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Development of Highly Modularized Object Oriented Real Time Engineering Simulator for the HANARO Research Reactor

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Abstracts

The PC based engineering simulator for the HANARO research reactor is being developed. This simulator runs faster than real time. The simulation program is coded in object oriented programming language and modularized highly. Simulator runs in MS Windows 98 environment and interacts with graphical user interface with the operator. Reactor is modeled by two point kinetics and thermal hydraulic behaviors are modeled in a simple form because the operational and accidental conditions are ordinary compared with the power plants. The results show reasonably good performance.

1. Introduction

The simulator in the engineering field is well known tool for demonstrating and verifying the design and the performance and for training of humans and for testing of equipment's and systems. Especially NPP full-scope simulators for operator training have been widespread since TMI-2 accident [4][5]. Contrarily there are a few simulators for the research reactor because the configuration of research reactor is changed frequently and many events for demonstration can be implemented using the real plant if it is supported by reactor design. HANARO has no simulator for training yet. Some events or experiments for training can not implemented at HANARO without any risk because HANARO is medium scale 30MWth research reactor. In this paper the PC based engineering concept simulator is introduced. The simulator models reactor, process systems, and instrumentation systems faster than real time. Although the main purpose is the operator training, it can be used for verification and validation tool for design change and

for test bed for controllers and field instruments by addition of input and output devices. The mathmatical model is based upon simulation code of KMRRSIM that simulates dynamics of the HANARO nuclear research reactor and predicts the transient's behavior of the reactor by solving a set of differential equations. So it inherits most assumptions made in the KMRRSIM and simplifies some models and expands to implement simulations efficiently in real time. The performance of the simulator is verified by comparing results with the KMRRSIM.

2. Scope and Assumptions

The simulator is PC (personal computer) based real time simulator and designed for following purposes:

- Operator training by demonstrating concepts and trends of wide range of normal and abnormal transients,
- Design analysis with simple procedure,
- Engineering studies for control design, set point study, and design change,
- Implement useful graphical use interface,
- Incorporate object oriented programming method for future development.

The simulator makes a number of simplifications and assumptions to implement of real time simulation as follows:

- The two point reactor kinetics model is used to describe the thermal neutron flux in the core. But the spatial effects are not considered.
- The Incompressibility assumption is used to de-couple the momentum and energy conservation equations. This assumption holds if variations in coolant density are negligible.
- Direct energy deposition in the coolant, reflector, pool, and reactor structure is neglected.
- Linear superposition approximation is assumed to hold when calculation the total reactivity.
- Dynamic equations with a time constant much smaller than 0.1 second are treated as instant.
- Dynamic equations with time constant between 0.01 and 0.1 second are assumed to have a 0.1 second time constant.
- The heat transfer coefficients are assumed to be constant.
- All temperature and flow elements are modeled as first order time lags.
- Primary cooling pumps and heat exchangers are assumed identical.
- Reactor regulating system and protection system is included.

3. Theory and Mathematical Models

The Basic Models were originated from the simulation code, KMRRSIM, and the other codes used for design of HANARO [1][2][6][7]. Two point kinetics model is used for reactor power calculation and a

reduced–node approach is used to model primary cooling system. The heat transfer is modeled in one-dimensional.

3.1 Reactor Kinetics

3.1.1 Two point neutron kinetics

Two Point kinetics model with six delayed neutron group and reactivity control from external sources such as control rods and feedback from moderator temperature, fuel temperature, and poisons is expressed by

$$\frac{dN_c}{dt} = \frac{(r_{tot} - g_c)}{\Lambda} N_c + \sum_{i=1}^{I} \frac{g_{ci}}{\Lambda} C_i - w \frac{a_{cr}}{\Lambda} (1 - t_{cr})(N_c - N_r) + S$$

$$\frac{dC_i}{dt} = l_{ci} (N_c - C_i)$$

Neutron power generated at the reflector zone is expressed by

$$\frac{dN_r}{dt} = \frac{1}{w} \left[\sum_{j=1}^{J} \frac{g_{dj}}{\Lambda} D_j + \frac{a_{rc}}{\Lambda} (1 - t_{rc})(N_c - N_r) - \frac{g_d}{\Lambda} N_r \right]$$

$$\frac{dD_j}{dt} = l_{dj} (N_c - D_j) .$$

3.1.2 Xenon and Iodine

The concentration of Xenon and Iodine is calculated using the following two equations:

$$\frac{dI}{dt} = l_I (N_c - I)$$

$$\frac{dX}{dt} = \frac{l_X + l_e}{g_I + g_X} (g_X N_c + g_I I) - (l_X + l_e N_c) X$$

3.1.3 Thermal Power

The energy released by the nuclear fission process appears as heat in the fuel. The concentration of each decay heat power is negligible so the fuel power is regarded as *Nc.*

The thermal power produced in the fuel is given by

$$Q_{tot} = N_c Q_o$$

So the thermal power produced in the core is expressed by

$$Q_c = Q_{tot} h_c$$

And the thermal power produced in the reflector region is expressed by

$$Q_r = Q_{tot} (1 - h_c)$$

3.2. Heat Transfer Model

3.2.1 Primary Cooling System

The theory of the thermal hydraulics of the mathematical model is the first-principle in mass and energy balance. Because the temperature and the pressure of the primary system are slightly higher than ordinary environment condition, the coolant system is regarded as single-phase subcooled liquid.

Figure 1 shows the loop diagram of the primary cooling system. The coolant comes into the pool in two directions. About 90 % of the coolant pass through the core and 10% of the coolant bypasses the reactor. The coolant flows upward in the core and the pool and then it is mixed at the chimney. The mixed coolant separated into two loops.

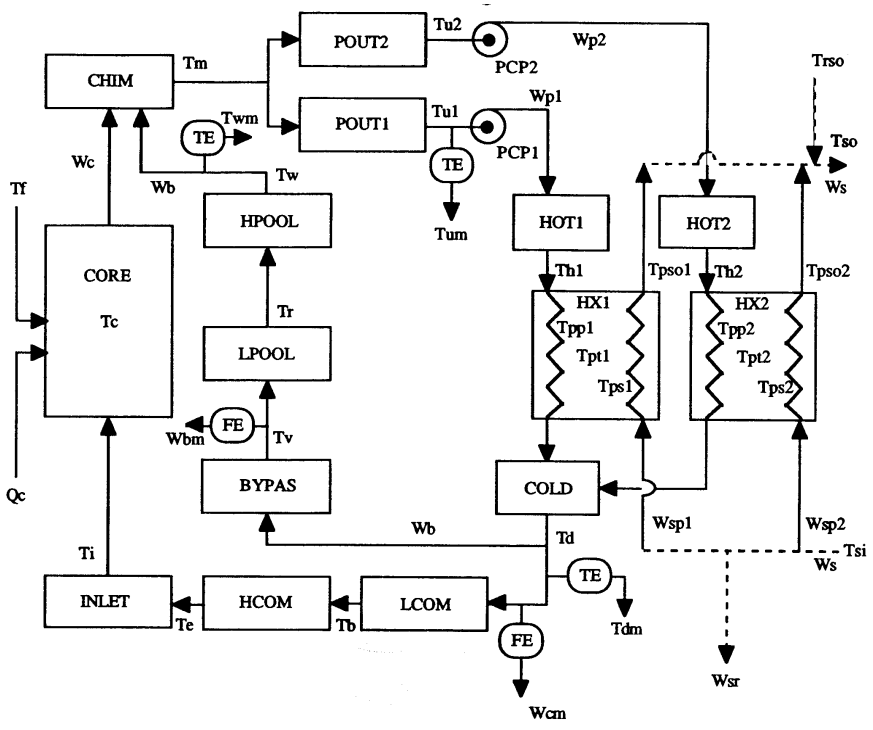

Figure 1 Loop diagram of the primary cooling system

The temperature at the surface of the fuel element is given by

$$M_{fe}C_{fe}\frac{dT_f(t)}{dt} = h_f Q_C - U_f A_f (T_f - T_C)$$

$$M_{fe}C_{fe} = M_f C_f + M_{cl}C_{cl}$$

Temperature of the coolant passing through the reactor flow channels is expressed by

$$M_c C_c \frac{dT_c(t)}{dt} = (1-h_f) Q_C + U_f A_f (T_f - T_C) - 2W_c C_c (T_c - T_i)$$

Temperature at chimney is

$$M_m C_c \frac{dT_m(t)}{dt} = W_c C_c (2T_c - T_i) + W_b C_c T_w - (W_{p1} + W_{p2}) C_c T_m$$

Temperature at hot legs (HOT1 andHOT2) is expressed by

$$M_{hk} C_c \frac{dT_{hk}(t)}{dt} = Q_{pk} + W_{pk} C_c (T_{uk} - T_{hk})$$

where the temperature is increased a little due to the heat produced in the pump.

The balance equations of the nodes in the piping system for the calculation of temperatures at each node are given as followings

$$M_{uk} C_c \frac{dT_{uk}(t)}{dt} = W_{pk} C_c (T_m - T_{uk})$$

$$M_d C_c \frac{dT_d(t)}{dt} = W_{p1} C_c (2T_{pp1} - T_{h1}) + W_{p2} C_c (2T_{pp2} - T_{h2}) - (W_{p1} + W_{p2}) C_c T_d$$

$$M_b C_c \frac{dT_b(t)}{dt} = W_c C_c (T_d - T_b)$$

$$M_e C_c \frac{dT_e(t)}{dt} = W_c C_c (T_b - T_e)$$

$$M_i C_c \frac{dT_i(t)}{dt} = W_c C_c (T_e - T_i)$$

$$M_v C_c \frac{dT_v(t)}{dt} = W_b C_c (T_d - T_v)$$

$$M_r C_c \frac{dT_r(t)}{dt} = W_b C_c (T_v - T_r)$$

$$M_w C_c \frac{dT_w(t)}{dt} = W_b C_c (T_r - T_w)$$

3.2.2 Heat Exchanger

The plate type heat exchanger used in both primary and reflector cooling system is modeled into three parts such as primary side coolant, plate metal, and secondary coolant.

For the primary cooling system the heat exchanger is modeled as

- Temperature at primary side

$$M_{ppk} C_c \frac{dT_{ppk}(t)}{dt} = 2W_{pk} C_c (T_{hk} - T_{ppk}) - U_{ppk} A_{ppk} (T_{ppk} - T_{ptk})$$

- Temperature at plate

$$M_{ptk} C_c \frac{dT_{ptk}(t)}{dt} = U_{ppk} A_{ppk} (T_{ppk} - T_{ptk}) - U_{psk} A_{psk} (T_{ptk} - T_{psk})$$

- Temperature at secondary side

$$M_{psk} C_c \frac{dT_{psk}(t)}{dt} = U_{psk} A_{psk} (T_{ptk} - T_{psk}) - 2W_{spk} C_c (T_{psok} - T_{si})$$

The heat exchanger for the reflector system is modeled also in a same scheme.

$$M_{rp} C_r \frac{dT_{rp}(t)}{dt} = 2W_r C_r (T_{ro} - T_{rp}) - U_{rp} A_{rp} (T_{rp} - T_{rt})$$

$$M_{rt} C_r \frac{dT_{rt}(t)}{dt} = U_{rp} A_{rp} (T_{rp} - T_{rt}) - U_{rs} A_{rs} (T_{rt} - T_{rs})$$

$$M_{rs} C_c \frac{dT_{rs}(t)}{dt} = U_{rs} A_{rs} (T_{rt} - T_{rs}) - 2W_{sr} C_c (T_{rs} - T_{si})$$

3.2.3 Reflector Cooling System

HANARO has reflector tank filled with D2O around the core and some heat is generated in it. The loop diagram of the reflector cooling system is given in figure 2.

The temperature of the coolant (D2O) is modeled as follows

$$M_{rc} C_r \frac{dT_{rc}(t)}{dt} = Q_r - 2W_r C_r (T_{rc} - T_{ri})$$

$$M_{ro}C_r \frac{dT_{ro}(t)}{dt} = W_r C_r (2T_{rc} - T_{ri} - T_{ro})$$

$$M_{ri}C_r \frac{dT_{ri}(t)}{dt} = W_r C_r (2T_{rp} - T_{ro} - T_{ri})$$

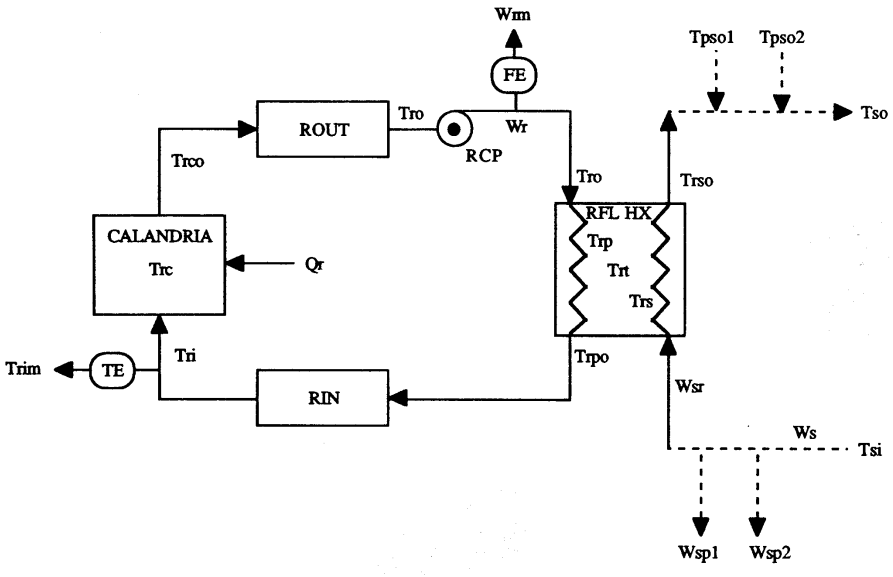

Figure 2 Loop diagram of reflector cooling system

3.2.4 Secondary cooling system

The heat conducted from the primary coolant through the heat exchanger is dissipated to the environment at the secondary cooling system. The secondary cooling system is a closed system and uses the cooling tower as heat sink. In this paper it is assumed that the cooling capacity of secondary cooling system is sufficient and the temperature of it is maintained in a constant value to eliminate the effects of environment condition, especially the weather.

The model for the temperature at the header of the secondary common return pipe is given as

$$T_{so} = \frac{W_{sp1}T_{pso1} + W_{sp2}T_{pso2} + W_{sr}T_{rso}}{W_s}$$

where

$$T_{psok} = 2T_{psk} - T_{si}$$

$$T_{rso} = 2T_{rs} - T_{si}$$

3.2.5 Temperature measuring instruments

All temperature measuring elements in the primary loop are modeled by a first order time delay with a time constant between 15 secs and 20 secs. The specific models for the instrument at primary heat exchanger outlet, high pool, and the secondary heat exchanger outlet temperatures, are given by

$$\frac{dT_{som}}{dt} = (T_{so} - T_{som}) / t_t$$

$$\frac{dT_{dm}}{dt} = (T_d - T_{dm}) / t_t$$

$$\frac{dT_{wm}}{dt} = (T_{r2} - T_{wm}) / t_t$$

3.3 Hydraulic Model

3.3.1 Primary cooling system

The continuity and mechanical energy balance equations are used to model the system with the empirical relationships between mass flow rate and acceleration, viscous pressure drop. The primary cooling system is modeled to 4 path loops and the hydraulics is represented by the four differential equations.

Equation for flow rate in pump #1 path and pump#2 path are given by

$$I_{p1}\frac{dW_{p1}}{dt} = (P_a - P_b) - K_{p1}W_{p1}^{g} - g[\,r(T_{u1})H_{u1} + r(T_{h1})H_{h1} + r(T_{pp1})H_{p1} + r(T_d)H_d\,] + \Delta P_{p1}$$

$$I_{p2}\frac{dW_{p2}}{dt} = (P_a - P_b) - K_{p2}W_{p2}^{g} - g[\,r(T_{u2})H_{u2} + r(T_{h2})H_{h2} + r(T_{pp2})H_{p2} + r(T_d)H_d\,] + \Delta P_{p2}$$

where γ=1.8

Equation for flow rate in core path is given by

$$I_c\frac{dW_c}{dt} = (P_b - P_a) - K_cW_c^{g} - g[\,r(T_b)H_b + r(T_e)H_e + r(T_i)H_i + r(T_{cd})H_c + r(T_m)H_m\,]$$

Equation for flow rate in bypass path is given by

$$I_b\frac{dW_b}{dt} = (P_b - P_a) - K_bW_b^{g} - g[\,r(T_v)H_v + r(T_r)H_r + r(T_w)H_w\,]$$

Material balance equation at junction (COLD) in differential form is

$$\frac{dW_{p1}}{dt} + \frac{dW_{p2}}{dt} - \frac{dW_c}{dt} - \frac{dW_b}{dt} = 0$$

With the above equations a set of ordinary differential equations are setup. And with the pump head a nd troque balance equations, the mass and energy balance can be solved.

3.3.2 Reflector system and Secondary System

These two systems are operated continuously during reactor operation without any variation of flow rate and temperature. So the pump hydraulic model was not setup for the simplicity.

3.4 Reactivity model

The reactivity is the sum of all the sources of reactivity, control rods, safety rods, fuel temperature feedback, and effects of xenon and is represented by

$$r_{tot} = r_{CAR} + r_x + r_f + r_c + r_{ext}$$

where

$$r_f = a_f[T_f(t) - T_{f0}]$$
$$r_c = a_c[T_c(t) - T_{c0}]$$
$$r_x = a_x \bullet X(t)$$
$$r_{ext} = external\_source$$

where T_{f0}, T_{c0} are temp erature at initial state.

3.5 Automatic Controller

Reactor power is controled by Multi-Loop Controller (MLC). The MLC calculates thermal power and neutron power and control the reactor power in accordance to the demand power automatically. The thermal and neutron power calculation is described in previous section. The control algorithm is given in figure 3. The entire algorithm blocks are implemented in the simulation model.

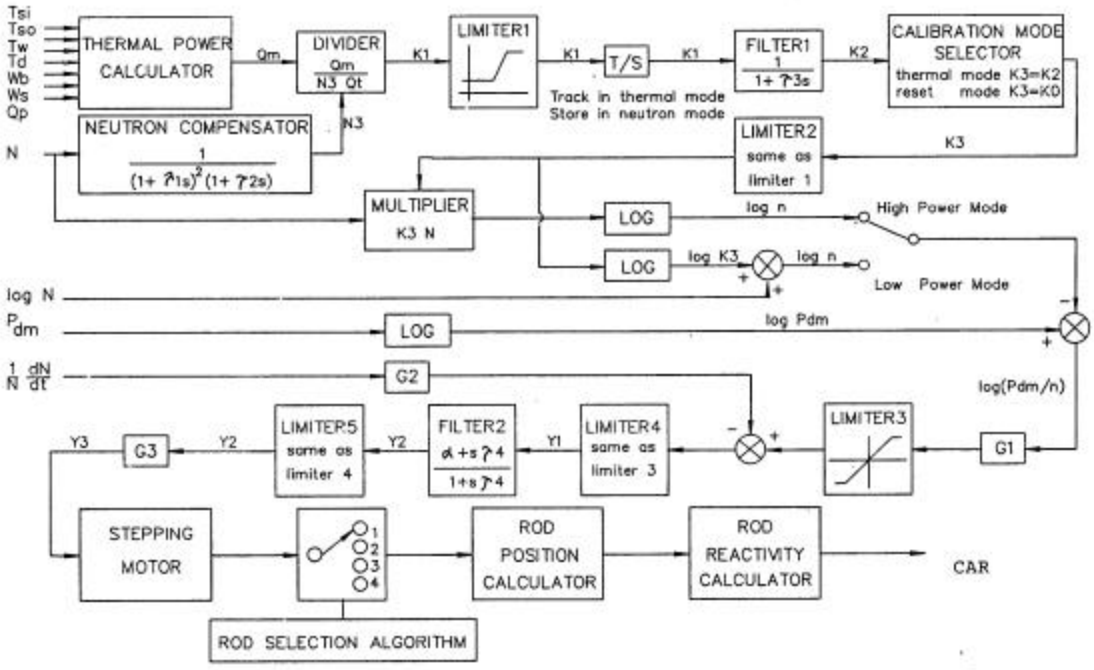

Figure 3 Control algorithm of HANARO

3.6 Protection Logic

In addition to the control algorithm the bi-stable protection logic also implemented in simulation model. Whenever the reactor condition is approaching or passing its design limit as witnessed by certain parameter exceeding a set margin, the reactor protection system is initiated by inserting all the control and safety rods. The variables considered are as follows

- Linear neutron power high
- LOG neutron power high
- Neutron AMP high volt low
- Lograte high
- RX outlet temp high
- Primary cooling system(PCS) Coolant flow high
- PCS coolant flow low
- PCS coolant flow low low
- PCS pressure low
- PCS pressure low low
- Manual trip

4. Simulation control and man machine Interface

The mathematical models are coded with object oriented programming language, Delphi [3]. Each functional block is coded into object and can be executable respectively. This structure makes developer

easy to develop and maintain the program. The timing is controlled by the high resolution timer object. The development tool, Delphi, supports the user interface capability such as controls and graphic tools. The graphical user interface was developed using these tools and National Instrument's Component Works Package [8]. Main display screen is shown in figure 4. Main screen is consisted of three panels. The first panel is control area in where the reactor control command buttons and input boxes are located. The second panel is display area in which the mimic and the trend graph are displayed. The last is the menu area in where the mode selection buttons are located. The mimic diagram is shown figure 5. The trend curves for the simulated parameters are displayed in the trend display module that is shown in figure 6. Five trending modules show temperature, flow rates, power levels of reactor system, primary system, secondary system, and reflector system.

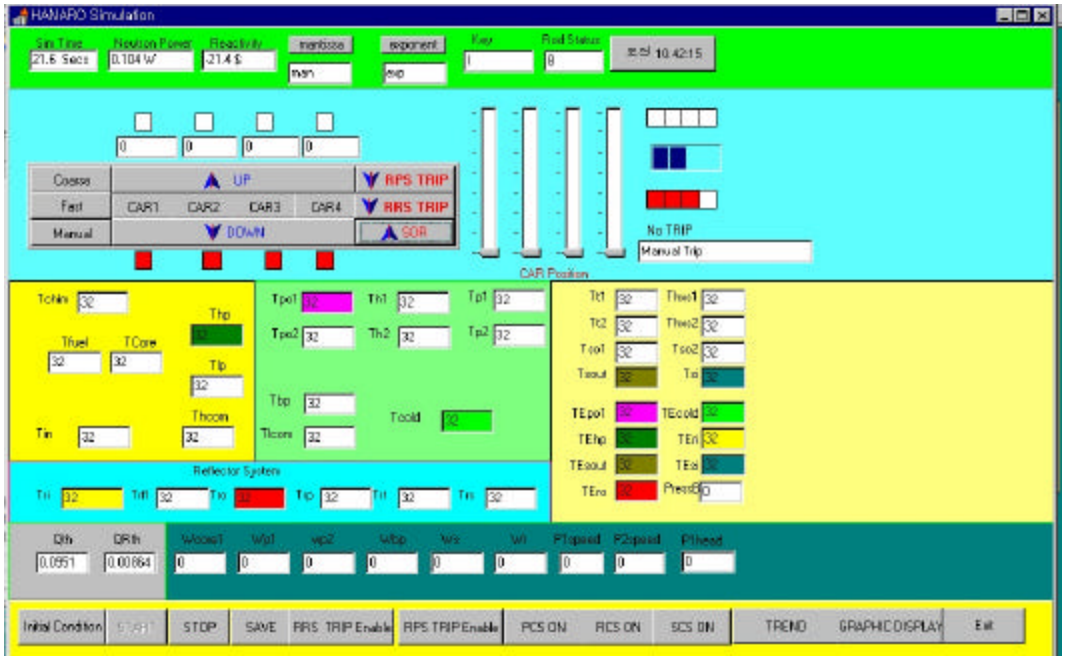

Figure 4 Main screen display

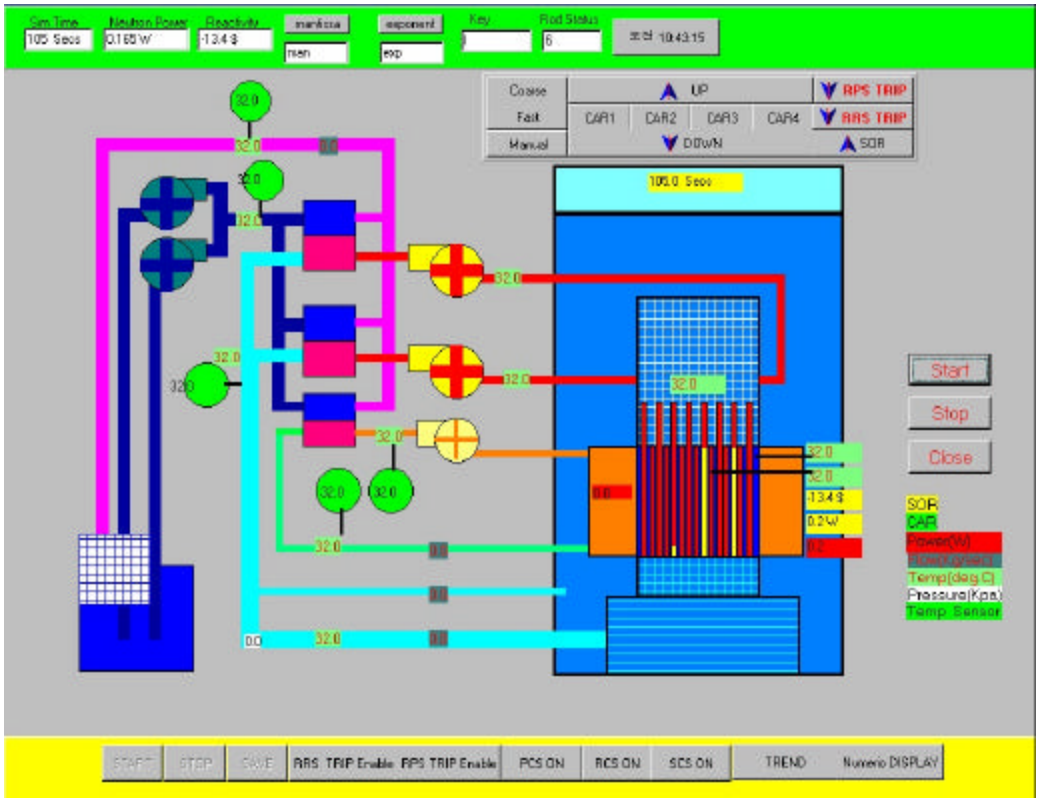

Figure 5 Mimic diagram

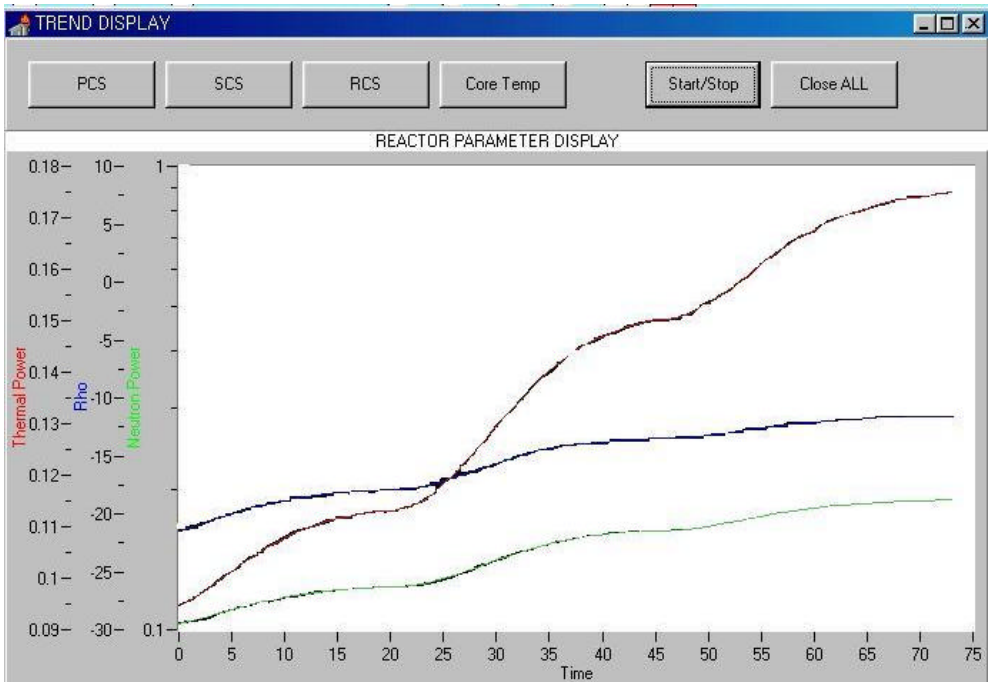

Figure 6 Trend display

5. Result and discussions

After the development of simulator, various operation modes were simulated to verify the performance of the simulator. The result is compared with the results of the computer code, KMRRSIM that was used for design of control algorithm. The start–up and shut down situation from the normal operational events are included for discussion in this paper. And two primary pump stop ecent uponr loss of electrical power is simulated. The simulated events are ordinary events expected during operations and these are design basis events considered in the Safety Analysis Report. Two results are shown in figure 7 and figure 8.

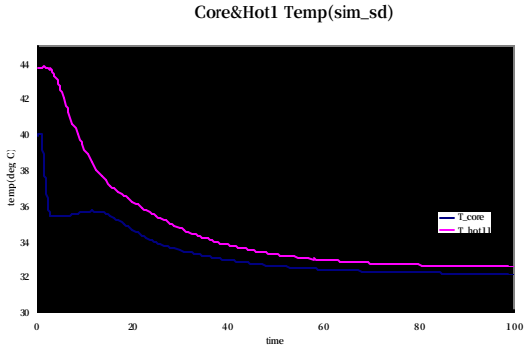

Figure7 Result for shut down (1)

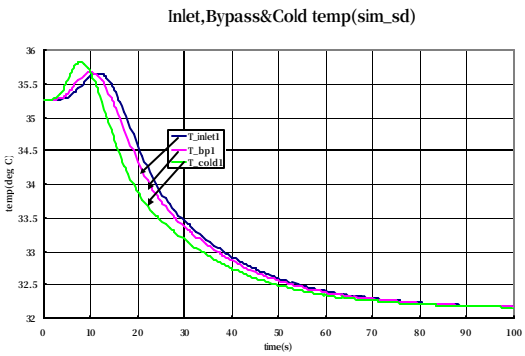

Figure8 Result for shut down (2)

6. Conclusion and Further studies

The real time engineering simulator for the HANARO is being developed and the performance is compared with the design code. The user interface of the simulator is fancy and the overall performance is good for training the operator and for introducing reactor concept for the students. The simulator uses a personal computer and a color monitor only. And the operation environment is a Microsoft' s window 98. Most of the control is performed using mouse and only demand power is entered with the keyboard.

The reactor modeled as two point kinetics and the cooling system was simplified except primary cooling system. The result shows that the simulator looks good in overall view but it needs to more tuning to get more accuracy.

In the near future, this simulator consistes with sevaral PCs to act as real plant and each part can be run as stand alone simulator for dededicated system like MLC. This means that the simulator can be replaced by real plant signals one by one. The author will continue developing and tuning to upgrade the performance of the simulator also.

Nomenclature

N_C = neutron density

ρ_{tot} = total reactivity

β = delayed neutron fraction

Λ = neutron life time

λ_i = decay constant

C_i = precursor concentration

S = Neutron source

I = concentration of Iodine-135

l_I = decay constant of Iodine-135

X = Concentration of Xenon-135

l_x = decay constant of Xenon-135

l_e = effective decay constant of Xenon-135

g_I = yield fraction of Iodine-135

g_X = yield fraction of Xenon-135

Q_{tot} = total power produced in the fuel

Q_0 = conversion factor into thermal power

Q_c = thermal power of the core

h_c = power fraction of the core region .

Q_r = thermal power produced in the reflector

K= script for corresponding pump

I_{mp} = inertia of the pump impeller and motor rotor

τ_m = motor torque at the rated speed

τ_{hy} = pump hydraulic torque

τ_{fr} = pump frictional torque

M= mass

C= specific heat

U = heat transfer coefficient

A = heat transfer area

W= flow rate

ρ = water density

H = height of the node

I = inertia

T= temperature

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