INVESTIGATING SPATIAL POWER EFFECTS USING 3D REAL-TIME MODEL

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ABSTRACT
Fuel assemblies were used in our nuclear power plant initially for 3 years, now for 4 years and soon they will stay in the core for 5 years. Each year only 1/3rd, 1/4th later 1/5th of them is replaced; therefore the change of the fuel type is a lengthy process, with mixed cores used in between. The full-scope simulator is upgraded to simulate the exact behavior of these mixed cores. The RETINA is a 3D thermo-hydraulic code (Hazi, 2001), the KIKO3D is a 3D neutron-kinetics code (Kereszturi, 2003), are operating parallel in real-time. Models were presented on WAMS2010 workshop in Buzios, Brasil (Janosy, 2010).

Verification and validation of these models are extremely difficult because the lack of experimental data. Since the Chernobyl accident no experiments with nuclear power are encouraged. The paper describes the experience gained during the V&V process – driving these coupled 3D models up to extreme conditions.

Keywords: NPP simulation, parallel processing, real-time simulation, Coupled 3D thermo-hydraulics and neutron kinetics.

INTRODUCTION

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 bars and 320°C - and the power density in some reactors reaches 90 kW/liter and more. 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, most of the 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 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.

THE 3D MODEL RQUIREMENTS

Earlier we could use simpler models with great success (Janosy, 2003, 2007 and 2008). Now we have 349 very different 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.

The water flowing through the core of PWRs acts not only as coolant but as moderator, too - that means if fulfills the task of slowing the neutrons down in order to optimize the neutron balance and making the chain reaction stable and possible. Careful design of the reactors 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 must be solved simultaneously. Describing very different physical phenomena they contain very different equations - that causes the problems of the simultaneous numerical solution. The required time step for the accurate numerical integration can be very different, too.

The crucial point is: how to nodalize 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 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.

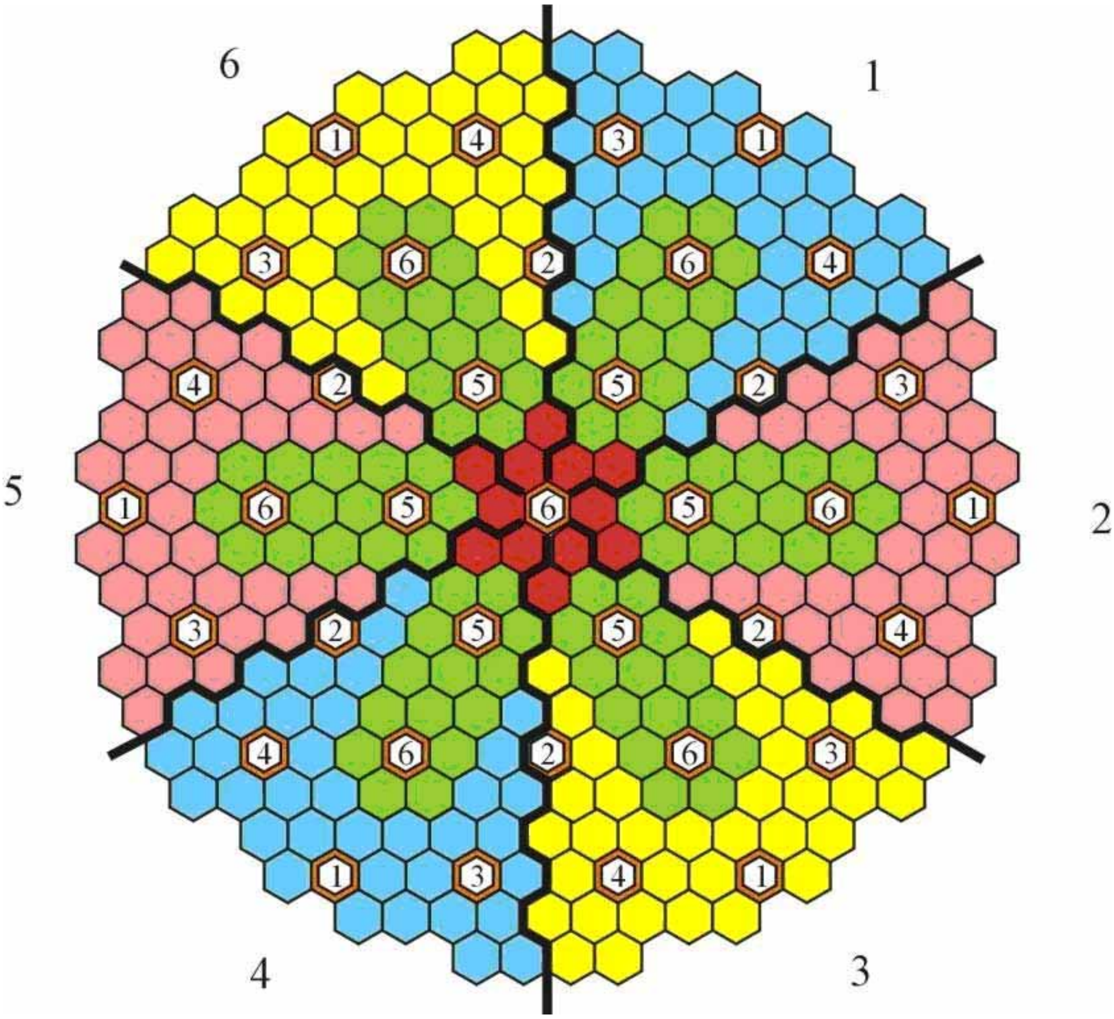


Fig 1. The map of the core with the 349 fuel assemblies, including the 37 control ones.

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.

NODALIZATION: NEUTRONICS

As it is shown on Pic. 1, 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, they absorbents are pulled out and their fuel assemblies are inserted. Lowering them the reactor is shut down and the spatial distribution is not important 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 nodalization 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 particular assembly should be a separate node – we are going to have as much as 349 nodes horizontally.

As to the vertical nodalization, 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.

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 finite number of processors means to separate the time and space problem. The result can be written as a product **of two functions:** the amplitude ***function of tim***e and the distribution ***function of space***.

NODALIZATION: THERMOHYDRAULICS

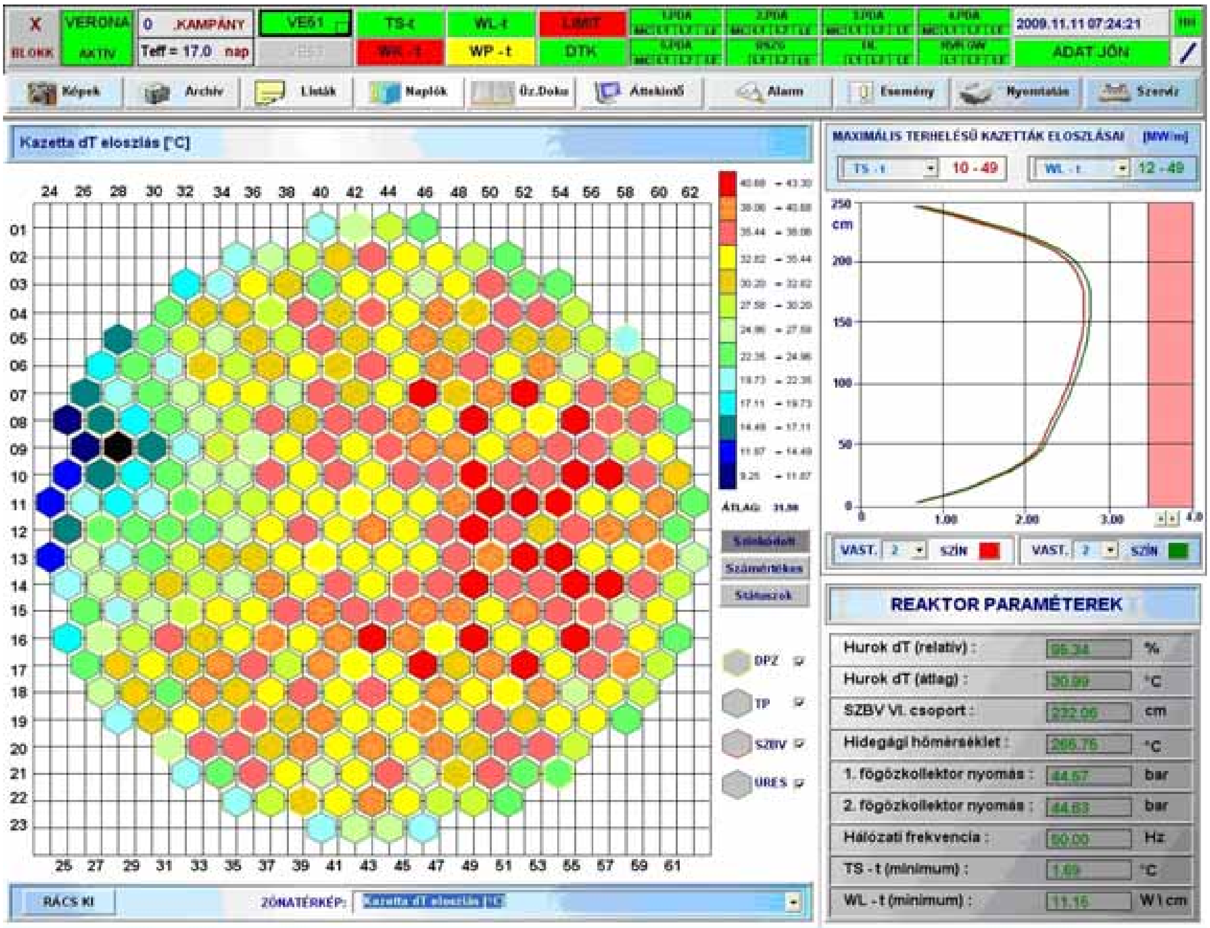
Thermo-hydraulic nodes should be much larger in space than the neutron-kinetic nodes. It is connected with the 0.2 sec. time step of the full scope replica simulator of the power plant. If we want to avoid large number of iterations, the amount of the steam/water leaving/entering the node each time step 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. Creating relatively large nodes we have to group fuel assemblies very carefully, in order to get as detailed simulation results as possible. The color coding of Pic. 1 shows our results.

The central (red) node on Pic. 1 contains 13 fuel assemblies, including the central "control rod" (from group No. 6). Six inner (green) nodes contain 16 fuel assemblies including 2 control assemblies each (one form Group 5 one form Group No. 6). The peripheral six large nodes, shown in different colors, contain 40 fuel assemblies each. Vertically we divide the core into 5 termo-hydraulical layers; it is easy to fit them with the 10 layers of the neutron-kinetical model.

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

- 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.

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

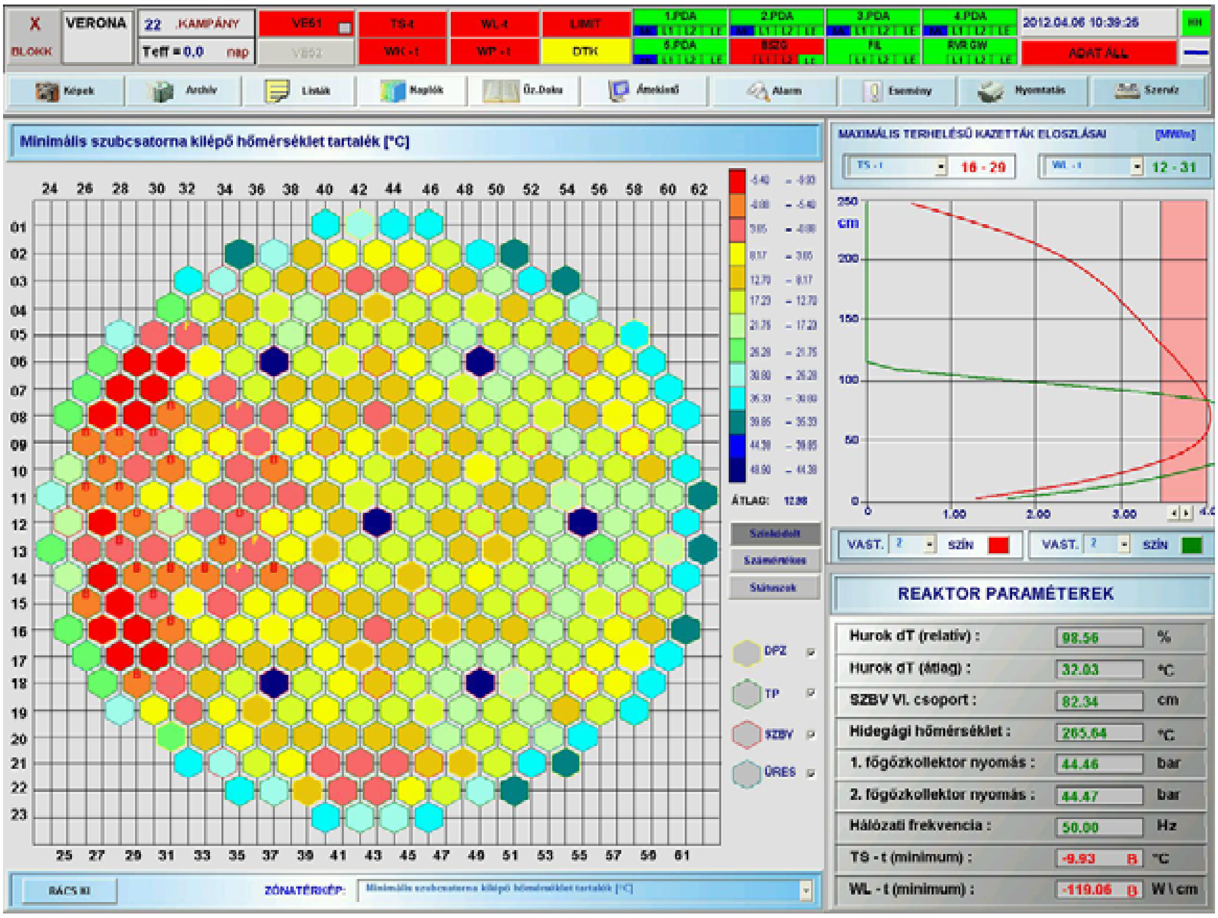


Pic. 2. Picture on the in-core surveillance system VERONA - driven by "rod drop" state data from the simulator

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 – see Pic. 2. - is not so strongly distorted than it could have been expected. Details about out RETINA thermo-hydraulic are reported by Janosy, 2010, Hazi 2001, and Hazi, 2002.

Another experiment with the coupled spatial neutron kinetic and thermo-hydraulic models can be seen on Pic. 3. The controller keeps the power permanent moving the control rods. First we inserted some boron acid solvent to get all rods pulled out. (Boron acid is an absorber for the neutrons participating in the chain reaction). Next, we addressed the "control rod stuck" malfunction to the leftmost control rod. It will not move any more, remains in "pulled out" condition. Now extracting slowly the boron acid the controller has to move all the other control rods down, in order to keep the power constant. The restructuring neutron power distribution results in a serious overload at the left part of the core causing intensive boiling. The plant is not permitted to operate under such conditions: these situations can be studied on the simulator only.



Pic. 3. Six rods are "in", the leftmost 7th is "out". Note the overloaded and distorted axial distribution on the right side

VERIFICATION AND VALIDATION PROBLEMS

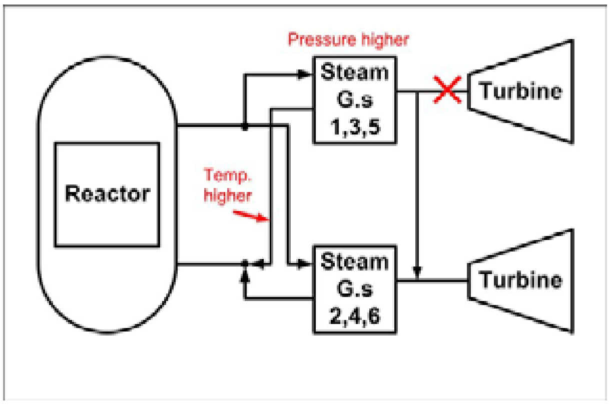
The cornerstone of all simulation is the verification and validation method used for the constructed models. In our case the ***verification*** means that the computer program representing our model is error-free and calculates the numerical solution of that differential equation system exactly that has been described in the Technical Design document During ***validation,*** the exact value of the rather numerous free parameters of the model should be determined optimally in order to achieve the highest confidence of the model system - ensuring the best similarity to the modeled real object.

The validation is much more difficult than the verification process. The problem lies in the lack of proper experimental data. No experiments are allowed to perform on the real plant, and only the transient recordings of the **a**nticipated **o**perational **o**ccurrences (AOO) are available. This term stands for all events which are common: start-up, shutdown, operation on different power levels, control of the frequency of the electrical network, turbine start-up and trip, pump trips, synchronization of the electrical generators, physical measurements verifying the parameters of a new core after re-fueling, etc. Careful investigation of the archives provided by the plant surveillance computer systems after a given transient produces great amount of important information.

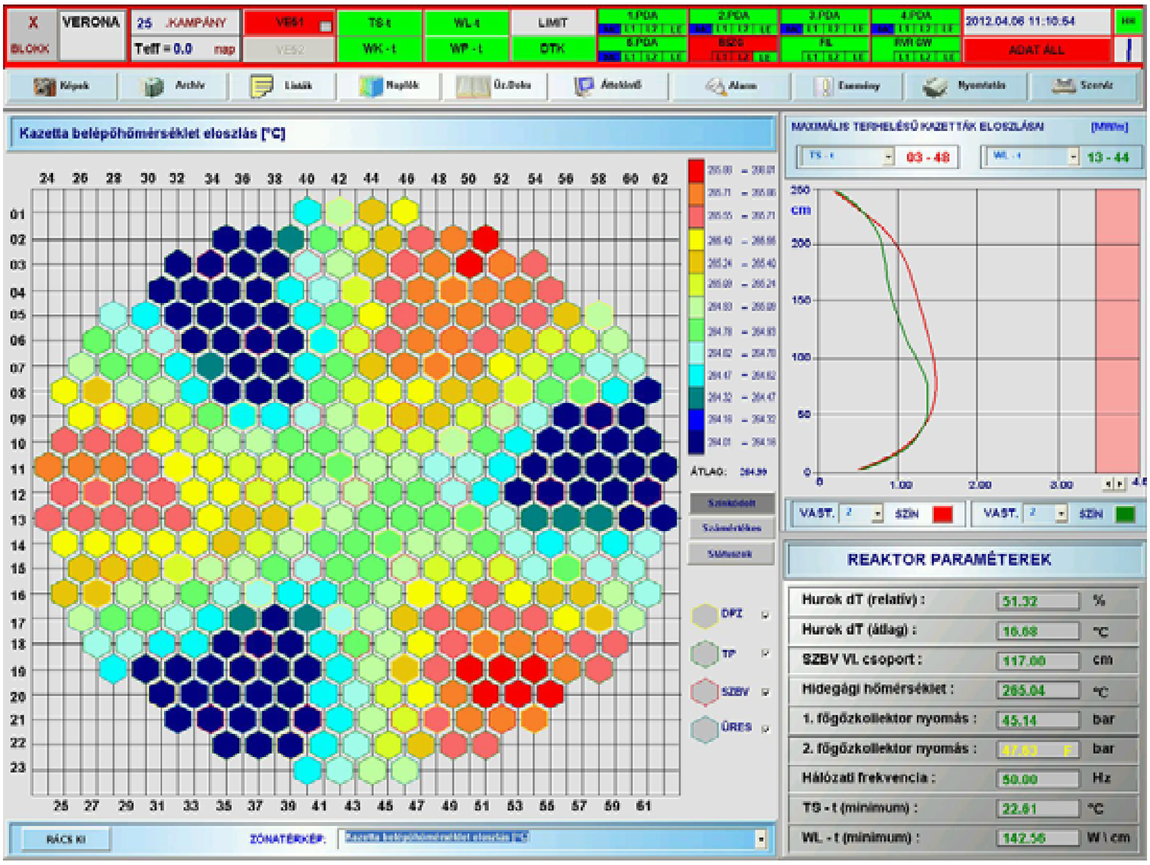
There are very well elaborated models and programs verified and validated by numerous and expensive experiments performed on dedicated experimental facilities. These models are used mostly to prepare the Safety Report of the given plant for the national authorities. The basic problem of the comparison of a training simulator models with them that the training simulator is based on the "best estimate" philosophy, while the programs mentioned above and used to evaluate the actual safety are based on the "worst case" methodology and scenarios. This difference becomes significant when the models have to handle uncertainties. "Best estimate" models usually take the estimated mean value, whereas the "worst case" models take the value which "hurts" most to the safety of the nuclear power plant.

Sometimes simple events help a lot. Turbine trips are not very frequent events, and it is not allowed to operate with only one turbine available. Sometimes, however, it is a simple electrical overload what happens and the protections disconnect the generator in question from the grid. If the operators are able to re-start the turbine and recover the full power soon, they do not shut down the plant. Meanwhile precious data can be collected.

The operation with one turbine is asymmetric. Three steam generators feeding the steam header of the operating turbine remain in a quite similar condition, but the other steam header to which the other three generators are connected remains without turbine. This steam header can feed the other one, but because of the connection losses the pressure of this header becomes higher by 2.5 bars than the other one. Correspondingly, the water temperature on the secondary side of them becomes higher by 2°C. Obviously, those parts of the core fed with coolant of higher temperature reduce somewhat the power (due to the negative temperature feed-back) therefore the output temperatures of these sectors are less warmer than the inlet difference of 2°C.

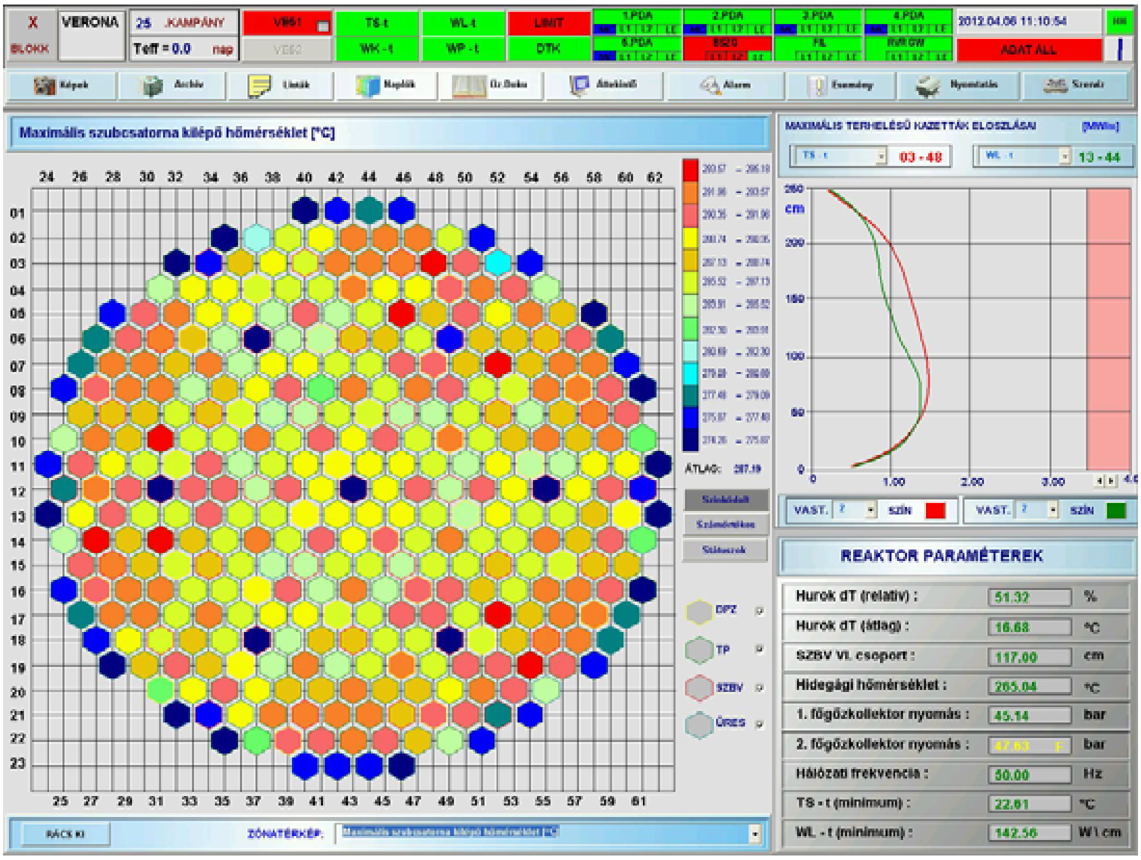


Pic. 4. Asymmetric operation with one turbine



Pic. 5. One steam turbine is out, and three from the six loops have higher cold loop (i.e. reactor inlet) temperatures

The reactor power controller had to reduce the thermal power of the core to about 50% (51.2% on the VERONA display below), and therefore all the seven control rods are lowered somewhat; the corresponding part of the fuel elements move out and down from the core and the outlet temperature of these channels decrease. (VERONA: in-core surveillance system for our plant.) All these effects can be studied on the Pic. 6.



Pic. 6. Fuel element outlet temperatures shown by the VERONA in-core surveilance system

CONCLUSIONS

After accomplishing a long project, we are able to simulate all important processes of our pressurized-water power reactor practically in all necessary states and in all necessary detail in order to train our operators to the upcoming new fuel and the corresponding new procedures. It is very important that the extremely fast-growing computer power can be used not only to enhance the quality of the GUI – as it is nowadays unfortunately usual - but it is used for more detailed and correct simulation of sophisticated systems.

The real trouble we have always to encounter: thanks to the growing computer power, even if we are trying to formulate as detailed models as possible, it is very difficult to obtain useful measurement data from the real plant to compare our models with.

The standard instrumentation existing on the plant - being fully satisfactory to control the operation and ensure safety – is usually inadequate to record data for comparison with the results of 3D calculations made using elaborated model systems. Lack of consistent data – this is the main problem for our V&V procedures. Up to now we do not see how to overcome this problem.

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