SIMULATION OF THE DYNAMICS OF A LWR POWER PLANT WITH THE USE OF A HYBRID COMPUTING SYSTEM
J. Machaliček, J. Sedláček

SIMULATION OF THE DYNAMICS OF A LWR POWER PLANT WITH
THE USE OF A HYBRID COMPUTING SYSTEM

Reg. č. ÚVTEI 73307

ŠKODA WORKS
Nuclear Power Construction Department, Information Centre
PLZEŇ, CZECHOSLOVAKIA
Abstract.

This report deals with the simulation of the dynamics of the primary loop of the nuclear power plant with light water reactor using the hybrid computing system. The mathematical model serving as a basis for the design of the analog computer circuit diagram, the method of analog connections and control program checking are described. A test problem and its solution are presented.

Hybrid computing system LAI 500 was used to solve the presented problem.
1. Introduction.

The simplified model of the primary loop dynamics simulation was chosen to verify the convenience of the use of the hybrid computation system to the solution of problems associated with the nuclear power plant dynamics. The problem is used in this report to illustrate in detail the classical approach to the hybrid simulation. Especially emphasized is the computer oriented part of the problem - checking of a computing model realized in the analog part of the hybrid computation system with the use of the language HOI (Hytrane Operations Interpreter) and description of the FORTRAN program controlling simulations and outputs of results.

The problem was solved in cooperation with the Technical Cybernetics Group of the Skoda Works Central Research Institute and the Nuclear Plant Heat Engineering Group of the Skoda Works Nuclear Power Plant Division.
2. Mathematical model.

For the analysis of the dynamic properties of the nuclear power plant primary loop we use the method based on the construction of differential equations describing individual part of the system. The system of differential equations for a given simulation dealing with the behaviour of the system subject to varying perturbations is derived supposing average conditions. Further we suppose that during all the transition period the flow volume in the primary circuit and the temperature of the secondary medium in the steam generator are constant. These assumptions are limiting in our simulation of the primary loop dynamics.

2.1. Reactor point kinetics equations.

Reactor point kinetics with delayed neutrons is described by equations

\[
\frac{dn(t)}{dt} = \delta \varphi(t) \cdot n(t) - \sum_{j=1}^{6} \frac{dc_j(t)}{dt}
\]

(1)

\[
\frac{dc_j(t)}{dt} = -\beta_j \cdot n(t) - \lambda_j \cdot c_j(t)
\]

(2)

The time dependence of the number of neutrons is determined by both prompt and delayed neutrons. Equations (1) and (2) form a system of linear differential equations of the first order, generally with variable coefficients depending on reactivity \( \delta \varphi(t) \). The reactivity \( \delta \varphi(t) \) is defined as
where \( k(t) \) is a multiplication coefficient. From the values of the multiplication coefficient \( k(t) \) or the reactivity \( \delta \phi (t) \) we can make conclusions about the state of the reactor. For the purposes of computations the total reactivity is usually expressed as a sum of partial reactivities,

\[
\delta \phi (t) = \delta \phi_f (t) + \delta \phi_p (t) + \delta \phi_t (t) + \delta \phi_c (t)
\]

where \( \delta \phi_t (t) \) denotes temperature contribution to reactivity,
\( \delta \phi_p (t) \) denotes reactivity involving reactor poisoning,
\( \delta \phi_f (t) \) denotes the excess of reactivity in the fuel,
\( \delta \phi_c (t) \) denotes the contribution of control rods reactivity.

Although the reactivity coefficient \( \delta \phi_f (t) \) is time dependent — it depends e.g. on the fuel burn-up — we can regard it constant during a short time period. The same holds for reactor poisoning. Therefore if we neglect their time variations, then all reactivity changes depend on the effects of fuel temperature and control rod positions changes.

Reactivity change caused by the fuel temperature change can be described by the equation
\[ \delta p(t) = \alpha_r (T_f(t) - T_0) \]  
where \( T_0 \) is the reference fuel temperature.

Now, we can write equation (4) in the form

\[ \delta \phi(t) = \phi + \alpha T_f(t) + \mu(t) \]  
where

\[ \mu(t) = \delta \phi_c(t) - \delta \phi_c(0) \]

\[ \phi = \delta \phi_c(0) + \delta \phi_p + \delta \phi_f - \alpha_r T_0 \]

2.2. **Equation of thermal balance in the fuel element.**

If we regard the fuel element, cladding and others as a whole, then the differential equation describing the heat transfer in the fuel element is

\[ M_f C_f \frac{dT_f(t)}{dt} = n(t) \cdot \Delta H_f - \alpha A (T_f(t) - T_c(t)) \]  

In (9) we suppose that the heat generation is proportional to the neutron flux and \( \Delta H_f \) denotes the energy released in fission.

2.3. **Heat transfer from fuel element to coolant.**

Equation describing heat transfer between the fuel
element and the circulating coolant has a form

\[
M_c \, c_c \, \frac{dT_c(t)}{dt} = A \left( T_f(t) - T_c(t) \right) - W_c \, c_c \left( T_{oc}(t) - T_{ic}(t) \right)
\]

(10)

To simplify the last equation we linearize it using the average temperature of the coolant circulating through the core

\[
T_c(t) = \frac{T_{ic}(t) + T_{oc}(t)}{2}
\]

(11)

Substituting (11) into (10) and rearranging, we get

\[
\frac{dT_c(t)}{dt} + \frac{A + 2 \, W_c \, c_c}{M_c \, c_c} \, T_c(t) = A \, T_f(t) + 2 \, W_c \, c_c \, T_{ic}(t)
\]

(12)

2.4. **Mixing in collecting chambers.**

For collecting chambers considered as mixing tanks we can write down the following equations:

\[
M_i \, \frac{dT_{ic}(t)}{dt} = W_c \left( T_{oc}(t) - T_{ic}(t) \right)
\]

(13)

\[
M_i \, \frac{dT_{ic}(t)}{dt} = W_c \left( T_i(t) - T_{ic}(t) \right)
\]

(14)

where \( T_{ic}(t) \) is a temperature of the coolant in the inlet collecting chamber and \( T_{oc}(t) \) is a temperature of the coolant in the outlet collecting chamber.

Substituting (11) into (13) we get

\[
M_i \, \frac{dT_{ic}(t)}{dt} = W_c \left( 2 \, T_c(t) - T_{ic}(t) - T_{oc}(t) \right)
\]

(15)
2.5. **Transport delay.**

To simulate the coolant flow in the piping between the outlet collecting chamber and the steam generator inlet and between the steam generator outlet and the inlet collecting chamber it is necessary to take into account the transport delay \( T \) determined by the coolant velocity \( v \) and the piping length \( l \). We can write

\[
T_{ix}(t) = T_0 (t - \tau_o) \quad (16)
\]

\[
T_i(t) = T_{ox} (t - \tau_i) \quad (17)
\]

where

\[
\tau_o = \frac{l_o}{v_o} \quad \tau_i = \frac{l_i}{v_i} \quad (18)
\]

2.6. **Heat transfer in the steam generator.**

This equation is similar to (10).

\[
M_x c_x \frac{dT_x(t)}{dt} = W_0 c_c (T_{ix}(t) - T_{ox}(t)) - d_x A_x (T_x(t) - T_s) \quad (19)
\]

where index \( x \) corresponds to the steam generator and \( T_s \) is the average temperature of the secondary medium in the steam generator.

We introduce the average temperature \( T_x(t) \) and linearize equation (19)

\[
T_x(t) = \frac{T_{ox}(t) - T_{ix}(t)}{2} \quad (20)
\]
2.7. Control system.

The automatic control of the reactor power is accomplished by the motion of control rods in accordance with the actuating signal representing the difference between demanded and actual power levels. Instantaneous power is considered as directly proportional to neutron flux. Demanded value of the controlled variable is set up by the programmed power regulator which can be described by equations

\[ n_c(t) = T_c k_c E(t) + k_c \int_0^t E(t) \, dt \]  \hspace{1cm} (22)

\[ E(t) = T_{ref} - T_{ave}(t) \]  \hspace{1cm} (23)

where \( T_c \) is a time constant and \( k_c \) an amplification constant.

Comparing circuit defined mathematically by equation (23) compares the reference coolant temperature with the average coolant temperature and at its output we obtain the difference signal \( E(t) \). The reference coolant temperature predeterminates the demanded power. The average coolant temperature is defined as

\[ T_{ave}(t) = \frac{T_{ox}(t) + T_{oc}(t)}{2} \]  \hspace{1cm} (24)
The contribution to reactivity depending on the control rod position is generally described by a nonlinear function. To simplify the problem we suppose a linear dependence

\[ f_p(t) = \frac{k_m}{s(1 + \zeta_m s)} \left( \frac{n_o(t) - n(t)}{n(t)} \right) \]  

where \( \zeta_m \) is a time constant, \( s \) an operator and \( k_m \) a modified amplification constant.

Using \( \mu(t) \) defined by equation (7) and adapting equation (25) we derive the differential equation describing control rods:

\[ \frac{d^2 \mu(t)}{dt^2} = \frac{1}{\zeta_m} \frac{d \mu(t)}{dt} - \frac{k_m}{\zeta_m} \left( \frac{n_o(t) - n(t)}{n(t)} \right) \]  

This equation completes the mathematical model of a system illustrated in Fig.1.

On the basis of the mathematical model presented above we have suggested the analog wiring diagram (see fig. 3,4) and logical control flow sheet (see Fig.4).

For values \( n^*(t) \), \( k^* \) and \( n_0^*(t) \) appearing in the analog wiring diagram it holds

\[ n^*(t) = \frac{n(t)}{n_m} \]  

where \( n_m \) is a maximum value of \( n(t) \).
Analog elements are denoted in agreement with the actual connections in the analog part of the hybrid computing system EAI 690 and it is necessary to point out that potentiometers 1-39 and used digital-analog (D/A) and analog-digital (A/D) converters invert.

Logical connection safeguards the "accident protection": If neutron flux reaches the prescribed maximum value, the relay disconnects the closed circuit and the negative reactivity simulating the fall of control rods is introduced into the reactor.

3. Hybrid simulation.

For the solution of our problem we adopted the classical approach, mostly used for hybrid simulations. Using the mathematical model we propose the analog wiring diagram (see Fig. 2,3), then we estimate standards and perform the off-line checking.

To check the correctness of the wiring diagram and its realization on the programming desk we used the programming language HOI. Its use is advantageous for it enables both-sided communication between the computer and the programmer.

Program in HOI checking the analog wiring is subdivided into blocks and these are composed of individual steps. Each command is labeled by a decimal number AA.BBB, where AA is the block number and BBB is the step number (A,B are digits 0-9). Programs in HOI follow the standard program; therefore in blocks denoted in the same way we can always find specific types of commands, which makes the orientation in the program easier.
Block 1 is a so called "control block" controlling the program operation. First of all, necessary constants are determined (in block: 10, 11, 12) and differential equations are described (in block 13). Equations of the mathematical model are used to determine values of potentiometer coefficients (block 21), inputs to integrators (block 22), outputs of all amplifiers (block 23) and outputs of potentiometers (block 31).

These values are compared with those determined using the analog wiring diagram - in block 30 with outputs of inverters and in block 32 with inputs of integrators - and this is the proper off-line checking. If compared values are different, then error message indicating the relevant step and both different values is printed. An appearance of the error message implies either an error in the program or the analog wiring diagram does not represent correctly the mathematical model.

After the off-line checking is completed, on-line checking takes place. Program sets up D/A converters (block 20), potentiometers (block 21) and compares actual outputs of inverters (block 30), potentiometers (block 31) and inputs to integrators (block 32) with values computed on the basis of output values of units specified as inputs to these elements.

For example, in Fig. 2 outputs of potentiometers 60, 61 and 66 are fed to input of integrator 60 and this part of the connection is checked by the command

\[
32.060 = 1D060 = 1P060 + 1P061 + 1P066
\]
It means that values on outputs of potentiometers 60, 61, 66 are measured, summed up and compared with the value measured on input to integrator 60.

On-line checking verifies the correctness of the actual connection in the analog part of the hybrid computing system and reveals defective analog units, poor contacts, partially pulled-out connectors etc., by printing a message of the same form as in the off-line checking.

If neither the off-line nor the on-line checking reveals any errors, we are assured that the analog wiring diagram represents correctly the mathematical model, actual wiring corresponds to the diagram and units work with given static accuracy.

Programming language HOI allows to intervene into the process proceeding in the hybrid computing system, to change parameters easily and therefore to check different alternatives interesting for the user. Further, it allows to correct program easily as commands are stored in the computer memory in a non-compiled form, and are interpreted at the moment of command execution. Corrections are performed by writing a new command with block and step numbers on the control typewriter and computer replaces the old, unsatisfactory command by the new one without a necessity to compile the program.

Program controlling the proper simulation was written in FORTRAN. Its flow sheet is shown in Fig. 4. After input of data and their print-out necessary constants are computed and potentiometers and D/A
inverters are set up. Then the hybrid computing system is switched over to the "initial condition" (IC) mode, integration rate is determined, parallel logic is released and initial values of requested functions are read. In our case they are neutron flux, fuel temperature, temperatures of coolant in the core, in the outlet collecting chamber, in the steam generator and in the inlet collecting chamber, total reactivity and temperature deviation $E(t)$. The analog part of the hybrid computing system is switched over to the integration (OP) mode and the system of differential equations is solved. In time increments $\Delta t$ the values of the above mentioned functions are scanned from A/D inverters and function values after equations 15 and 16 are set up on D/A inverters. The initial value of the time increment $\Delta t$ is chosen so as to allow to describe changes in neutron flux and reactivity. After time $T_1$, determined with respect to the character of both above mentioned functions, time increment is suitably prolonged. When the requested final time $T$ is reached, the analog part of the hybrid computing system is switched over to the IC mode and results are printed out.

In programs for the hybrid computing system are used subroutines controlling the analog part and providing transfers of information from analog to digital part and vice versa (their names begin by letter Q). Hybrid subroutines used in the solution of our problem are listed in Tab.1.

Other subroutines used in the program are:

MEROGA - measures a time interval $\Delta t$

MSPIT - determines the maximum values of a real function
SPL3 - determines coefficients of cubic spline interpolating of a given function
SPLINE - provides a graphical output.

As a graphical output the terminal TEKTRONIX 4002 A is used. This device allows to display graphically on the picture tube results stored in the hybrid computing system digital part memory to describe them and to easily obtain the photocopies.

4. Test problem.

Program was tested on a test problem simulating the primary loop dynamics following the model illustrated in Fig.1. Values of parameters are listed in Table 1.

4.1. Test problem results.

Results of a series of solved problems obtained after successful static solution are presented in Figs. 5 - 12. The basic coolant reference temperature of the proposed system was 260°C; this value is in agreement with initial conditions and with the setting up of potentiometers. Therefore in the static solution with the reference temperature of 260°C the relative neutron flux must stabilise at the value of 0.5 (see Fig.5). Fig.6 illustrates the dependence of the neutron flux on the coolant reference temperature. In Figs.7 - 10 are presented fuel temperatures $T_p(t)$, temperatures of the coolant in the core $T_c(t)$ and in the outlet collecting chamber $T_o(t)$, mean temperature of the coolant in the steam generator $T_x(t)$, the deviation of temperatures
\( E(t) \) and reactivities for reference temperatures 260 and 320°C. The results for qualities described above when control rods fall down are presented in figs. 11 and 12.

5. Conclusions.

Presented problem in the primary loop simulation aimed to determine the dependence of system response on stepwise reactivity changes during reaching the demanded power, to determine reactor response to the control rods position changes, to estimate the possibility of manual control, and to determine reactor behaviour during shutdown. This task was solved successfully.

Results are sufficiently accurate and therefore satisfactory for the general analysis of system behaviour. Further, the suitability of the hybrid computing system for the dynamic systems analysis was confirmed. Its main advantage is the speed of the hybrid computing system analog part and the possibility of a parallel work - the whole system of differential equations describing a dynamic system is solved simultaneously. Further advantage of the hybrid computing system in comparison with a digital one is the possibility of the former to scan continuous functions; these functions describe better the actual system than discontinuous ones do.

It is necessary to point out that it is more laborious to perform hybrid simulations than digital ones: the analog model must be connected manually and checked, the digital part must be checked and then both parts must be checked simultaneously.
We can conclude that the hybrid computing system can serve as the most efficient tool for simulations of systems for which a lot of variants and dependencies on parameters are to be studied.
List of symbols.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td>transfer area</td>
</tr>
<tr>
<td>( C )</td>
<td>specific heat</td>
</tr>
<tr>
<td>( \varepsilon_j )</td>
<td>concentration of neutrons of the ( j )-th delayed neutron group</td>
</tr>
<tr>
<td>( k )</td>
<td>reactivity</td>
</tr>
<tr>
<td>( m_0 )</td>
<td>mass of coolant in the reactor</td>
</tr>
<tr>
<td>( m_i )</td>
<td>mass of coolant in the inlet chamber</td>
</tr>
<tr>
<td>( m_o )</td>
<td>mass of coolant in the outlet chamber</td>
</tr>
<tr>
<td>( m_x )</td>
<td>mass of coolant in steam generator</td>
</tr>
<tr>
<td>( n_t )</td>
<td>mass of fuel, moderator etc.</td>
</tr>
<tr>
<td>( n )</td>
<td>operator</td>
</tr>
<tr>
<td>( T_c )</td>
<td>mean temperature of coolant in the reactor</td>
</tr>
<tr>
<td>( T_f )</td>
<td>mean temperature of fuel in the reactor</td>
</tr>
<tr>
<td>( T_i )</td>
<td>coolant temperature at reactor inlet (in the inlet collecting chamber)</td>
</tr>
<tr>
<td>( T_o )</td>
<td>coolant temperature at reactor outlet (in the outlet collecting chamber)</td>
</tr>
<tr>
<td>( T_s )</td>
<td>mean temperature of secondary coolant in steam generator</td>
</tr>
<tr>
<td>( T_x )</td>
<td>mean temperature of coolant in steam generator</td>
</tr>
<tr>
<td>( T_{ic} )</td>
<td>mean coolant temperature at reactor inlet</td>
</tr>
<tr>
<td>( T_{oc} )</td>
<td>mean coolant temperature at reactor outlet</td>
</tr>
</tbody>
</table>
- reference temperature
T_{ave} °C - mean temperature of coolant in the system
W [W m^{-2} K^{-1}] - total heat transfer coefficient in the core
v [m s^{-1}] - mean velocity of coolant
w_c [kg s^{-1}] - coolant flow rate
x [-] - control rod position
j [-] - index of delayed neutron group
l_i [m] - effective length of inlet piping
l_o [m] - effective length of outlet piping
l [s] - effective neutron lifetime
n [neutron m^{-3}] - volume density of neutrons
n^* [-] - reduced density of neutrons
n_m [neutron m^{-3}] - maximum allowed neutron density
n_n [neutron m^{-3}] - demanded neutron density
v_o [m s^{-1}] - mean velocity of coolant in the inlet piping system
v_j [m s^{-1}] - mean velocity of coolant in the outlet piping system
\alpha [°C^{-1}] - temperature coefficient of reactivity
\beta_j [-] - yield of delayed neutrons of j-th group
\delta \phi [-] - reactivity
\delta \phi_t [-] - temperature contribution to reactivity
\delta \phi_p [-] - reactivity involving reactor poisoning
\delta \phi_e [-] - excess reactivity
\delta \phi_c [-] - control rods reactivity
\( \varepsilon(t) \text{ [°C]} \) - difference signal

\( \lambda_j \text{ [-]} \) - decay constant of the j-th delayed neutron group

\( \mu(t) \text{ [-]} \) - deviation of control rods reactivity from the initial value

\( \tau_i \text{ [s]} \) - time constant of the inlet piping system

\( \tau_o \text{ [s]} \) - time constant of the outlet piping system
References.

/1/ Simulation of the Primary Loop of a Nuclear Power Plant with Small General Purpose Analog Computer.
SAI Applications Manual, Bulletin No. 6500

/2/ Kotva L.: Introduction to hybrid computers programming.


/4/ SAI Manuals - 563, 767.

/5/ Ariel C.: Status of Related Reaction Data Panel on Reaction - Product Data, Cologne, Nov. 1972, P.M.
### Table 1. List of basic actions

<table>
<thead>
<tr>
<th>Code</th>
<th>Action</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSCH</td>
<td>Setting of the parallel logic</td>
<td>15 ms</td>
</tr>
<tr>
<td>C1</td>
<td>Setting of the &quot;initial condition&quot; mode</td>
<td>12 µs</td>
</tr>
<tr>
<td>C0P</td>
<td>Setting of the &quot;interaction&quot; mode</td>
<td>12 µs</td>
</tr>
<tr>
<td>CSPL</td>
<td>Setting of the &quot;potentiometers setting up&quot; mode</td>
<td>15 ms</td>
</tr>
<tr>
<td>CGH</td>
<td>Setting of the &quot;old&quot; mode</td>
<td>15 ms</td>
</tr>
<tr>
<td>CSSCH</td>
<td>Interaction via control line</td>
<td>15 ms</td>
</tr>
<tr>
<td>CSSCP</td>
<td>16 times faster interaction</td>
<td>15 µs</td>
</tr>
<tr>
<td>QRML</td>
<td>Reading of the A/D converter</td>
<td>116 µs</td>
</tr>
<tr>
<td>ANPL</td>
<td>Setting of the D/A converter</td>
<td>121 µs</td>
</tr>
<tr>
<td>GKLL</td>
<td>Testing of &quot;sense line&quot;</td>
<td>25 µs</td>
</tr>
<tr>
<td>QCLL</td>
<td>Setting of the &quot;control line&quot;</td>
<td>45 µs</td>
</tr>
<tr>
<td>QCMPL</td>
<td>Reading of computer</td>
<td>57 µs</td>
</tr>
<tr>
<td>QCMCH</td>
<td>Setting of the electronic potentiometer</td>
<td>95 µs</td>
</tr>
<tr>
<td>QCMD</td>
<td>Reading of the electronic potentiometer</td>
<td>95 µs</td>
</tr>
<tr>
<td>QWMX</td>
<td>Initiation of the analog computer</td>
<td>100 µs</td>
</tr>
<tr>
<td>HFL</td>
<td>Setting of the servopotentiometer</td>
<td>300 ms</td>
</tr>
<tr>
<td>HFLH</td>
<td>Setting of the servomechanical relay</td>
<td>3 ms</td>
</tr>
</tbody>
</table>

**control line** - transfers one-bit signal from digital to analog part of the hybrid computing system

**sense line** - transfers one-bit signal from analog to digital part of the hybrid computing system
Table 2. Values of test problem parameters.

<table>
<thead>
<tr>
<th>No. of potentiometer</th>
<th>Parameter name</th>
<th>On-line</th>
<th>Simulation run no.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\beta_1 / (1^* . 10)$</td>
<td>0.0226</td>
<td>0.0226</td>
</tr>
<tr>
<td>2</td>
<td>$\lambda_1$</td>
<td>0.0124</td>
<td>0.0124</td>
</tr>
<tr>
<td>6</td>
<td>$\beta_2 / (1^* . 10)$</td>
<td>0.015</td>
<td>0.015</td>
</tr>
<tr>
<td>7</td>
<td>$\lambda_2$</td>
<td>0.0305</td>
<td>0.0305</td>
</tr>
<tr>
<td>11</td>
<td>$\beta_3 / (1^* . 100)$</td>
<td>0.0134</td>
<td>0.0134</td>
</tr>
<tr>
<td>12</td>
<td>$\lambda_3$</td>
<td>0.111</td>
<td>0.111</td>
</tr>
<tr>
<td>16</td>
<td>$\beta_4 / (1^* . 100)$</td>
<td>0.027</td>
<td>0.027</td>
</tr>
<tr>
<td>17</td>
<td>$\lambda_4$</td>
<td>0.301</td>
<td>0.301</td>
</tr>
<tr>
<td>21</td>
<td>$\beta_5 / (1^* . 100)$</td>
<td>0.00788</td>
<td>0.00788</td>
</tr>
<tr>
<td>22</td>
<td>$\lambda_5 / 10$</td>
<td>0.114</td>
<td>0.114</td>
</tr>
<tr>
<td>26</td>
<td>$\beta_6 / (1^* . 10)$</td>
<td>0.0288</td>
<td>0.0288</td>
</tr>
<tr>
<td>27</td>
<td>$\lambda_6 / 10$</td>
<td>0.301</td>
<td>0.301</td>
</tr>
<tr>
<td>45, 46, 47</td>
<td>scaling</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>48</td>
<td>$1 / (1^* . 2000)$</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>51</td>
<td>$K_m / \bar{\alpha}_m$</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>52</td>
<td>$1 / 10 . \bar{\alpha}_m$</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>53</td>
<td>20 K</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>60</td>
<td>$UA/L_f C_f$</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>61</td>
<td>$n_m H_f/2000 L_f C_f$</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>62</td>
<td>$2 UA/L_c C_c$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>63</td>
<td>$4 \times 10^4 (\alpha)$</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>No. of potentiometer</td>
<td>Parameter name</td>
<td>On-line</td>
<td>Simulation run no.1</td>
</tr>
<tr>
<td>----------------------</td>
<td>---------------------------------------</td>
<td>---------</td>
<td>---------------------</td>
</tr>
<tr>
<td>64</td>
<td>( T_p , (o) / 2000 )</td>
<td>0.6</td>
<td>0.26</td>
</tr>
<tr>
<td>65</td>
<td>( T_c , (o) / 2000 )</td>
<td>0.8</td>
<td>0.26</td>
</tr>
<tr>
<td>66</td>
<td>( \frac{U_A}{2} , e , g , \gamma )</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>67</td>
<td>( \left( \frac{U_A - 2 , e , g , \gamma}{C_c} \right) / 10 , \tilde{N_c} \tilde{C}_c )</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>68</td>
<td>( 2 , \frac{\tilde{C}_c}{\tilde{N_c}} )</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>69</td>
<td>( \frac{e}{5} , \tilde{N_c} \tilde{C}_c )</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>70</td>
<td>( T_0 , (o) / 1000 )</td>
<td>0.601</td>
<td>0.316</td>
</tr>
<tr>
<td>71, 72</td>
<td>( \frac{e}{T_0} )</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>73</td>
<td>scaling</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>74</td>
<td>( \frac{U_A - 2 , e , g , \gamma}{C_c} )</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>75</td>
<td>( \tilde{T}_x , (o) / 1000 )</td>
<td>0.8</td>
<td>0.26</td>
</tr>
<tr>
<td>76</td>
<td>( \frac{\tilde{C}_c}{\tilde{T}_x} )</td>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>77</td>
<td>( \left( \frac{U_A - 2 , e , g , \gamma}{C_c} \right) / \tilde{T}_x \tilde{C}_c )</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>78</td>
<td>scaling</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>79</td>
<td>( T_{ref} / 1000 )</td>
<td>0.5</td>
<td>0.26</td>
</tr>
<tr>
<td>80</td>
<td>scaling</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>81</td>
<td>( 2 , n_0 , (o) / 10 )</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>82</td>
<td>( 200 , n_c )</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>83</td>
<td>( 200 , n_0 ) , \gamma , n_c )</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>84</td>
<td>( T_{1c} , (o) / 1000 )</td>
<td>0.6</td>
<td>0.204</td>
</tr>
<tr>
<td>86, 87</td>
<td>( \frac{e}{i} )</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Introduction</td>
<td>3</td>
</tr>
<tr>
<td>2. Mathematical model</td>
<td>4</td>
</tr>
<tr>
<td>2.1. Reactor point kinetics equations</td>
<td>4-6</td>
</tr>
<tr>
<td>2.2. Equation of the thermal balance in fuel element</td>
<td>6</td>
</tr>
<tr>
<td>2.3. Heat transfer from fuel element to coolant</td>
<td>6-7</td>
</tr>
<tr>
<td>2.4. Mixing in collecting chambers</td>
<td>7-8</td>
</tr>
<tr>
<td>2.5. Transport delay</td>
<td>8</td>
</tr>
<tr>
<td>2.6. Heat transfer in the steam generator</td>
<td>8-9</td>
</tr>
<tr>
<td>2.7. Control system</td>
<td>9-11</td>
</tr>
<tr>
<td>3. Hybrid simulation</td>
<td>11-15</td>
</tr>
<tr>
<td>4. Test problem</td>
<td>15</td>
</tr>
<tr>
<td>4.1. Test problem results</td>
<td>15-16</td>
</tr>
<tr>
<td>5. Conclusions</td>
<td>16-17</td>
</tr>
<tr>
<td>List of symbols</td>
<td>18-20</td>
</tr>
<tr>
<td>References</td>
<td>21</td>
</tr>
<tr>
<td>Tables</td>
<td>22-24</td>
</tr>
<tr>
<td>Figures</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 1: Model of the system
Fig. 2: Analog wiring diagram
Fig. 3: Analog wiring diagram

1. $\beta_1 \rightarrow \frac{10}{1}$
2. $\lambda_1 \rightarrow 0.1$
3. $c_1 \rightarrow \frac{n_m \cdot 10}{m}$
4. $20 \delta k \cdot n^*$
5. $6. \beta_2 \rightarrow \frac{10}{1}$
6. $\lambda_2 \rightarrow 0.1$
7. $c_2 \rightarrow \frac{n_m \cdot 10}{m}$
8. $11. \beta_3 \rightarrow \frac{100}{1}$
9. $\lambda_3 \rightarrow 0.1$
10. $c_3 \rightarrow \frac{n_m \cdot 10}{m}$
11. $16. \beta_4 \rightarrow \frac{100}{1}$
12. $\lambda_4 \rightarrow 0.1$
13. $c_4 \rightarrow \frac{n_m \cdot 10}{m}$
14. $21. \beta_5 \rightarrow \frac{100}{1}$
15. $\lambda_5 \rightarrow 0.1$
16. $c_5 \rightarrow \frac{n_m \cdot 10}{m}$
17. $26. \beta_6 \rightarrow \frac{10}{1}$
18. $\lambda_6 \rightarrow 0.1$
19. $c_6 \rightarrow \frac{n_m \cdot 10}{m}$
20. $n^*$
21. $+ \delta n^*$

Note: The diagram shows a series of electronic components and connections, with various symbols and labels indicating different parameters and connections.
Fig. 4: Logical control flowsheet

1. Input and print-out of data
2. Calculation of parameters
3. Setting up of potentiometers, D/A-1, D/A-2
4. Reading of A/D converters
5. "Integration" mode
   - Release of timer
6. $q' = \Delta t$?
   - No
   - Yes
     - Setting up of D/A-1, D/A-2
     - Reading of A/D converters
   - $t = T$?
     - No
     - Yes
     - "Initial condition" mode
     - Print-out of results
   - SENSW/4/ = "1"?
     - Yes
     - No
     - Plotting of results on a graphical terminal
7. K
NEUTRON FLUX

$T_{REF} = 260 ^\circ C$
Fig. 6

NEUTRON FLUX

$T_{REF} = 320 \degree C$
290\degree C
260\degree C
230\degree C
200\degree C

$t/Ls$
$T_{REF} = 260 \degree C$

Graph showing:
- $T_F$
- $T_O$
- $T_C$
- $T_X$
- $\varepsilon$

Time $t$ in seconds.
TOTAL REACTIVITY

$T_{REF} = 260 \, ^\circ C$
$T_{\text{REF}} = 320 \, ^\circ\text{C}$