1

Simulation and Simulators for Nuclear Power Generation

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1. Introduction

This chapter deals with simulation, a very powerful tool in designing, constructing and operating nuclear power generating facilities. There are very different types of power plants, and the examples mentioned in this chapter originate from experience with water cooled and water moderated thermal reactors, based on fission of uranium-235. Nevertheless, the methodological achievements in simulation mentioned below can definitely be used not only for this particular type of nuclear power generating reactor.

Simulation means: investigation of processes in the *time domain*. We can *calculate* the characteristics and properties of different systems, e.g. we can design a bridge over a river, but if we calculate how it would respond to a thunderstorm with high winds, its movement can or can not evolve after a certain time into destructive oscillation – this type of calculations are called *simulation*.

For simple systems we probably can reach an analytical solution to show that a given system is damped enough to stay stable without oscillation even in very different circumstances. Simulation steps in when the systems are too sophisticated to reach any analytical solution. Unfortunately, if we want to reach correct and accurate results we usually end up with very sophisticated and non-linear system description. This unavoidable leads us to simulation.

According to some authors, probably the last engineering achievement made completely without simulation was the Empire State Building. The Boeing 777 was mentioned as the first construction the design of which was completely unthinkable without simulation. (Janosy, 2003)

We need simulation if:

- The processes are too sophisticated and they have too many physical states just to think about everything
- It is too expensive and/or dangerous to build a prototype just for testing – or even if we have a prototype, we are very limited in testing and checking it under very different circumstances due to the costs and unavoidable dangers
- We want to check properties and compare different solutions under extreme conditions.

All these conditions are present in designing, constructing or operating a nuclear power generating system (Janosy, 2007 November).

The process of simulation can be accomplished with or without human interaction. Earlier the common way of doing it was to write a simulation program, to prepare input data sets, run the program on a powerful computer system and wait for the results. Most of the analyses of accident scenarios are being done this way even nowadays.

We already know for long time that we can save significant time and effort if we can *participate* in the process of simulation. We should watch the results from the very beginning, and we should have means to *interact* with the process, to change inputs and influence this way the sequence of the events. If our computer is capable to do that, then we have a *simulator*.

2. Modeling and simulation

It is easy to understand that no simulation can be done without prior modeling. Modeling nowadays means exceptionally *mathematical modeling*. We have to study the processes in question, and try to find the proper formalism to describe them correctly with mathematical expressions and tools.

Even nowadays, in the era of cheap and abundant computational power it is essential to differentiate between *dominant* and *unimportant* processes. Even if we can afford extremely fast computers, not eliminating the unimportant processes and modeling everything we can think of, leads to enormous problems during *verification* and *validation* of our models.

2.1 Types of mathematical models

Continuous processes can be described by set of differential equations. If only the time dependence is important, we construct a set of ODEs (Ordinary Differential Equations), where all derivatives are taken only by time. Sometimes these models are called as *'point models'* because they have no space dependence; they depend only upon the time. If all the derivatives can be described by separate functions, we get the following (rather simple) form:

$$\begin{aligned} \frac{dy_i}{dt} &= f_i(y_1, y_2, \ldots y_n, p_1, p_2, \ldots p_k, t); & i &= 1, \ldots n \\ z_j &= g_j(y_1, y_2, \ldots y_n, p_1, p_2, \ldots p_k, t); & j &= 1, \ldots l \end{aligned}$$

where y: the state variables; p: the input; z: the output variables

Sometimes these functions f and g cannot be separated so nicely and easily, sometimes we have to iterate, etc. Nevertheless, practically all numerical solution methods need to get the values of all derivatives explicitly.

If we have to take into account the space dependence as well, we get a set of PDEs, (Partial Differential Equations). Presuming again that we can define separate functions for each derivative, we get:

$$\begin{aligned} \frac{\partial y_i}{\partial x_j} &= f_{i,j}(y_1, y_2, \ldots y_n, x_1, x_2, \ldots x_k, p_1, p_2, \ldots p_m, t); & i &= 1, \ldots n, j = 1, \ldots k \\ \frac{\partial y_i}{\partial t} &= g_i(y_1, y_2, \ldots y_n, x_1, x_2, \ldots x_k, p_1, p_2, \ldots p_m, t); & i &= 1, \ldots n \\ z_j &= g_j(y_1, y_2, \ldots y_n, x_1, x_2, \ldots x_k, p_1, p_2, \ldots p_m, t); & j &= 1, \ldots l \end{aligned}$$

where y: the state variables; p: the input; z: the output variables; x: the space coordinates.

2.2 Discretisation in time and space

If we want to solve our equations numerically, we have to discretise them by time and space. Discretisation in time means that instead of the continuous solution for each state variable and each output we get time series, e.g. discrete values valid only at given time instances. The time difference between two consecutive time values is called as *'time step of integration'*. Instead of time derivative the differences of the consecutive values of the state variables are used, divided by the time step.

The same is true for space discretisation, frequently called as *nodalisation*. Instead of continuous functions we get discrete time series of state variables for each node, having finite volume and finite distance between them. (The same way, instead of the space derivatives this finite distance is used in the equations to divide the difference of the state variables in two neighboring nodes.)

The stability and accuracy of the numerical solution highly depends upon the time step of the integration and of the space distance of the nodalisation. It is quite obvious that the smaller is the time step, the smaller are the nodalisation distances and the sizes of the nodes, the better is the stability and accuracy of the solution. On the other hand, making the time step and the nodalisation grid smaller increases the number of the state variables and the necessary computer power.

Sometimes physical processes happening at the same time and space are divided and solved separately. Usually the neutron-physical processes of heat generation and thermo-hydraulic processes of the heat removal are solved by two separate programs. The first calculates the heat to be removed from the core of the reactor, the second the temperatures of coolant and fuel as result of the cooling process. The time step of the data exchange between these two simulation programs should be small enough not to generate remarkable errors as a consequence of this separation.

There are advanced mathematical methods to solve a system of differential equations. Remarkable computer resources can be spared using so called *multistep methods*, that means the next value of a variable is calculated not only using the previous one, but a sequence of previous values. Unfortunately these multistep methods cannot be used if discrete events happen between two acts of solution (e.g. rod drop or valve closure). These events are causing discontinuities in the high-order derivatives, which are usually not allowed if using multistep methods.

Logical functions and event sequences usually are not simulated by differential equations, but by separate programs dedicated to this purpose. Protections, interlocks and other similar functions of the process instrumentation are modeled this way.

2.3 Model verification and validation

After the modeling has been finished and before any simulation is started, we have to verify and validate our simulation system.

In our case *verification* means, that our model and the numerical solution system is working according our intentions. The model equations are correct and free from programming errors, and the same is true for the numerical solving programs. The solution is stable and accurate.

This can be verified using so called benchmark tests. These are well-known experimental results, measured on different experimental facilities. They are usually much smaller than a nuclear power generating unit, but specially tailored to demonstrate sophisticated physical phenomena which are not allowed to test on a real plant - e.g. pipe break causing the coolant to flow out. Usually we have a two-phase outflow (steam and water) coming with the speed of the sound.

Sometimes it is not necessary to develop sophisticated model programs with elaborated numerical solving schemas. For example, to simulate thermo-hydraulic processes inside the primary circuit of a pressurized water reactor (**PWR**) we can use the **RELAP** program (developed in the USA), the **ATHLET** code (developed in Germany) or the **CATHARE** code (developed in France). Several millions of dollars and hundreds of man-years have been spent to develop and validate them, against great many experiments.

Even using well-validated and certified codes we cannot omit the *validation* process. During validation we have to show that the input data made for these codes correctly describes the nuclear power generating unit in question. The nodalisation corresponds to the actual geometry of our plant and it is prepared according to the rules prescribed in the user manual to the given code. All masses, heat exchange surfaces, heat capacities, heat conductance etc. are calculated for each node correctly. Some simple transients which happens sometimes on the plant and are not regarded as accident (e.g. pump trips, turbine trips, network frequency control acts etc., usually called as AOO - anticipated operational occurrences) are calculated with the code and compared with the measurements in order to show, that the current and parameterized for the given plant model is *valid*.

3. Classification of simulators

The simulation of the desired process can go faster or slower than the real time, even both can happen during one act of simulation. The beginning of an accident or even a transient may require more computational power than the (asymptotic) end of it. If we do not care the relation between the simulated time and the real time too much, then we have an *engineering simulator*. The only thing what differs it from an off-line simulation program is the *interactivity* provided by the *man-machine interface* to the simulation code.

Sometimes it may happen that we want to test a *ready-made controller hardware* before putting it into operation on the real plant, or we want to teach people how different scenarios should be handled in the control room. In this case we should have a simulator which *always runs in real time*. (Controllers or people cannot tolerate a simulator running faster or slower than the real process.) This way we get a *development simulator* or *training simulator*.

The best way to teach people is to have a *replica control room* for interaction, and therefore a *replica simulator*. Only these simulators can provide the so called “hand-on” training, showing an environment very similar to that on the real nuclear power plant. Moreover, if the operations are not limited only to some panels in this control room but all switches, meters and annunciators of the real control room are handed correctly by the simulator, then we have the king of all simulators – the *full-scope replica training simulator*.

The simulation time step of the modern training simulators is around 0.1...0.2 seconds. For the processes shown in the control room practically we do not need smaller ones. Of course, there are some processes faster than that but usually they cannot be presented to the operators in the real control room, either. Several decades ago because of the slower computers the time step was chosen around 1 second, and this was not too bad, either.

However, the man-machine interface between the simulator and the operator is a different question. If an analogue meter moves only once per second it is very unrealistic and disturbing for the operator. The same is true for the actuator. Pushbuttons sensed only once per second are not very realistic but control actions performed in the control room are even worse. It is impossible to set a valve or control rod to an exact position if the time resolution of these inputs is only one second or even 0.2 second. It can happen that the new valve position is calculated only once per second but the time of action (how long a pushbutton has been pushed) must be measured and presented to the model programs with much greater accuracy.

Therefore the scanning frequency of the control room must be not slower than once per 50 msec or once per 100 msec. Analogue values shown on the meters should be interpolated with this frequency and each operation in the control room - pushing or releasing switches, etc. - should be accomplished with a time stamp of this resolution.

3.1 The absolute necessity of the training simulators

It is quite understandable, that we need simulator training if the device to be learned

- is very expensive to build and operate
- can lead to dangerous and even lethal consequences if operated erroneously.

Everybody understands easily that e.g. jet pilots should be trained on simulators. In case of nuclear power we have *two more reasons* to do so:

- Jet pilots are taking off and landing daily. Probably they can maintain their knowledge having this kind of practice. On the other hand, nuclear power plants are started and shut down for re-fueling normally once per year. During the whole year practically they are operating on the maximal possible power. The knowledge and the preparedness of the operators to deal with any situation may be kept on necessary level only with regular simulator training.
- Since the Chernobyl accident emerged from a not-properly-designed-and-executed experiment, it is practically impossible to get authorization to make experiments on an existing nuclear power plant. New ideas, new control and protection systems, new types of technological units are required to be tested thoroughly on development simulators. If they have man-machine interface consequences, then the required simulators should be replica – even better: full-scope replica simulators.

These considerations increase significantly the importance of simulators in the nuclear power generating industries.

3.2 Simulation in design and authorization

Nowadays it is more difficult to get the approval of the authorities for constructing a new nuclear power plant than to accomplish the construction itself. The design and the authorization are “handshaking” processes with many stages. Not going into detail, during these processes the so called *Safety Report* has to be worked out, too. Part of this report deals with different possible scenarios. Some definitions of basic importance:

The design basis accident is defined as follows:

A postulated accident that a nuclear facility must be designed and built to withstand without loss to the systems, structures, and components necessary to ensure public health and safety.

The beyond design basis accident is defined as follows:

This term is used as a technical way to discuss accident sequences that are possible but were not fully considered in the design process because they were judged to be too unlikely. (In that sense, they are considered beyond the scope of design basis accident that a nuclear facility must be designed and built to withstand.) As the regulatory process strives to be as thorough as possible, "beyond design-basis" accident sequences are analyzed to fully understand the capability of a design.

Naturally, all these accidents, transients and scenarios are evaluated and studied by means of simulation programs. These programs are being developed by few nations only (USA, Russia, Germany, and France) because the development and the verification is a rather expensive and lengthy process: not every country can afford it and on the other hand, it is not necessary to do so, too. These programs are usually developed for a given reactor type and can be used for a certain family of nuclear power plants. Usually there are no restrictions in participating in the development and in the usage of these simulation programs. It is done on the basis of bilateral agreements.

Practically there are three phases of the usage of these programs:

- *Development of the simulation package* itself, *verification and validation* using different benchmark test results
- *Model construction for the simulation package*, using design data of the nuclear power plant in question; *verification and validation* of the constructed models using data available from similar nuclear power plants
- Generating different *accident and transient scenarios for the safety report* using the “worst case” philosophy in handling of the uncertainties.

4. Simulators for training and development

It is common for these simulators that - dealing with people and real equipment under test

- they should be running *in real time*.

4.1 Model programs and data storage requirements

First it has to be defined, what are the basic requirements to the model programs and the data storage facilities of the training simulator.

The simulator programs are started together with the whole training simulator. During the initialization phase it is allowed to set up different data tables etc., even reading files. After initialization the programs of the mathematical models are waiting for the command of the main control program of the simulator, the *real-time executive*.

All state variables defining the current state of the model - and therefore the state of the simulated power plant - should be located in the *real-time data base* (see Fig. 1). This 'data base' is usually just a manageable piece of a shared memory. The exact (binary) copy of this piece of memory can be used as a fully defined snapshot of the state.

After getting the proper command from the real-time executable the model programs advance one time step and based on the previous state (the results of the previous step) they calculate the state of the plant in the next step. Meanwhile, the actions of the operators in the Control room are scanned by the man-machine interface (MMI programs) asynchronously with a much shorter time step. The actions are stored in the I/O data base and are used by the model programs.

If the time step is short enough (e.g. 0.2 sec or less) then the model programs can use only one copy of the state variables. Before the actual step it contains data belonging to the last step. During the execution of the model programs the state variables are calculated for the next step one by one, and after the execution they all belong to the next step. Frankly speaking, it is not exactly correct that some model programs should use data form the previous and the next step simultaneously, but if the time step is small enough - and it is - then this fact cannot cause big errors.

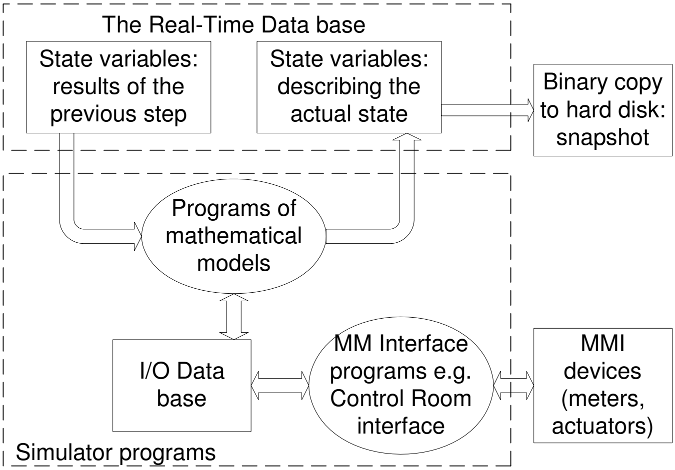

Fig. 1. Simulator programs and data storage

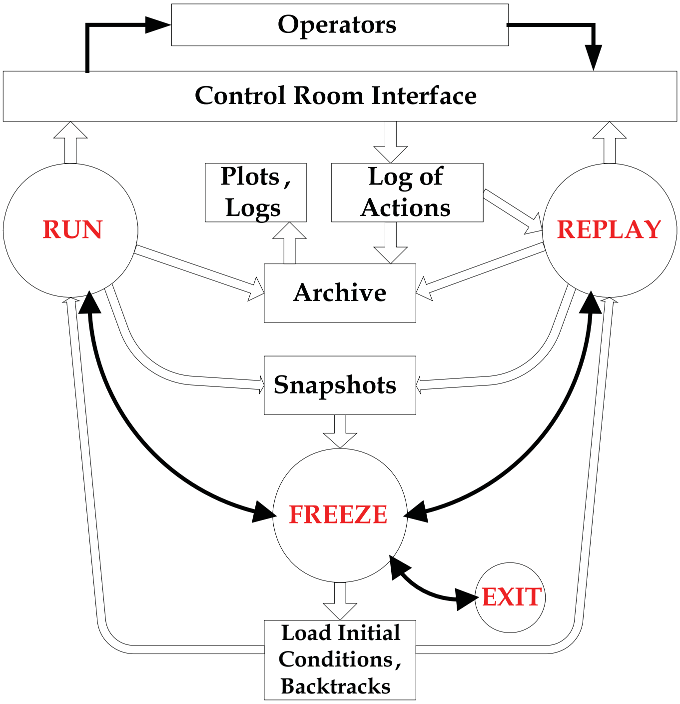

Fig. 2. States of the training simulator

If we decide to use this approach - having only one copy of state variables in the memory; it is quite common in simulators - then we have to consider not to allow access to these state variables until the actual act of integration is not finished. Accessing the state variables any time means that other programs may fetch values not belonging to the same time instance. For analogue values it is not a big problem, but solving logical circuitry it can lead to confusion and incorrectness.

The different states of the simulator are presented on Fig. 2. Black arrows are state transitions, white arrows symbolize data flow.

After starting up the simulator and all related programs (from the **EXIT** state) we reach the **FREEZE** state. All programs are able to run, but practically neither of them is actually running.

During the **FREEZE** state we are able to initialize the simulator, either loading in a saved *Initial Condition*, or a previously saved *snapshot* (loading it is often called *backtracking*).

Adjusting switches in the Control room to the actual loaded state may become necessary; it is done using the Control room set-up report made by the CR I/O system.

From the **FREEZE** state we can move to the **RUN** state.

The model programs calculate cyclically the actual state every time step and all the analogue meters and annunciators of the Control room are driven accordingly. All the operations of the staff are scanned in and stored in the Log of actions, and are added to the Archive, together with the history of the most important parameters - there are several hundreds of them. After the simulation session is finished, different logs and plots can be generated for evaluation of the trainees.

During the simulation snapshots are taken regularly, or at any instant if the Instructor of the actual simulation session commands to do so. Any time the instructor can stop the simulation and return to the **FREEZE** state. During **FREEZE** state the parameters are displayed in the Control room, and the situation can be analyzed. No operations can be performed, though.

From the **FREEZE** state we can re-play how the operations happened earlier in the control room. Backtracking using a snapshot, made earlier, we can enter the **REPLAY** state. During the **REPLAY** state all the simulation is performed and the control room is driven as during the **RUN** state, with the exception that no actions are accepted from the operators. All operations are taken from the Log of actions, with their time stamps together, therefore the trainees are able to follow what and how it happened earlier in the Control room.

Any time the **REPLAY** can be stopped, the state turns to the **FREEZE** state, and real operations can commence entering the **RUN** state again. This is a very useful ability for the Instructor, to go back in time, to show when and how a mistake was done, what are the consequences and how it should be continued in a correct way.

4.2 Architecture of the simulators

Practically the full-scope replica simulator consists of the following parts:

- Computer system of the simulator. It incorporates the model programs, the simulation control programs, the loggers, plotters, the archive etc. necessary to conduct a simulation session.
- Control room and interface devices - a replica of the real control room equipped with all meters, switches, pushbuttons, screens, memo-schema etc. and the hardware/software devices (the MMI, the man-machine interface) enabling the computer system of the simulator to handle them quickly and correctly.

- Instrumentation and control devices taken from the real power plant. It is very advantageous if we can take over the plant computer system, the core surveillance system and other systems directly from the plant.
- The Instructor's system, the basic tool of the Instructors to control the simulation session. The Instructor's system is usually hidden from the trainees, but sometimes, when the Instructor is present in the Control room, he/she can use a remote control unit to activate different pre-programmed events.

It is obvious that it is much better to use the real plant computer, the real core surveillance system instead of simulating them. The operators feel the real controls; the real functions of these units can be studied. The problem lies in the simulator functions to which these real instruments are poorly suited. No real plant computer etc. is prepared to the stopped and standing time, or even worse: to the backtracking, going back in time. It is difficult to accommodate the real equipment to the new initial condition loaded into the simulator (e.g. nominal state immediately after the cold shutdown state). It is obvious that all functions somehow connected to the time (logging, making archives, and plotting) should be excluded if possible. If they cannot be excluded: we have to refuse to integrate the real units, we have to model their functions.

That is the main reason that all time-related functions are incorporated to the Instructor's system: logging, plotting, making archives etc. etc. On the other hand, all simulator-specific functions are evaluated in the simulator.

Fig. 3. The replica control room of the Paks NPPs training simulator

The most important function is the pre-programming of the malfunctions. All valves can leak, all pipes can break, all pumps can be tripped, and there are very many equipmentspecific malfunctions. They can be activated promptly, or at a given time instance, and/or when a logical function becomes 'true' (e.g. IF the temperature is higher than ... AND the flow is less than ... etc.)

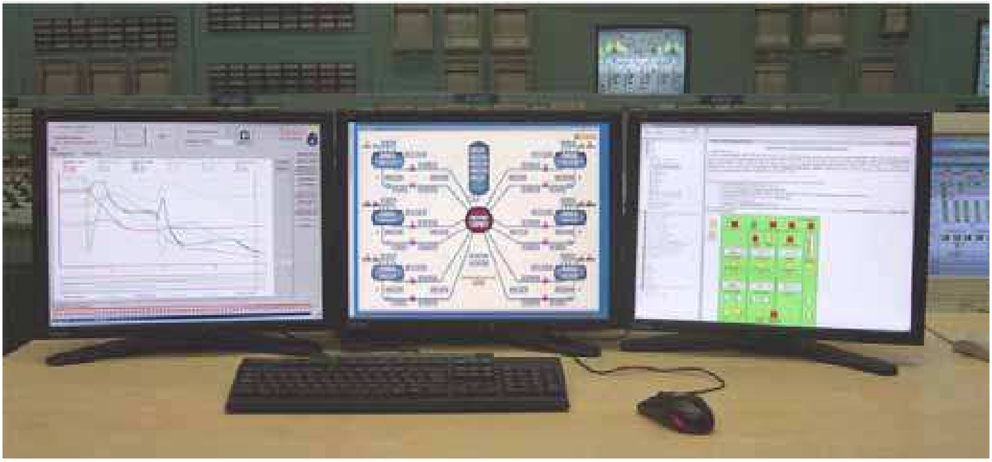

Fig. 4. The instructor's workstation of the Paks NPPs training simulator

4.3 Protection system refurbishment using simulator

The existing nuclear power plants were licensed earlier usually for 30 years; most of these licenses expire in the next decade. Nowadays it is a common practice to prolong the operation of the NPPs up to 50-60 years.

After the Chernobyl accident in 1986 requirements to the safety of nuclear power generation units has been changed dramatically. As a result, many enhancements have been introduced not only to the Instrumentation & Control (I&C) and Protections circuitry but to the technological systems as well. Practically all these changes have been introduced on the simulators first, in order to show the results of the forthcoming changes.

Even without that the “moral” and practical lifetime of the I&C systems is much less than 50-60 years, let say only 8-10 years. If they contain computers (and nowadays they do) this becomes even shorter, about 5-7 years. The “aging” IT systems cannot be kept running for a longer time. Spare parts and even software drivers become obsolete.

Replacing protection and control systems is relatively easy if the functionality remains the same. Fig. 5. shows how it can be done.

First, while the old system is still in charge, the new system is placed parallel to it. Both controllers (or others, as protections, interlocks) get the same inputs. The new controller should be tuned until the response becomes the same in rather different situations, too. Then the old controller can be replaced. This method cannot be used when it is dangerous or just it is not allowed to test the equipment in extreme conditions. It is a rather new practice to use *simulators* for I&C or other system’s refurbishments (Janosy, 2007 March). First the simulators are used during the design of the new systems (Janosy, 2008). Integrating software models of the newly designed models into the simulator in an interchangeable way the proposed functionalities can be tested in normal, accidental and even extreme circumstances (software-in-the-loop tests). After approval of the demonstrated functions

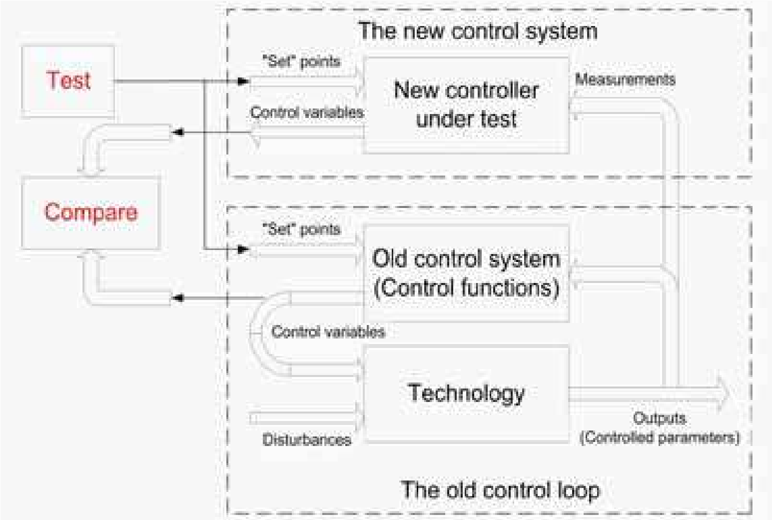

Fig. 5. Old and new controllers tested in parallel

and performance, the manufacturing of the new hardware can be authorized. The new hardware should be attached to the simulator, too, and the functionalities and the performance can be compared with its already existing software model (hardware-in-the-loop tests).

As it was mentioned before, it is not very easy to integrate real I&C hardware to the simulator because of the special simulator functions of **FREEZE**, **BACKTRACK**, **REPLAY**. This procedure had to be organized as it can be seen on Fig. 6.

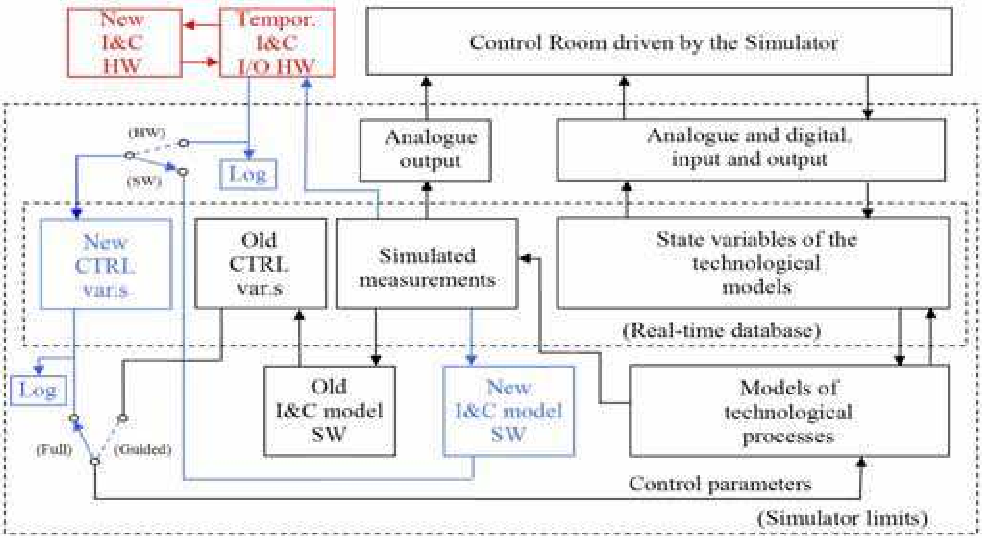

Fig. 6. Instrumentation and control system (I&C) is tested on the training simulator

The black color indicates the original functions of the simulator. The technological models advance in time using their state variables. The value of the measurements are calculated and the old I&C models calculate the control parameters (e.g. control valve and rod positions) governing the technological models. The development of the new system is made in four consecutive steps.

1. The new controllers' mathematical models are constructed and their simulation models are placed parallel with the old one (blue boxes). On the basis of the same measurements the new model calculates the control parameters. In this phase the (software) switch is placed to the (Guided) position, that means that the control actions of the new controller are only logged, the old controller model is in charge.
2. If everything looks perfect, the switch is thrown into (Full) position, and the *'software in the loop'* mode is achieved.
3. After thorough testing the new controller is manufactured and using some temporary I/O hardware interface (red boxes) it is connected to the simulator. (Spare parts of the Control room I/O can be used). The new hardware is driven by the measurements, too, but the new software governs the simulator - (SW) and (Full) position of the switches.
4. If according to the logged response of the hardware is OK, the upper switch can be thrown to (HW) position. This is the *'hardware in the loop'* mode of operation.

Thanks to the simulator, the new I&C equipment can be tested under extreme conditions, too, without the slightest economic and environmental risks.

Practically everything can be tested before the plant stops. During the refueling - which usually takes more than 20 but less than 30 days - the new equipment can be integrated to the real unit and in the same time the idling operators can study the behavior of the new I&C on the simulator in 'software in the loop' mode.

5. Nodalisation problems of the reactor models

The most important and difficult part of the simulation programs and the simulators is the reactor model. Fuel elements, integrated into fuel assemblies produce heat in the nuclear reactors in rather difficult, harsh conditions. The pressure and temperature is high - up to 160 bar and 320°C - and the power density in some reactors reaches 90 kW/liter and above. They are made from expensive metals using expensive technologies. They should not leak - the cladding represents the first barrier between the radio-active materials and the environment (usually there are at least three barriers). If there is a remarkable leak, the reactor should be stopped and the leaking fuel assembly replaced - a procedure causing significant economic loss.

Nevertheless, some fuel assemblies are well made and they practically never leak. During the 20-year-history of the four-unit Paks NPP there was detectable leak only once or twice. The fuel elements originally spent three years in the core, nowadays they stay for four years - with slightly higher uranium content, of course. If they should stay for five years, the increasing of the enrichment is not enough - the control system of the reactor is not designed to cover the excessive reactivity of the core, produced by the higher enrichment of the fresh fuel.

The solution is the Gadolinium (Gd) which is a burnable neutron poison. In the first year - or so - it helps to cover the excessive reactivity by absorption of neutrons, then it burns out and do not causes any problem in the upcoming years. Now we replace at the Paks NPP every year 1/4th of the fuel elements with fresh ones. If we start to replace them with the new types, supposed to stay for five years, it means that we are going to use mixed cores at least for four years. These cores need special treatment and the operators should be trained to it. The core surveillance system must be fitted to these mixed cores, too. To train the operators to their more sophisticated duties we had to replace the reactor model and the model of the primary circuit with more elaborated 3D spatial models.

We have 349 fuel assemblies in the core; each of them can be of different age and different composition. The core configuration is carefully optimized each year to ensure that the power distribution and burn-out corresponds to the maximal safety and to the best fuel economy. Careful design of the reactor loads results in negative temperature and volumetric coefficients that means that the reactor is capable to self-regulate its power - because making the coolant hotter and thinner means worse neutron balance and therefore it decreases nuclear power.

These effects make the neutron kinetic model of the reactor and the thermo-hydraulic model of the primary cooling circuit tightly coupled; therefore they mathematical models must be solved simultaneously. Describing very different physical phenomena we get very different equations - that leads to severe problems of the simultaneous numerical solution. (Hazi, Kereszturi et al., 2002)

The crucial point is: how to nodalise the nuclear reactor and the primary circuit in order to achieve high fidelity of simulation with reasonable computer loads - in other words achieving accurate simulation and still remaining in real-time. It looks easy to divide the equipment to very small parts, and solve the problem using them as coupled nodes. Decreasing the size of the individual nodes not only increases their number according to the third power, but in the same time it significantly decreases the necessary time step of the numerical integration.

5.1 Nodalisation problems: Neutronics

As it is shown on Fig. 7, we have in the core 349 hexagonal fuel assemblies (the numbers outside the core refer to the six cooling loops). The 37 numbered fuel assemblies are used to control the chain reaction. They are twice as long as a normal fuel assembly. The upper part is made from special steel designed do absorb the proper amount of neutrons in order to be able to control the chain reaction. The lower part is a usual fuel assembly containing usual amount of fuel. Pulling out this control assembly means that the lower part enters the core, lowering it causes this part to leave and to be replaced by the neutron absorber assembly.

The 37 control assemblies are organized into 6 groups, containing 6 assemblies except the 6th one, which contains 7 (this 7th is the central one). The first five groups with 30 assemblies are used as the "safety rods", fully pulled out during normal operation and fully lowered during reactor shut-down. The 6th group is normally used as "control rods", during normal operation they are always in different intermediate positions according to the prescribed power of the reactor. In some very rare situations the 5th group is helping to the 6th one, sometimes staying in intermediate position, too.

That evidently means that the first four groups do not influence the spatial distribution of the neutrons, their absorbents are pulled out and their fuel assemblies are inserted. Lowering them the reactor is shut down and the spatial distribution is not interesting any more. In the same time, the last two groups - the 5th and the 6th - can seriously influence the 3D distribution of the neutrons, being in different intermediate positions according to the different operating conditions of the reactor and the primary circuit.

The nodalisation of the core from the neutron kinetics point of view does not leave us too much freedom: each "neighbor" to each assembly can be of different "age" in the reactor (zero to four, later zero to five years), with or without Gadolinium content accordingly. Different "age" means different burn up, thus different stage of enrichment and different isotope content. That means that in horizontal plane each assembly should be a separate node.
As to the vertical nodalisation, we must have not less than 8 or 10 planes to get enough resolution (8 to 10 points) to describe the axial neutron (and heat) distribution. We have chosen 10 planes vertically - that means, we have finally 349 x 10 nodes for the KIKO3D model (Kereszturi et al., 2003).
Real-time spatial (3D) simulation of 3490 nodes in several groups of neutrons according to their actual energy requires huge computer power. The only way to do it using several processors; it means to separate the time and space problem. The result can be written as a product of two functions: the amplitude function of time and the distribution function of space. Solving the equations in different processors means that these programs have access to the data of the other only after finishing the actual time step, and this means that delays are introduced.

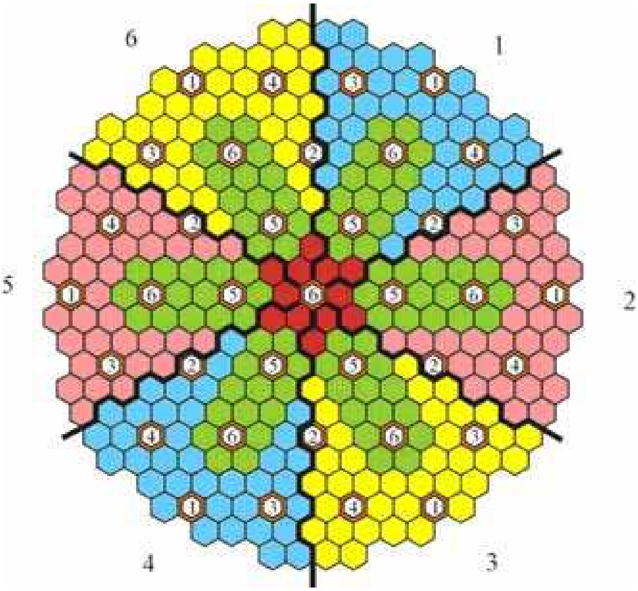

Fig. 7. The map of the core with the 349 fuel assemblies, including the 37 control ones

5.2 Nodalisation problems: Thermo-hydraulics

Thermo-hydraulic nodes should be much larger in space than the neutron-kinetic nodes. It is connected with the 0.2 sec. time step of the full scope replica simulator of the power plant. If we want to avoid large number of iterations, the amount of the steam/water leaving/entering the node each time step must be probably less than the full amount of the steam/water inside the node. It means that if we multiply the maximal feasible volumetric flow-rates with the 0.2 sec. integration time step, we get the minimal volumes for the nodes in question.

Fig. 7. shows the thermo-hydraulic nodalisation of the reactor as well. According to the reasons explained above, we have much less thermo-hydraulic nodes radially in the core, and the number of the axial layers is only half that of the number of neutronic nodes: we are limited here to only five layers. The reactor core is divided radially to only six outer, six inner and one central node: altogether 13 nodes.

Each of the outer six nodes marked with different colors consists of 40 fuel assemblies. The inner six nodes - all are marked as green - contain 16 fuel assemblies each but one of them belongs to the 5th control rod group, one of the to the 6th control rod group. The 13th, the innermost small node contains 13 fuel assemblies, one of them - the central - contains the 7th rod of the 6th group.

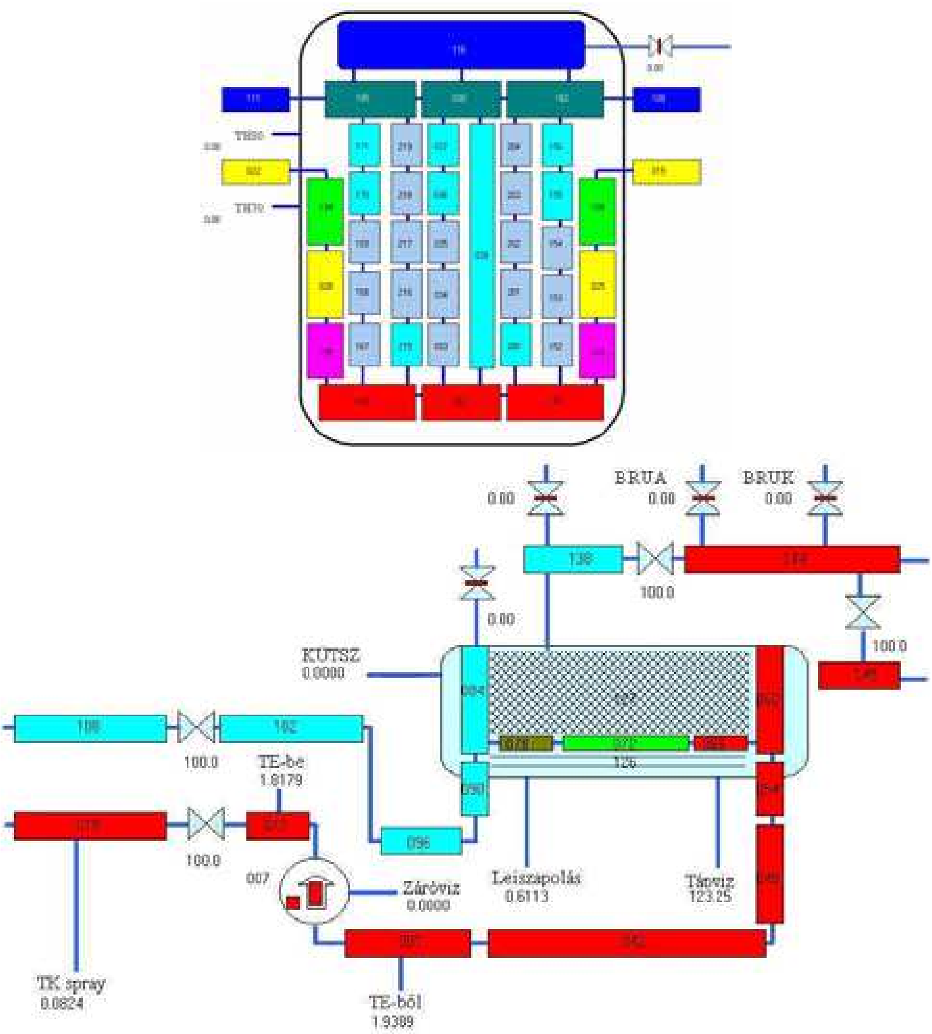

Fig. 8. Debugging tool for the core nodalisation and for the six cooling loops

This kind of thermo-hydraulic nodalisation provides the following benefits:

- During operation on power, only control rods of the 5th and 6th control rod group may have intermediate positions, influencing the spatial distribution of the neutrons. The inner 6 nodes and the central node are responsible for the calculation of these effects.
- One or more cooling loops may fail, usually because of the tripped main circulating pumps (MCPs). The six outer large nodes can respond spatially to these effects.

The thermo-hydraulic model has to deal not only with the reactor vessel but the six cooling loops of the primary circuit.

The original instrumentation of the nuclear power plant can not show the power, the pressure, the temperature and the steam content of the water in each simulation node of our simulator. It is not necessary to measure these parameters in such detail for the operation of the plant. It means that the full-scope replica simulator has no tools to follow the actual values in these nodes. For development and debugging we had to develop special debugging tools (programs) to display these data on different windows on the screen in order to follow the performance of our model programs closely (see Fig. 8).

Thanks to the nodalisation scheme described above, different spatial effects in the core can be studied. As an example, the "rod drop" malfunction is presented.

If a control rod erroneously drops into the core, the negative reactivity caused by it can be compensated by the power controller, pulling all the other rods a little out from the core. However, the power locally will be less around the fallen neutron absorber.

All well-designed reactors are self-regulating, that means overheating causes negative reactivity thus decreases the heat power, and overcooling does the opposite - it leads to positive reactivity and the power increases a little. This effect compensates the locally introduced (by the fallen rod) negative reactivity, and that's why the distortion of the power field - and the resulting temperature field - is not so strong than it could have been expected, not taking into account the temperature effects and the resulting self-regulating features.

However, the resulting asymmetry of the temperature field is remarkable, as it can be seen on Fig. 9.

5.3 Reactor thermo-hydraulics

Normally the primary circuit of a pressurized water reactor is filled up with water and there is no boiling. Nevertheless, we have the pressurizer with the steam cushion, the secondary parts of the steam generators with boiling, the steam headers, therefore we have to construct a two-phase-flow (steam, water) model anyway.

Moreover, in case of LOCA (Loss of Coolant Accident) if the water flows out through the break of some pipelines, the emergency core cooling circuits step in, pump water into the primary circuit and the reactor vessel in order to keep the core covered with water and cooled. Air and other non-condensable gases may enter the primary circuit. During the startup of the plant the initial pressure is reached by nitrogen cushion in the pressurizer. Because these states the simulation model should handle not only water and steam, but non-condensable gases (third component.)

The best tool to simulate these states is the so called "6 equation" model - energy, mass and momentum balance equations for steam and water separately, but with enabled state changes (boiling, condensation). (The non-condensable gases usually are added to the steam phase but state changes are disabled for them).

Solving 6-equation models in real time is an exceptionally demanding task, requiring very powerful computers. Things are getting much simpler using 5 equation models (common

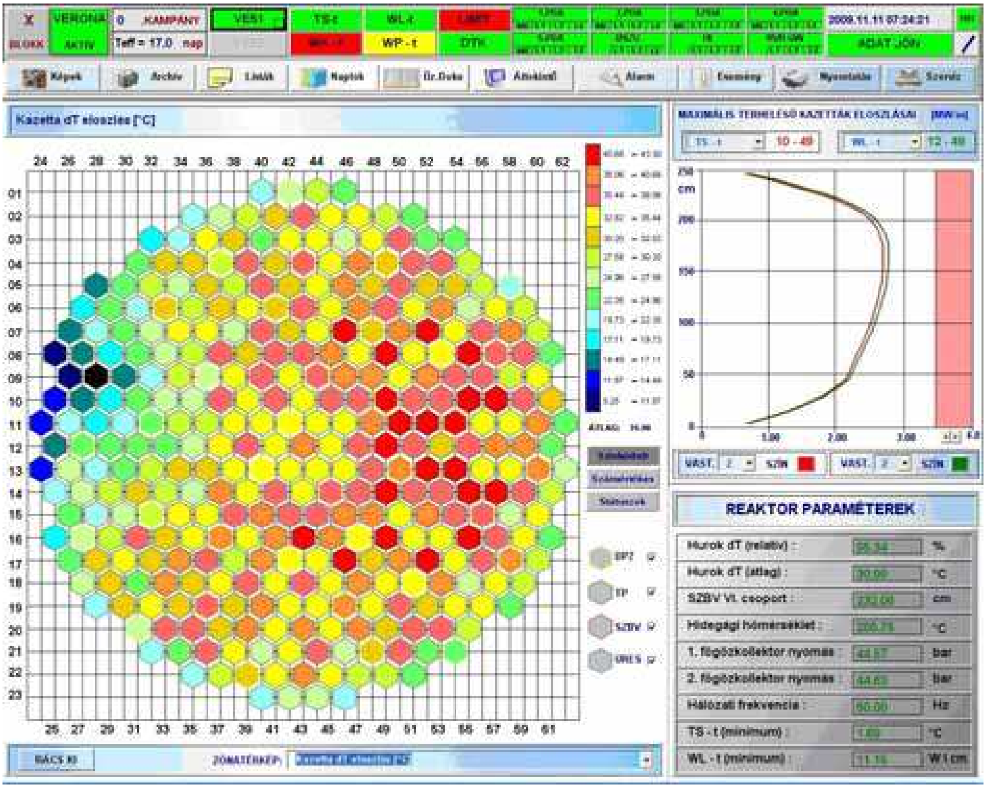

Fig. 9. Picture of the in-core surveillance system VERONA - driven by "rod drop" state data from the simulator

equation for the momentum of steam and water) but in this case the water and steam velocity should be the same - these models are accurate only in case of low steam content (emulsion flow). Higher steam content or stagnant flow causes phase separation and different speeds. The commonly used solution is the so called "5½-equation" model - one momentum equation but so called "drift flux model" which allows different speeds for water and steam but handles them with algebraic approximations. The RETINA code (Reactor Thermo-Hydraulics Interactive) can solve both the 6 and the 5½ equation systems (Hazi et al, 2001)

The most demanding task during the tuning and V&V of the simulator is to tailor these drift-flux correlations to behave correctly in very different circumstances - stagnant, layered coolant in the pressurizer vessel, isolated loop, etc

We have very different situations - normal operating and transients, stopping, cooling down, heating up, reaching criticality of the reactor, loading up, and separating loops with main gate valves (a rare feature possible only for Soviet/Russian reactors). There real art during the V&V of the models lies in handling and tuning of the drift flux correlations (nodes above each other, separating, nodes horizontally following each others, pipes and stagnant coolants in vessels, etc.)

As non-condensable gases are carried with steam, boron acid solvent (used to absorb neutrons) and radio-nuclides carried with water (in case of leakage) are simulated, too, but this task is much simpler than the correct simulation of the two-phase-flow. (However, "aging", decaying radio-nuclides continuously are changing the concentration of different isotopes and this has to be taken into account, too.)

The simulation of the normal operating modes of the power plant are the less demanding for the stability of the numerical integration of the models, and in the same time we have ample data and recordings to fit the parameters of our models. On the other hand, the training of the operators to anticipated (but rarely happening) transients and accidents is the most important and valuable, but these are difficult physical states with no data (so far, so good) to verify and validate the simulation.

The scope of simulation - by definition of the full-scope, replica simulators - covers anything that can happen to the filled-up primary circuit with the closed reactor vessel. (Up to now we do not simulate open reactor vessel with interrupted circulation, as it is usual during the refueling outage.)

Covering only the events happening to the hermetically closed primary circuit (with pipe breaks and loss of coolant accident of course) that means:

- normal operation with normal transients (load changes, frequency regulation)
- bringing to power (heating up, reaching criticality with the reactor, producing steam, speeding and heating up the turbines, reaching the nominal power
- stopping the reactor, cooling down, changing to natural circulation without the pumps, etc.
- malfunctions of any kind, pump trips, valve jams, valve leaks, short circuits, failures of electrical supplies, island mode of operation (separation from the electrical grid)
- accidents up to the design basis accident, which means a large-break LOCA - breaking of the pipe of the pipeline of the main cooling loop.

According to the integration of the models described above, all these transients can be studied in "4D" in the reactor - that means in time and space, too.

6. Conclusions

Simulation is not a profession: it is a way of life - I was told on my first international conference I participated - 'Simulation 1977' in Montreaux, Swiss. I can add to that after 34 years: *it is a way of thinking*, too. The first Reference shows the first book I had to study after I started with simulation in 1970 (Ralston, 1965).

My greatest mentor, Assoc. Prof. Dr. Richard Zobel retired, and went out to his garden with a pint of beer. The next day he started to model and simulate the sounds produced by the small plashing waterfall in the corner of his garden, with great success, resulting in excellent papers. After being invited later as Assoc. Professor in the Prince of Songkla University, Hat Yai and Phuket Campuses, Thailand, where he survived the big tsunami in the Indian Ocean on 2004, he became one of the leading experts in tsunami simulation. Dr. Zobel is going definitely to model and simulate things up to the last minute of his life.

At the beginning the simulation was very different from the simulation we are making today. We had no powerful digital computers available that time or they were used for different purposes secretly - ordinary scientists had no access to them. We used sometimes analogue computers with integrators made from operational amplifiers. Sometimes they were not electrical, but pneumatic 'operational amplifiers'. Modeling meant not always mathematical modeling - we had to use e.g. electrical analogy, representing long pipelines by inductance, vessels and tanks by electrical capacity; pressure meant voltage and flow was represented by electrical current.

Numerical analysis was very different when the maximal calculating capacity was represented by desktop calculators, first mechanical and after a while electrical. Methods of Runge-Kutta, Fowler-Warten, Hindmarsch-Gear were studied and used widely, together with the flourishing predictor-corrector multistep methods. Everybody had his/her favorite numerical integrating algorithm and praised it to the others.

Nevertheless, even that time and ever since simulation is a *great way of learning*: Observing a natural phenomenon we gain an imagination how it works and try to build a model selecting the most dominant processes of it. Using powerful computers in a proper way we can learn whether our imagination was good or wrong, or just not enough: something is still missing. Finally, if the results of simulation are really very close, very similar to the real behavior of the studied phenomenon, we get the unforgettable feeling: we are able to understand and describe what Mother Nature had been doing and how!

Back to the nuclear industry, it is obvious that power generating nuclear power plants cannot be used as test facilities to check out different new ideas. (Some people do not like even the doctors "practicing" - they should not *practice*, they should *already know* what they are doing before treating a patient.) As matter of fact, simulation is taking all over - working on models is much safer and much cheaper than doing anything else.

The practice of modeling nuclear power plants show that the up-to-date and state-of-art modeling techniques are fully adequate to support all tasks of design, licensing, construction and operation of nuclear power generating plants or other nuclear facilities. Even the cause and the circumstances of different accidents can be determined the best and easiest way by simulation studies.

Simulation is widely used by students of the universities, by design institutes and companies, by the authorities, by research institutes, during the construction and start-up of new nuclear power plants, designing re-fueling, and keeping up the knowledge of experienced operators and for teaching the new ones. Normally, new plants already have the simulator before the real construction is going to be started. (They should be always slightly modified and adjusted to the local circumstances, anyhow. There are no units being exactly identical to each other.)

We are operating and continuously developing the Paks NPP's full-scope replica simulator already 23 years. We have been able to replace the Reactor Protection System, to develop different enhancements to the technology of the NPP and study spatial behavior of very different mixed cores using this simulator successfully. Originally the simulator was called as the '5th unit', because all changes of the four energy generating units had to be performed later to the model system of the simulator, too. Now the simulator became the '1st unit', because any enhancement, development or change has to be demonstrated on the simulator first before getting the approval to do so on the real units, too.

The simulator is busy working in two shifts to teach and keep up the knowledge of the operating personnel of the NPP. It is very difficult to obtain simulator time for other purposes. The most expensive part of the training simulator is the Control room and the corresponding real-time I/O interface to it. Replacing the Control room with a couple of high resolution touch-screens we will be able to reproduce it in several copies, that way to make it affordable for different studies and planned refurbishments, and for teaching students and non-operative personnel, too. Having multiple copies definitely increases the quality of service and support to the operation of our nuclear power plant, producing close to 40% of electricity of our country.

7. Acknowledgment

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8. References

Anthony Ralston: A First Course in Numerical Analysis. Published by McGraw Hill Inc., 1965. Hungarian translation: Műszaki Könyvkiadó, 1969.

Gábor Házi, Gusztáv Mayer, István Farkas, Péter Makovi and A. A. El-Kafas: "Simulation of a small loss of coolant accident by using RETINA V1.0D code", *Annals of Nuclear Energy*, Volume 28, Issue 16, November 2001, Pages 1583-1594

István Farkas, Gábor Házi, Gusztáv Mayer, András Keresztúri, György Hegyi and István Panka, "First experience with a six-loop nodalisation of a VVER-440 using a new coupled neutronic-thermohydraulics system KIKO3D-RETINA V1.1D" *Annals of Nuclear Energy*, Volume 29, Issue 18, December 2002, Pages 2235-2242

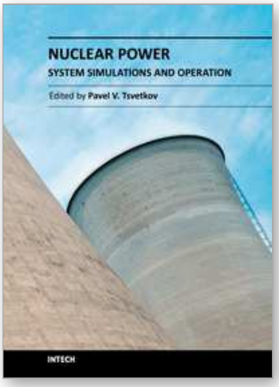
Janos Sebestyen Janosy: Modeling and Simulation of Nuclear Energy in Eastern Europe. *Business and Industry Simulation Symposium, 2003 Advanced Simulation Technologies Conference*, Orlando, Florida, March 30 - April 03, 2003, ISBN 1 56555 263 6

A. Keresztúri, Gy. Hegyi, Cs. Maráczy, I. Panka, M. Telbisz, I. Trosztel and Cs. Hegedűs, Development and validation of the three-dimensional dynamic code - KIKO3D, *Annals of Nuclear Energy* Volume 30 (2003) pp. 93-120.

Janos Sebestyen Janosy: Simulation Aided Instrumentation and Control System Refurbishment at Paks Nuclear Power Plant. *First Asian International Conference on Modeling and Simulation,* AMS 2007, 27-30 March 2007, Phuket, Thailand, ISBN 0 7695 2845 7

Janos Sebestyen Janosy: Simulators and Simulation used in Nuclear Power Plant Related Projects. Keynote speech, *CUTSE 2007 Curtin University of Sarawak Engineering Conference*, 26-27 November, 2007, Miri, Sarawak, Malaysia.

Janos Sebestyen Janosy: Simulators are the key for large-scale Instrumentation and Control System Refurbishment Projects. *Keynote speech, Second Asian International Conference on Modeling and Simulation,* AMS 2008, May 12-15, 2008, Kuala Lumpur, Malaysia.



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At the onset of the 21st century, we are searching for reliable and sustainable energy sources that have a potential to support growing economies developing at accelerated growth rates, technology advances improving quality of life and becoming available to larger and larger populations. The quest for robust sustainable energy supplies meeting the above constraints leads us to the nuclear power technology. Todayâ€™s nuclear reactors are safe and highly efficient energy systems that offer electricity and a multitude of co-generation energy products ranging from potable water to heat for industrial applications. Catastrophic earthquake and tsunami events in Japan resulted in the nuclear accident that forced us to rethink our approach to nuclear safety, requirements and facilitated growing interests in designs, which can withstand natural disasters and avoid catastrophic consequences. This book is one in a series of books on nuclear power published by InTech. It consists of ten chapters on system simulations and operational aspects. Our book does not aim at a complete coverage or a broad range. Instead, the included chapters shine light at existing challenges, solutions and approaches. Authors hope to share ideas and findings so that new ideas and directions can potentially be developed focusing on operational characteristics of nuclear power plants. The consistent thread throughout all chapters is the â€œsystem-thinkingâ€ approach synthesizing provided information and ideas. The book targets everyone with interests in system simulations and nuclear power operational aspects as its potential readership groups - students, researchers and practitioners.

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