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Development of Nuclear Plant Specific Analysis Simulators with ATLAS

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ABSTRACT

On the basis of ATLAS simulation environment, several detailed analysis simulators for German NPP's have been developed at GRS in last years, specifically six for pressurized water reactors (PWR) and four for boiling water reactors (BWR). The paper presents the approach to building of specific analysis simulators with ATLAS. A general overview of ATLAS is given, describing its configuration and tools that enhance the functionality of simulator for a range of application in the field of reactor safety analyses. Different modelling aspects of thermal-hydraulics and Balance of Plant (BOP) systems, such as a modelling technique or verification and validation procedures are discussed. Special emphasis has been put on the BOP model builder based on the methodology developed at GRS. The validation procedure and selected analyses results compared to measured plant data are presented. The use of graphical technique, both for BOP model building and for visualisation of simulation results is briefly described. The examples of graphical displays are presented. Also the simulation range and examples of simulators applications are described.

1 INTRODUCTION

In order to determine parameters important to safety of Nuclear Power Plants (NPP's), comprehensive safety analyses are required. Usually, such analyses should be executed in very short time without costly and time consuming data acquisition and their processing. Therefore NPP's specific analysis simulators with high model confidence are required.

In order to reach these goals several specific analysis simulators have been developed at GRS. Within the project "Technical Assistance of Suitable Supervision on Licensing of Nuclear Reactors", sponsored by the Federal Minister for Environment, Nature Conservation and Nuclear Safety, ten specific analysis simulators for German NPP's have so far been developed, specifically six for pressurized water reactors (PWR) of Brokdorf, Neckarwestheim-2, Unterweser, Philippsburg-2, Neckarwestheim-1, Grafenrheinfeld and four for boiling water reactors (BWR) of Grundremingen, Krümmel, Philippsburg-1 and Isar-1. The simulator for Biblis-B is under development at present.

The ATLAS simulation environment has been used as developing tool. The model basis of simulators is provided by best-estimate code ATHLET. The thermal-hydraulic system code ATHLET is being developed by GRS for the analysis of transients and leaks in light water reactors. Due to the high automation level of German NPP's, a significant part of simulation models are the Balance of Plant (BOP) models. These models have been generated by a simulation language GCSM (General Control System Module) built into the ATHLET, and equipped with the interactive graphical interface based on the expert system G2.

2 ATLAS ARCHITECTURE

The basic tasks of ATLAS [1] are simulation, visualization and data management. All processes run as separated computing processes (clients). The communication and the synchronisation are realized according to a client/server principle, as shown in Figure 1.

The database (Q-Server) takes a central position. It administers the resulting data of the simulation models and keeps them ready for all systems that are linked to the network. The models are sending the simulation results and receiving the control commands generated by the user in the visualisation processes from graphical displays.

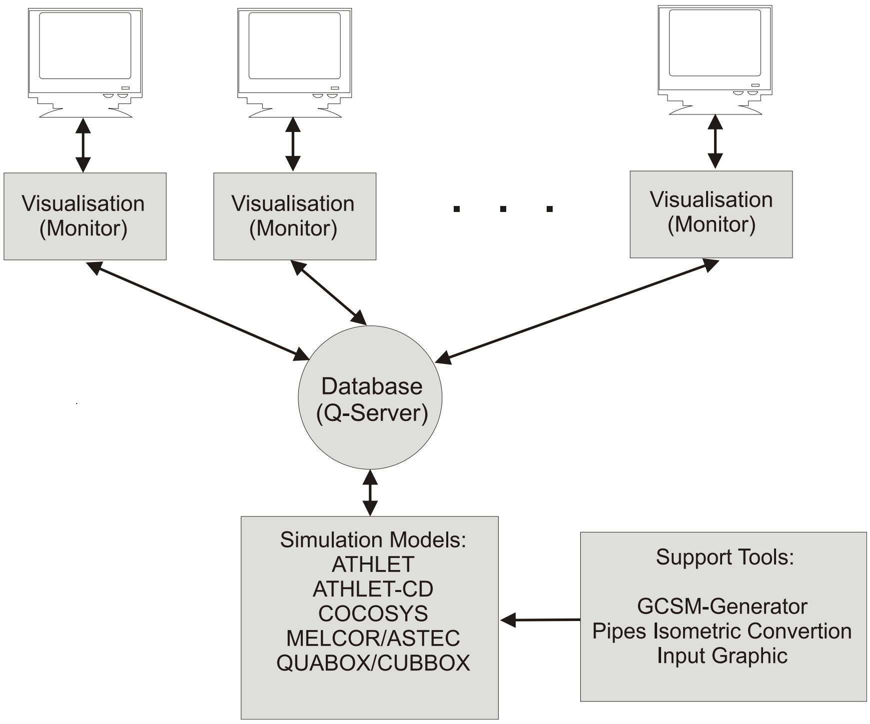

Figure 1: The architecture of ATLAS

A number of German best estimate codes used in the licensing processes have been included into ATLAS. The ATHLET [2] as basis code is used for plant models for different designs as well as for experimental facilities. For the description of processes within the containment the GRS code COCOSYS [3] is used, and for the simulation of severe accidents the ATHLET-CD [4] and the integral codes ASTEC [5] and MELCOR [6]. The coupling of ATHLET code to neutron kinetic models QUABOX/CUBBOX [7] and SIGMAS [8] is available.

The visualization system, referenced as Monitor, is the front end of ATLAS and presents the simulation data in manifold graphical displays. Also it serves as the primary user interface to access the execution of the models as well as procedure simulation and documentation. Many concurrent Monitors may be run at different locations of the network or by different persons to gain access to the same simulation process.

The Q-Server is a fast running database for handling of a large amount of temporal data. It keeps track of historical data and stores it in a compressed form on disk as necessary. In ATLAS every simulated value has unique name that is composed of a hierarchical set of keywords. These keys and the time stamp are the standard identifiers in the database.

As far as all software is based on standards there are no limitation in machine and operating systems and ATLAS is currently available for the professional WINDOWS as well as different UNIX platforms.

3 MODELLING OF THERMAL HYDRAULIC PROCESSES WITH ATHLET

The main features of code ATHLET are: advanced thermal-hydraulics, modular code architecture, separation between physical models and numerical methods.

The ATHLET contains four different thermal-hydraulic models for one dimensional water/steam flow. The above mentioned simulators have been constructed using six-equation model (separated equation for energy, mass and momentum) or five-equation model (separated equation for mass and energy and a mixture momentum equation).

The simulations modules of ATHLET covers all physical phenomena involved in the operation of NPP. The modules correspond to the following physical processes: thermo-fluid dynamics (module TFD), heat conduction and heat transfer (module HECU), neutron kinetics (module NEUKIN), and BOP (module GCSM). In order to describe the thermal-hydraulics of a given system two basic elements are used: control volumes (CV's) comprising volume specific parameters like mass and energy, and junctions comprising flow related parameters. In ATHLET these elements are combined using three classes of objects: pipe, branch and single junction pipe. Pipe objects are a stack of CV's connected via junctions to form pipe models. Branches allow for coupling of more than two pipes and provide particular features to control the momentum flux calculation for individual incoming and outgoing junctions. Single junction pipes comprise flow related entities only. Additional features may be attributed to the objects for simulation of boundary conditions (time dependent volumes, fill junctions), valves, pumps, accumulators, steam separators, single/double ended breaks and special components.

For symmetrical disturbances of parameters at the core inlet or inside, ATHLET provides either a point- or a one-dimensional neutron kinetics model. The coupled code ATHLET-QUABOX/CUBBOX should be applied, if asymmetrical disturbances in the core are expected. A multi-channel description of thermal-hydraulics in reactor vessel and core is necessary in such case. As well as the classical point kinetics model, recently developed point- and one-dimensional models are available based on consistent neutron kinetics data generated by the nodal code SIGMAS, exploring 3D-kinetics results.

The models built out of modules, objects and BOP blocks are connected together to form the plant specific simulator. Their description and connections are done via input data deck.

4 MODELLING OF BALANCE OF PLANT SYSTEMS

BOP system can be defined as a closed control loop consisting of thermal hydraulic process, control systems (measuring equipment, control unit, limitation, protection, interlocks) and final control elements (e.g. pumps, valves).

The modelling of BOP systems is an iterative procedure, in which the basic documentation, the model building technique, and the verification procedure have the fundamental importance when it comes to modelling efficiency. The basic documentation, provided by utilities, includes the full information about structure and data of systems to be modelled. The basis for model construction has been mainly data flow diagrams. The models have been completed as functional models.

BOP systems in a plant have both a discrete and a continuous nature. In ATHLET, a combined approach based on the continuous view is used and incorporated in the GCSM simulation language. GCSM input consists of standardised statements, called controllers. Plenty of controllers are available to provide functionality of analogue and discrete operators, different switches, function generators and rather complex library objects. The controllers have to be attributed to (at least one) GCSM-blocks. A GCSM-block is to be understood as a defined dynamic model unit with an individual time integration procedure.

The calculation of the controllers in a block can be performed at the end of an ATHLET time step, or additionally at intermediate time steps used by the numerical solver to achieve convergence in the system of differential equations.

Additionally, GCSM provides a general interface to thermal hydraulic models and to external libraries of particular functions.

Model building with GCSM uses a combination of structural and object-oriented approach, [9]. The whole BOP system should be decomposed into modules that may be represented by GCSM-blocks. The set of GCSM-blocks establishes the BOP dynamic model. The sequence of blocks determines the time relationship of controllers. The partitioning of BOP into blocks allows much greater flexibility, when created in a team.

To allow for a simulation of the high complexity of plant specific BOP systems and to generate a high quality documentation of models, the so called “GCSM Generator” has been developed by GRS as an application of the open expert system shell G2, [10]. The information flow in GCSM Generator during modelling of BOP system is shown in Figure 2.

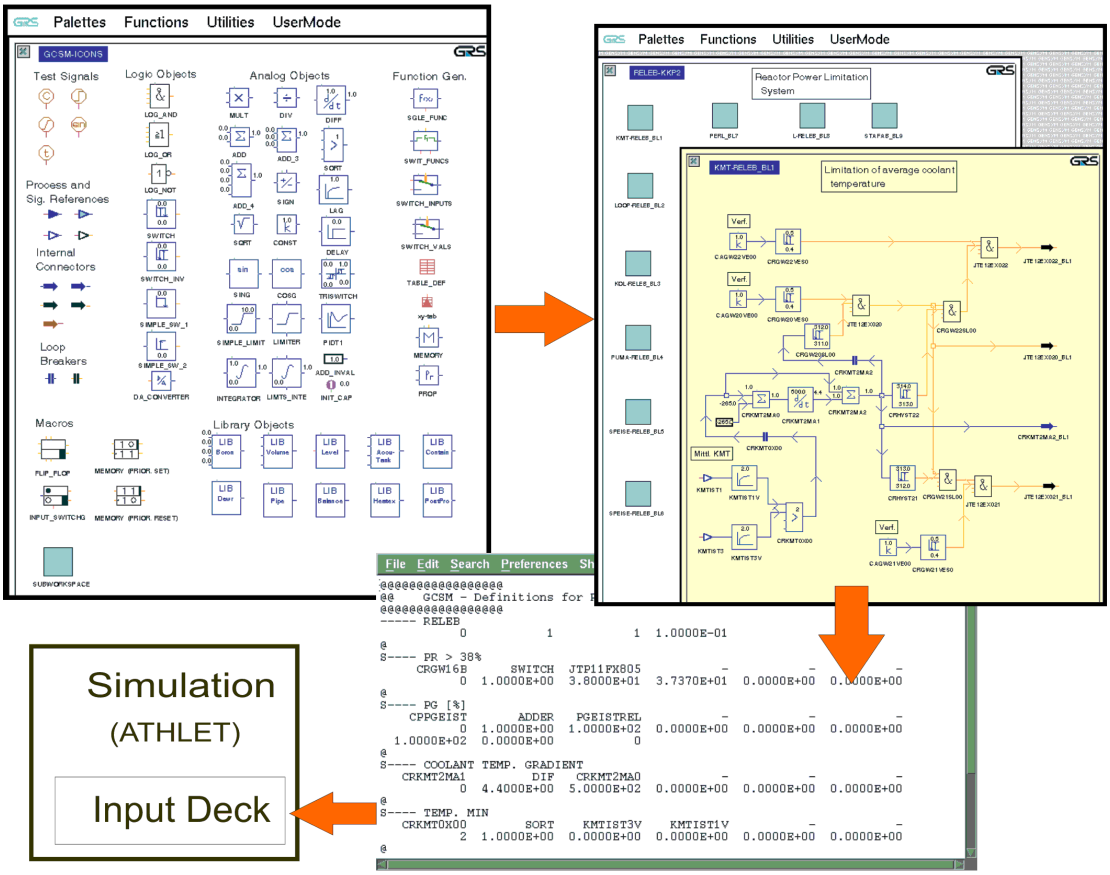

Figure 2: Information Flow in GCSM Generator

The user interface for the GCSM Generator is the window-based, Graphical User Interface of G2. The GCSM Generator provides a graphics editor, formatted drawing workspaces, a library of predefined objects represented by icons, evaluating and test functions. The predefined objects can be selected by the user and placed on the drawing workspace using drag-and-drop technique. Specific icons exist for all GCSM-controllers and additional library objects, as shown in Figure 2. These icons can be treated as generic objects with default attributes. Placing an icon on a workspace makes it a specific object. The attributes of it may be customized.

The specific objects can be linked by lines according to the GCSM linkage rules to form a knowledge base. To cope with the complexity of BOP system to be simulated, the knowledge base may be spread over a hierarchically arranged set of workspaces. A simulation function supported by plots and screen output tags allows for a test of the knowledge base within the G2 environment. Finally, an evaluation process will prove the conformity with GCSM internal rules and generate the GCSM-input (ASCII-text). That is to be included in the ATHLET input deck. The work around with GCSM Generator is attended to create a single GCSM-block.

5 SIMULATION RANGE

The simulation objectives of analysis simulators were defined originally rather broadly, and comprised the whole spectrum of operational and abnormal transients, small and intermediate leaks, up to the large breaks for German reactors of type PWR and BWR. With regard to the calculation efficiency, it was decided to develop advanced versions with detailed representation of thermal-hydraulic processes in reactor and primary circuit, in addition to basic version of simulator for each NPP.

A manifold of BOP systems have been modelled in the simulators. The standardized set of BOP systems is simulated in all the simulator versions. As an example for reactor coolant circuit of PWR's have been modelled following safety, control and auxiliary systems: reactor protection system, power limitation, rod drop functions, coolant temperature control, coolant pressure control, rod position control, pressurizer level control, boric acid and demineralised water control, emergency core cooling and residual heat removal system, volume control system, operational borating system, extra borating system.

The secondary circuit of PWR's have been represented by following models: main steam lines, turbo generator, turbo generator power control, steam generator level control, condenser control, max-steam- pressure control, min-steam-pressure control, auxiliary steam control, emergency feed water control, turbine control valves, main steam valve station, bypass station, main condensate system, main feed water system, start-up and shut-down pumps, electrical system.

The complexity of simulator could be very well estimated by the number of control volumes used for thermal-hydraulic analysis, the number of GCSM elements used to model BOP systems and the total number of variables (continues and discrete) available from simulator, respectively. The estimated complexity of basic versions of simulators constructed at the GRS is shown in the Table 1.

Table 1: The complexity of analysis simulators constructed at the GRS (only basic versions)

NPP	TYP	Control Volumes	GCSM Elements	Variables
Gundremmingen	BWR	151	3006	7775
Krümmel	BWR	190	5907	12818
Brokdorf	PWR	400	4719	25864
Neckarwestheim 2	PWR	347	14232	31572
Phillipsburg 1	BWR	183	11844	20647
Unterweser	PWR	437	17322	36084
Phillipsburg 2	PWR	470	22380	40948
Isar 1 (KKI 1)	BWR	156	11837	18650
Neckarwestheim 1*	PWR	650	15940	44804
Grafenrheinfeld	PWR	549	15877	40838

*) 3-loop model

6 VALIDATION AND VERIFICATION OF SIMULATORS

The verification and validation program is very important part of simulators development process at GRS. Model verification is usually defined as “ensuring that the computer program of the computerized model and its implementation are correct”, [13]. In the framework of preparing and verification of the ATHLET input deck different tools were used for data processing and documentation. The PC-code MATHCAD was used for calculation of geometrical data and initial value of thermo-hydraulic parameters. Particularly, for creation of input data for pipes the isometric conversion program with visual pipe editor has been used. For verification of geometric details of thermo-fluid objects and their connections in ATHLET, the Input Graphics Program is designated.

To ascertain the usefulness of BOP models, the comparison check of the graphical implementation of models with data flow diagrams was carried out. Using animation and a limited number of disturbance signals the models generated with GCSM Generator have been checked.

The validation is defined as “the process carried out by comparing code predictions from experimental measurements, or measurements in a nuclear power plant”. Accordingly, the ATHLET code has been validated against relevant experimental data, [11]. The overall results of the code calculations are validated mainly by means of data from integral test facilities representing the primary and secondary coolant systems. At GRS a systematic approach, base on validations matrices, is used, [12]. The validation matrices collect together the best sets of test data for code validation and improvement from the wide range of experiments that have been carried out worldwide in the field of thermal-hydraulic.

The use of validated ATHLET code as simulations basis allows skipping over the conceptual and programmed model validation of simulators. During the development process of plant specific simulators, an additional validation based on sufficient simulation of the plants BOP system is necessary.

The most definitive test of simulators validity is comparing of output data from the overall simulation to measured plant data, called results validation. A number of measured transient data sets, such as scram, turbine trip, trip of one main coolant pump, load rejection, simulated steam generator U-tube leak, are available for each plant. As an example, Figure 3 shows a comparison of 4 different parameters measured in a BWR plant during a load rejection event with the results of simulation.

The thermal power (Figure 3a) is given as a core model output in the calculation but measured in the plant by thermal-hydraulic techniques. This explains the missing peak in the measurement at beginning of the transient. Over the 360 s, calculated and measured data are in good agreement. The rise in measured power at about 335 s is due to problems with the live steam mass flow measurement.

The Pressure (Figure 3b) and the level (Figure 3c) in the reactor vessel show also a good agreement between measurement and calculation.

Figure 4 shows the post calculation of intentional power let down before refuelling outage in a PWR. The electrical power (Figure 4a) was lowered using the turbine controller identically to the plants measurement. Calculated thermal power is in good agreement with measurement over a wide power range. Calculated averaged coolant temperature (Figure 4b) is kept by the controller slightly above the set-point. This is due to the lowering of power and compares well to the measurement.

Calculated pressure in the live steam collector (Figure 4c) also meets the measurement well and causes identical time points for opening of turbine bypass valves (Figure 4d). The positions of the valves largely differ in the measurement but the average position is comparable. The operational let down process of power and pressure has been experienced as a valuable validation means with respect to the entire calibration of a simulator.

Satisfactory results were also obtained for all PWR and BWR simulators. Other techniques which have been used for validation of simulators were plausibility tests, comparison to results of other (valid) models and event validity.

Validation does not end with the current simulation application but continues during the use of the simulators by the customer. In that way, the “validity level” of simulators developed by GRS generally increases with their application.

Very useful for promoting application of simulators as a standard post-processing tool are animation capabilities and graphical plots accessible with visualization system of simulators.

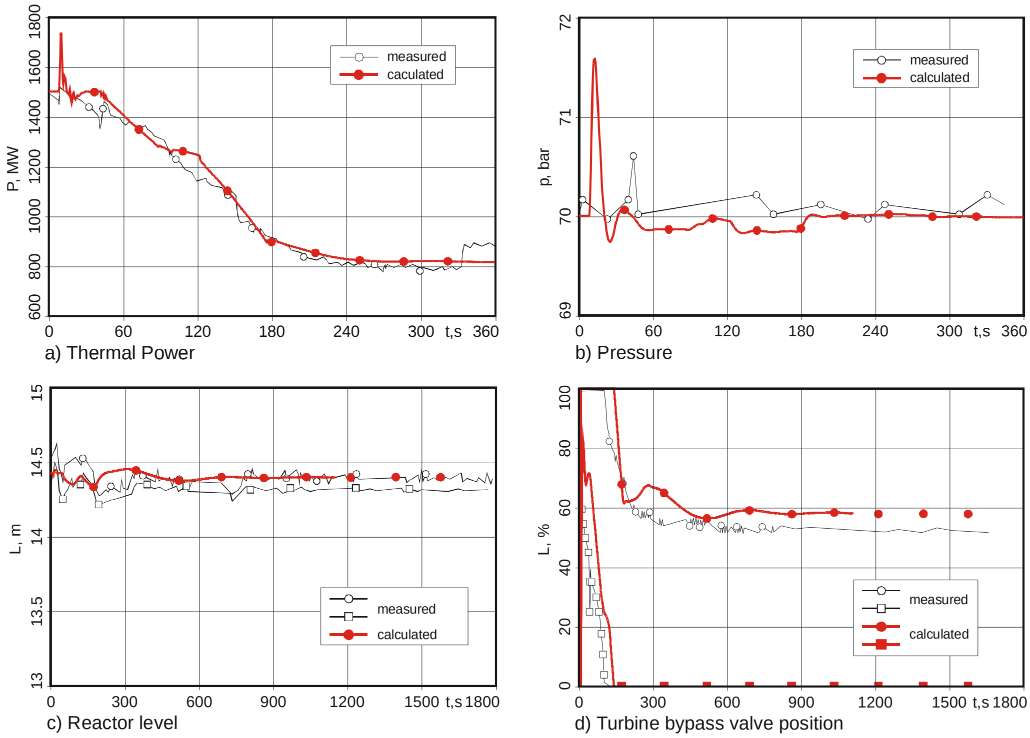

Figure 3: Validation Sample BWR

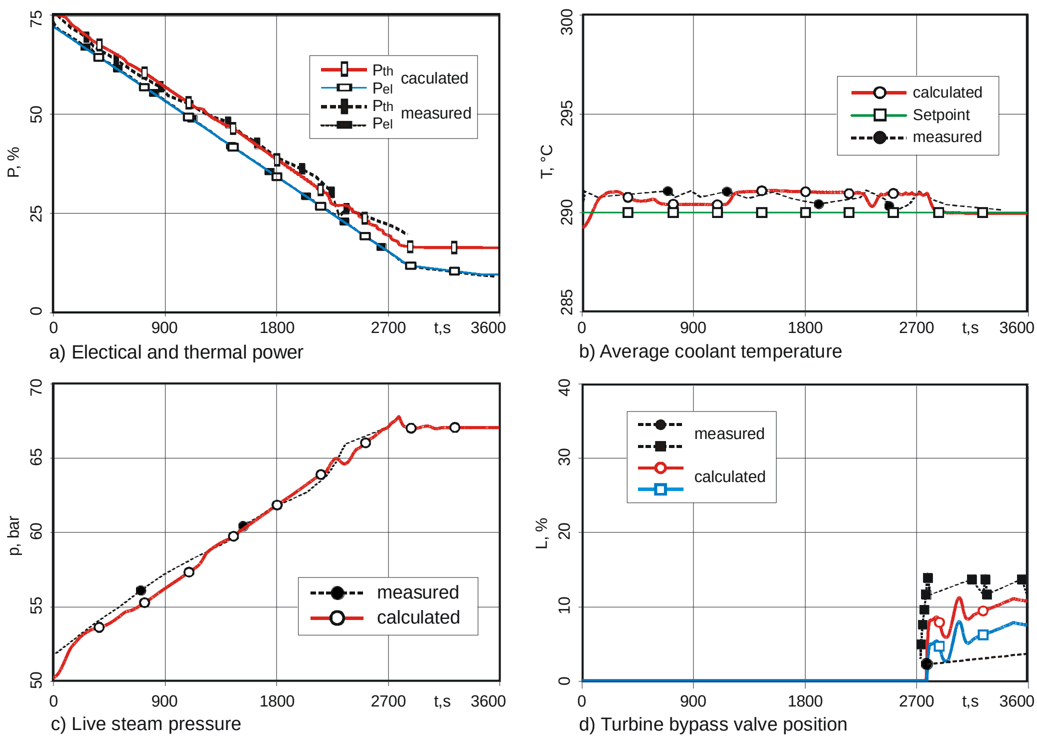

Figure 4: Validation Sample PWR

7 VISUALIZATION OF SIMULATION RESULTS

The visualization system of the ATLAS presents graphically the results of the simulation and allows interactively influencing the execution of the simulation process (malfunctions, manual control). The PC version of the visualization system is based on the OpenGL libraries. The visual display system is supplemented by a graphics editor (APG) for creating the images interactively and preparing them for adaptation to the dynamic data.

Analysis simulators constructed by the GRS are equipped with a set of synopses and system-oriented displays. They enable the manual control of modelled systems and allow the user to start the initiating events or malfunctions. The single events as well as sophisticated incident or accident scenarios composed from event sequences can be simulated.

Figure 5 shows the example of synopsis display of analysis simulator for German 3-loop - PWR. The functions which convert a numerical data value to colour have been used in the display. A user defined colour scheme is used to depict the thermal dynamic state of the fluid along the primary circuit. For visualisation of abnormal states (to high/low level in steam generators, Scram, Turbine Trip) a simple function is used, which displays one or more user defined colours depending on whether the data value is above, or below the user defined threshold value.

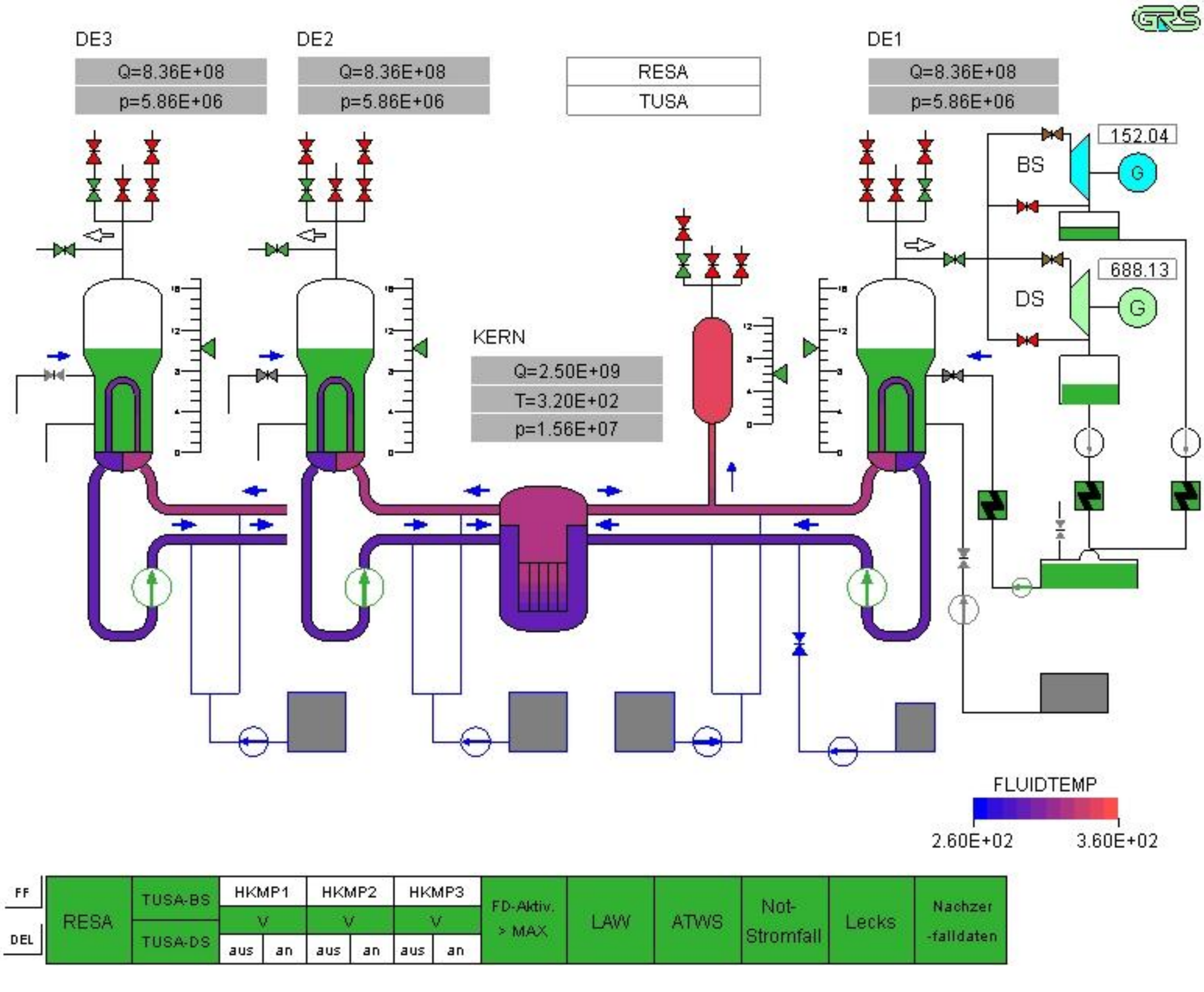

Figure 5: Synopsis Display of Analysis Simulator for German 3-loop PWR

Figure 6 shows the image of turbine control system, as example of the system-oriented display. The display is divided into a technological part (left-up) and control diagram (right-down). The technological part shows schematically the steam lines with valves and reheaters, turbine and generator. The status of main parameters (mass flow, turbine speed, valve position) is presented.

Clicking “V” areas initiate the malfunctions of steam valves. The control diagram presents the status of turbine control system. It allows the user to change set point values for power and power gradient of generator.

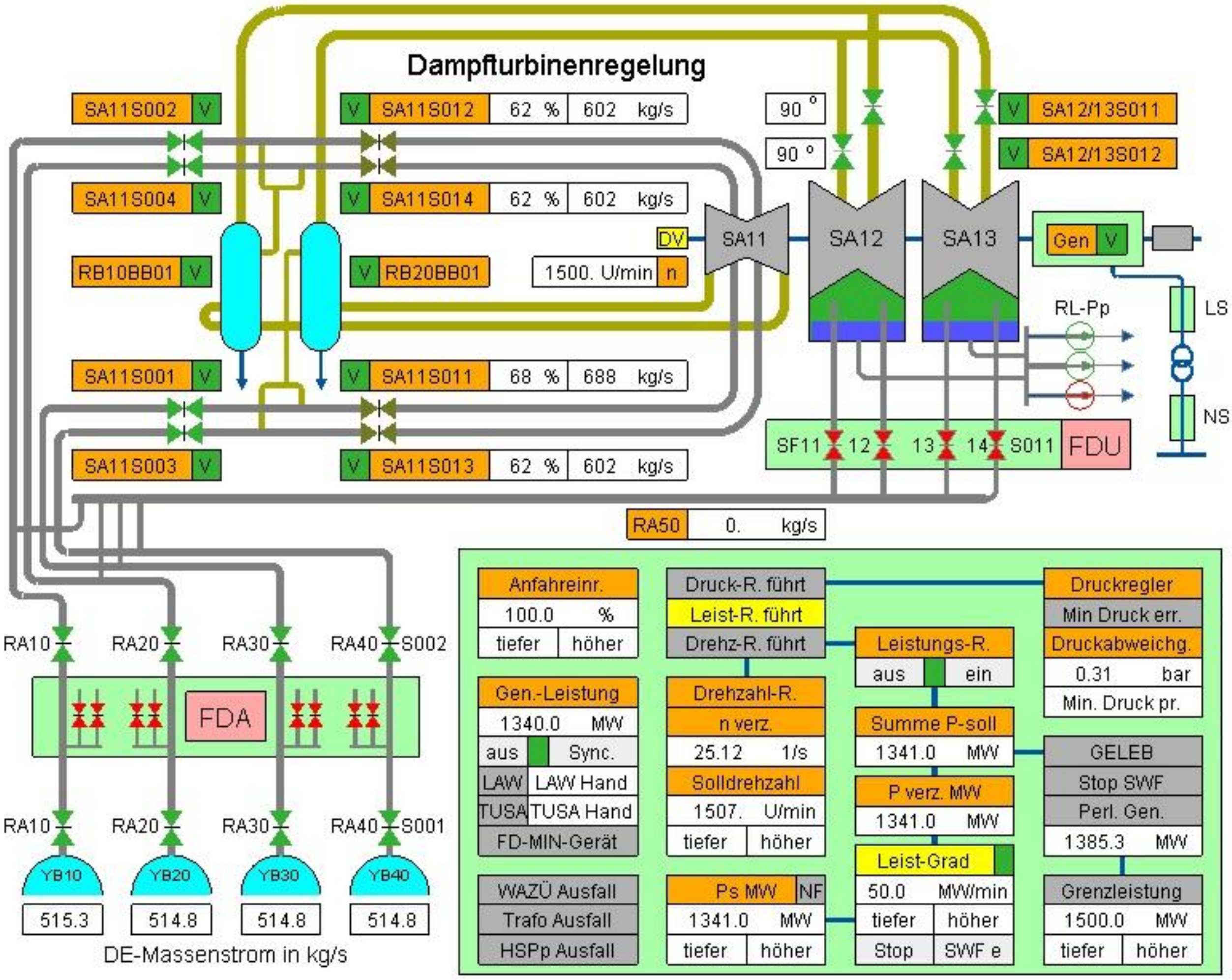

Figure 6: Display of Turbine Control System

Using the standard solution, the ATLAS provides navigation per drop-down list and window technique. Additionally, using programming possibilities of graphics editor (APG), the creation of application specific navigation system is possible.

8 APPLICATIONS

The nuclear plant specific analysis simulators constructed at GRS have been used in many activities in the nuclear area, focus on the realization of thermo-hydraulic studies and safety analysis for the NPP’s of type PWR and BWR. As an example following cases can be mentioned:

- The study of effects of boron dilution when taking place during a reflux-condenser phase followed by natural circulation
- Analyses of Anticipated Transients Without Scram (ATWS) for different boundary conditions
- Analyses within a Probabilistic Safety Assessment (PSA)
- Licensing analyses related to NPP’s modernization.

In addition, the simulators provide training tools for engineers involved in activities in nuclear energy and are used in different seminars and workshops.

The use of simulators for investigation of human factors and ergonomic aspects of graphical displays is possible, [14].

9 CONCLUSION

Based on the reliable and detailed documentation, advanced simulation methodology and well designed graphical user interface, easy to use tools for very efficiently safety analysis have been developed at GRS.

The modular and graphical approach in building models with ATLAS leads to a reduction of model development time and a substantial increase in the quality of model documentation.

The comparison of different parameters, measured in the plants during transients, with results of simulation shows the satisfactory agreement of data for all PWR and BWR simulators.

The simulators on the ATLAS basis are employed in many applications at GRS, research organizations, utilities and supervisory authorities in Europe.

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