Nuclear Power Plant Simulation and Safety Analysis with ATLAS

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ABSTRACT
A survey of the ATLAS environment, a tool for the simulation of nuclear power plants and reactor safety analyses, is presented. The basic configuration, including a wide spectrum of simulation models, the interactive visualization system and a data server, is described. The modelling capabilities comprise general fluiddynamics and thermal-hydraulics, core damage, neutron dynamic models and the containment models for the pressurization and fission product behaviour. The visualization provides interactive process diagrams that may be designed by a graphic editor. A 3D-visualization tool is also integrated. Several analysis support tools are added for extended safety studies. Uncertainty analyses, operational procedure simulation and a leak estimation system are explained in more detail. Examples for the application of ATLAS in detailed plant specific analysis simulators, in the training of severe accident phenomena and for human factor analyses are given. The present development is focused on transient recognition and the increase of the simulation speed of the models.

KEY WORDS
Nuclear power plant, Simulator, Reactor safety,

1. Introduction

In reactor safety analysis complex modelling software is used for the simulation of all relevant physical and technical processes. The reactor coolant system is simulated by thermal-hydraulics, heat transfer, generic component, and control systems models, the reactor core by multidimensional neutron dynamic codes, the containment simulation includes models for the pressurization, H2 deflagration, pyrolysis, aerosol and fission product behaviour. The basic goal of the ATLAS development was to provide a common interface for accessing and operating these models and to support the interactive pre- and post-processing of the simulation. Beside the process simulation there are other important engineering tasks in safety analysis that can be supported by ATLAS. Thus uncertainty analyses have been integrated to evaluate the confidence ranges of the simulation results. Especially in accident conditions nuclear power plants have to be operated manually according to written procedures. Automation and testing of these procedures are available in ATLAS. Additionally ATLAS may be applied for human factor analyses of operator behaviour or the ergonomics of the pictures used in the digital control systems. Finally ATLAS offers tools for the detection and estimation of small leaks in the reactor. These methods may be applied in operator support or an emergency center in order to select correct boundary conditions in case of prognostic simulation. Currently this diagnosis of transients is extended by a more general approach based on neural nets.

2. Basic architecture

In ATLAS the basic tasks, simulation, visualization and data management, are separated into different processes. The communication and the synchronisation are realized by a client/server architecture as shown in figure 1.

The simulation models are connected to the central database (Q-Server) by a set of standard interface routines. The models are sending the simulation results and receiving the control commands generated by the user in the visualization processes. Additional data used by post processing tools are stored to files. As mentioned in the introduction a wide spectrum of simulation capabilities is covered by the different models. Many German best estimate codes used in the licensing process have been included into ATLAS. The thermo-fluid dynamics of the reactor is modeled by the system code ATHLET [1]. The ATHLET is employed for plants of different designs as well for experimental facilities. As a part of the ATHLET a General Control System Module (GCSM) is used for simulation of control and auxiliary systems. For the description of processes within the containment, the GRS code COCOSYS [2] is employed, and for the simulation of severe accidents the ATHLET-CD [3] and the integral codes ASTEC [4] and MELCOR [5]. In the ATHLET code different neutron kinetic models are available as QUABOX/CUBBOX [6] and SIGMAS [7]. In all cases the standard versions and the newest releases of the codes may be used, because the interface routines are a substantial part in the codes.

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

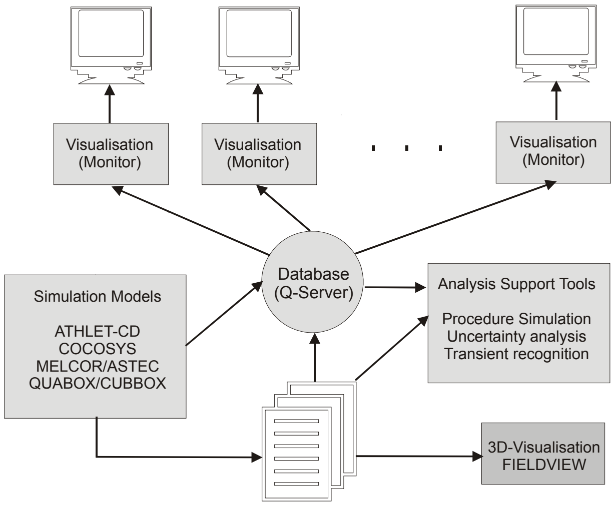

Figure 1. Basic configuration of ATLAS

interactive user interface to access the execution of the models as well as procedure simulation, documentation and other support tools. It polls the database for the data required by the user and sends back the user requests, e.g. manual operation of components. 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 designed for the handling of a large amount of temporal data. It keeps track of historical data and stores it in a compressed format on disk as necessary. In ATLAS every simulated value has a unique name that is composed of a hierarchical set of keywords. These keys and the time stamp are the standard identifiers in the database.

The different processes may be distributed to one ore more computers within a network. As far as all software is based on standards there are no basic limitations in machine and operating systems and ATLAS is currently available for the professional WINDOWS as well as different UNIX platforms (Monitor on WINDOWS only).

3. Visualization system

The development of the ATLAS simulation environment was started more than 20 years ago at GRS. The graphic systems needed special graphic engines and hardware for efficient visualization [8]. This has changed with the availability of powerful and affordable PC hardware and modern graphic standards. The wide propagation of WINDOWS PC's on the desktop was followed by a complete redesign of the formerly X-Windows based visualization system of ATLAS, the Monitor. The drawing engine now employs OpenGL as basic software for the process diagrams. The Monitor is realized as a standard WINDOWS application with Microsoft foundation classes (MFC). The graphic diagrams are composed of basic objects (e.g. valves, pumps, pipes), which in turn consist of other graphic primitives (lines, filled areas, texts). The elements may have attributes as colors, transparency, textures, pick identifiers and transformations. The diagram is then defined in an ASCII file by a list of basic graphic drawing commands. Special commands for the definition of the dynamics (e.g. color, size, value display, visibility) may be added. The generation of the pictures is supported by the interactive graphics editor APG. The graphic elements are available in a toolbar and can be added to the drawing pane by the mouse. Every element has a property dialog to apply changes. Several elements may be combined into a single object, which can be duplicated or transformed. The editor allows an efficient definition of dynamic effects for the elements. The keywords of the simulation are available in a list inside the editor window and may be dragged on any graphic element. This operation is associated with predefined dynamics, e.g. the change of color, if a standard limit is exceeded. There are special dialogs for further modifying of the dynamic definitions.

The display of trend curves is managed by a commercial ActiveX control to provide users with the most powerful, high quality 2D charts with manifold layout properties that can be set interactively. The control has been fully integrated into the Monitor and a simple click on the keyword bar displays a standardized trend window. This window can be extended by additional charts and trend curves. All settings may be stored to disk for later reuse.

A typical visualization window of ATLAS is depicted in figure 2. On the top the main ATLAS toolbar is located and it contains a display of the problem time, buttons for running, pausing and replaying the simulation and dropdown lists of the available pictures. The main window shows a schematic drawing of the vessel of a PWR with the current position of the control rods and the current values of some important process parameters. The temperature distribution of the coolant in the vessel and the fuel is depicted according the color scales on the left. On the right the reactor level is displayed both in a bar display and a time curve. There are additional dialogs available giving direct access to all simulated values by a simple mouse click, i.e. the display of a time chart or the definition of a malfunction.

For the analysis and the display of 3D neutron kinetic data the commercial software FIELDVIEW, a post processor for Computational Fluid Dynamics (CFD) by Intelligent Light, is applied. This tool is very powerful in visualizing both complex geometries and 3D spatial data and even transient changes (time sweep). An interface to FIELDVIEW has been added to ATLAS, which automatically provides the input files with geometric and nodal data from the simulation results and also takes care of the synchronization with the Monitor.

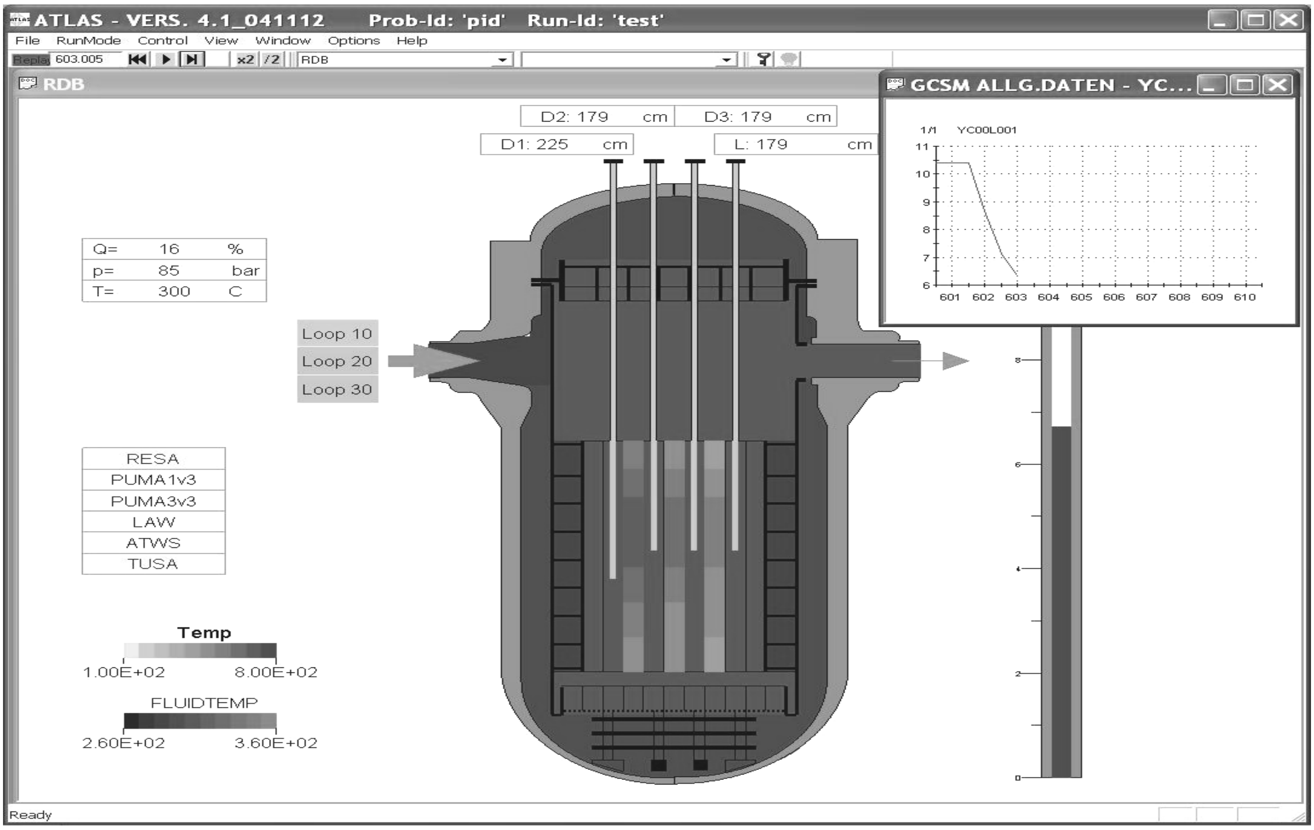

Figure 2. Visualization window of the ATLAS Monitor

A visualization example of the power distribution in the reactor core is shown in figure 3. Axial position and color shading may be controlled interactively.

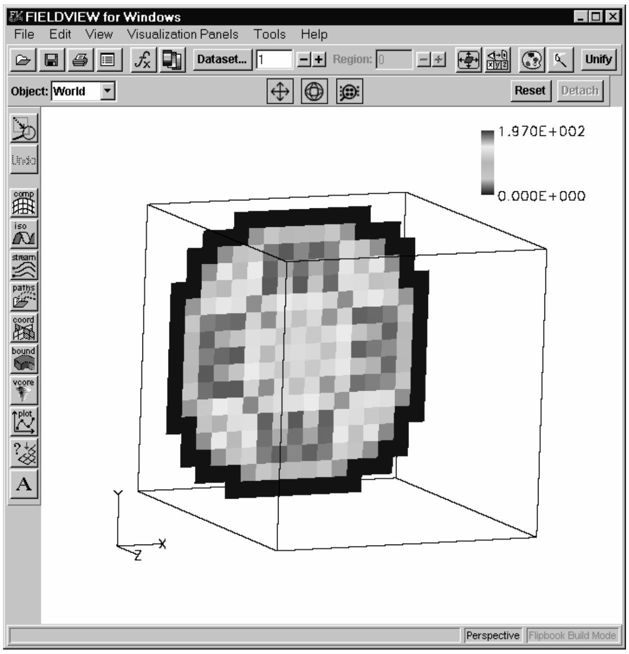

Figure 3. 3D Visualization in ATLAS by FIELDVIEW

4. Analysis support tools

All tools have been developed with the common goal to increase efficiency and quality of reactor safety analyses. Uncertainty analyses are an increasing demand for best estimate simulations. They allow the calculation of the tolerance limits of the model results and the identification of the parameters with the highest sensitivity. The applied software system is the GRS code SUSA [9]. At first the uncertain model parameters and the probability distribution have to be specified. For the calculation of the tolerance limits with the probability of 95% at least 93 simulation runs with random parameter vectors have to be performed and evaluated. The generation of the ATHLET input decks with the parameter vectors has been automated and the necessary calculations are started automatically. After completion the confidence ranges for all simulated values are computed by SUSA and the results may be displayed in the trend charts of ATLAS. Current work is concentrating on the distribution of simulations in a cluster of WINDOWS workstations.

Emergency procedures play a significant role in the accident management of nuclear plants. Therefore the analysis of the appropriateness and practicability is an important safety issue. ATLAS offers different tools for supporting this task. The procedures are available as operation manuals and have to be automated for an in-depth analysis. There is a quick and code independent way to model simple procedures efficiently in the Monitor. The procedure may be defined as a set of triggers and actions (figure 5), while the simulation is running. Triggers are procedural steps that check if simulated values exceed user specified limits. Actions are procedural steps that control the simulation by operating components automatically. The actions are initiated by an arbitrary Boolean combination of triggers. If the procedure is stored and activated, a new picture is generated automatically reflecting the logic of the procedure by a network of basic blocks. Actions, triggers and Boolean blocks change their colors whenever they are activated.

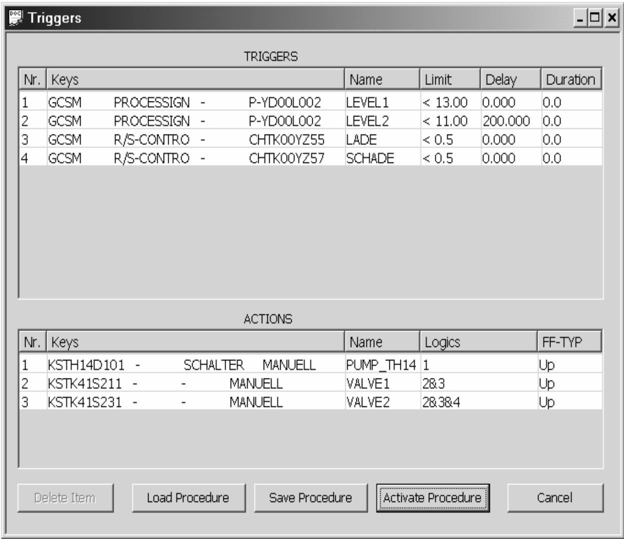

Figure 5. Procedure definition dialog

Limits and monitored values are faded into the blocks. An example is given in figure 6, displaying a part of a procedure to maintain the reactor core cooling in the case of the loss of feedwater supply and a decreasing reactor level. An initial step is to start the high pressure injection pump, if the level falls below 13 m. An additional measure is the manual opening of relief valves after a further decrease below 11 m and the failure of the automatic depressurization system LADE.

More complex procedures may also be simulated by the means of GCSM within the ATHLET, but it requires a pre-processing phase for input generation. Another procedure simulation tool has been realized by a commercial expert system shell that enables the modelling process very close to the written manuals [10] enabling tests of the ergonomics.

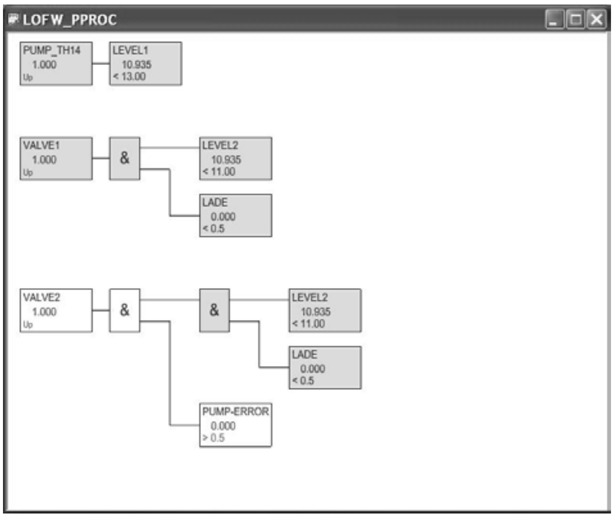

Figure 6. Dynamic Procedure display

In many cases the setup of the simulation requires initial or boundary conditions that are not provided by measurements. A first step to provide this information was done by the implementation of a small leak estimation algorithm for PWR [11] in ATLAS. The method uses Kalman filters for the pressurizer, the primary circuit and the steamgenerator to estimate the leak mass flow and enthalpy. By these values the leak position (coldleg or hotleg) and the leak area may be calculated. The method is restricted to leaks between 20 and 130 cm^2, because the models assume a subcooled primary circuit without steam during the estimation time. As inputs for the Kalman filters several measurements, temperatures, levels, flow rates and pressures are used. The method was tested by a simulated steam generator tube rupture and showed reasonable results for the leak mass flow after 30s. Anyway the limitation of this approach with respect to the covered transients requires additional work in the field of transient recognition (see development).

5. Applications

Numerous applications have been built on ATLAS and only some of the most outstanding ones can be mentioned.

Within the framework of licensing and supervision of German NPPs, various plant specific analysis simulators have been developed [12]. These simulators have very detailed models of the thermohydraulics, the auxiliary systems and the reactor control and safety systems. They also include a large picture library of all important systems as well as nodalization schemes. With the means of the diagrams the expert can quickly access all the states of many variables, operate the systems and components by the mouse and introduce faults and malfunctions. This gives the basis to investigate in a short time the plant behaviour for essential incidents detected in safety and risk analysis. Similar modelling work has been done for the Russian VVER-1000/320 reactor in cooperation with VNIIAES and OKB Gidropess.

The flexible and powerful visualization abilities make ATLAS a valuable tool for training and education. It was used in a seminar on the phenomenology of severe accidents for the shift personnel and management staff of German nuclear power plants [13]. As an example the total loss of feedwater supply in a PWR steamgenerator was precalculated with the integral code MELCOR. This case includes core heat up and melting, core slumping, vessel failure, fission and hydrogen generation and containment behaviour. A demonstration of the use of accident management procedures was added. These courses extend the abilities of training simulators to achieve a better understanding of severe accidents based on plant specific simulation.

ATLAS may also be employed for human factor analyses. Operational experience showed that a large amount of events is caused by human errors and in 10% of the cases communication problems of the operators were the major cause. In order to understand the detailed communication behaviour in NPP operation, a simulator study in the frame work of the GIHRE-Project [13] was carried out. The experiments with students and operators were performed at the test control room of GRS and included eye tracking, video recording, behaviour observation and interviews of the participants. The task of the participants was to manage the simulated transient according to the operational procedures. In the study not only procedural tasks such as manual interactions with the user interface of the simulator, but also communicative tasks were assigned. Communicative problems such as delayed response or the disregard of messages were observed especially under heavy workload or in unexpected situations.

6. Development

The main focus of the further development of ATLAS is in the field of transient recognition and the increase of the simulation speed of the ATHLET code. Also analysis support will be enhanced by the integration informational module, a transient related picture library and the access to the plant documentation.

The diagnosis of transients employs the neural network approach ALADDIN developed at the Halden Reactor Project [14]. The basic idea is, that any transient class generates a unique set of dynamic responses of monitored plant variables. In ALADDIN a recurrent artificial neural net, that is able to deal with time dependent inputs, has to be set up and trained for the different fault classes. Special techniques, e.g. wavelet transformation of input and network decomposition, are applied in order to reduce the effort of this process with respect to the amount of required data and the necessary training time. First tests with a set of 5 different fault classes, which are very relevant for German PWRs, have showed up reasonable result. For each class only 2 training calculation were performed by ATHLET and the results fed into the neural net. The recognition capability of untrained transients of the same type was very high and quick, even in the case of additional faults in a transient.

Simulation speed is a key topic for uncertainty analyses and applications that require real time simulation. Both types suffer of high computing times of the best estimate codes for some types of calculations. In a first step a parallelization algorithm for the ATHLET codes is being implemented. The method is based on standard on the parallel standard OpenMP [15] for shared memory systems. The solution algorithm in ATHLET and the program structure enable this approach with minor program changes. The theoretical acceleration is about the factor 10, but initial tests showed some bad scalability with an increasing number of used processors. The second way under consideration is the parallelization of the main models in ATHLET, the thermo hydraulics, the control systems, the neutron kinetics and the fission products transport in the coolant circuit, by MPI [16] in a computer cluster with distributed memory.

The parallel execution of hundreds of parameterized simulations needed for the uncertainty analyses will scale almost ideally on a cluster as well and will be supported by the automated distribution of the runs and the collection of the results.

7. Conclusion

ATLAS is an engineering tool for nuclear power plant simulation and may enhance quality and efficiency of reactor safety studies. The most important German safety analysis codes for thermo hydraulics, neutron and containment simulation as well as integral codes for severe accidents are accessible by a common user interface in ATLAS. The safety studies are supported by the integration of uncertainty analyses, the simulation of operating procedures and tools for the identification of unknown boundary conditions (e.g. leaks). ATLAS is employed in many applications at GRS, research organisations, utilities and supervisory authorities in Europe. Opposite to training simulators real time simulation is not guaranteed for all transients. Current developments as transient recognition and model speedup aim at the use of ATLAS in emergency support.

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