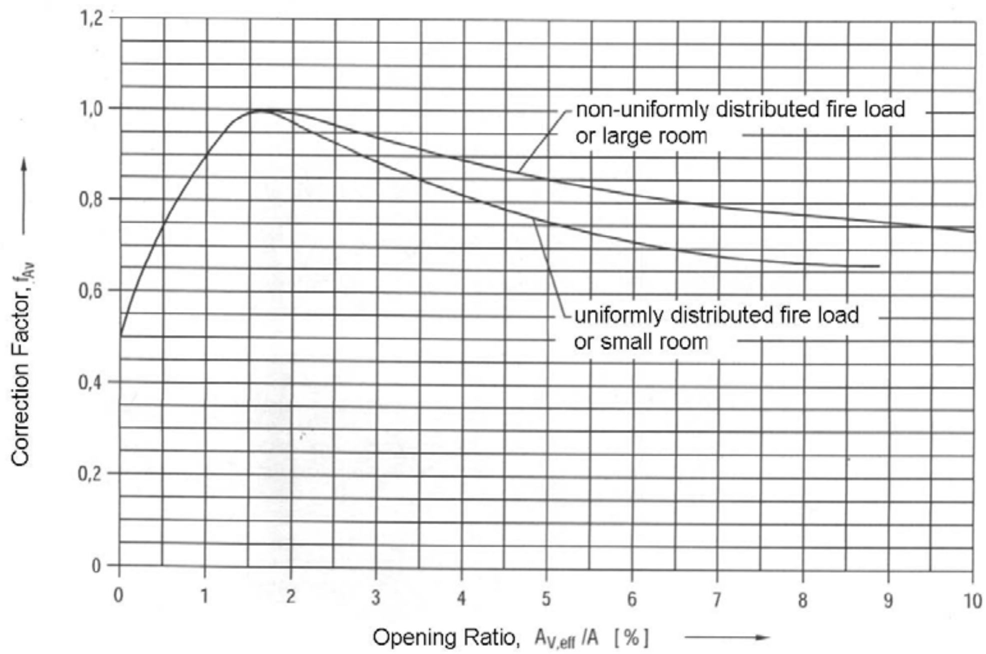

Figure 2 Correction factor, f_{Av}, as a function of the relative effective ventilation area, $A_{V,eff}/A$ [1]

Required Fire Resistance Rating and Safety Factor

The required fire resistance, *erf* t_f in min, of the structure related fire protection measures results from the multiplication of the equivalent fire duration, t_e, with a safety factor, γ:

$$erf\ t_f = \gamma * t_e \qquad (6)$$

The safety factor, γ, is given in Table 2. The factor depends on the fire fighting category (A to D), the ventilation conditions ("planned" (p) or "unplanned" (u)), and the fire safety class SK_b 1 to SK_b 3.

Table 2 Safety factor, γ, for the design of structure related fire protection measures, corresponding to [1]

Fire Fighting Category	Ventilation	Safety Factor, γ, for Fire safety Class		
		SK_b 3	SK_b 2	SK_b 2
A	P	1.45	1.10	0.70
	U	0.85	0.50	0.50
B	P	1.35	1.00	0.60
	U	0.80	0.50	0.50
C	P	1.10	1.00	0.50
	U	0.50	0.50	0.50
D	P	0.75	0.50	0.50
	U	0.50	0.50	0.50
p: ventilation conditions as intended ("planned") u: unintended ventilation conditions				

With the fire fighting categories A to D the reliability of the fire fighting means is accounted for:

- Category A:
  Manual fire fighting after on-site verification of the situation; action starts more than 10 min after occurrence of the fire.
- Category B:
  Manual fire fighting by on-site personnel; action starts less than 10 min after occurrence of the fire.
- Category C:
  Stationary (fixed) fire extinguishing systems actuated manually; actuation starts less than 10 min after occurrence of the fire.
- Category D:
  Stationary (fixed) fire extinguishing systems actuated automatically or manually, either on site or remote controlled from the main control room immediately after fire alarm (less than 2 min after occurrence of the fire).

Hereby it is considered, that the sooner the fire fighting activities start, the more likely a fully developed fire, which might jeopardize the structural fire safety, can be prevented. The assumed failure probabilities for manual fire fighting or fire suppression by stationary extinguishing systems are given in Table 3.

Different actuation times can be achieved depending on the fire fighting organization.

For an adequate fire resistance rating, the structural elements to be designed must be assigned to one of three so-called safety classes SK_b 1 to SK_b 3, depending on the significance of the element in the structural framework:

- SK_b 1:
  Subordinate structural elements with fire resistance requirements, e.g., parts of the secondary support structures;
- SK_b 2:
  Closures of openings or penetration seals of structural elements for separation (partitioning) of compartments;
- SK_b 3:
  Structural elements representing either structural fire barrier elements of fire compartments or sub-compartments according to the requirements to fire compartments in [1] or those supporting these fire barrier elements as well as all building elements of the load bearing support structures.

Table 3 Average failure probabilities assumed in the safety concept for fire fighting categories A to D according to [3]

Fire Fighting Category	Type of Fire Extinguishing	Actuation Time	Failure Probability
A	Manuel fire fighting	> 10min	0.8
B	Manuel fire fighting	< 10 min	0.5
C	Fixed fire extinguishing system	< 10 min	0.2
D	Fixed fire extinguishing system	< 2 min	0.05

Under consideration of these parameters the safety factor, γ, is defined in Table 2. The more reliable the fire fighting corresponding to the categories A to D and the less important the structural element to be rated, the lower the safety factor can be. Concerning the ventilation conditions, the unintended conditions (u) lead to a smaller or the same safety factor than for the intended conditions (p). This is because the unintended case is assumed less probable than the intended one.

For the resulting required fire resistance rate, $erf\ t_f$, according to eq. (6), both cases must be considered:

- For the planned ventilation the safety factor, γ, might be larger, however the equivalent fire duration, t_e, is shorter due to the lower correction factor for ventilation, f_{Av}.
- For the unplanned ventilation the situation could be vice versa. The maximum of the two values for the required fire resistance, $erf\ t_{f,p}$ and $erf\ t_{f,u}$ is to be taken for required design.

Finally, the required fire resistance rating is estimated by rounding up the required fire resistance, $erf\ t_f$, to the next higher value for standard rating corresponding to the standard fire curve of ISO 834 [2], e.g. with $erf\ t_f$ = 67 min the required rating becomes 90 min according to ISO 834. Standard rating values are typically 30 min, 60 min, 90 min, and 120 min.

APPLICATIONS

Example 1: Fire Resistance Rating for a Pipe Seal in a Fire Barrier of a 150 m² Compartment with Oil Fire Load of 500 MJ/m²

An oil storage room has got an inventory of 1785 kg of oil. The compartment has a floor area of A = 150 m^2 and a room height of H = 2.5 m. The potential ventilation in this compartment is by forced ventilation with an air exchange rate of $\dot{V}_{zu}$ = 3000 m^3/h and, in addition, two fire door openings of together A_V = 3.9 m^2. The forced ventilation is supposed to be switched off during fire. Fire fighting is performed by a stationary fire extinguishing system actuated manually from an adjacent room or remote controlled from the main control room within less than 10 min after occurrence of the fire.

The task for the analyst is to calculate the required fire resistance rating for pipe penetration seals in a fire wall separating fire compartments from each other.

In the design fire scenario, a leaking oil vessel is assumed as fire source. Therefore, the complete oil fire load has to be considered (Ψ_j = 1). The combustion efficiency of oil is χ = 1 according to Table 1. The resulting fire effective load density is calculated to q_R = 500 MJ/m^2 (139 kWh/m^2) (cf. eq. (1)).

Assuming an oil spill and the resulting fire covering about 1/3 of the compartment floor area, this corresponds to a non-uniformly distributed fire load. According to Figure 1, the fire load density of 139 kWh/m^2 requires the basic equivalent fire duration of $t_{e,0}$ = 118 min.

As the compartment height is the reference height of H = 2.5 m, the factor f_H becomes 1 according to eq. (3).

Concerning the ventilation, the “intended” (p) and “unintended” (u) conditions need to be distinguished. For (p) it is assumed that the forced ventilation will be successfully switched off during the fire ($\dot{V}_{zu,p}$ = 0 m^3/h) and that one of the two fire doors is left open resulting in $A_{V,p}$ = 2.0 m^2. According to eq. (5), $A_{V,eff,p}$ = $A_{V,p}$ = 2.0 m^2, therefore $A_{V,eff,p}$ / A = 1.33 %. From Figure 2 it can be concluded that the correction factor for planned ventilation is $f_{Av,p}$ = 0.98.

For (u) it is assumed that doors are inadvertently open that regularly would be closed in the event of fire ($A_{V,u}$ = 3.9 m^2) *or* that the forced ventilation that regularly would be stopped after fire occurrence continue to operate ($\dot{V}_{zu,u}$ = 3000 m^3/h). From eq. (5) it can be assessed that the contribution by vertical openings is larger than those by forced ventilation. Therefore, fire doors being left open are taken as relevant unintended scenario, resulting in $A_{V,eff,u}$ / A = 2.6 %. From Figure 2 it can be concluded from the curve for “non-uniformly distributed fire load” that the correction factor for unintended ventilation is $f_{Av,u}$ = 0.96.

From eq. (2) the equivalent fire duration for conditions as intended (p) becomes $t_{e,p}$ = 118 min * 1.0 * 0.98 = 116 min and for unintended conditions (u) $t_{e,u}$ = 118 min * 1.0 * 0.96 = 113 min respectively.

The last parameter to calculate the required fire resistance duration, *erf* t_f, (cf. eq. (6)) is the safety factor, γ. The fire fighting category is “C” (stationary fire extinguishing system actuated manually within less than 10 min). The pipe penetration seals to be designed belong to structural elements of SK_b 2. According to Table 2, the safety factor with the fire fighting category C for a structure or structural element of the fire safety class SK_b 2 becomes γ_p = 1.00 for conditions as intended (planned) and for unintended ones γ_u = 0.50.

Finally, from eq. (6) the required fire resistance duration is estimated to:

$$erf\ t_f = \text{Max}\ (t_{e,p} * \gamma_p,\ t_{e,u} * \gamma_u) = 116 \text{ min.}$$

In the given example, the ventilation conditions as intended (p) in the event of fire were decisive for the fire barrier element design. Therefore the required fire resistance rating of the pipe seal needs to be 120 min, representing the next higher standard rating value.

Example 2: Fire Resistance Rating for a Hatch in a Concrete 250 m² Cable Tunnel with PVC Fire Load of 300 kWh/m²

A cable tunnel made of concrete structures equipped with cables has got an average fire load density from PVC cable insulation material of in total 300 kWh/m². The tunnel has a floor area of A = 250 m² and a height of H = 4.0 m. The ventilation in the cable tunnel is by forced air supply of $\dot{V}_{zu}$ = 10000 m³/h by an air duct. The air is led out through a 2 * 1 m² fire door with an electrically controlled hold-open device. An additional emergency exit is available through a 1 m * 1 m fire hatch in the ceiling, for which the required fire resistance rating needs to be analyzed. The forced ventilation is supposed to be switched off during fire. Fire fighting is performed manually after on-site verification of the situation, i.e. fire fighting starts more than 10 min after occurrence of the fire.

No shielding or protection of the fire loads can be assumed for the cable fire scenario, therefore the total cable fire load has to be considered as unprotected fire load (Ψ_j = 1). However, due to the combustion efficiency of χ = 0.5 according to Table 1 (the value is currently under discussion, see below) the effective fire load density is estimated to be q_R = 150 kWh/m²) (cf. eq. (1)). As the cables are nearly homogeneously distributed over the tunnel, a basic equivalent fire duration of $t_{e,0}$ = 107.5 min can be derived from Figure 1.

With the tunnel height of H = 4.0 m, the factor f_H becomes 0.87 according to eq. (3).

Concerning the ventilation it is considered that switching off / or blocking the forced ventilation is quite reliable, since this may happen at the inflow air duct or at the outflow door vent. If a single failure occurs at switching off the air inflow, the air exchange rate is strongly reduced, because the fire door for outflow will close. If a single failure occurs at closing the fire door, the fire door becomes a passive vent. Assuming the fire hatch to stand open would be meaningless, since this is the structural element to be designed. Therefore “intended” (p) ventilation conditions are assumed by forced ventilation to be switched off successfully during the fire ($\dot{V}_{zu,p}$ = 0 m³/h) and by the fire doors to be closed, resulting in leakages only of $A_{V,p}$ = 0.2 m². According to eq. (5), $A_{V,eff,p}$ = $A_{V,p}$ = 0.2 m², therefore $A_{V,eff,p}$ / A = 0.08 %. From Figure 2 it can be concluded that the correction factor for intended ventilation conditions (p) is $f_{Av,p}$ = 0.53. Unintended (u) conditions are given by a single failure of the self-closing function of the fire door, which thus acts as a passive vent of $A_{V,u}$ = 2.0 m², resulting in $A_{V,eff,u}$ / A = 0.8 %. From Figure 2 it can be concluded that the correction factor for unintended ventilation is $f_{Av,u}$ = 0.83.

From eq. (2) the equivalent fire duration for conditions as intended (p) becomes $t_{e,p}$ = 107.5 min * 0.87 * 0.53 = 50 min and for unintended conditions (u) $t_{e,u}$ = 107.5 min * 0.87 * 0.83 = 78 min respectively.

With the fire fighting category “A” (manual fire fighting after more than 10 min) and the hatch belonging to structural elements of SK_b 2 the safety factor becomes γ_p = 1.10 for intended and γ_u = 0.50 for unintended conditions (cf. Table 2).

Finally, from eq. (6) the required fire resistance duration is estimated to:

$$erf\ t_f = \text{Max}\ (t_{e,p} * \gamma_p,\ t_{e,u} * \gamma_u) = 55\ \text{min}.$$

In the given example, the ventilation conditions as intended (p) in the event of fire were decisive for the fire barrier element design. Therefore the required fire resistance rating of the fire hatch needs to be 60 min, representing the next higher standard rating value.

RECOMMENDATIONS FOR FURTHER CONSIDERATIONS

The approach for fire resistance rating of structural elements as given in the German fire safety standards KTA 2101.2, Appendix A [1] covers the boundary conditions, which have to be considered in case of fire in a NPP compartment. Over the last one and a half decades, the rating approach has proven to be relatively simple and straightforward in application. In the context of the actually ongoing update of all three parts of the German KTA 2101 standard on “Fire Protection in Nuclear power Plants”, the approach will also be reviewed and improved according to the state-of-the-art and insights from practical applications. In the following, some considerations are given.

Combustion Efficiency for PVC Insulated Cables

In Table 1, the value of the combustion efficiency for PVC insulated cables is χ = 0.5. This quite low value is currently under investigation. In [3], a value of χ = 0.8 was assumed. Later, based on experiments [5], a value of χ = 0.6 was found. However, this is a mean value for different types of cables with a corresponding heat of combustion of H_u = 21.0 MJ/kg (cf. Table 1, PVC cables: H_u = 18.0 MJ/kg). In this study [5], the effective heat of combustion of PVC cables measured by a cone-calorimeter was observed to be $H_{u,eff}$ = 11 to 16 MJ/kg.

An effective heat of combustion of 16 MJ/kg is proposed for all cable types including PVC insulated cables for the simplified cable fire spread model (“FLASH-CAT”) developed within the recent CHRISTIFIRE project of U.S. NRC [8]. Taking all these data into account, there is some evidence that the effective heat of combustion of PVC insulated cables needs to be increased in Table 1.

Prevention of Overestimation of the Compartment Opening Ratio

From Figure 2 it can be seen that for compartments with an opening ratio larger than 1.6 % the factor f_{Av} decreases the equivalent fire duration up to only 67 % for large opening ratios. This is attributed to increased convective heat losses out of the compartment. Care has to be taken not to overestimate the heat losses by natural and forced ventilation by an over-assessment of A_V and $\dot{V}_{zu}$. Therefore it is recommended by Hosser et al. [3] not to add up A_V and $\dot{V}_{zu}$/6000 for the unintended (u) case, if the result for the opening ratio is larger than 1.6 %.

Equivalence Between Natural and Forced Ventilation

The different contributions of natural and forced ventilation as defined by eq. (5) also need consideration. From this equation it can be derived that a forced ventilation of $\dot{V}_{zu}$ = 6000 m^3/h equals the inflow through an A_V = 1 m^2 vertical vent. A volume flow of 6000 m^3/h equals an air mass flow about 2 kg/s at 20 °C.

This value is compared to the air mass flow through vertical vents as given by the equation of Kawagoe, which is also quoted by Drysdale [9]:

$$\dot{m}_{air} \approx 0.52 * A_v * H_v^{\,0.5} \quad \text{[kg/s]} \qquad (7)$$

where H_V is the door height of typically 2 m. According to this equation a standard door (A_v = 2 m^2) to open atmosphere provides an air inflow of $\dot{m}_{air}$ ≈ 1.47 kg/s. This is only 0.735 kg/s per m^2 of vertical vent and only about one third of the value of 2 kg/s, which is incorporated in eq. (5). In [3], it is mentioned that the different contributions of natural and forced ventilation were found by an evaluation of different fire simulation results. Own studies with the zone model CFAST [10] give some evidence that the factor 6000 m^3/s in the empirical equation (5) needs to be decreased and becomes closer to the analytical solution for the factor of 2206 m^3/s from eq. (7).

This is demonstrated by two examples of different compartments where the resulting upper layer temperatures are studied under different types of ventilation. The first example is a concrete compartment of A = 125 m^2, H = 2.5 m, heat release rate of 3125 kW for 30 min and $A_{V,eff}$ / A = 1.6 %. The ventilation is provided by a passive door w_v = 1 m, H_v = 2 m (A_V = 2 m^2) that is replaced for comparison by forced ventilation of $\dot{V}_{zu}$ = 12000 m^3/h corresponding with eq. (5) and alternatively by $\dot{V}_{zu}$ = 4412 m^3/h from eq. (7). As can be seen from Figure 3, the result according to eq. (5) is about 50 K lower than the upper layer temperature from natural ventilation, whereas the result from the analytical solution meets the comparative curve with a difference of less than 10 K.

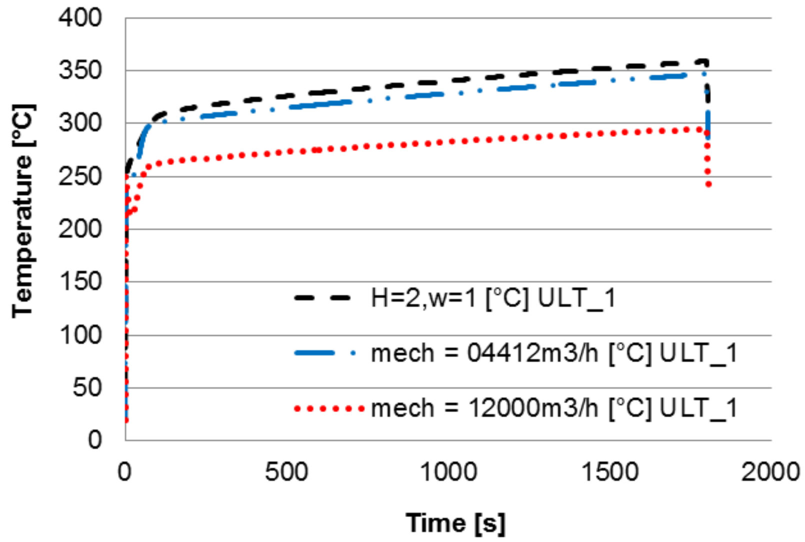

Figure 3 Upper layer temperature with the natural ventilation A_V = 2 m^2 (black) replaced by 12000 m^3/h corresponding with eq. (5) (red) from [1] and by 4412 m^3/h according to the analytical approach by eq. (7) (blue)

The second example is a somewhat larger concrete compartment of A = 150 m^2 and H = 2.5 m with the heat release rate increased nearly fourth times to 15000 kW for 125 min and $A_{V,eff}$ / A increased to 6.7 %. The ventilation is provided by a passive door w_v = 5 m, H_v = 2 m (A_V = 10 m^2) that is replaced by forced ventilation of $\dot{V}_{zu}$ = 60000 m^3/h according to eq. (5) and alternatively by $\dot{V}_{zu}$ = 22062 m^3/h from the analytical approach (cf. eq. (7). Again, the result according to eq. (5) does not reach the comparative curve from natural ventilation, whereas the fitting of the curve from the analytical approach with the comparative curve is very reasonable (cf. Figure 4).

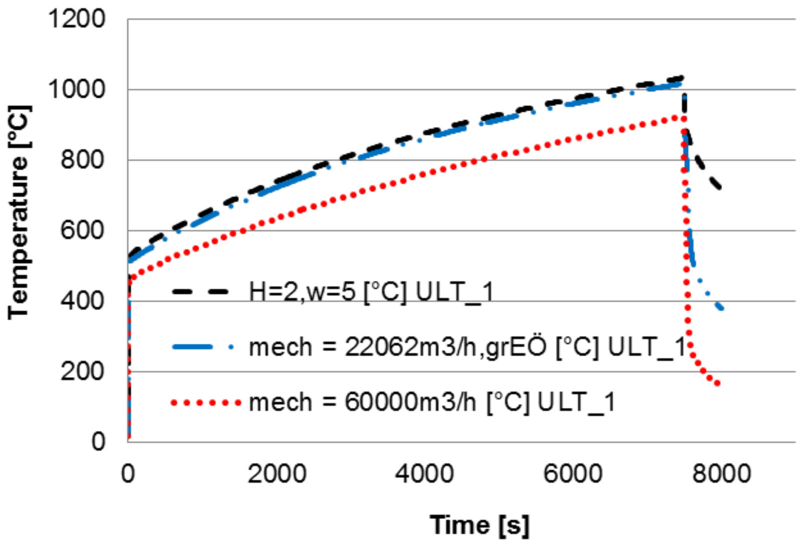

Figure 4 Upper layer temperature with the natural ventilation A_V = 10 m^2 (black) replaced by 60000 m^3/h corresponding with eq. (5) (red) from [1] and by 22062 m^3/h according to the analytical approach by eq. (7) (blue)

In both examples the results for the upper layer temperatures from the high forced ventilation rate are too low because the fire compartment is cooled. However, it may also happen that the compartment temperatures become higher than from natural ventilation if the setting is according to eq. (5). This is because a stoichiometric fire from forced ventilation set in correspondence with eq. (5) allows for a much larger heat release rate inside the compartment than from corresponding natural ventilation. The heat release rate is discussed below.

Natural and Forced Ventilation under Conditions of NPP Compartments

Taking into account the real conditions of compartment fires in NPP, there are additional influences on natural and forced ventilation to be considered:

- The natural ventilation through doors that do not open to atmosphere but to adjacent compartments is even smaller than given by eq. (7). This happens because the adjacent room is filled by hot smoke that is decreasing the pressure difference between the compartments.
- Forced ventilation of compartments is typically carried out by a combined push and pull system. Due to the compartment gas temperature, the smoke gas expands and the mass flows according to design will be reduced. The extent of this effect depends on the actual pressure-flow-characteristics of the HVAC system.

As natural and forced ventilation are principally overestimated with regard to real fire conditions in NPP compartments, the design with the nominal values is conservative as long as the relative effective ventilation area, $A_{V,eff}$ / A, is lower than 1.6 % (cf. Figure 2). This will stay valid for most of the compartments in the controlled area of a NPP and for practically all compartments in case of intended ventilation conditions.

Heat Release Rate per Unit Compartment Area

The fact that the maximum fire resistance is reached for a relative effective ventilation area of $A_{V,eff}$ / A = 1.6 % should also be analyzed with respect to the heat release rate per unit compartment area [kW/m^2]. Given a forced ventilation condition, the optimum of 1.6 % relative effective ventilation area by eq. (5) implies a ventilation per square meter of 96 m^3/(h*m^2) which corresponds to an air supply rate per floor area of 3.2 g/(s*m^2). Respectively for natural ventilation conditions via doors of H_V = 2 m, the optimum of 1.6 % results in a value of 1.18 g/(s*m^2). If the complete air supply is used for combustion, with a postulated heat release per unit mass of oxygen of 13100 kJ/kg, the heat release rate per unit compartment area becomes 96 kW/m^2 for forced ventilation and 35 kW/m^2 for natural ventilation. Both values are relatively low for a fully developed post-flashover fire. However, as long as the ventilation of a fire compartment is given by a relative effective ventilation area of approx. $A_{V,eff}$ / A = 1.6 %, which was the result of the survey in [3], the assumption of a low heat release rate per unit area is justified.

In case that a specific compartment is equipped with more effective ventilation, the rating approach may not be conservative anymore. An example for such boundary conditions might be a fire in a compartment of the electrical (switchgear) building in case that the smoke extraction mode is still running under post-flashover conditions.

CONCLUSIONS AND OUTLOOK

The methodological approach for fire resistance rating of structural elements as provided in appendix A of the German fire safety standard KTA 2101. Part 2 on “Fire Protection of Structural Plant Components” is an engineering method considering the physical effects of compartment fires with particular respect to the typical boundary conditions in German nuclear power plants. The approach has proven to be relatively simple and straightforward to apply.

The actual and still ongoing review has already shown that the combustion efficiency of cables with PVC insulations frequently used in existing nuclear power plants may currently be underestimated. Due to the declining influence of the fire load on the equivalent fire duration (cf. Figure 1) the possible effect of an underestimation on the equivalent fire duration is less than linear.

Different aspects of the real ventilation conditions in compartments of a nuclear power plant are considered. The exact contributions of these effects need further examinations. This may provide evidence to decrease the factor 6000 of eq. (5) which considers different contributions of natural and forced ventilation. Furthermore, the curve of Figure 2 which declines for $A_{V,eff} / A$ > 1.6 % to reflect cooling effects from increased ventilation may need to incline above one because the heat release rate possibly might increase with increased ventilation.

These potentials for improvements in the methodology being applied for adequate fire resistance rating of fire barrier elements are intended to be discussed within the presently ongoing update of the German nuclear standard KTA 2101 on “Fire Protection in Nuclear Power Plants”.

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IMPROVEMENT MEASURES OF GERMAN NUCLEAR POWER PLANTS AFTER THE FUKUSHIMA DAI-ICHI REACTOR ACCIDENTS

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TÜV SÜD Industrie Service GmbH, Germany

ABSTRACT

On March 11th, 2011 the Tōhoku earthquake (magnitude $M_w = 9.0$) caused severe tsunami waves - and consequently a devastating flooding - which hit amongst others the nuclear power plant of Fukushima Daiichi in Japan. The flooding led to a prolonged station blackout throughout the plant, as well as to a complete loss of the cooling water supply of units 1, 2 and 3 as well as loss of the spent fuel pool cooling of unit 4 [1]. As a result of the outage radioactive steam and water were exposed to the environment.

After this incident, several of German local state authorities directed special safety inspections (SSI) at several German nuclear power plants (NPP) to identify findings and optimization potentials as a basis for possible necessary improvement measures.

During the further procedure, as an outcome of the SSI, several improvement measures have been developed, tested and installed in German NPP since 2011.

This paper shows the safety-related improvement measures with regard to fire protection in order to contain the effects of fires in consequence of external nature induced events (e.g. earthquakes) or human induced events (e. g. aircraft crash).

With the installation of these measures the accessibility of buildings, the availability of fire protection related systems and fire-fighting equipment and thus the robustness of NPP can be increased and improved.

INTRODUCTION

As a result of the Fukushima Daiichi reactor accident several selected German NPP went through special safety inspections. TÜV SÜD was assigned to execute the SSI in order to provide a report on findings and optimization potential (OP) considering specific assumptions with regard to the Fukushima Daiichi reactor accident (cf. our paper in [2]).

Based on these results the licensees of the NPP developed several improvement measures for compensation in order to meet the nuclear safety requirements.

RELEVANT GERMAN AND IAEA NUCLEAR SAFETY REQUIREMENTS WITH RESPECT TO FIRE SAFETY IN NPP

The requirements related to fire safety derived from the fundamental nuclear regulations for the construction and operation of NPP. Figure 1 shows the order of importance and relevance of the German nuclear regulations descending from the basic law down to technical specifications and manuals. According to the German Atomic Energy Act [3] licensees have to take precautions following the state-of-the art of science and technology in order to prevent damages resulting from the construction and operation of NPP. The specific events and hazards which have to be considered are defined in the Safety Requirements for NPP of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) [4] (cf. Figure 2). According to [4], all equipment required for the safe shutdown of the nuclear reactor, for maintaining it in a shutdown state, for residual heat removal or the prevention of a release of radioactive materials shall be designed as and constantly kept in a condition that they can fulfill their safety related functions even in the event of any internal or external hazard including very rare human induced ones.

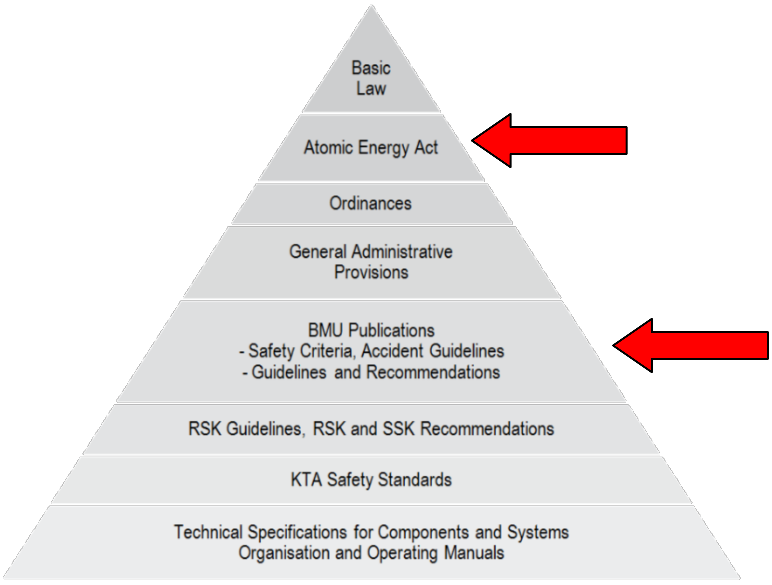

Figure 1 German nuclear regulatory pyramid

Figure 2 gives an overview of all events and hazards which need to be considered in terms of German Safety Requirements for NPP [4]:

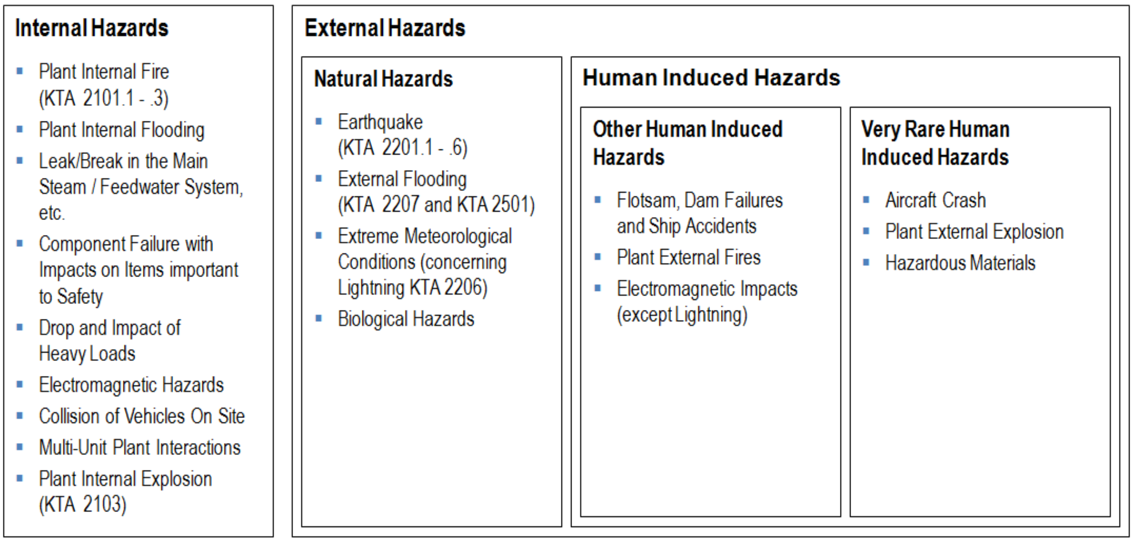

Figure 2 Overview and all events and hazards according to [4]

As a result of the SSI in 2011 several optimization potentials were identified by TÜV SÜD (cf. [2]). In order to improve the robustness of NPP in respect to fire safety the licensees developed, tested and installed improvement measures for the external hazards earthquake, flooding and aircraft crash. The specific requirements for these hazards and for the plant internal hazard fire are given in the German Safety Requirements for NPP [4] as well as in the KTA Safety Standards on Fire Safety in Nuclear Power Plants (KTA 2101) [5].

According to [5] the access to buildings has to be ensured for rescue and fire fighting purposes in case of the following event combinations: an earthquake induced internal fire, a centenary flooding and a consequential plant internal fire and an external flooding and an unrelated internal fire.

Furthermore, the effects of kerosene fires at the plant site need to be considered in case of an aircraft crash (cf. [5]).

At the international level, the requirements of the IAEA Safety Standards need to be met. Figure 3 shows the relevant IAEA regulations in a descending manner from Safety Fundamentals (SF) down to Specific Safety Guides (SSGs):

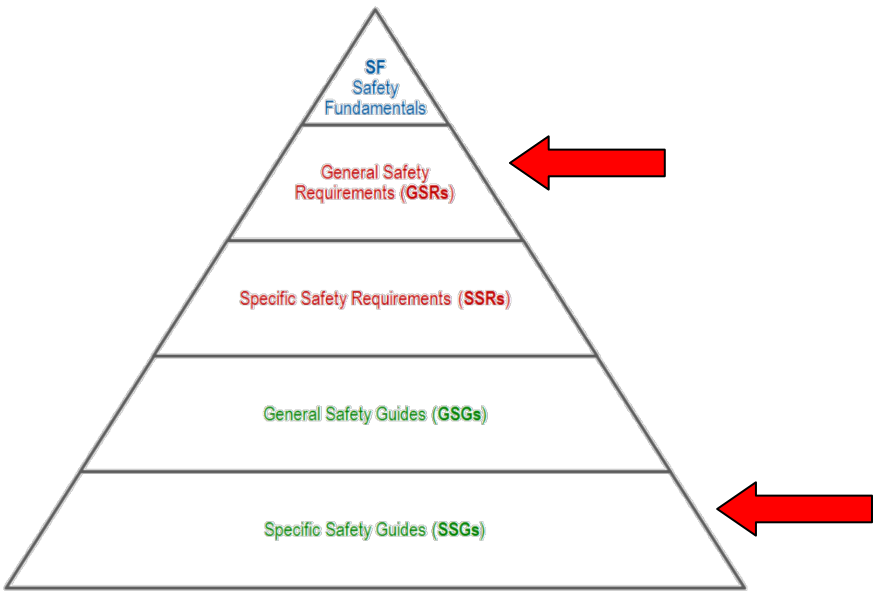

Figure 3 IAEA Safety Standards pyramid

Similar to the German requirements, the GSR Part 4 “Safety Assessment for Facilities and Activities” [6], the NS-G-1.5 “External Events excluding Earthquakes in the Design of Nuclear Power Plants” [7] and NS-G-1.6 “Seismic Design and Qualifications for Nuclear Power Plants” [8] define the types of events and hazards which need to be considered. Therefore the same internal and external hazards have to be taken into account.

The specific international safety requirements with respect to fire safety are derived from the IAEA Specific Safety Guides (SSG).

According to [7] the access to buildings in case of a flooding has to be ensured.

Furthermore the effects of kerosene fires at the plant site need to be considered in case of an aircraft crash (cf. [7]). Therefore special equipment (e.g. foam generators) needs to be provided and available to prevent fuel fires from penetrating structures containing items important to safety.

IMPROVEMENT MEASURES AS A RESULT OF THE SSI

As a result of the 2011 SSI – carried out at several German NPP – several optimization potentials (OP) have been identified to improve the robustness of NPP. Basically, all fire safety-related OP were related to the accessibility of buildings and availability of fire fighting equipment in case of earthquake, external flooding or a human induced aircraft crash (cf. [2]). These improvement measures will be presented in the following.

Earthquake-related Improvement Measures

The seismic design of all German nuclear power plants considers earthquakes with a magnitude range between about 4 and 6.5 (Richter Scale). For the identification of earthquake-related improvement measures site specific design basis earthquakes were considered.

The following example of a two unit pressurized water reactor (PWR) power plant (cf. Figure 4) shows the possible effects of an earthquake on the plant.

Current situation:

- Security entrance doors (here: doors of the switchgear building (3)) are not seismically qualified.
- The plant entrance building (7) has only non-nuclear seismic design.
- Access keys to all buildings are located inside the entrance building.
- The fire station (9) has only non-nuclear seismic design.
- The fire alarm control cabinet is not seismically qualified.

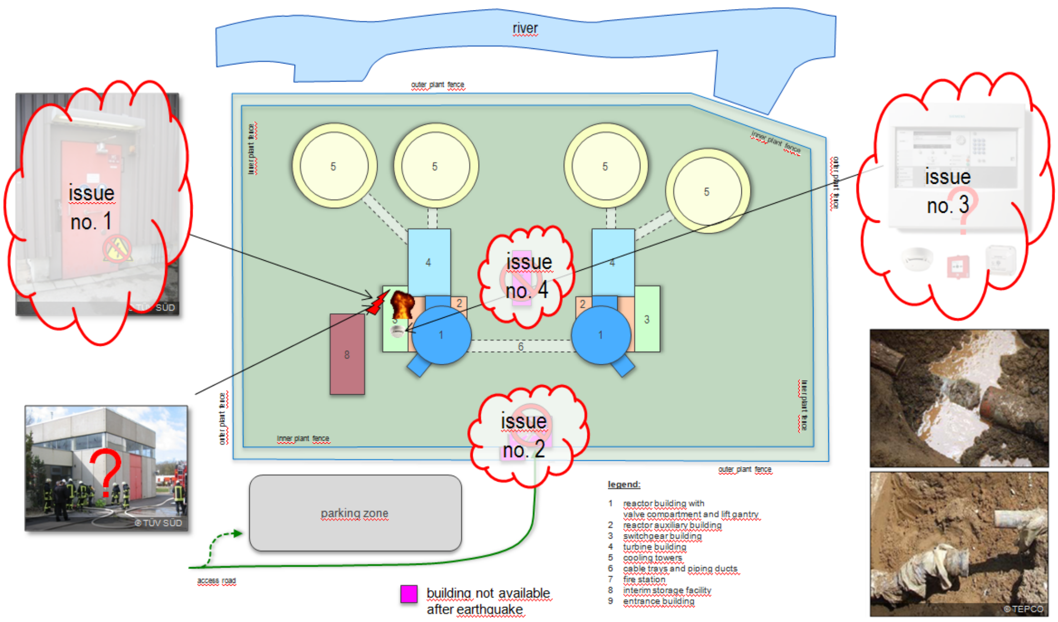

Figure 4 Earthquake-related Issues

According to [5] an earthquake induced fire needs to be taken into account. An earthquake induced fire inside the switchgear building might have the following effects:

- Security entrance doors are not working / do not open due to:
  - Electrical malfunction or structural damage (Issue 1);
  - Limited availability of the entrance building – access keys of security doors might not be available (Issue 2);
- Fire alarm control cabinet might not be operable → fires possibly remain undetected (Issue 3);
- Limited availability of the fire station → equipment and vehicles for firefighting measures might not be available (Issue 4).

In order to meet the specific safety requirements the following improvement measures were developed, tested and installed:

Issue 1: Damaged or blocked security doors

Solution: Seismic qualification of security doors per multi-axis simultaneous vibration test:

Figure 5 Seismic qualification of a security door

The seismic qualification test was done by the German company iABG at the facilities of iABG in Ottobrunn near to Munich, Germany. iABG is well known for seismic testing and certification of equipment. The multi-axis simultaneous vibration test is a generally accepted procedure for seismic qualification.

The door was tested for a covered earthquake range. Afterwards the door was inspected for visual and mechanical defects. As a result, the simulated earthquake (vibration test) did neither generate any damage to the door nor to the door frame impairing the functionality of the door. The door was mechanical fully functional after the test.

Issue 2: No site-specific seismic design of the entrance building (key depot)

In case of an earthquake an electrical malfunction of security doors can occur, so that these doors need to be unlocked with keys. These keys are only available to the security service. They are located in a key depot inside the entrance building. The entrance building has only a conventional seismic design. Consequently the keys might be unavailable if an earthquake occurs.

To increase the availability of the access keys the licensee decided to build a separate key depot building at a different location at the plant. The key depot building has a site specific seismic design. To prevent theft the building is constantly monitored with a state of the art security system and the keys can only be removed from the building by a two-person-principle.

Issue 3: Non-seismic qualification of fire alarm control cabinets

Similar to the non-seismically qualified doors (Issue 1), the fire alarm control cabinet of a buildings fire alarm system might be damaged during or as a result of an earthquake, although the fire alarm system needs to be functional after an earthquake.

To improve the availability of the fire alarm system the fire alarm control cabinet was tested with the multi-axis simultaneous vibration test by iABG, Germany.

Two different fire alarm control cabinets have been tested for site specific earthquake ranges.

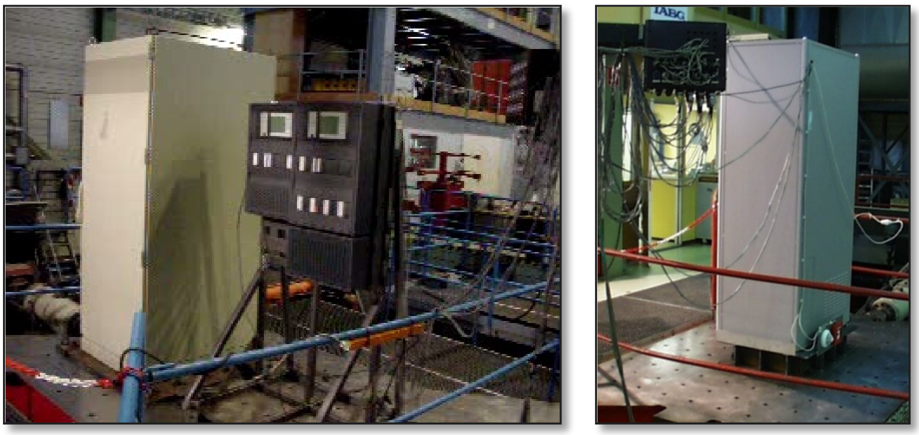

Figure 6 Seismic qualifications of fire alarm control cabinets

After the vibration tests were performed both systems were fully functional. Because of the seismic qualification and installation of these systems, the availability of the fire alarm system of both NPP units was increased.

Issue 4: Limited availability of the fire station

The fire station has no site specific seismic design. Vehicles and equipment might not be available for manual fire fighting in case of an earthquake. To improve the availability of the equipment, a fire emergency container was developed and placed at a different location at the plant where it is of the range of possible debris from non-seismic designed buildings.

The container (cf. Figure 7) is equipped with:

- 2 mobile fire pumps (800 l/min, 8 bar) including fittings,
- 10 suction hoses (Ø 110mm, length: 1.6 m),
- 35 fire hoses (Ø 75mm, length: 15 m) = 525 m,
- 35 fire hoses (Ø 75mm, length: 20 m) = 700 m,
- 40 fire hoses (Ø 42mm, length: 20 m) = 800 m,
- Miscellaneous fittings.

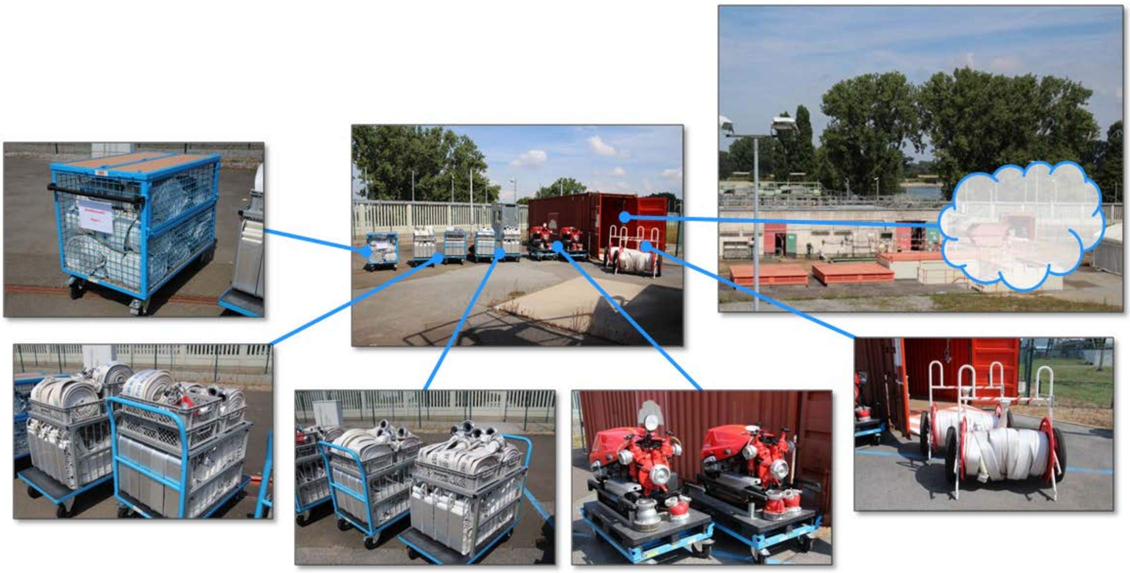

Figure 7 Fire emergency container

In addition, two mobile fire pumps already existed at the plant to improve the possibility of manual firefighting. These fire pumps, manufactured by Hytrans Fire System, are able to feed from a nearby river (onsite). The HydroSub-System features the following specifications and accessories (cf. Figure 8):

- Type: HydroSub 150
- Flow rate: 3500 l/min, 10 bar
  4500 l/min, 4 bar
- Fire hoses: 800 m, Ø 150 mm, single length: 5m / 50 m
- Miscellaneous fittings

Figure 8 Hytrans Fire System - HydroSub 150

Flooding-related Improvement Measures

The following example of a two unit boiling water reactor (BWR) power plant (cf. figure 9) shows the possible effects of a flooding on the NPP.

Current situation:

- Security entrance doors (here: doors of the reactor building (1)) are unprotected in case of a flooding;
- Although inside the building the ground floor level is at +1.5 m (stairs behind door), the door might not unlock / open due to electrical malfunction or high water level on the outside.

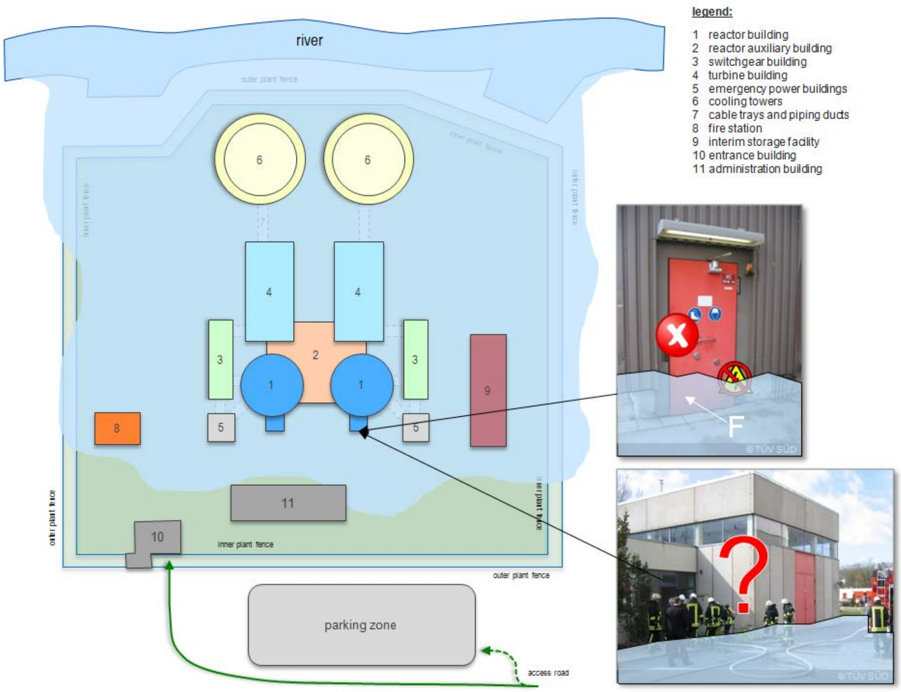

Figure 9 Flooding-related Issue

To improve the accessibility of the security doors the licensee installed a barrier wall system (cf. Figure 10). This barrier wall system is an approved system already used for flooding protection at non-nuclear facilities. To install the barrier wall system, it is necessary to build a concrete foundation for the posts. The required posts have to be installed permanently into the ground. In case of a flooding, the aluminum panels need to be placed between the posts to build the barrier. The panels are equipped with a sealing gasket to seal the barrier wall system.

Figure 10 Flooding barrier wall

By using the barrier wall system security doors are available during a flooding. Even the video-phone box by the door can be used for the access procedure. Of course the availability of the doors is related to the height of the wall system and the occurring flooding level.

Aircraft Crash-related Improvement Measures

The following example of a pressurized water reactor power plant (cf. Figure 11) shows the possible effects on the NPP after an aircraft crash into the fire station (9) located next to the emergency power building (5).

Current situation:

- All fire brigade vehicles (fire trucks) are parked and all equipment (e.g. foam generators) is stored inside the fire station.

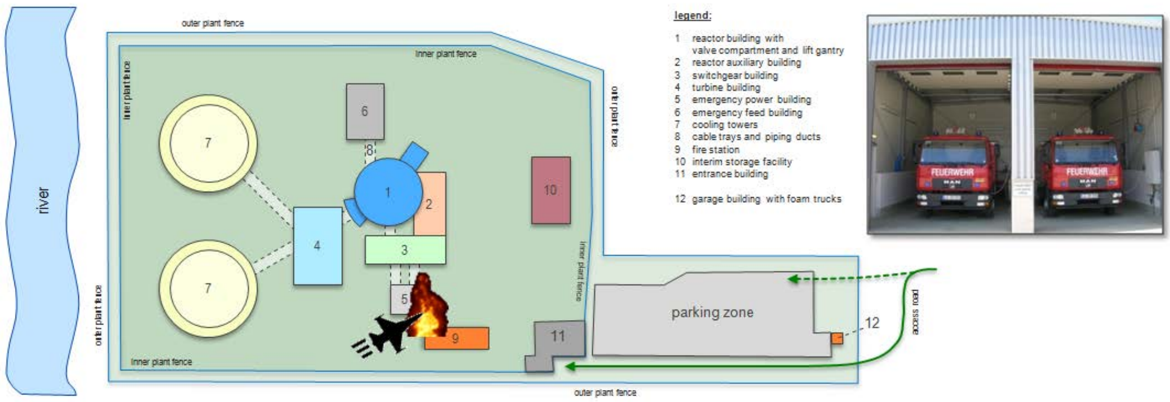

Figure 11 Aircraft Crash

If an aircraft crash into the fire station occurs, the fire brigade vehicles and equipment are unavailable for fire fighting. Consequently, a kerosene fire cannot be extinguished and could lead to damages of safety related buildings or equipment. To prevent this situation the licensees of all German NPP constructed a second, separate fire brigade building at a different location (here outside the inner plant fence) for two new foam trucks SLF 25/25 (cf. Figure 12).

Figure 12 Foam trucks SLF 25/25

The SLF 25/25 is manufactured by GIMAEX Schmitz. Each one of the trucks can carry 2.500 l of aqueous film forming foam (AFFF) and is equipped with a foam pump with a flow rate of 2.500 l/min. AFFF is the most effective type of foam to extinguish flammable liquid based fires (e.g. kerosene fires) and is typically used by airport fire brigades.

CONCLUSIONS

This paper gives an overview of the fire safety-related improvement measures which are the result of the review process of the 2011 SSI. It demonstrates how licensees can improve the robustness and increase the safety of their NPP by implementing moderate measures at their plants. Thus, the accessibility of buildings and the availability of equipment in case of earthquake, external flooding or an aircraft crash were increased and improved.

The presented results are limited to fire safety aspects. In addition, the licensees have developed, tested and installed further improvement measures related to other nuclear fields, such as systems engineering and radiation protection.

Fire protection means should be reviewed constantly to ensure the most possible availability of buildings, systems, and equipment in case of emergency. The presented improvement measures should give a variety of examples to licensees of other NPP. These or similar measures should be taken into consideration to improve their NPP.

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PICTURE REFERENCES

Figures 1, 3	BMU
Figures 2, 4, 9, 11, 12	TÜV SÜD
Figure 5	Fa. Heintzmann
Figure 6	Fa. BOSCH
Figure 7	RWE Power AG
Figures 8, 10	KGG
Figure 12	MRN-Blaulichter.de

Recent Lessons Learned in Fire-Induced Spurious Operation (SO) Probability and Duration

13th SMIRT Post-Conference Seminar on

Fire Safety in Nuclear Power Plants and Installations

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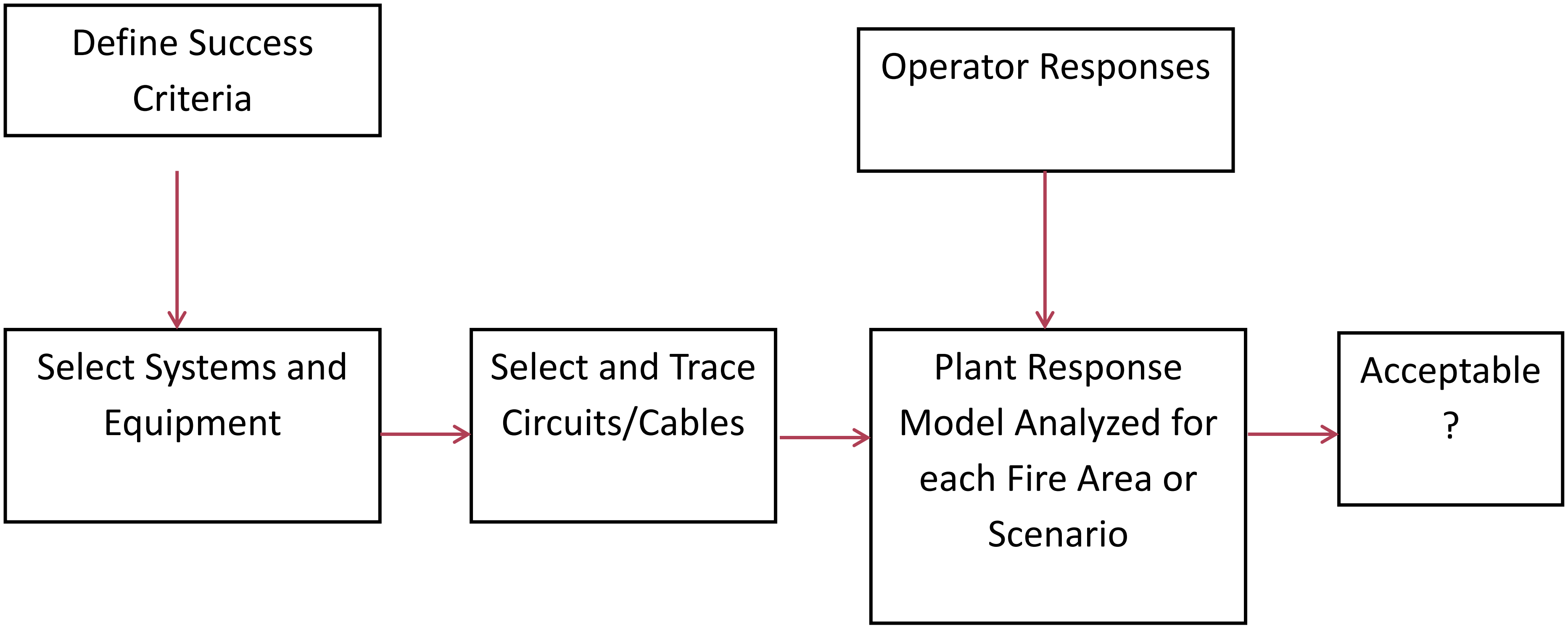
Background

- Both Fire Safe Shutdown Analysis (SSA) and Fire Probabilistic Risk Analysis (FPRA) have significantly changed over the past 20 years;
  - The improvements to both have much in common:
    - Methodology Improvements resulted in new documents issued post-2000, as well as continued improvements since issuance:
      - SSA – NEI 00-01, now in revision 3
      - NUREG/CR-6850 (EPRI TR-1011989), now with Supplement 1.
    - Both were greatly affected by the lessons learned in Fire-Induced Circuits Testing:
      - Original estimate for fire-induced spurious operation (SO) ~0.068
      - Post-Testing estimates ~ 0.3 to 0.6 for intra-cable failures.
        - Newer estimates will be issued later this year. Typically 0.3 to 0.4 for most intra-cable faults, but could be as high as 0.9 for Ungrounded Armored Cable.

Simplified SSA and FPRA Process



Historical

- Older circuit analysis methods involve simplifications, limitations and assumptions:
  - Loss of offsite power is assumed (not analyzed)
  - Single train of safe shutdown credited for each area.
  - Single spurious operations (hot shorts).
  - Less rigor in analysis of support systems (e.g., HVAC), actuations, and associated circuits.
- FPRAs have also been simplified;
  - Spurious operation was assumed to be ~ 0.068; resulted in limited analysis of spurious operations.
  - IPEEE analysis typically involved a sub-set of the internal events PRA equipment.

Historical

- Improved methods have been developed:
  - Deterministic: NEI 00-01
  - Probabilistic: NUREG/CR-6850
- Improvements continue:
  - Multiple Spurious Operations methods and generic list in NEI 00-01, R3.
    - This MSO list is used both in deterministic SSA as well as building a fire PRA to meet the PRA Standard.
  - NUREG/CR-7150, Volume 2:
    - New FPRA Spurious Operations Probabilities
    - Methods and probabilities to address spurious operation duration

NEWER FAILURE MODES CONSIDERED

Failure Modes Considered from NEI-00-01:

- Intra-Cable, Inter-Cable, Grounded cables.
- Compatible Polarity Multiple Hot Shorts for Ungrounded AC and DC Circuits.
- Coincident Independent Hot Shorts On Separate Cables.
- Multiple Intra-cable Hot Shorts.

New Failure Mode from our recent Expert Panel Report (NUREG/CR-7150).

- Multiple Shorts to Ground (ungrounded DC and Distributed AC).

What Has Changed in SSA and FPRA?

- **Equipment Modeled:** New Failure Modes and higher SO probabilities results in more equipment being modeled:
  - SSA; An older SSA may be less than 100 components per plant, but is now 600-800 components (one example).
    - Much of the increase is due to SO concerns (diversions, electrical interlocks, associated circuits, etc.).
  - FPRA: Older FPRAs may analyze and trace 200-400 components, but is now > 1000 components and growing (again, one example):
    - SO concerns
      - Possible initiating events
      - Possible failure of credited components
    - Credit for offsite power and additional non-safety systems
    - Often times used "assumed routing" versus actual for BOP components.

What Has Changed in SSA and FPRA?

- **Circuits Analyzed:**
  - Both SSA and FPRA should consider multiple hot shorts affecting the same component:
    - NEI 00-01 suggests considering up to 4 hot shorts.
      - Fire PRA includes multiple SO for a given function, but combines the SO using the PRA model to well beyond 4 hot shorts.
    - New FPRA Expert panel will have additional guidance, where specific failure modes are considered highly unlikely.
  - Scope of associated circuits expanded:
    - Some circuit failures do not require hot shorts in order to fail a function.
      - For example; level instruments damaged.

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What Has Changed in SSA and FPRA?

- **Operator Actions:**
  - NEI 00-01, Revision 3, incorporates the latest NRC Guidance on acceptable local operator actions. New Operator actions may be required due to SO. However, acceptable approach is different for:
    - Fire Affected Train
    - Credited Train (needs NRC approval).
  - NUREG/CR-6850 includes:
    - Inclusion of SSA Actions
    - Consideration of spurious alarms, resulting in possible detrimental actions.
    - Impact of fire-fighting on credited functions;
      - Water spray
      - Removal of electrical power to stop the fire

CIRCUIT FAILURE MODE LIKELIHOOD ANALYSIS *- Notes*

- DC Circuit Testing (DESIREE-FIRE) was performed at Sandia National Labs (2009), funded by the NRC.
  - New observations will result from the testing, including the possible influence on HS probability and duration from:
    - AC versus DC power
    - Component type or fuse size
    - In or out of the flame (general indication there may be differences here).
  - Testing resulted in new values for DC circuits or a re-evaluation of AC circuit results.
- The results of these tests as well as other fire-induced circuits testing were reviewed for issuance of NUREG/CR-7150:
  - Volume 1: Electrical PIRT Panel (Deterministic)
  - Volume 2: PRA Expert Panel (Probabilistic) – not yet issued.

Testing Programs reviewed (See the following slides)

- EPRI/NEI – 2001 (Used for NUREG/CR-6850)
- DUKE ARMORED CABLE - 2006
- CAROLFIRE – 2008
- DESIREE-FIRE – 2010
- KATE-FIRE - 2011

EPRI Test Report 1003326, Dec 2002

- HRR: 70-450kW
- ac MOV circuits
- CPTs
- Raceway: Tray, conduit, air
- Raceway Fill: 1-4 rows
- Orientation: Horizontal, Vertical
- Plume, HGL, Radiant
- Insulation type: TS, TP, Armored

- 18 Tests
- SNL IRMS

EPRI Test Report 1003326, Dec 2002

- EPRI Testing is the basis for the NUREG/CR-6850 tables, following performance of an expert panel process (for areas with limited or no testing).

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CAROLFIRE (NUREG/CR-6931, V1-3)

- 78 small scale
- Radiant
- 3.7-87.5 kW/m^2 (260-900°C)
- RIS 2004-03, Bin 2
- 15 cable types
- IRMS & SCDU

- 18 Intermediate
- Multiple exposures
  - Flame, plume, HGL
- 200kW
- THIEF model
- ac MOV

CAROLFIRE (NUREG/CR-6931, V1-3)

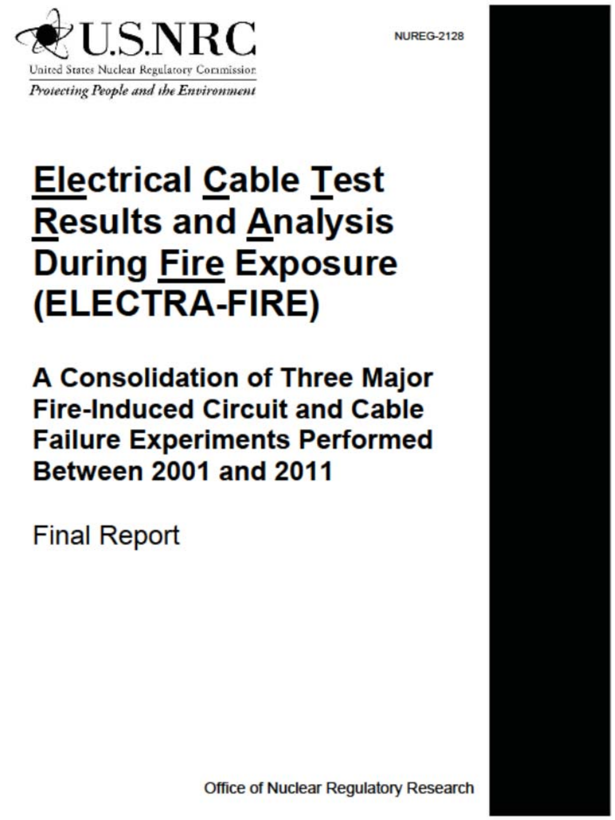
- CAROLFIRE and the EPRI testing were used to estimate the present AC circuit hot short duration curves.

DESIREE-FIRE (NUREG/CR-7100)

- 59 small scale
- Radiant
- 3.7-87.5 kW/m^2 (260-900°C)
- 7 CAROLFIRE cables, 10 EPRI cables
- 8 surrogate circuits + inter-cable rig + ac MOV

- 17 Intermediate
- Multiple exposures
  - Flame, plume, HGL
- 200kW

Data Consolidation
NUREG-2128


U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

NUREG-2128

Electrical Cable Test Results and Analysis During Fire Exposure (ELECTRA-FIRE)

A Consolidation of Three Major Fire-Induced Circuit and Cable Failure Experiments Performed Between 2001 and 2011

Final Report

Office of Nuclear Regulatory Research

- Supports PIRT and PRA work
- Systematic evaluation of test data for parameters affecting failure mode likelihood and duration (intra-cable only).
- Summary of inter-cable data
- Evaluation of dc test data to identify ground equivalent hot short phenomena

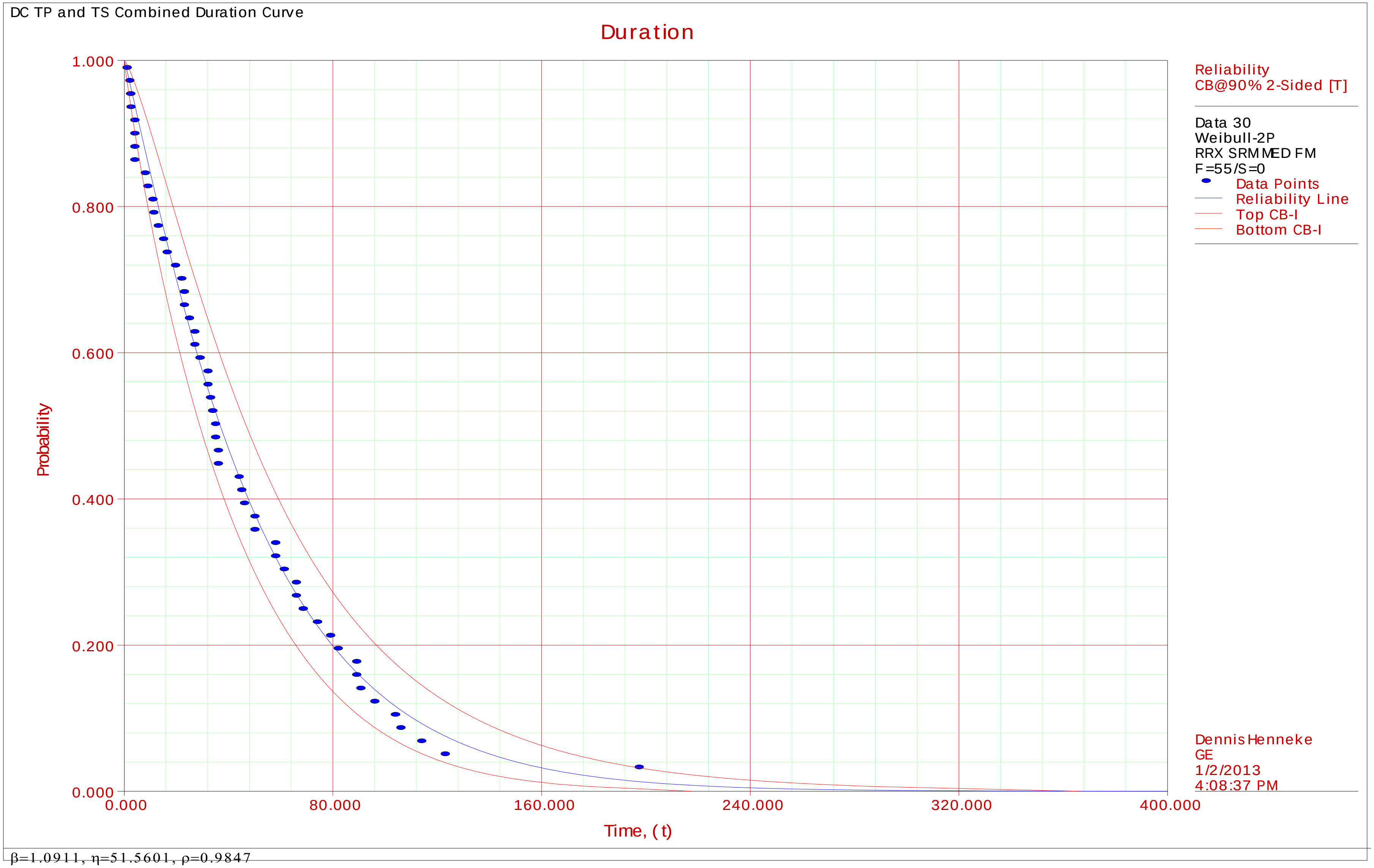
Parameters Evaluated

- Conductor count
- Thermal exposure
- Cable orientation
- Raceway routing
- Raceway fill
- Insulation type
- Insulation material
- Circuit Type
- Insulation/jacket
- CPT size (ac only)
- Circuit Grounding
- Wiring Configuration
- Conductor size
- Fuse Size
- Shielding

Fire Expert Panel

1. Fire Testing was reviewed for the Circuits FPRA Expert Panel Process:
    - Process is continuing; report in draft.
    - Revised HS Probabilities will result, with new factors:
        - Credit for CPT in MOVs will likely be removed.
            - However, a lower MOV and DC Switchgear value is being recommended (20% lower)
        - Method 2 from Appendix J of NUREG/CR-6850 is considered invalid.
    - New HS duration estimates will be provided:
        - Duration may be impacted by location in or out of the flame.
        - Likely, DC circuits will have a minimum probability (~0.02)

Example combined Duration Curve



What is next?

- **SSA:**
  - Need to reconsider circuit analysis guidance in NEI 00-01 based on the PIRT and FPRA Expert Panel Results
    - May be a reduction of the requirements based on unlikely fire-induced failure modes.
    - Need to include the DC hot short duration results:
      - AC duration is accounted for by being able to screen AC SO failures where the SO has to last longer than 20 minutes.
- **FPRA:**
  - New FPRA tables will be included in the PRA expert panel, along with guidance on how to use the new results in the FPRA.
  - New SO duration should be included in a FPRA.
  - FPRA Circuit Analysis needs to consider Multiple-Shorts-To-Ground, especially for DC circuits.

Questions?

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