NUMERICAL SIMULATION OF REACTOR COOLANT PUMP TRIPS IN A TWO-LOOP PRESSURIZED WATER REACTOR

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ABSTRACT

NUMERICAL SIMULATION OF REACTOR COOLANT PUMP TRIPS IN A TWO-LOOP PRESSURIZED WATER REACTOR. A numerical model of a two-loop pressurized water reactor has been developed. This model is utilized for analyzing three postulated accident scenarios involving reactor coolant pump trips. The first two scenarios are due solely to reactor coolant pump trip(s). The last accident scenario involves an additional failure in the secondary loop. The temperature and mass flow rate distribution inside the system are monitored, reported, and evaluated. Although this numerical model is relatively simple in nature, this code can potentially be expanded to include more thermal hydraulics properties so that it can be utilized to perform more complicated analysis.

Keywords: core simulator, PWR, reactor coolant pump trips.

ABSTRAK

SIMULASI NUMERIK TERHENTINYA POMPA AIR PENDINGIN REAKTOR AIR TEKAN DUA-UNTAI. Suatu model numerik reaktor air tekan dua-untai telah dikembangkan. Model ini digunakan untuk menganalisis tiga skenario kecelakaan reaktor yang berhubungan dengan terhentinya pompa air pendingin reaktor. Dalam dua skenario yang pertama, kecelakaan yang terjadi hanya disebabkan oleh kegagalan pompa air pendingin untuk berfungsi sebagaimana mestinya. Dalam skenario yang terakhir, ada tambahan kegagalan yang terjadi di bagian untai-sekunder. Distribusi suhu dan laju aliran masa di dalam sistem ini telah dimonitor, dilaporkan, dan dievaluasi. Walaupun model numerik ini masih sederhana, program ini dapat dikembangkan dengan mengikutsertakan variabel-variabel termohidrolika lainnya, sehingga program ini dapat dimanfaatkan untuk menganalisis kecelakaan yang lebih pelik.

Kata kunci: Simulator Teras, Reaktor Air Tekan, Kegagalan Pompa Air Pendingin.

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INTRODUCTION

The purpose of this study is to develop a simple model for analyzing the fluid conditions through the core and loops of a pressurized water reactor (PWR). The data from the normal operation of the reactor can be used to validate and to benchmark this code since in this condition the fluid conditions are well controlled and their behaviors are predictable. Once the code has been validated, it can then become useful to study the behavior of the flows during accident scenarios. An example of a US licensed code which performs this task is the RELAP code [1]. In a more sophisticated code, like RELAP, the code is developed to describe the behavior of water-cooled nuclear reactors subjected to postulated transients, such that those resulting from loss-of-coolant, pump failure, or power excursions. The program calculates fluid conditions such as quality, pressure, mass inventory, and flow; thermal conditions such as temperature and energy distributions; and heat fluxes in the power generating elements.

In this paper, the development of a simple numerical model to monitor the fluid conditions inside the core and loops of a PWR will be presented. The code is developed using the MATLAB® program [2]. The code is utilized to analyze three accident scenarios involving reactor coolant pump (RCP) trips. In Section 0, the nodalization of the loops, the data utilized, and the derivation of the system of equations will be presented. Section 0 will summarize the results from the numerical experiments. Finally, some closing remarks will be given in Section 0.

PROBLEM DATA AND DERIVATION OF THE SYSTEM OF EQUATIONS

A simplified flow diagram of a two-loop PWR is shown in Figure **1**. The physical components are represented by nodes and the assignments are shown in Table 1. The dimensions of these components as well as some thermal data are summarized in Table 2.

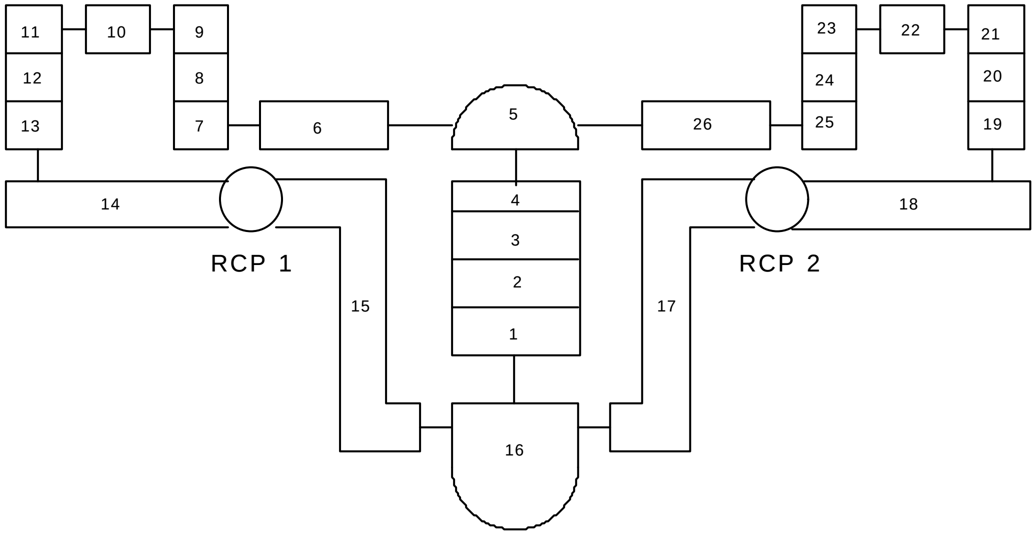

Figure 1. Simplified two-loop pressurized water reactor

The following is the discretization of fluid conservation equations for a flow system.

Momentum equations:

Loop 1:

$$\frac{1}{g_c}\sum_i \frac{L_i}{A_{xi}}\left[\frac{\dot m_1^{t+\Delta t}-\dot m_1^t}{\Delta t}\right] = -\Delta P_{\text{core}}^{t+\Delta t} - \left[\sum_i \frac{f_{1i}^t L_i}{D_{ei}}\left(\frac{\dot m_1^{t+\Delta t}}{A_{xi}}\right)^2 \frac{1}{2\,\boldsymbol{r}g_c} + \sum_j \frac{k_{1i}}{2\,\boldsymbol{r}g_c}\left(\frac{\dot m_1^{t+\Delta t}}{A_{xj}}\right)^2\right] - \left(\sum_k \boldsymbol{r}_{1k}^t \frac{g}{g_c}\Delta H_k + \Delta P_{P1}\right) \tag{1}$$

Loop 2:

$$\frac{1}{g_c}\sum_i \frac{L_i}{A_{xi}}\left[\frac{\dot m_2^{t+\Delta t}-\dot m_2^t}{\Delta t}\right] = -\Delta P_{\text{core}}^{t+\Delta t} - \left[\sum_i \frac{f_{2i}^t L_i}{D_{ei}}\left(\frac{\dot m_2^{t+\Delta t}}{A_{xi}}\right)^2 \frac{1}{2\,\boldsymbol{r}g_c} + \sum_j \frac{k_{2i}}{2\,\boldsymbol{r}g_c}\left(\frac{\dot m_2^{t+\Delta t}}{A_{xj}}\right)^2\right] - \left(\sum_k \boldsymbol{r}_{2k}^t \frac{g}{g_c}\Delta H_k + \Delta P_{P2}\right) \tag{2}$$

Core:

$$\frac{1}{g_c}\frac{L_c}{A_{xc}}\left[\frac{\dot{m}_c^{t+\Delta t}-\dot{m}_c^{t}}{\Delta t}\right]=\Delta P_{\text{core}}^{t+\Delta t}-\left[\sum_i \frac{f_{ci}^{t}L_i}{D_{ei}}\left(\frac{\dot{m}_c^{t+\Delta t}}{A_{xi}}\right)^2\frac{1}{2rg_c}+\sum_j \frac{k_{ci}}{2rg_c}\left(\frac{\dot{m}_c^{t+\Delta t}}{A_{xj}}\right)^2\right]$$
$$-\left(\sum_k \boldsymbol{r}_{ck}^{t}\frac{g}{g_c}\Delta H_{ck}\right) \qquad (3)$$

The summation over *i*,*j*,*k* denote the summation over all nodes, nodes with local loss coefficients, and all vertical nodes, respectively.
Mass equation:

$$\dot{m}_c^{t+\Delta t}=\dot{m}_1^{t+\Delta t}+\dot{m}_2^{t+\Delta t} \qquad (4)$$

Energy equation:

$$V_k\,\boldsymbol{r}_k C_p\left[\frac{T_k^{t+\Delta t}-T_k^{t}}{\Delta t}\right]+\dot{m}^{t+\Delta t}C_p\left[T_k^{t+\Delta t}-T_{k-1}^{t+\Delta t}\right]=\dot{q}_k^{t+\Delta t} \qquad (5)$$

where $\dot{q}_k=U(t)A_s\left(T_k-T_{\text{sat}}\right)$ in the steam generator.

State equation:

$$\boldsymbol{r}_k=\boldsymbol{r}(T_k,P) \qquad (6)$$

The momentum equation should be rewritten in the following form to ensure that the friction and form losses always act to oppose the flow.

Loop *L* (*L*=1,2):

$$\frac{1}{g_c}\sum_i\frac{L_i}{A_{xi}}\left[\frac{\dot{m}_L^{t+\Delta t}-\dot{m}_L^{t}}{\Delta t}\right]=-\Delta P_{\text{core}}^{t+\Delta t}-\left[\sum_i\frac{f_{Li}^{t}L_i}{D_{ei}}\frac{1}{A_{xi}^2}+\sum_j\frac{k_{Li}}{A_{xj}^2}\right]\frac{\dot{m}_L^{t+\Delta t}\left|\dot{m}_L^{t+\Delta t}\right|}{2\,\boldsymbol{r}g_c}$$
$$-\left(\sum_k \boldsymbol{r}_{Lk}^{t}\frac{g}{g_c}\Delta H_k+\Delta P_{PL}\right) \qquad (7)$$

Core:

$$\frac{1}{g_c}\frac{L_c}{A_{xc}}\left[\frac{\dot{m}_c^{t+\Delta t}-\dot{m}_c^{t}}{\Delta t}\right]=\Delta P_{\text{core}}^{t+\Delta t}-\left[\sum_i \frac{f_{ci}^{t}L_i}{D_{ei}}\frac{1}{A_{xi}^2}+\sum_j \frac{k_{ci}}{A_{xj}^2}\right]\frac{\dot{m}_c^{t+\Delta t}\left|\dot{m}_c^{t+\Delta t}\right|}{2\,rg_c}-\left(\sum_k r_{ck}^{t}\frac{g}{g_c}\Delta H_{ck}\right) \tag{8}$$

The momentum equations are non-linear in the new time mass flow rates. Therefore, these equations should be linearized to give the following expressions:

Loop L (L=1,2):

$$\frac{1}{g_c}\sum_i \frac{L_i}{A_{xi}}\left[\frac{\dot{m}_L^{n+1}-\dot{m}_L^{n}}{\Delta t}\right]=-\Delta P_{\text{core}}^{n+1}-\left[\sum_i \frac{f_{Li}^{t}L_i}{D_{ei}}\frac{1}{A_{xi}^2}+\sum_j \frac{k_{Li}}{A_{xj}^2}\right]\frac{\left(2\dot{m}_L^{n+1}-\dot{m}_L^{n}\right)\left|\dot{m}_L^{n}\right|}{2\,rg_c}-\left(\sum_k r_{Lk}^{n}\frac{g}{g_c}\Delta H_k+\Delta P_{PL}\right) \tag{9}$$

Core:

$$\frac{1}{g_c}\frac{L_c}{A_{xc}}\left[\frac{\dot{m}_c^{n+1}-\dot{m}_c^{n}}{\Delta t}\right]=\Delta P_{\text{core}}^{n+1}-\left[\sum_i \frac{f_{ci}^{t}L_i}{D_{ei}}\frac{1}{A_{xi}^2}+\sum_j \frac{k_{ci}}{A_{xj}^2}\right]\frac{\left(2\dot{m}_c^{n+1}-\dot{m}_c^{n}\right)\left|\dot{m}_c^{n}\right|}{2\,rg_c}-\left(\sum_k r_{ck}^{t}\frac{g}{g_c}\Delta H_{ck}\right) \tag{10}$$

Mass equation:

$$\dot{m}_c^{n+1}=\dot{m}_1^{n+1}+\dot{m}_2^{n+1} \tag{11}$$

The mass conservation equation and the three linearized momentum equations can be solved for the mass flow rates and core pressure drop at each iteration. These equations can be written in matrix form as

$$\begin{bmatrix} a_1 & 0 & 0 & 1 \\ 0 & a_2 & 0 & 1 \\ 0 & 0 & a_c & 1 \\ 1 & 1 & -1 & 0 \end{bmatrix} \begin{bmatrix} \dot{m}_1^{n+1} \\ \dot{m}_2^{n+1} \\ \dot{m}_c^{n+1} \\ \Delta P_{\mathrm{core}}^{n+1} \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ b_c \\ 0 \end{bmatrix}, \tag{12}$$

where a_n and b_n can be derived from previous equations.

Energy Equation with Flow Reversal

In the derivation of the momentum equations above, the flow is allowed to reverse during the transient. In order for the whole system of equations to hold, the same treatment should be done in the energy equation. There are two cases that will be examined below: straight pipe and pipe with multiple inlets/outlets.

Straight Pipes

According to the nodalization given in the problem statement, the following nodes are of this type: nodes 1 to 4, nodes 6 to 15, and nodes 17 to 26. Nodes of this type can be described by the following diagram

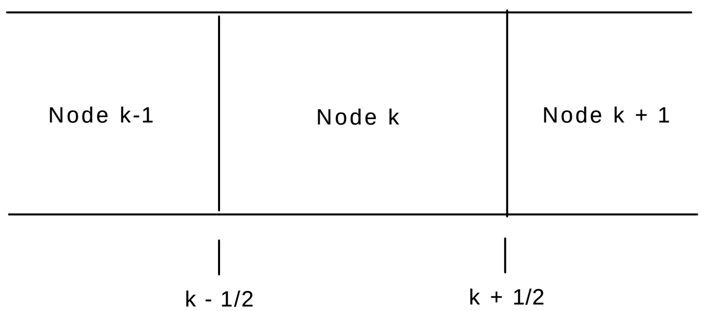

Figure 2. Flow in a straight pipe

The final form of the energy equation for this case (allowing flow reversals) is

$$M_k C_p \left\{ \frac{T_k^{t+\Delta t} - T_k^t}{\Delta t} \right\} + \frac{C_p}{2} \left(\dot{m}_k - \left| \dot{m}_k \right| \right) T_{k+1}^{t+\Delta t} + \left| \dot{m}_k \right| C_p T_k^{t+\Delta t} - \frac{C_p}{2} \left(\dot{m}_k - \left| \dot{m}_k \right| \right) T_{k-1}^{t+\Delta t} = \dot{Q}_k \tag{13}$$

This equation can be rearranged to give the following expression

$$-\frac{C_p}{2}\left(\dot{m}_k - \left|\dot{m}_k\right|\right)T_{k-1}^{t+\Delta t} + \left\{\frac{M_k C_p}{\Delta t} + \left|\dot{m}_k\right| C_p\right\}T_k^{t+\Delta t} + \frac{C_p}{2}\left(\dot{m}_k - \left|\dot{m}_k\right|\right)T_{k+1}^{t+\Delta t} = \dot{Q}_k + \frac{M_k C_p}{\Delta t}T_k^t \qquad (14)$$

Pipe with Multiple Inlets/Outlets

According to the nodalization shown in the problem statement, the following nodes are of this type: node 5 and node 16.

Node 5
The final equation for node 5 will look like:

$$-\frac{C_p}{2}\left(\dot{m}_4 - \left|\dot{m}_4\right|\right)T_4^{t+\Delta t} + \left\{\frac{M_5 C_p}{\Delta t} + \frac{C_p}{2}\left(\left|\dot{m}_{26}\right| + \left|\dot{m}_6\right| + \left|\dot{m}_4\right|\right)\right\}T_5^{t+\Delta t} + \frac{C_p}{2}\left(\dot{m}_6 - \left|\dot{m}_6\right|\right)T_6^{t+\Delta t},$$

$$+\frac{C_p}{2}\left(\dot{m}_{26} - \left|\dot{m}_{26}\right|\right)T_{26}^{t+\Delta t} = \frac{M_5 C_p}{\Delta t}T_5^t \qquad (15)$$

Node 16
The final equation for node 16 will look like:

$$\frac{C_p}{2}\left(\dot{m}_1 - \left|\dot{m}_1\right|\right)T_1^{t+\Delta t} + \left\{\frac{M_{16} C_p}{\Delta t} + \frac{C_p}{2}\left(\left|\dot{m}_1\right| + \left|\dot{m}_{15}\right| + \left|\dot{m}_{17}\right|\right)\right\}T_{16}^{t+\Delta t} - \frac{C_p}{2}\left(\dot{m}_{15} - \left|\dot{m}_{15}\right|\right)T_{15}^{t+\Delta t}$$

$$-\frac{C_p}{2}\left(\dot{m}_{17} - \left|\dot{m}_{17}\right|\right)T_{17}^{t+\Delta t} = \frac{M_{16} C_p}{\Delta t}T_{16}^t \qquad (16)$$

Table 1. Reactor system components and corresponding nodes

Nodes	Component
1 – 4	**Reactor Core**
5	**Upper Plenum**
6 and 26	**Hot Legs**
7-13 and 19-25	**Steam Generators**
14 and 18	**Cold Legs**
15 and 17	**Downcomer**
16	**Lower Plenum**

Table 2. Reactor system data

REACTOR			
Power	3800 MW	Inlet Temperature	558 ^{o}F
Active Core Height	150 inches	Outlet Temperature	615 ^{o}F
Number of Fuel Rods	54764	Pressure	2250 psi
Rod Diameter	0.382 inches	Effective Flow Area	60.9 ft^2
Rod Pitch	0.506 inches	Pressure Drop	16.8 psi
Mass Flux	2.64 x 10^6 lbm/hr-ft^2	Rod Plenum Height	8 inches
UPPER [LOWER] PLENUM			
Length	5.7 [3.2] ft	Effective Diameter [Upper Plenum]	5.8 ft
Pressure Drop	16.8 [14.3] psi	Flow Area [Lower Plenum]	32.5 ft^2
HOT [COLD] LEGS (each)			
Number	2 [4]	Length	14 [43.6] ft
Diameter	42 [30] inch.		
STEAM GENERATORS [2 S/G; all parameters per S/G]			
Length of S/G Tube	61.2 ft	Secondary Side Pressure	1000 psi
Maximum Height of Steam Tubes above Hot Leg	34.46 ft	Number of S/G Tubes	12,113
S/G Tube Diameter	0.75 inches	Pressure Drop	27 psi
DOWNCOMER			
Length	21.4 ft	Flow Area	33.8 ft^2
Pressure Drop	10 psi		
PUMPS (each)			
Pressure Increase	85 psi		

RESULTS AND DISCUSSIONS

There are three accident scenarios analyzed in this study. All of them are related to the failure of the reactor coolant pump(s) to operate properly. The descriptions of these cases as well as the results from numerical experiments of these transients are described in the following sub-sections.

SINGLE RCP FAILURE

In the first accident scenario analyzed in this study, it is postulated that the reactor coolant pump of Loop 1 trips. The trip is followed by a reactor trip. As a result, the remaining heat generation rate in the system is only due to the decay heat which is approximated as 7% of the normal rate. Figure 3 shows the changes in the mass flow rates during the transient. As clearly indicated by this figure, immediately after the coolant pump trip, the mass flow rate in Loop 1 rapidly decreases. The mass flow rate inside the core also decreases due to the fact that the forced flow in the core only depends on one reactor coolant pump. The mass flow rate in Loop 1 goes negative six seconds into the transient since in the formulation it is allowed to have flow reversals in the Loops. Needless to say that it is also assumed that the failed pump is not considered as an additional flow obstruction. The mass flow rate in Loop 2 increases since there is no longer interference of flow from Loop 1 when pumping the coolant into the core. Figure 4 shows the temperature distribution in the system during the transient. As the heat generated in the core decreases significantly, the temperatures across the system also decrease. Figure 5 shows the behavior of the temperatures at the upper and lower plenums as well as the core average temperature. This figure also shows the decrease in temperature observed as a result of the RCP and reactor trips. Note that the core average temperature is calculated as the arithmetic average of the upper and lower plenum temperatures.

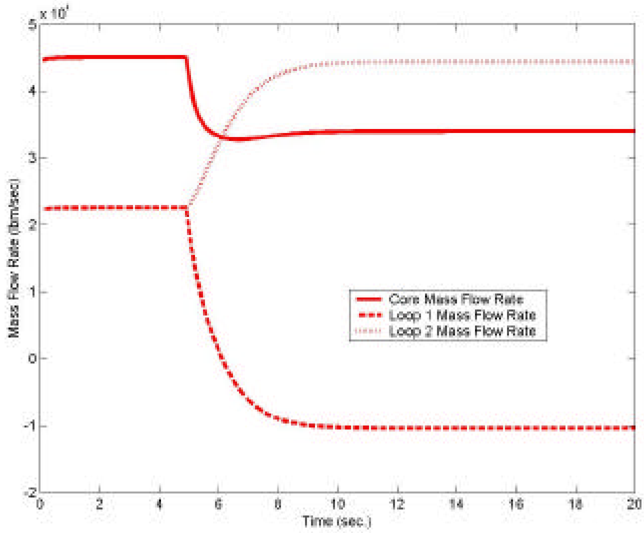

Figure 3. Single RCP failure: mass flow rates in the core and both loops

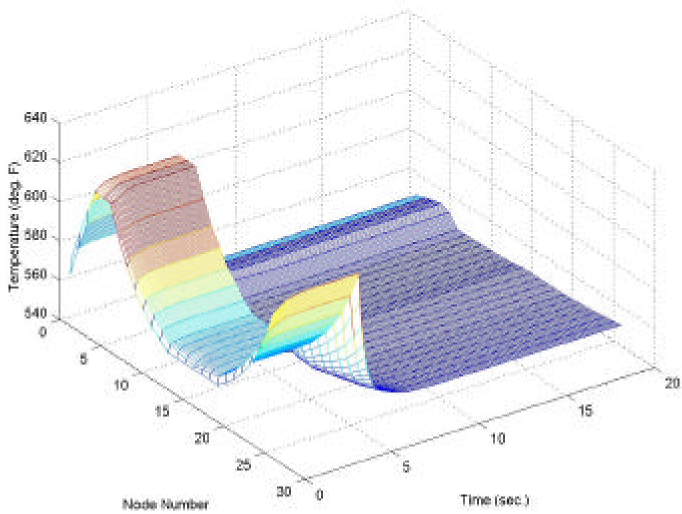

Figure 4. Single RCP failure: temperature distribution

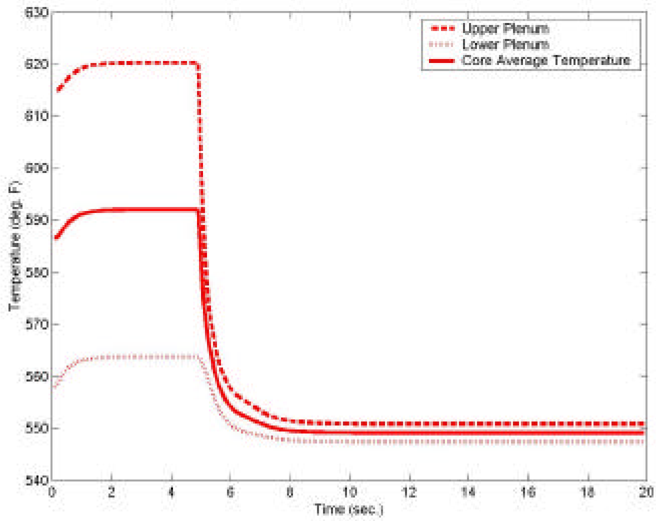

Figure 5. Single RCP failure: core temperature

FAILURE OF BOTH RCPS

In the second accident scenario, it is postulated that both RCPs trip. This trip is also followed immediately by a reactor trip since these trips imply that the forced flow inside the core is non-existent. Figure 6 shows the mass flow rates in the core and both loops during the transient. This figure shows a significant decrease in the mass flow rates in the system. A symmetric behavior between the two loops is observed since we have assumed that the mechanical and thermal properties of both loops are identical.

Figure 7 shows the temperature distributions for all nodes in the system. The temperatures in the core are higher than in the first case since the mechanisms for removing heat provided by the reactor coolant pumps are completely removed. Figure 8 depicts the temperature across the core for this transient. Clearly shown in this plot how the core average temperature is higher than in the single RCP failure case. The temperature reaches a new equilibrium value since the decay heat is maintained at a constant rate. This assumption is valid since the transient modeled only represent the first few seconds of the accident.

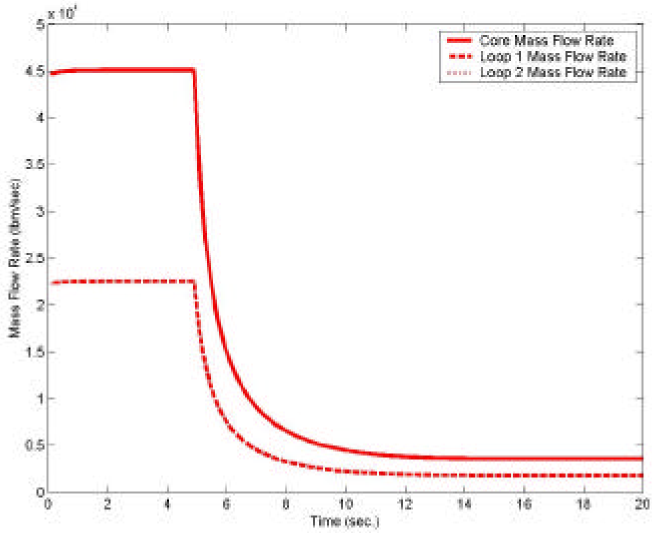

Figure 6. Failure of both RCPs: mass flow rates in the core and both loops

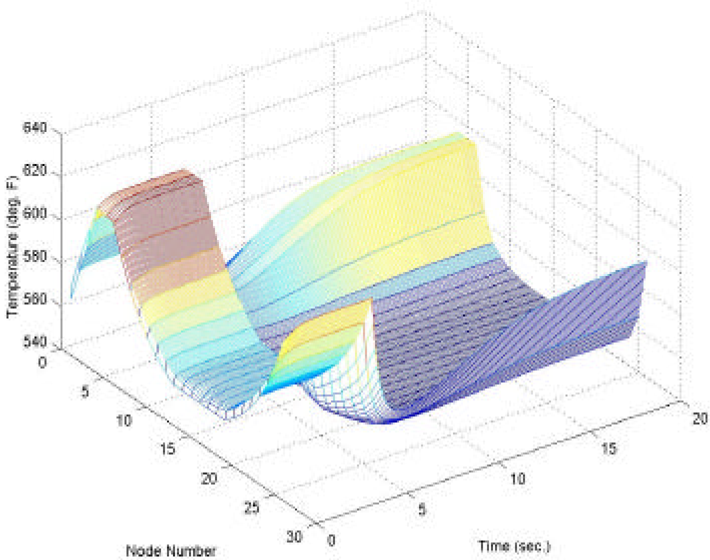

Figure 7. Failure of both RCPs: temperature distribution

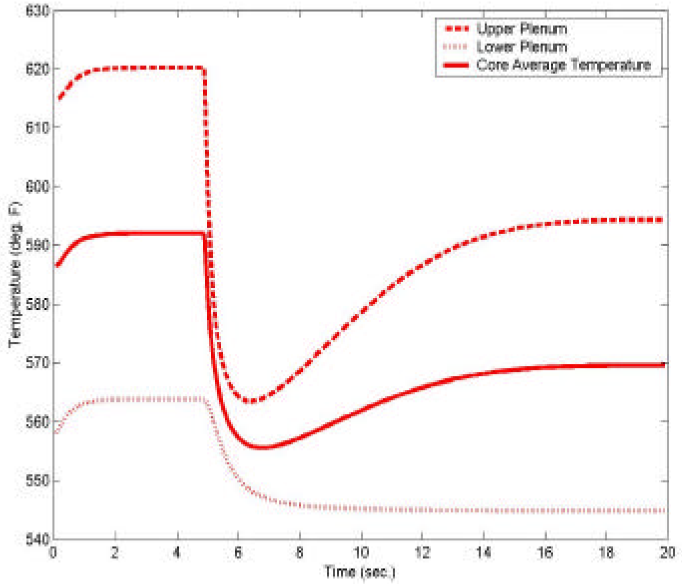

Figure 8. Failure of both RCPs: core temperature

FAILURES OF BOTH RCPS ACCOMPANIED BY LOSS OF HEAT TRANSFER CAPABILITY IN THE STEAM GENERATOR

In the third scenario analyzed in this study, it is postulated that in addition to the failures of both of the reactor coolant pumps, at the same time the ability to remove heat from one of the steam generators is removed (Loop 1). This implies that there is another abnormality in the secondary part of the system. Several things can cause this problem such as the malfunction of the feed water pump, steam line break, inadvertent opening of the atmospheric dump valve, and so forth. Figure 9 shows the mass flow rates in the system. Clearly shown in this figure is the non-symmetric behavior of the flow caused by the problem in one of the steam generators. The non-symmetric distribution is also observed in the distribution of temperature in the system as shown in Figure 10. Figure 11 presents the temperature inside the core. The initial temperature drop observed at the hot leg, *i.e.* the upper plenum, is due to the transition from full power generation to the decay heat mode. However, the hot leg temperature quickly increases as a result of no heat removal capability in one of the steam generators.

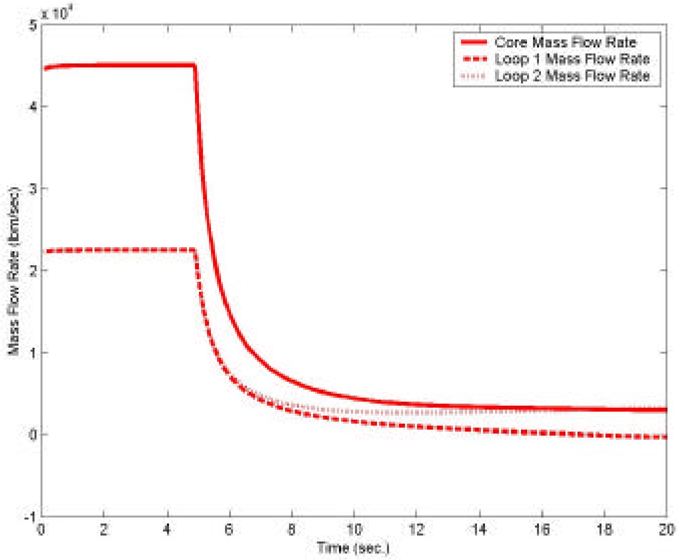

Figure 9. Failure of both RCPs & loss of heat transfer: mass flow rates in the core and both loops.

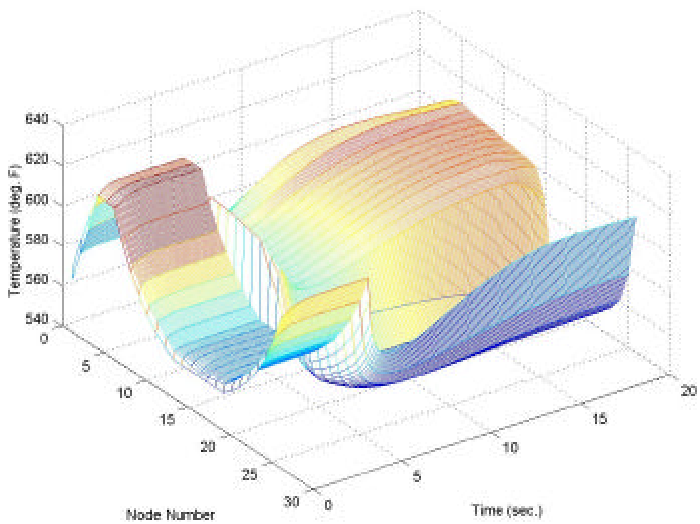

Figure 10. Failure of both RCPs & loss of heat transfer: temperature distribution

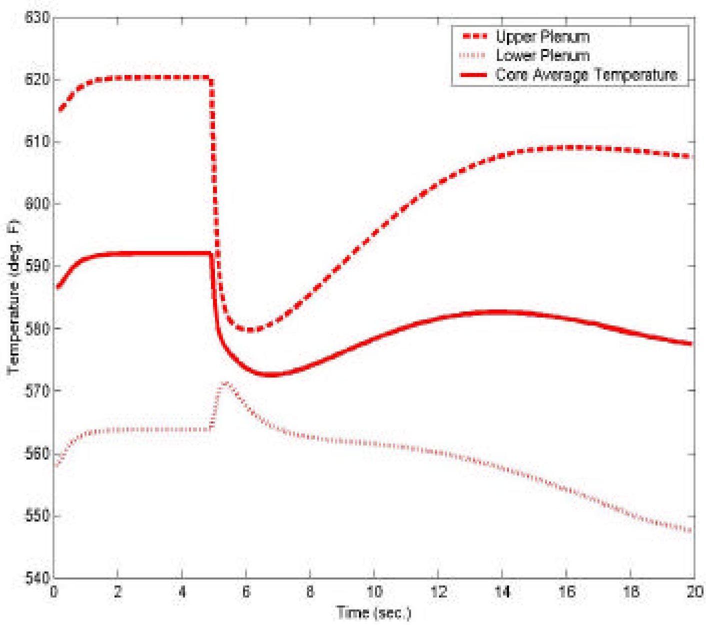

Figure 11. Failure of both RCPs & loss of heat transfer: core temperature

CONCLUSIONS AND RECOMMENDATIONS

A numerical model of the flow inside a two-loop pressurized water reactor has been successfully established in a form of a computer code written in MATLAB®. The code is used to perform three postulated accident scenarios related to the failure of RCP to work properly. Results from these numerical experiments behave as expected. The temperature and mass flow rate distributions are used as indicators of what happen during the transients. This code can potentially be expanded to include more thermal hydraulics properties in the analysis and can be used as a starting point to analyze other accident scenarios.

NOMENCLATURE

$\dot{m}$	: Mass flow rate (lbm/sec)
r	: Density (lbm/ft^3)
t, t	: Time, Change in time (sec)
ΔP_{core}	: Pressure drop across the core (psi)
ΔP_{Pn}	: Pressure increase across the pump in loop n (psi)
L_i	: Length of segment i (ft)
A_{xi}	: Area of segment i (ft^2)
D_{ei}	: Equivalent diameter for segment i (ft)
ΔH_k	: Height of segment k (ft)
k_{ni}	: Local loss coefficient for segment i in loop n (unitless)
V	: Volume (ft^3)
T	: Temperature (^{o}F)
C_p	: Specific heat (BTU/lbm.F)
$\dot{q}$	: Heat generation rate (BTU/hr)

REFERENCES

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2. MATLAB® The Language of Technical Computing, Version 6.1.0.450 Release 12.1, the MathWorks, Inc., 2001.

DISKUSI

RULIJANTI PARDEWI

1. Fungsi pompa air pendingin pada sistem reaktor?
2. Apakah pengaruhnya pada kegagalan pompa air pendingin pada sistem reaktor secara keseluruhan?.

DODDY KASTANYA

1. Fungsi pompa air pendingin adalah seperti namanya yaitu memompa air masuk ke dalam teras melalui lower plenum dari teras tersebut.
2. Kegagalan pada RCP akan diikuti dengan *reactor trip* / pemadaman reaktor. Sehingga sesudah RCP trip, hanya panas dari decay heat yang harus ditanggulangi untuk menjamin integritas teras/bahan bakarnya.

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