CERNAVODA NPP STEAM GENERATOR ANALYSIS

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This paper presents the modeling and simulation results for the Cernavoda N.P.P. steam generators performed using the acslXtreme version 2.0.1.2 produced by Xcellon – The Aegis Technologies Group, Inc. A steam generator analysis was performed by Budu Madalina as the subject for her License Thesis "Modeling and simulating of the processes in the steam generator with application on CERNAVODA N.P.P.". The thesis contains also a comparison with the results of the MMS (Modular Modeling Language) for the same system.

Three regimes are analyzed:

- *full power steady state regime;*
- *transition from full power to the 80%full power*
- *transition from full power to 60%full power.*

The modeling and simulation of the steam generator for the Cernavoda N.P.P. was performed using block diagram modules that model the steam generator, the water level control system in the secondary circuit of the steam generator that actuate the flow control valve for supply water entering the steam generator, the pipes in the primary and secondary circuit linked to the steam generators.

The paper includes the evolution of the main parameters in the steam generator and explanation regarding the choices made in the mathematical model and in the block diagrams used.

Keywords: Steam generator analysis, acslXtreme, MMS

1. Introduction

The steam generator is one of the most complex pieces of equipment in a nuclear power plant, its integrity being the basis for the entire electric power technologic process. In the general management of the plant the steam generator is the key stone, being the interface between the nuclear reactor and the turbine-generator group, between the primary and the secondary circuits. In consequence, the analysis of the steam generator for different regimes is very important.

This paper shows a simplified mathematical model for the steam generator, on which we implemented in the acslXtreme software a scheme that includes the level control.

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The simplifications made in the mathematical model do not stray it from the normal operation of the steam generator, the results obtained are close to the ones obtained with other models studied on the MMS software in some research activities made by CITON.

The obtained results show that the model is useful for the simulation of any functioning regime of the steam generator, is easy to use and has a very short response time.

2. The steam generator and the mathematical model in brief

The steam generator for the CANDU 600 system is the upright type, with U tubes and integrated preheater and an drum.

The main components are: the heat exchanger, relatively uniform in the outer diameter, and the steam drum, with a greater outer diameter.

On the primary side heavy water circulates from the heat transport system through two inlets at the base of the steam generator. The border between the two circuits, the primary and the secondary, is the end plate and the pipes from the tubular bundle which brake through the plate. The secondary side of the steam generator is composed of all the pieces that come in contact with the water in the secondary circuit (light water).

The mathematical model used in this paper is a simplified version, which does not follow in particular the detailed evolution of the parameters and phenomena within the steam generator. It differs from the existing detailed models in the fact that all the properties in the secondary circuit are calculated for the same pressure, the live steam pressure in the dome of the steam generator. Therefore this model does not take the preheater separately, thus avoiding an instable zone in which the boiling point in the preheater is reached, due to the abrupt variation of the density derivative in report with the enthalpy, which is present in other models.

In this paper, the modeling technique is the one with concentrated parameters.

In the making of the mathematical model the following hypothesis where made:

- the sub cooled and superheated fazes in the boiling region and in the unheated zone above the U tubes on the secondary side are in thermal-dynamic equilibrium.
- the steam does not superheat in the steam generator, the steam exits on the saturation curve in the nominal functioning regime.
- the humidity separators have a efficiency of 100%; all the vapors humidity is retained by the separators;
- the secondary agent in the preheater zone has a ascending flow.

The models equations are derived from the conservation laws of mass, energy and momentum applied to the control volumes of the considered regions. In addition, the heat transfer equations are written between the primary and secondary agent and the void fraction is taken into account in the boiling region and the unheated zone through to the separators.

The primary circuit is divided into 4 distinct regions (fig1)

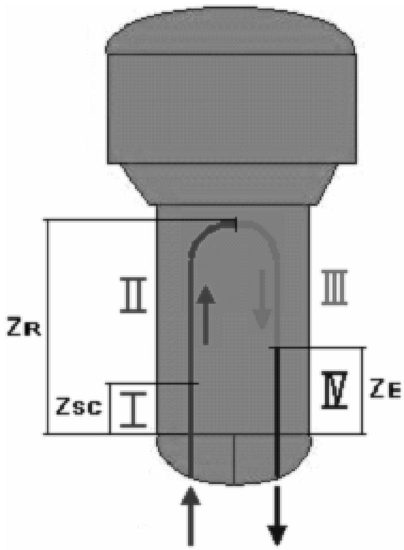

Fig.1. Primary circuit dividing scheme

The equations on the primary side for zone I are:

Mass conservation:

$$D_{Pin} = D_{p1} \tag{1}$$

D_{Pin} - primary agent flow, kg/s

D_{P1} - primary agent flow that leaves zone I, kg/s

Energy conservation:

$$\frac{d}{dt}\left[\rho_{p1}\left(Z_{SC}A_P/2+V_{PI}\right)h_{P1}\right]=D_P h_{PIn} f_{PIn}-D_{P1}h_{P1}-Q'_{P1}+\left(A_P Z_{SC}/2+V_{PI}\right)\frac{dp}{dt} \tag{2}$$

ρ_{P1} - primary agent density in zone I, kg/m3

A_P - cross section area of the primary circuit pipes, m2

Z_R - U tubes height , m

V_{PI} - primary circuit inlet fitting volume, m3

h_{PIn} - primary agent entering enthalpy, j/kg

h_{P1} - primary agent leaving zone I enthalpy, J/kg;

p - primary fluid pipe pressure, Pa;

Q'_{P1} - heat transferred from the primary agent in zone I, W.

Momentum conservation:

$$P_{Pin} - P_{Pout} = r_h D_{Pin}^2 \tag{3}$$

D_{Pin} - primary flow (through one pipe), kg/s

r_h - hydraulic resistance,

Zones II, III and IV of the primary circuit are addressed similarly to zone I, the unknown being each time the enthalpy of the primary agent leaving that zone.

The secondary side of the steam generator is divided in three big regions: a mixing region, a boiling region (riser), and the dome.

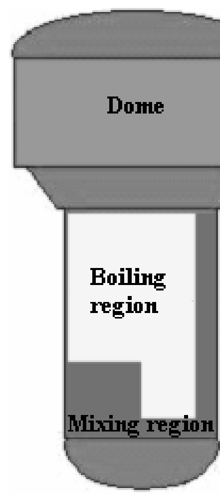

Fig 2. Secondary circuit dividing scheme

The equations for the mixing region are:

$$h_B = \frac{D_{AL} h_f + D_{DC} h_{DC}}{D_{AL} + D_{DC}} \tag{4}$$

$$h_{DC} = \frac{1}{\tau_{DC}} \left(h_D - h_{DC} \right) \tag{5}$$

$$\tau_{DC} = \frac{M_{DC}}{D_{DC}} \tag{6}$$

h_B - secondary agent enthalpy entering the boiling region, J/kg;

h_f - saturated liquid enthalpy at the steam pressure in the dome, J/kg;

h_{DC} - fluid enthalpy in the down-comer, J/kg

D_{AL} - feed water flow, kg/s;

D_{DC} - recirculated fluid flow through the down-comer, kg/s;

h_D - water enthalpy in the dome, J/Kg;

τ_{DC} - time constant for the down-comer, s;

M_{DC} - fluid mass in the down-comer, kg.
The equations for the boiling region are:

$$h_r^* = h_B + \frac{Q_{VAP}}{D_{AL} + D_{DC}} \tag{7}$$

$$h_r = \frac{2}{\tau_r}\left(h_r^* - h_r\right) \tag{8}$$

$$\tau_r = \frac{M_r}{D_r} \approx \frac{\rho_f\left(V_r + V_s\right)\left(1-\alpha\right)}{D_r} \tag{9}$$

$$x_r = \frac{h_r - h_f}{h_{fg}} \tag{10}$$

$$\bar{\alpha} = \frac{1}{x_r}\int_0^{x_r}\alpha_r dx = \frac{1}{1-\gamma\left(\frac{\rho_g}{\rho_f}\right)}\left\{1 - \frac{1}{x_r\left(\frac{\rho_f}{\rho_g}-1\right)}\ln\left[1 + x_r\left(\frac{\rho_f}{\gamma\rho_g}-1\right)\right]\right\} \tag{11}$$

$$\bar{\rho} = \rho_f\left(1-\alpha\right) + \alpha\rho_g \tag{12}$$

h_r - water-vapor mix enthalpy at the boiling region exit, J/kg;
Q_{VAP} - heat received by the secondary agent in the boiling region, W;
τ_r - time constant of the boiling region, s;
M_r - fluid mass in the boiling region, kg;
D_r - fluid flow through the boiling region, kg/s;
ρ_f - saturated fluid density at the steam pressure in the dome, kg/m3;
V_r - boiling region volume, m3;
V_s - unheated area and separator volume, m3;
α - mean void fraction on the secondary side;
x_r - steam-water mix quality at the boiling region exit;
h_{fg} - latent heat calculated at the dome steam pressure, J/kg;
α_r - void fraction at the exit of the boiling region;
ρ_g - saturated vapor density at the dome steam pressure, kg/m3;
γ - sliding ratio, considered constant and equal to 1.7.
$\bar{\rho}$ - fluid mean density on the secondary side of the steam generator, kg/m3

The equations for the dome are:
Mass conservation:

$$\frac{d\rho_g}{dt} = \frac{1}{\left[V_D - V_W + \alpha\left(V_r + V_s\right)\right]}\left[\left(x_r W_r - W_S\right) - \rho_g\left[\left(V_r + V_s\right)\frac{d\alpha}{dt} - \frac{dV_W}{dt}\right]\right] \tag{13}$$

V_W - water volume in the dome, m3;

V_D - dome volume, m3:
V_S - steam volume that leaves the steam generator,
Energy conservation

$$\frac{dh_D}{dt} = \frac{1}{\rho_{fD} V_W}\left[(1-x_r)D_r(h_r - h_D) + D_{RH}(h_{RH} - h_D)\right] \tag{14}$$

h_{RH} - returned condense enthalpy from the intermediary superheating, J/kg;
For the described model results the block scheme in Fig. 3.

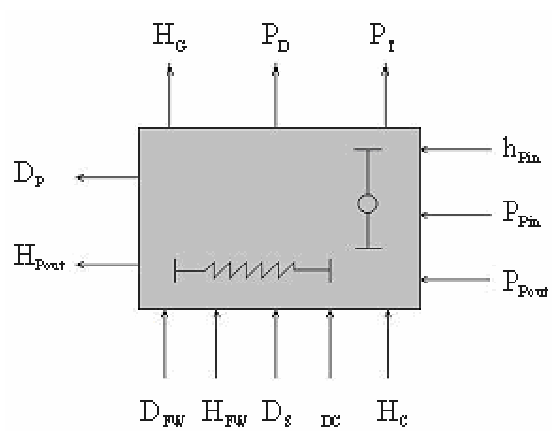

Fig. 3 Block scheme for the steam generator model

3. About acslXtreme

The software used for the steam generator analysis in this paper is acslXtreme, produced by The AEgis Technologies Group, Inc., Xcellon division.

Functionally, acslXtreme includes ACSL 11.8 Sim, Graphical Modeller and Math characteristics in one program. The next list presents some of the new features provided by acslXtreme in addition than the ACSL 11.8 software:

- Integrated Development Environment (IDE), comprehensive for the complete design, the development, the execution and the capacity to analyze the model in one pack.
- The possibility to choose the target language between C, C++ and Fortran.
- GNU C compiler offered through the distribution media.
- Interactive elimination of errors in both the modeling environments, graphic and text.
- Radical improvement of the plotting capacity including 2D, 3D and run plot
- Improved export capacities for resulted data and graphs.
- Advanced CSL code editor with color coding sensitive to the context.
- Improved support for C, Fortran and M external files.
- API model increased with C, .NET (C++, C# and VB.NET) connections.

- Communication possibility with ACSL v11.8 GM.

4. Steam Generator in acslXtreme and MMS

For the study of the operational stationary and transitory regimes of the steam generator we created and used the block diagram in Figure 4.

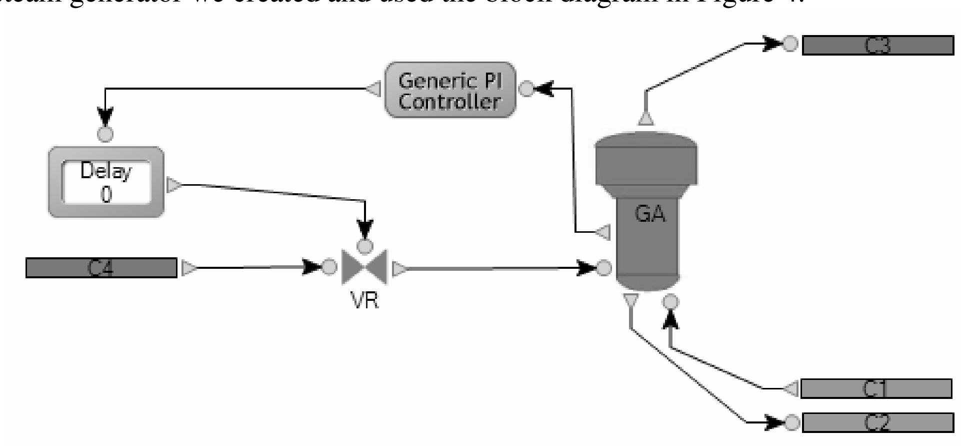

Fig. 4 Block diagram used in acslXtreme

The blocks that compose the diagram and their ports are:

1. GA – steam generator
    a. primary agent entry from pipe C1
    b. primary agent exit to pipe C2
    c. feed water entry from pipe C4 and valve VR
    d. steam exit to pipe C3
    e. level output to Generic PI Controller
2. C1 – primary agent entry pipe to GA (short type, without volume)
    a. primary agent pipe exit
3. C2 – primary agent exit pipe from GA (short type, without volume)
    a. primary agent pipe entry
4. C3 – steam pipe (short type, without volume)
    a. steam pipe entry
5. C4 – feed water pipe (short type, without volume)
    a. feed water pipe exit
6. VR- feed water flow control valve
    a. feed water valve entry from pipe C4
    b. flow correction input from the Generic PI Controller
    c. feed water exit from VR to GA
7. Generic PI Controller (predefined) – for the GA level control

a. the input of the margin between the liquid mass corresponsive to the level set point and current liquid mass

b. the flow correction output to VR

8. Delay (predefined) – linear operator which introduces a delay in the flow signal in order to eliminate the errors occurred in the first run step

a. flow correction input from the Generic PI Controller

b. flow correction output to VR

Comparative analyses with similar models, realized in the activities developed under CITON contracts, in the MMS modeling environment, were made in order to verify and validate the obtained results.

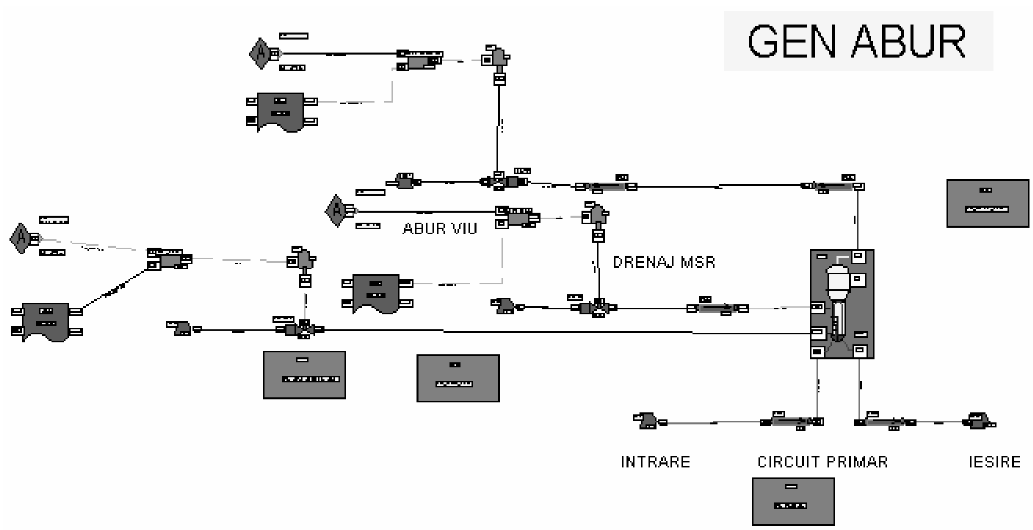

Fig. 5 MMS block diagram

All the blocks used in this diagram are from the RTC libraries of the MMS program.

The proposed steam generator analyses are made based on one stationary and two transitory regimes.

The evolution of the significant parameters will be included (graphic and numeric) for each of the three regimes, in order to dignify the operation mode of the steam generator in conditions similar to the ones met in real service.

The first transitory regime is a reduction of power from 100% to 80% full power. This situation is simulated by a corresponsive reduction of the primary agent enthalpy at the entry in the steam generator with a ramp variation over 200 s. The code for this operation is:

```
t1=400.
      t2=600.
      if (t.gt.t1.and.t.lt.t2) then
```

```
            hi_C1=1408320.-115.935*(t-t1)
      end if
      if (t.ge.t2) then
            hi_C1=1408320.-115.935*(t2-t1)
end if
```

It is seen that the ramp varation of the primary agent enthalpy was realized by the equation of a straight line defined by two points (classic geometry). This was applied to the C1 block (primary agent entry pipe to GA).

In MMS, all the studied regimes were realized by SETBC blocks (Set Boundary Conditions), in which the variation periods, the parameters that vary (the primary agent enthalpies at the steam generator entry) and their values were defined.

Following the real operating conditions, where the set point for the steam generator liquid level is function of the reactor power, a ramp variance of this value was introduced, as per the graph in Figure 5.

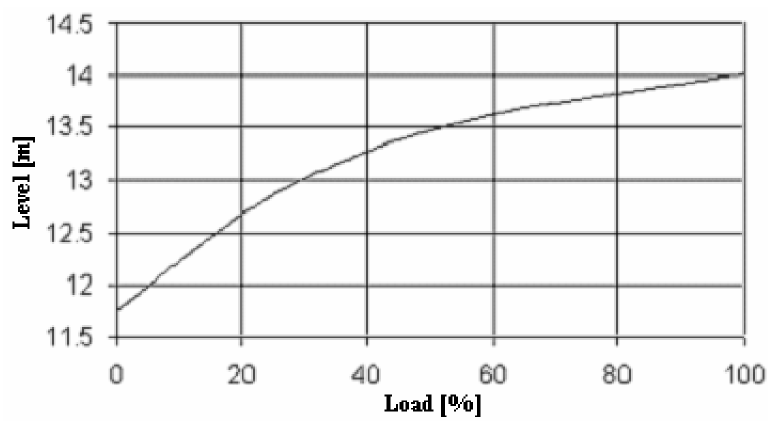

Fig. 6 The reference level in the steam generator function of reactor power

The code for this operation is:

```
t1=400.
      t2=600.
      if (t.gt.t1.and.t.lt.t2) then
            niv0=14.004- 0.00202*(t-t1)
            w_c_i=0
      end if
      if (t.ge.t2) then
            niv0=14.004- 0.00202*(t2-t1)
            w_c_i=0
end if
```

Simultaneous to the reduction of the power, the condensate flow from the drainage of moisture separation reheater MSR (w_c_i) becomes null.

The dependancy between the steam generator liquid level and the load was not modelled in MMS.

The second transitory regime is also a reduction of the reactor power, but this time from 100% to 60% full power, corresponsive to a turbine trip.

In reality, at the Cernavoda NPP, in case of a turbine trip the reactor power drops below 60%, being readuced to this value by the operators in order to avoid the poisoning of the reactor, but this aspect was not addressed in this paper.

The regime is modelled similarly to the one described above. The difference is that the final values of the enthalpy and the reference level are lower, corresponsive to 60% full power.

5. Results

Lettering:

T (s) – the time;
h_p_in (J/kg) – primary agent enthalpy at the entry in the steam generator;
h_p_out (J/kg) – primary agent enthalpy at the exit from the steam generator;
t_p_i (^{o}C) – primary agent temperature at the entry in the steam genearator;
t_p_o (^{o}C) – primary agent temperature at the exit from the steam generator;
niv (m) – liquid level in the steam generator;
w_s_in (kg/s) – feed water flow (excluding the MSR drainage flow);
w_s_out (kg/s) – steam flow;
Q (W) – thermal power transferred in the steam generator.

Stationary regime

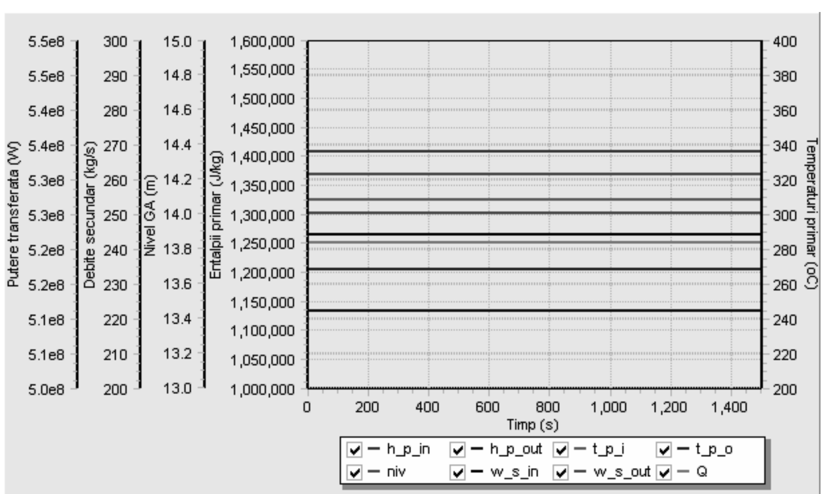

Fig. 7 Steam generator parameters in the stationary regime with acslXtreme

First transitory regime (reduction of reactor power from 100% to 80% full power)

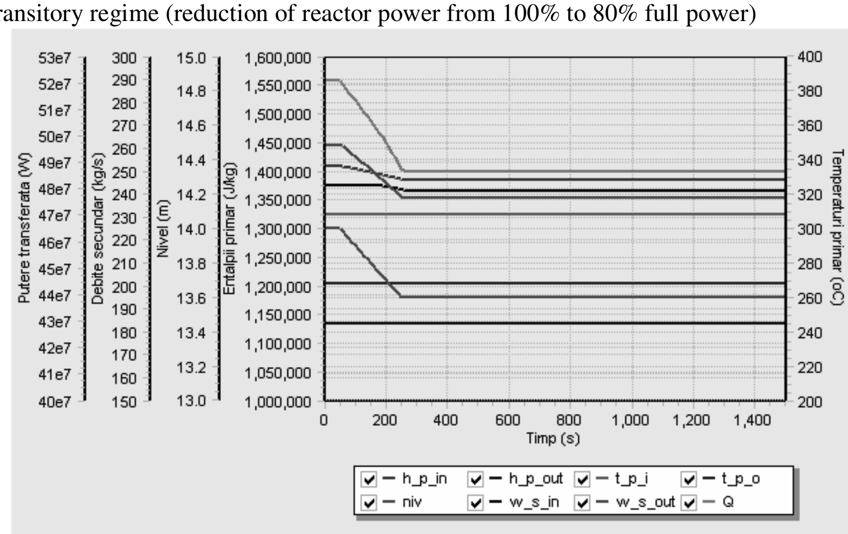

Fig. 8 Steam generator parameters in the first transitory regime with acslXtreme

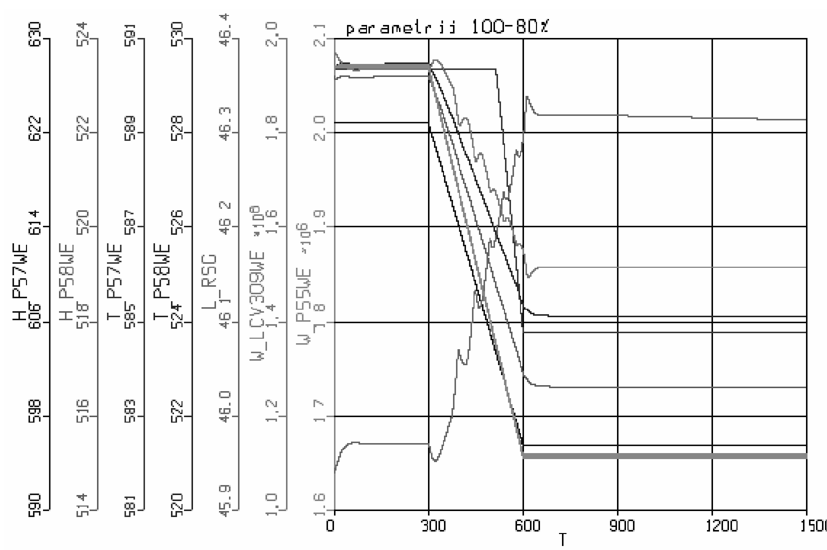

Fig. 9 Steam generator parameters in the first transitory regime with MMS

Second transitory regime (reduction of reactor power from 100% to 60% full power)

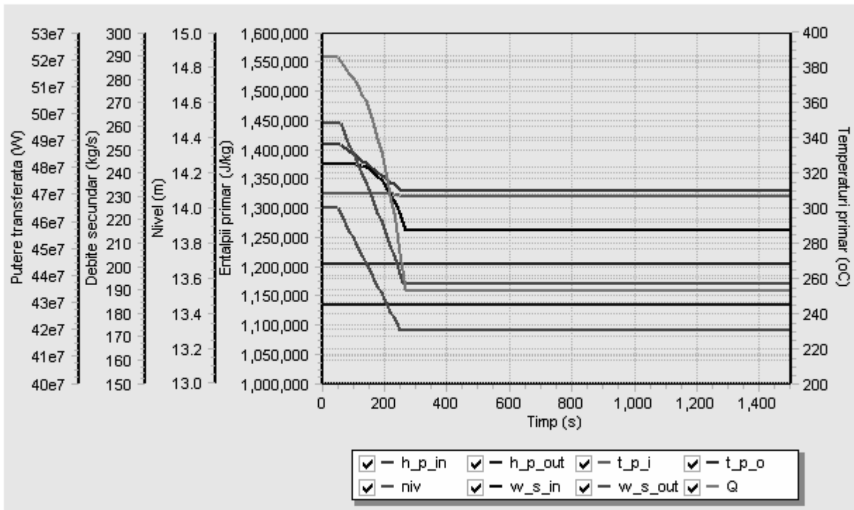

Fig. 10 Steam generator parameters in the second transitory regime with acslXtreme

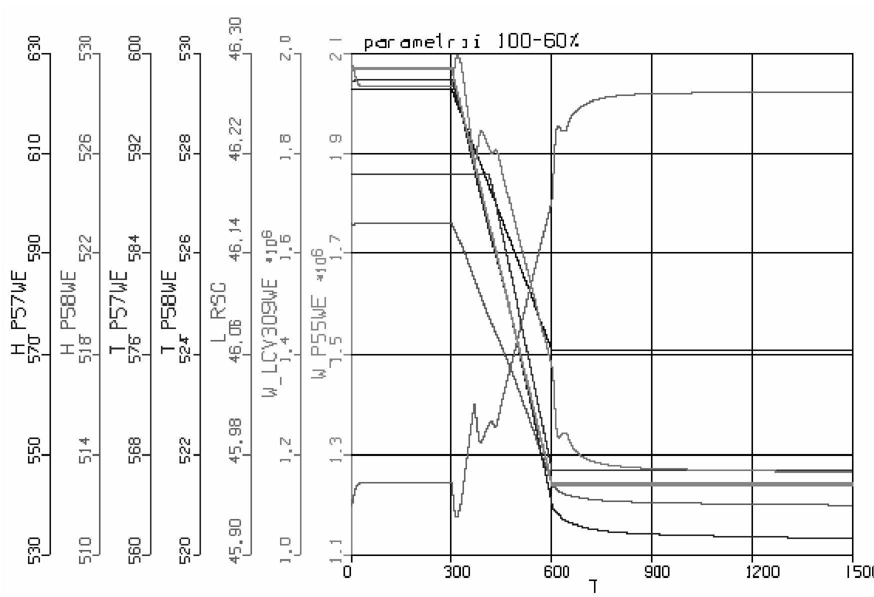

Fig. 11 Steam generator parameters in the second transitory regime with MMS

6. Conclusions

From the point of view of the functioning of the steam generator, the acslXtreme obtained results validate the analyzed model as being in accordance to the reality. They are similar to the MMS results and the operation data.

From the parameter evolutions presented it can be observed the modeling correctness of the heat transfer and of the steam generator liquid level control with the feed water flow control valve.

In comparison to other models, the primary agent enthalpy at the exit from the steam generator must be kept constant, due to the simplification considered in the analyzed mathematical model, that the economizer is not separate and the secondary agent parameters are calculated at the same pressure. This solution is necessary because the primary agent enthalpy drop (and thus the temperature drop) at the exit from the steam generator, at the same time with maintaining the secondary agent parameters (enthalpy, temperature) at constant pressure, modifies the temperature differences from the logarithmic mean temperature difference calculation as for obtaining negative values which make impossible the calculation of the thermal power transferred in the steam generator (Figure 12).

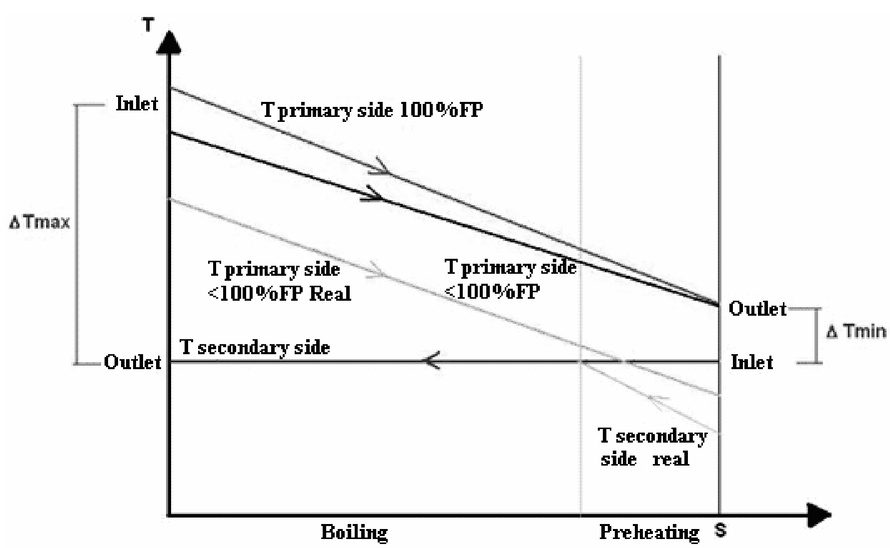

Fig. 12 T-S diagram for the steam generator

However, the steam generator simplified model abides by the reality, answers correctly to the analyzed regimes and can be easily used in the study of any transitory regimes.

In order to control the liquid level in the steam generator, a PI (Proportional Integrator) block was used. This block integrates the input signal, which is the difference between the liquid mass corresponsive to the level set point and the liquid mass corresponsive to the current steam generator liquid level. The output is directly the flow correction needed for the feed water flow.

The Delay block eliminates the errors occurred at the first integration step, errors that first propagated, by applying a delay to the input received from the PI block.

The software used for the steam generator analysis in this paper, acslXtreme, proved to be ideal for the performed analysis, providing a wide scale of advantages compared to the older variant ACSL 11.8, and even to MMS. It offers the possibility to realize and study the functioning of systems or parts of systems with block diagrams, in an easy and friendly manner to the user. The disadvantage from the power engineering point of view, and especially nuclear engineering, is that it does not contain a library with commonly used predefined modules (blocks) in this field (pipes, actuators, equipment etc.), but this library can easily be realized.

7. References

[1]. The Elaboration of the Data Base and Software Package for the Calculation of the Heavy Water Thermodynamic Properties, *CITON* contract no. 5/31.01.2001

[2]. Mathematical Modeling of the Process Components and Systems from CANDU 600 NPP – The Steam Generator, *FE-SITON* contract no. 12 007/23.03.2002, additional act no. 3/2004

[3]. The Adaptation and/or Elaboration of MMS Modules for the Operational Dynamic Regimes Study of the Cernavoda NPP Components and Systems, *CCEPM-CITON* contract no. 14-2/26.03.2002

[4]. *Ilie Prisecaru, Daniel Dupleac, Ioana Opris,* Thermal Installations Transitory Processes Simulation, Bucharest, 2005

[5]. *PhD. Eng. Prof. Ilie Prisecaru,* NPP Systems Modeling (course), Bucharest, 2005

[6]. acslXtreme Documentation

[7]. MMS Documentation