SEVERE ACCIDENT SIMULATIONS IN APROS NUCLEAR PLANT ANALYSER FOR VVER-440/213 REACTORS AND THE VISUALIZATION OF THE RESULTS

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Abstract

PC-based NPP basic principle simulators have been developed for over 15 years at Budapest University of Technology and Economics Institute of Nuclear Techniques (BME NTI) with two main goals: to provide the nuclear engineering education with tools capable to illustrate the fundamental physical processes of an NPP and to serve the regular basic retraining of the technical personnel of the NPP Paks (VVER440/213).

Our latest plant analyser is based on APROS which is a commercially available system code for modelling one-dimensional, two-phase flow processes in nuclear power plants and other industrial facilities. Numerical models for one- and three dimensional reactor kinetics, automation and electrical systems, containment processes and core degradation are also available. The code package contains a graphical user interface (GRADES) and pre-built component modules (pressurizer, steam generator etc). APROS is developed by VTT and Fortum in Finland.

A detailed APROS model of Paks Unit 3 (VVER-440/213) is under development at the BME NTI since 2000. The model contains the primary and secondary circuit with the emergency systems, the essential control and protection signals and the containment. The model was extended within the frame of a PHARE project, thus making capable to calculate beyond design basis accidents. The system code used for the modelling is the latest version of the APROS-SA software package.

Keywords: nuclear power plant, plant analyser, loss of coolant accident, severe accident.

Presenting Author's biography

Dr. Attila Aszódi. Director of BME NTI and Head of Department of Nuclear Energy. Main research and teaching areas are: nuclear energy; thermal-hydraulics; Computational Fluid Dynamics (CFD), 3D flow simulation; simulation and system analysis of nuclear power plants; investigation of the transmutation of high level radioactive wastes; safety analysis of nuclear reactors and new design nuclear power plants; development of simulation programs for education purposes.

1 Historical overview

PC-based NPP basic principle simulators have been developed for over 15 years at Budapest University of Technology and Economics' Institute of Nuclear Techniques with two main goals: provide the nuclear engineering education with tools capable to illustrate the fundamental physical processes of an NPP and serve the regular basic retraining of the technical personnel of the NPP Paks (VVER440/213).

The development of the first simulator called PC2 was started in 1988 for demonstrating the dynamic processes of the primary circuit. It was followed by an analyser program (STEGENA) for detailed studies on the thermodynamic and thermohydraulic processes going on in the horizontal steam generator of a VVER-440 plant. The next phase in the evolution was the development of a secondary circuit simulator (SSIM, see Fig. 1) in 1995. This program was written for MS Windows platform. The model describes the dynamic processes of the secondary circuit in quite fine details. The simulation extends for all the main components: steam generators, turbines, condensers and preheaters are all comprehensively modelled.

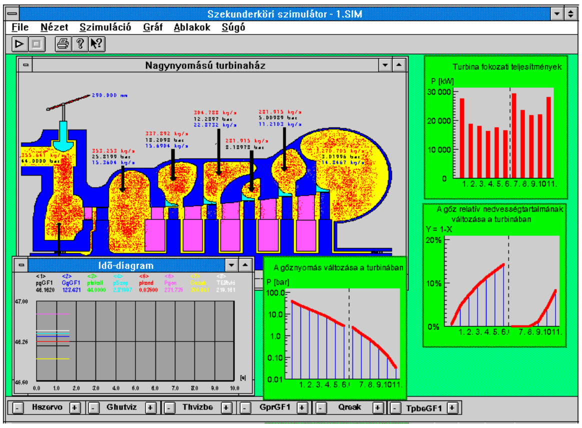


Fig. 1. A typical screen of the SSIM simulator with the scheme of HP turbine

The latest version of PC^2 (see Fig. 2) was released in 2000 also for MS Windows platform. This program can be used for demonstating the main reactorphysical processes and the most important thermal-hydraulics processes in the six primary loops for educational purposes.

Elaborate educational conception and student exercises belong to all three simulators. Both the simulators and the educational aids have proven to be useful and effective in the course of retraining at Paks NPP and the nuclear engineering education at the Budapest University of Technology and Economics, as well.

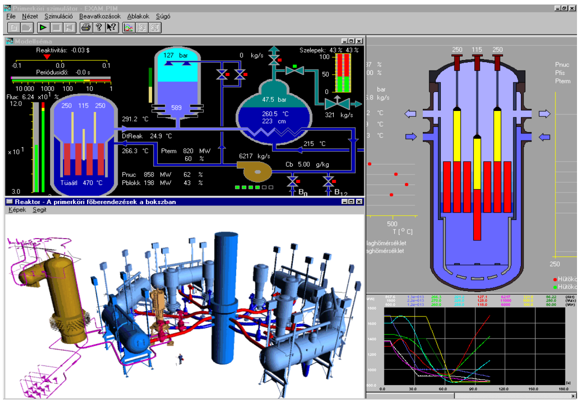


Fig. 2. A typical screen of the PC^2 v3.3 simulator

2 APROS model of Paks NPP

APROS (Advanced Process Simulator [1]) is basically a one-dimensional, two-phase thermal-hydraulic system code, similar to RELAP, ATHLET and CATHARE. Numerical models for one- and three dimensional reactor kinetics, automation and electrical systems, containment processes and core degradation are also available. The code package contains a graphical user interface (GRADES) and pre-built component modules (pressurizer, steam generator etc). APROS is developed by VTT and Fortum in Finland.

A detailed APROS model of Paks unit 3 (VVER-440/213) is under development at the BUTE Institute of Nuclear Techniques since 2000. The model was extended within the frame of a PHARE project, thus making capable to calculate containment processes and beyond design basis accidents [2].

2.1 DBA model

The model of the primary circuit contains the six primary loops, the reactor pressure vessel, and the pressurizer with the related control and protection signals. The model of the Emergency Core Cooling Systems (ECCS) contains the three independent trains of the active ECCS (high- and low pressure injection system), the four hydroaccumulators, and the related control and protection signals. The model of the secondary circuit contains the six steam generators with their steam- and feed water piping, the Main Steam Header, the two turbo generators, the condenser, the low- and high pressure preheaters, the feed water pumps, and the feed water tanks. The control and protection signals for the secondary circuit were built into the model too, with the auxiliary and emergency feedwater systems.

2.2 Containment model

The containment model of APROS uses a lumped parameter approach. The gas region is homogeneous mixture of non-condensable gases and steam. It was first used for modeling the Loviisa and Olkiluoto units, so the initial validation has been done for Westinghouse-type containment with ice condensers and for a typical BWR containment with a suppression pool. Before modeling the hermetic compartments and the passive pressure suppression system (bubble condenser tower) of a VVER-440/213 plant, the code was validated with EREC experiments.

In the current model of the Paks-specific VVER 440/213 unit the hermetic compartments are described with 24 nodes. The two halves of the steam generator (SG) room, the pump room, reactor pressure vessel cavity and ventilation center were modelled by one node each. Hermetic valve corridors, hydroaccumulator and pressurizer compartments and other smaller dead-ended volumes were modelled as one big "dead-ended" volume connected to both SG boxes. The connecting channel between the bubble condenser (BC) tower and the SG boxes was modelled as two identical nodes (the left and the right channel).

At the units the BC tower has 12 water trays for condensing the steam generated during a LOCA event. The BC tower has 4 air traps for capturing and holding non-condensable gases (3 water trays are connected to 1 air trap). In the APROS model the surface and the volume of the 12 water trays are considered in 4 water trays. All 4 air traps are modeled in APROS. The BC tower was modeled with 16 nodes: 8 nodes for tower atmosphere and 4-4 nodes for water trays and air traps.

2.3 Severe accident model

The severe accident calculation package of APROS consists of four modules for calculating different physical processes related to fuel damage and core melting. These modules are initialized and started in the model only after the maximum fuel cladding temperature reaches a preset value.

- GENFLO: thermal hydraulic model of the VVER-440 reactor pressure vessel. The calculation takes into account the degraded geometry of the core (swollen fuel pins, relocated fuel tablets etc.). The boundary conditions (pressures in and coolant injections into the downcomer and upper plenum) are provided by the thermal hydraulic model of the primary loops.
- SARELO: model for simulating the degradation of the reactor core. This module describes the behavior of the solid core structures from the solid state via relocation into the molten stage. The model describes the core overheating, oxidation, cladding melting, fuel relocation, control rod melting and finally fuel melting. Initially the materials are solid, but during the transient they can melt. The radiation and conduction heat transfer between zones are simulated. The chemical reaction between high temperature zirconium cladding and steam is also calculated.
- COPOMO: corium pool model simulating the behaviour of the melted core inside the reactor pressure vessel. It calculates transient behaviour of corium first on the core support plate, from which it relocates through the core barrel into the lower plenum of reactor pressure vessel. From corium heat is transferred into the surrounding steel structures of reactor pressure vessel or core barrel depending on the location of the corium. Due to the heat transfer part of the surrounding steel structures may melt and part of the molten corium may become solid again.
- FIPROMO: module for calculating the release, transfer and deposition of fission products. It keeps track of the fission product masses and decay heat production in each node of the simulation model. The fission products are divided into six independent groups depending on their chemical behavior:

The events after reactor vessel failure (direct containment heating, molten core-concrete interaction) are not modelled in the current version.

The above described model can be used to simulate the whole NPP unit in design basis accidents and even in severe accidents until the molten core penetrates the reactor pressure vessel. The APROS code with the VIPROS visualisation system can be used for safety analysis in the case of design basis accidents.

3 The VIPROS visualization tool

A new visualization program called VIPROS (Visualisation for Process Simulators) was developed for the plant analyzer at BME NTI. VIPROS can use the output data file of any simulation software (RELAP, ATHLET, ASTEC, APROS etc.) for illustrating the thermohydraulic processes by plotting time diagrams and graphical animations. For this reason the VIPROS program is a suitable tool for understanding the complicated thermohydraulic processes, and it can be used not only in research and engineering but in education as well. The code is written in C/C++ using the open source FLTK toolkit. VIPROS is a cross-platform application: it was successfully compiled and run on MS Windows, Linux and Mac OS X. The present version of VIPROS is generated for the visualization of APROS severe accident simulation model of Paks VVER-440/213 unit developed in the frame of the HU2002/000-632-04-02 PHARE project.

Examples of VIPROS windows can be seen on Fig. 3 through Fig. 7.

- Fig. 3 shows the temperatures in the primary side (and steam generator secondary side) nodes. The status of the pressurizer (PRZ), Main Coolant Pumps (MCP1 through MCP6), HPIS pumps (TH10, TH20, TH30), LPIS pumps (TJ12, TJ22, TJ32), hydroaccumulators (TH50, TH60, TH70, TH80) are shown in this window. Some information about the secondary side also can be seen here: data about the SG valves, turbine bypass valves (KR), atmospheric relief valves (AR) etc.

- Fig. 4 is very similar to Fig. 3, but it shows void fraction in the nodes instead of the temperatures.
- Fig. 5 shows the scheme for Emergency Core Cooling System (ECCS). The ECCS water tanks, pumps and valves of the High Pressure Injection System (HPIS) and Low Pressure Injection System (LPIS) can be seen here.
- Fig. 6 shows one of the steam generators. The void fraction in the secondary side nodes and the temperature in the primary side nodes are represented with the color scales. Positions and flowrates of the feedwater (FW), auxillary feedwater (AFW) emergency feedwater (EFW) and safety valves (SV1, SV2) are shown numerically and by color. The scale on the left side shows the collapsed level on the secondary side.
- Fig. 7 shows the temperatures in the confinement system (with numbers and color coding), and the status of the bubble condenser tower.

Complex thermohydraulic processes – which are very difficult to trace in a unit control room, or in a full-scope simulator, or even with time diagrams produced by system codes – can be visualized with VIPROS, for example two-phase flow in the primary loops, opening of loop seals, ECCS water injection, flashing in the core etc.

The APROS-VIPROS system is used for investigating different loss-of-coolant accidents with different break size and location. It is also used in university teaching.

4 References

[1] *APROS documentation* VTT, Finland, 2005.

[2] Ismo Karppinen, Markku Hänninen, Ari Silde, Dr. Attila Aszódi, András Csige, Győző Fejérdy, Mika Harti, Eerikki Raiko. Development of the APROS nuclear plant analyser for the Paks NPP, Hungary. *Final report, PHARE project: HU2002/000-632-04-02*. 2005.

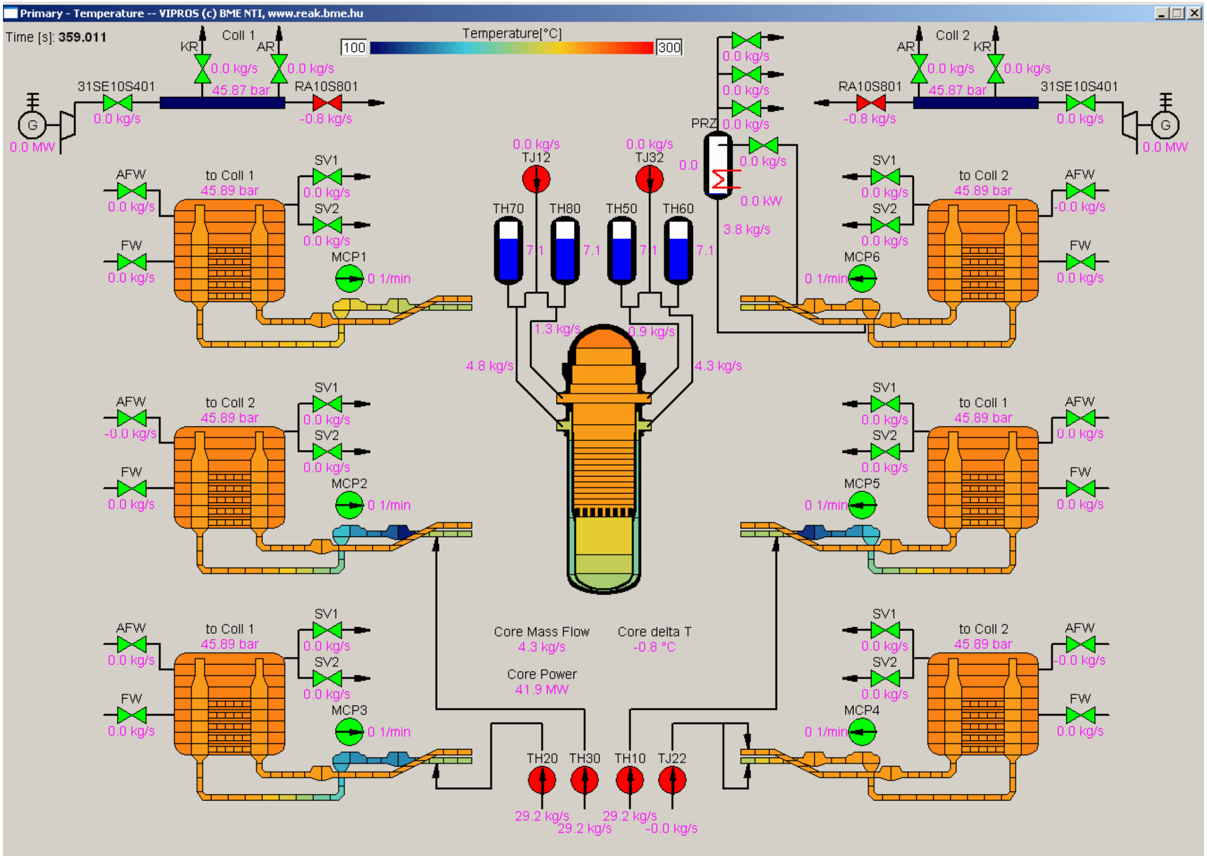


Fig. 3. Example of temperature distribution in the primary circuit nodes (VIPROS)

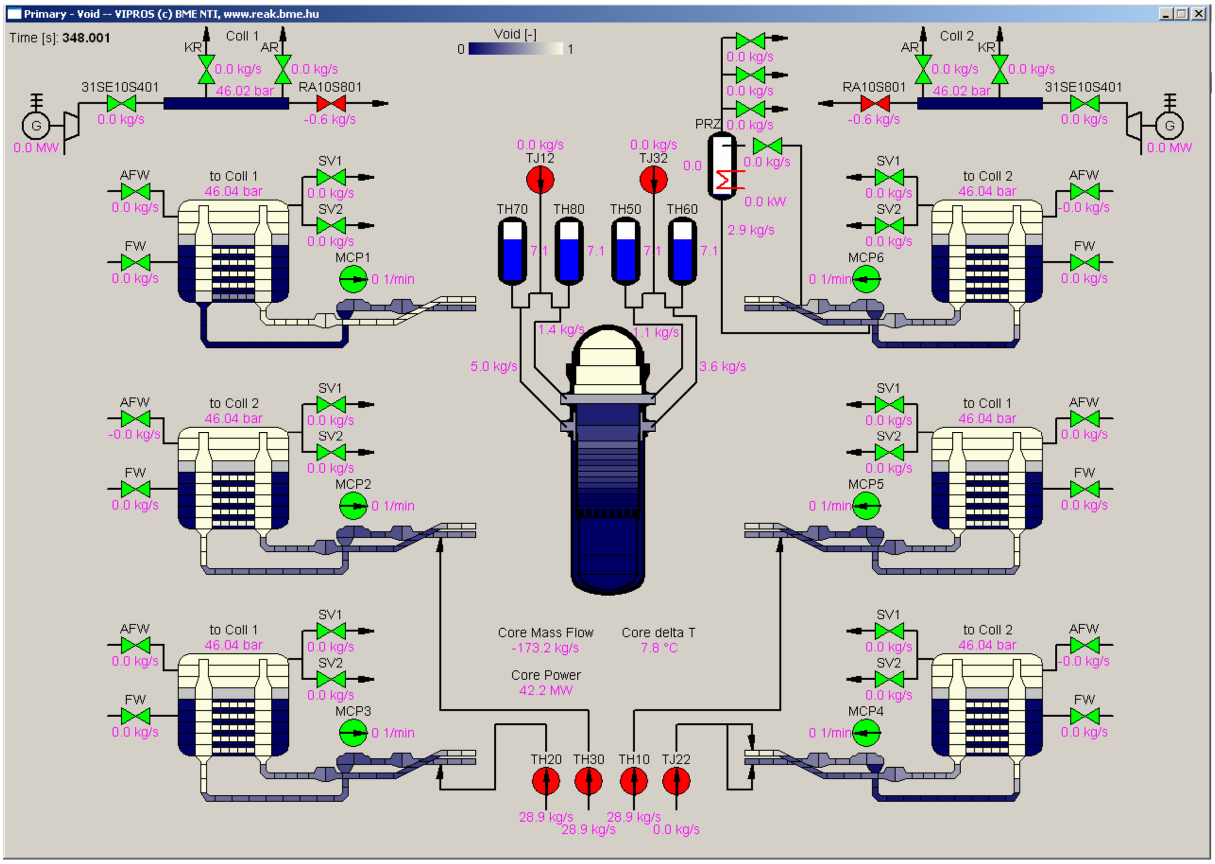


Fig. 4. Example of void fraction distribution in the primary circuit nodes (VIPROS)

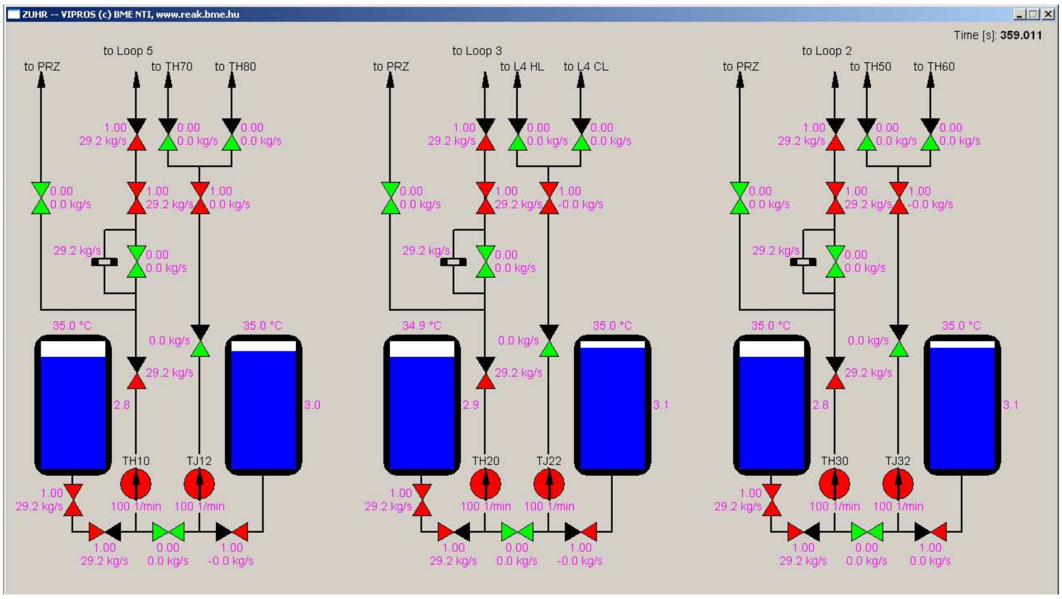


Fig. 5. Emergency core cooling system (VIPROS)

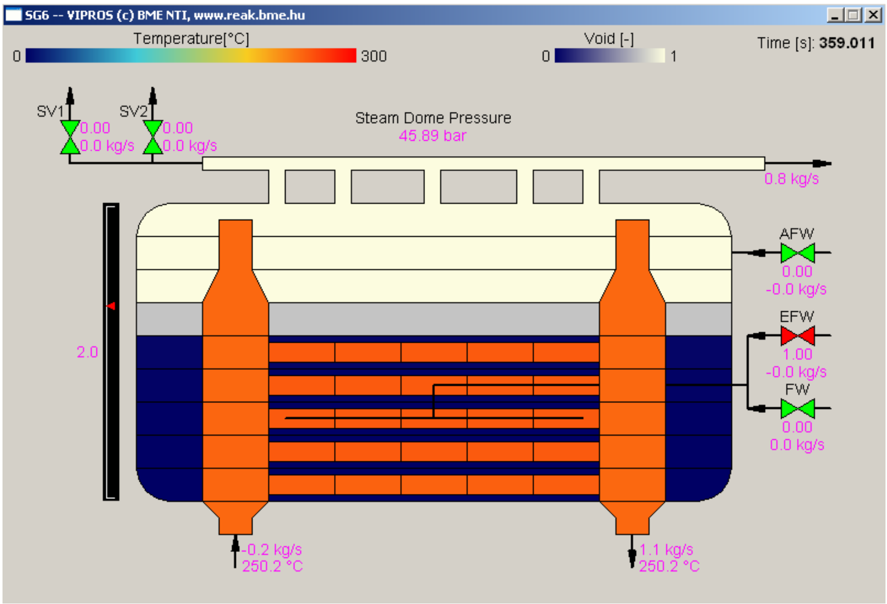
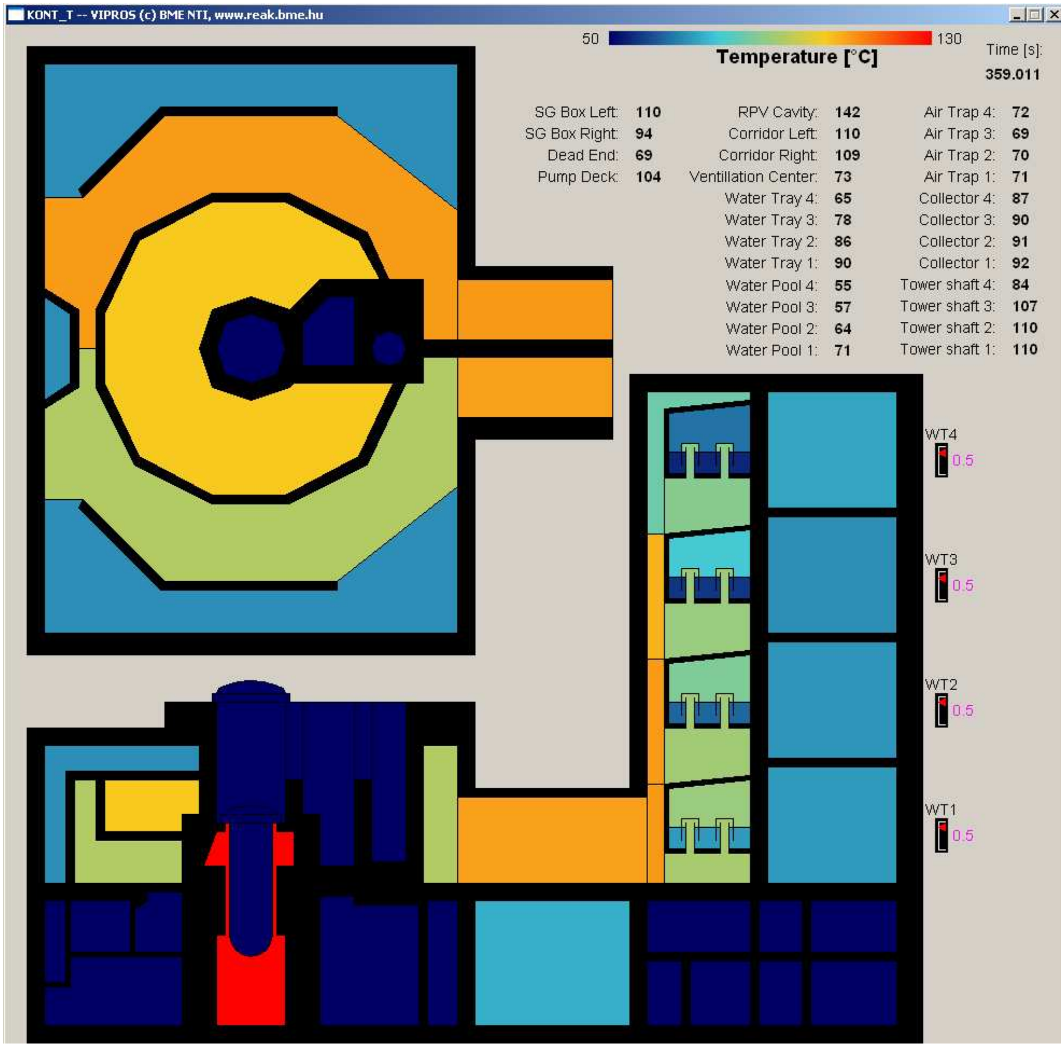


Fig. 6. Steam generator (VIPROS)



SG Box Left: 110
SG Box Right: 94
Dead End: 69
Pump Deck: 104

RPV Cavity: 142
Corridor Left: 110
Corridor Right: 109
Ventillation Center: 73
Water Tray 4: 65
Water Tray 3: 78
Water Tray 2: 86
Water Tray 1: 90
Water Pool 4: 55
Water Pool 3: 57
Water Pool 2: 64
Water Pool 1: 71

Air Trap 4: 72
Air Trap 3: 69
Air Trap 2: 70
Air Trap 1: 71
Collector 4: 87
Collector 3: 90
Collector 2: 91
Collector 1: 92
Tower shaft 4: 84
Tower shaft 3: 107
Tower shaft 2: 110
Tower shaft 1: 110

Fig. 7. Temperature in the hermetic confinement rooms (VIPROS)