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Fast Running System Code Development to Simulate Transient Behavior of Pool-Type LMFBRs

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풀형 고속증식로의 과도 현상을 모사하는 Fast Running System Code개발

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Abstract

A computer model is developed capable of simulating the transient behavior of a pool-type liquid metal-cooled fast breeder reactor (LMFBR). The model, SIMFARP, is a fast running computer code which may be used to simulate the loss of power to any pump(s), a complete loss-of-forced cooling, and the natural circulation behavior. Eight governing equations are derived and a Runge-Kutta algorithm is applied to integrate the eight differential equations. The developed computer program is applied to two cases; loss of electric power to any pump(s), and loss of all external electric supply power without scram in Super-Phenix-I.

요 약

풀형 고속증식로에서의 과도 현상을 모사할 수 있는 전산 모델이 개발되었다. 이 전산 모델 SIMFARP는 어떠한 펌프로의 전원 상실사고나 완전한 강제냉각 상실사고, 그리고 자연순환 과정 등을 모사할 수 있는 Fast Running Computer Code이다. 이에 따라 8개의 지배방정식이 유도되었으며, 이 8개의 미분 방정식을 풀기 위해 Runge-Kutta의 수치해석방법이 사용되었다. 개발된 전산 프로그램은 두가지 예제에 적용되었는데 이는 Super-Phenix-I에서의 펌프에의 전원상실사고 및 원자로가 정지되지 않는 상태에서의 외부전원 상실사고이다.

Nomenclature

a : inertial loss coefficient [/m]
C : friction loss coefficient [/m^4]
C_p : specific heat [joule/kg°C]
g : acceleration of gravity [m/sec^2]
N : number of loops
P : pressure [N/m^2]

g_c : incore thermal power [Watt]

q_{HX1} : heat removed by one loop intermediate heat exchanger [Watt]

q_{HX2} : heat removed by lumped loop intermediate heat exchanger [Watt]

T : temperature [°C]

V : volume[m^3]

W : mass flow rate [kg/sec]

Z : height [m]

ρ : density [kg/m^3]

Subscript

1 : one loop

2 : lumped loop

C : core

CH : chimney

CHO : chimney outlet

CI : core inlet

CO : coro outlet

CP : cold pool

CPL : cold pool level

HP : hot pool

HX1 : one loop intermediate heat exchanger

HX2 : lumped loop intermediate heat exchanger

HXO1 : one loop IHX outlet

HXO2 : lumped loop IHX outlet

IP : inlet plenum

PI : pump inlet

PIPE1 : one loop pipe

PIPE2 : lumped loop pipe

PO : pump outlet

PUMP1 : one loop pump

PUMP2 : lumped loop pump

RI : rector inlet

XI : IHX inlet

XO : IHX outlet

I. Introduction

Over the next several decades, the techniques of energy production throughout the world will undergo tremendous changes. Fossil fuels, such as coal, oil, and natural gas, are all exhaustible sources of energy. New and virtually inexhaustible sources of energy must be developed in the near future to provide sufficient energy for future generations. To date, the only technically feasible option capable of providing long-term energy on a large scale in the Liquid Metal-Cooled Fast Breeder Reactor (LMFBR). Two competing styles of LMFBRs have been developed; the loop-type and the pool-type. Most of the work in the United States (such as the design of the Clinch River Breeder Reactor) has concentrated on the loop-type of plant. Much of the work in other countries (particularly France) has been concerned with the pool-type LMFBR. International interest in fast breeder reactor development is illustrated in Fig. 1.

There are several systems codes to simulate the transient behavior of the liquid metal cooled fast breeder reactor (LMFBR), but most of them are intended to obtain highly detailed results and time-consuming. Then a fast running systems analysis code, SIMFARP (*Sim*plified *F*ast *R*unning *P*ool-type system code), has been written to analyze the time response of pool-type LMFBR. Transients which can be simulated include reactor trip, loss of electric power to any pump(s), loss of feed water flow and anticipated transient without scram (ATWS). The

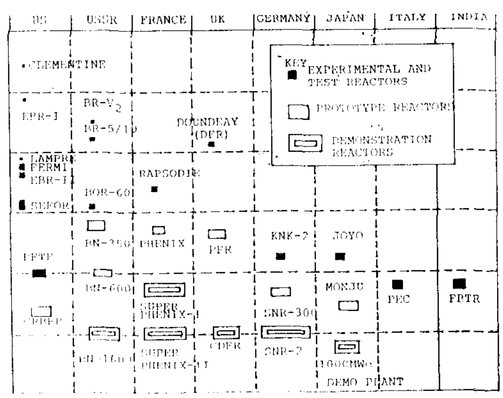

Fig. 1. International Fast Reactor Development through Demonstration Plant Phase(Size of box proportional to actual core dimensions)

present work is a simplified numerical investigation of a single-phase natural circulation system with eight intermediate heat exchanger. N-loop system is generally treated assuming that $(N-1)$ loops have the same behavior. The governing equations for eight unknowns can be derived from the law of momentum and energy conservations. Then sample calculations are carried out to examine the performance of the computer program and comparisons are made with reference 6) and 7).

Although it leaves much room for improvement, the program seems to be not bad in simulation of the transient behavior of the pool-type LMFBR. Some parts are not described in detail in this article because they are presented already in others.

Schematic drawings of the heat transport circuits for the pool-type and loop-type design are shown in Fig. 2 and 3.

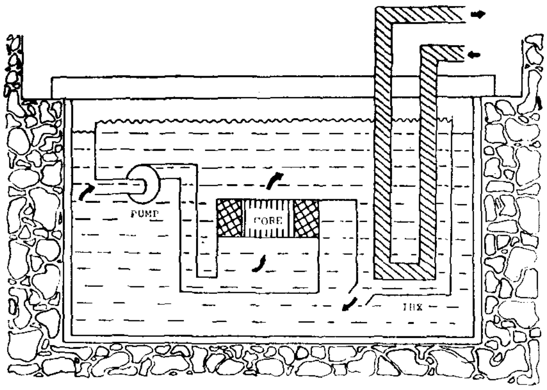

Fig. 2. Schematic of One Set of Loops in a Pool Type LMFBR

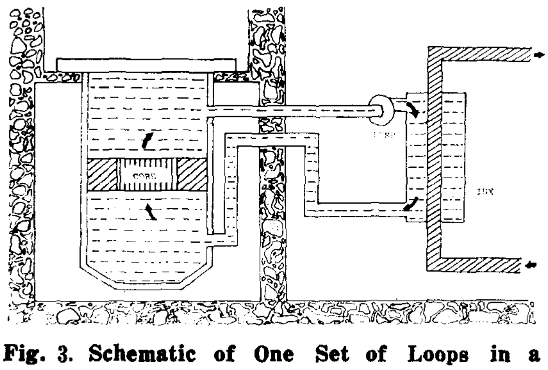

Fig. 3. Schematic of One Set of Loops in a Loop Type LMFBR

II. Modeling

II. 1. Assumptions

The important assumptions made in this study are as follows:

i) one-dimensional model.

ii) single phase and incompressible fluid.

iii) Boussinesq approximation is valid (i.e., the density, ρ, is regarded as constant in the governing equations except for the buoyancy force term.)

iv) the fluid is perfectly mixed in the region.

Other assumptions will be mentioned in subsequent sections whenever needed.

II. 2. System Simulation[1,2]

Schematic diagram of the simulated system is depicted in Fig. 4 as a block diagram. It consists of core, chimney, hot pool, intermediate heat exchanger (IHX), cold pool, primary pump, inlet plenum, and other connections.

Governing equations are derived to represent N-loop system, one loop of which behaves unlike other$(N-1)$ loops. With many assumptions, they are reduced to eight nonlinear differential equations.

II. 3 Governing Equations

II. 3. 1. Continuity Equation

The mean velocity and the flow rate $w(t)$ are uniform around the loop and depend only on the time, t. When the flow system includes parallel loops, the flow rates will be uniform

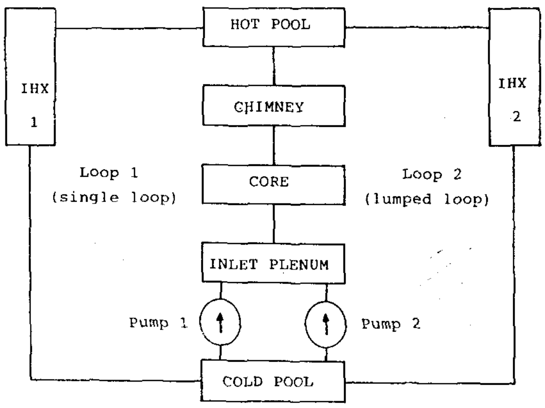

Fig. 4. Simulated System

in each loop and their sum will be equal to the total flow rate.

II. 3. 2. Momentum Equations

Momentum equations can be represented as the pressure drop relation. Because the sum of the pressure drops around any closed loop of channels must be zero (Kirchhoff's law), following relationships can be written.

$$\Delta P_C+\Delta P_{CH}+\Delta P_{HP}+\Delta P_{HX1}+\Delta P_{CP}+\Delta P_{PUMP1}+\Delta P_{PIPE1}+\Delta P_{IP}=0 \quad (1)$$

$$\Delta P_C+\Delta P_{CH}+\Delta P_{HP}+\Delta P_{HX2}+\Delta P_{CP}+\Delta P_{PUMP2}+\Delta P_{PIPE2}+\Delta P_{IP}=0 \quad (2)$$

Then following equations are obtained from eqs (1) and (2).

$$\begin{aligned}&(a_{PUMP1}+a_{PIPE1}+a_{IP}+a_C+a_{CH}+a_{HX1})\frac{dW_1}{dt}\\&+(N-1)\cdot(a_{IP}+a_C+a_{CH})\frac{dW_2}{dt}\\&=[\bar\rho_{CP}(Z_{CPL}-Z_{PI})+\bar\rho_{PUMP1}(Z_{PI}-Z_{PO})\\&+\bar\rho_{PXPE1}(Z_{PO}-Z_{RI})+\bar\rho_{IP}(Z_{RI}-Z_{CR})\\&+\bar\rho_C(Z_{CI}-Z_{CO})+\bar\rho_{CH}(Z_{CO}-Z_{CH})\\&+\bar\rho_{HP}(Z_{CH}-Z_{XI})+\bar\rho_{HX1}(Z_{XI}-Z_{XO})\\&+\bar\rho_{CP}(Z_{XO}-Z_{CPL})]\cdot g+\Delta P_{PUMP1}\\&-\Big[\Big(\frac{C_{PUMP1}}{\bar\rho_{PUM1}}+\frac{C_{PIPE1}}{\bar\rho_{PIPE1}}+\frac{C_{HX1}}{\bar\rho_{HX1}}\Big)W_1|W_1|\\&+\Big(\frac{C_{IP}}{\bar\rho_{IP}}+\frac{C_C}{\bar\rho_C}+\frac{C_{CH}}{\bar\rho_{CH}}\Big)\cdot(W_1\\&+(N-1)W_2|W_1+(N-1)W_2|\Big]\end{aligned} \quad (3)$$

$$\begin{aligned}&(a_{IP}+a_C+a_{CH})\frac{dW_1}{dt}+\Big\{a_{PUMP2}+a_{PIPE2}\\&+(N-1)(a_{IP}+a_C+a_{CH})+a_{HXZ}\Big\}\frac{dW_2}{dt}\\&=[\bar\rho_{CP}(Z_{CPL}-Z_{PI})+\bar\rho_{PUMP2}(Z_{PI}-Z_{PO})\\&+\bar\rho_{PIPE2}(Z_{PO}-Z_{PI})+\bar\rho_{IP}(Z_{RI}-Z_{CI})\\&+\bar\rho_C(Z_{CI}-Z_{CO})+\bar\rho_{CH}(Z_{CO}-Z_{CH})\\&+\bar\rho_{HP}(Z_{CH}-Z_{XI})+\bar\rho_{HX2}(Z_{XI}-Z_{XO})\\&+\bar\rho_{CP}(Z_{XO}-Z_{CPL})]\cdot g+\Delta P_{PUMP2}\\&-\Big[\Big(\frac{C_{PUMP2}}{\bar\rho_{PUMP2}}+\frac{C_{PIPE2}}{\bar\rho_{PIPE2}}+\frac{C_{HX2}}{\bar\rho_{HX2}}W_2|W_2|\\&+\Big(\frac{C_{IP}}{\bar\rho_{IP}}+\frac{C_C}{\bar\rho_C}+\frac{C_{CH}}{\bar\rho_{CH}}\Big)(W_1\\&+(N-1)W_2)\cdot|W_1+(N-1)W_2|\Big]\end{aligned} \quad (4)$$

The procedure to obtain Eqs. (3) and (4) is already known in other works (reference 8. Chapter 7).

where a is the inertial loss coefficient

$=L/A$

C is the friction loss coefficient

$=R_{\mathrm{fric}}+R_{\mathrm{form}}$

R_{fric} is the friction loss

$=\frac{1}{2}\cdot\frac{4f\cdot L}{d_H A^2}$

R_{form} is the form loss

$=\frac{1}{2}\frac{K}{A^2}$

f is the friction factor

d_H is hydraulic diameter of the channel

L is the length of the channel

A is the area of the channel

K is the form loss coefficient

II. 3. 3. Energy Equations

To derive time-dependent equations for temperatures of interest in the primary system, an energy balance must be performed in each region. Such an energy balance would be of the form;

$$\begin{bmatrix}\text{rate of change of}\\ \text{thermal energy}\end{bmatrix}=\begin{bmatrix}\text{energy added}\\ \text{to the node}\end{bmatrix}-\begin{bmatrix}\text{energy removed}\\ \text{from the node}\end{bmatrix} \quad (5)$$

Then the following general form of the time-dependent energy equation is derived.

$$\underbrace{(mC_P)\frac{dT}{dt}}_{\text{rate of change of energy}}=\underbrace{q'''\cdot V}_{\text{energy added of heat generation}}+\underbrace{WC_P(T_{IN}-T_{OUT})}_{\text{energy added or removed by fluid flow}}+\underbrace{UA\ (T_a-T)}_{\text{energy added or removed by conduction}} \quad (6)$$

where m is the total mass of the region

T is the average temperature of the region

q''' is the volumetric internal heat generation rate in the region

U is the heat transfer coefficient between the region and on adjacent region

T_a is the average temperature of the adjacent region

Then,

Core region

$$(\rho VC_P)_C\frac{d\bar{T}_C}{dt}=q_C-(W_1+(N-1)W_2)\cdot C_{P,C}\cdot(T_{CO}-T_{CI})+UA(\bar{T}_{CH}-\bar{T}_C) \quad (7)$$

Chimney region

$$(\rho VC_P)_{CH}\frac{d\bar{T}_{CH}}{dt}=-(W_1+(N-1)W_2)\cdot C_{P,CH}\cdot(T_{CHO}-T_{CO})+UA(\bar{T}_{HP}-\bar{T}_{CH}) \quad (8)$$

Hot pool region

$$(\rho VC_P)_{HP}\frac{d\bar{T}_{HP}}{dt}=-(W_1+(N-1)W_2)\cdot C_{P,HP}\cdot(T_{HXI}-T_{CHO})+UA(\bar{T}_{HXI}-\bar{T}_{HP}) \quad (9)$$

IHX1 region

$$(\rho VC_P)_{HX1}\frac{d\bar{T}_{HX2}}{dt}=-q_{HX1}-W_1\cdot C_{P,HX1}\cdot(T_{HXO1}-T_{HXI})+UA(\bar{T}_{CP}-\bar{T}_{HX1}) \quad (10)$$

IHX2 region

$$(\rho VC_P)_{HX3}\frac{d\bar{T}_{HX2}}{dt}=-q_{HX2}-(N-1)W_2C_{P,HX2}(T_{HXO2}-T_{HX1})+UA(\bar{T}_{CP}-\bar{T}_{HX2}) \quad (11)$$

Cold pool region

$$(\rho VC_P)_{CP}\frac{d\bar{T}_{CP}}{dt}=-(W_1+(N-1)W_2)\cdot C_{P,CP}\cdot(T_{CI}-T_{HXO})+UA(\bar{T}_C-\bar{T}_{CP}) \quad (12)$$

where

$$T_{HXO}=\frac{W_1\cdot T_{HX1}+(N-1)\cdot W_2\cdot T_{HX2}}{W_1+(N-1)\cdot W_2} \quad (13)$$

Equation (3), (4), (7), (8), (9), (10), (11) and (12) given the system behavior with the aid of state equations. Continuity equation is already introduced into above equations.

II. 4 Numerical Analysis

The reactor is modeled by a number of first-order differential equations of the form;

$$\frac{dX_i}{dt}=F_i(X_i, X_2, \cdots, X_i, \cdots X_n), \text{ for } i=1, 2, \cdots, n \quad (14)$$

where X_i is the state variables

F_i is the differential functions.

Eqs. (3), (4), (7), (8), (9), (10), (11) and (12) constitute eight governing equations for eight unknowns—W_1, W_2, T_{CI}, T_{CO}, T_{CHO}, T_{CHI}, T_{HXO1}, T_{HXO2}. These eight differential equations are integrated using Runge-Kutta method of order 4; i.e.,

$$X_i^{n+1}=X_i^n+\frac{1}{6}(k_1+Zk_2+Zk_3+k_4) \quad (15)$$

where

$$k_1=\Delta t\cdot F_i(X_1^n, X_2^n, \cdots, X_i^n, \cdots, X_n^n)$$

$$k_2=\Delta t\cdot F_i(X_1^{n+1/2}, X_2^{n+1/2}, \cdots, X_i^n+k_2/z\cdots, X_n^{n+1/2})$$

$$k_3=\Delta t\cdot F_i(X_2^{n+1/2}, X_2^{n+1/2}, \cdots, X_i^n+k_2/z, \cdots, X_n^{n+1/2})$$

$$k_4=\Delta t\cdot F_i(X_1^{n+1}, X_2^{n+1}, \cdots, X_i^n+k_3\cdots, X_n^{n+1})$$

To calculate one $(n+1)$-step and other n-step values are needed. Therefore, one $(n+1)$-step variable is calculated from other n-step and assumed $(n+1)$-step values. After all $(n+1)$-step values are replaced by calculated $(n+1)$-step values. Then, $(n+1)$-step variables are iterated again from n-step values and $(n+1)$-step values which are calculated previously. This procedure should be repeated until convergence appears. Then, the $(n+1)$-step values are used to calculate the next step values. Above discussions are shown as a flow chart in Fig. 5.

II. 5. Computer Program

Computer program, SIMFARP, is developed to simulate the loss of power to any pump(s), a completed loss-of-forced cooling, and the natural circulation phenomena in a multiloop system. It consists of one main program and a number of subprograms. Interconnections between these subprograms are shown in Fig. 6. And Table 1 describes the subprograms briefly. Many

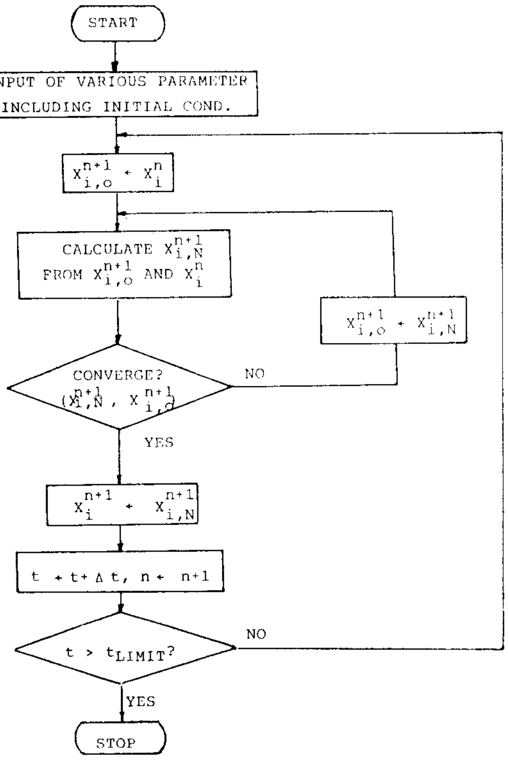

Fig. 5. Flow Chart for Numerical Scheme

Table 1. Brief Descriptions of Subprograms

Name	Functions
Main Program	• Input of various parameters including loop dimensions, initial conditions, etc. • Update time and call PRIM, IHX • Print all results
PRIM	• Execute iteration at each time step and find $W1$, $W2$, T_{CI}, T_{CO}, T_{CHO}, T_{HXI}, T_{HXO1}, and T_{HXO2}
IHX	• Calculate the heat removed by intermediate heat exchanger and the secondary outlet temperature
Other Subprogram	• Input of various parameters varying with time only—decay power, pump head, secondary loop conditions, etc. • Input of various fluid properties[3]

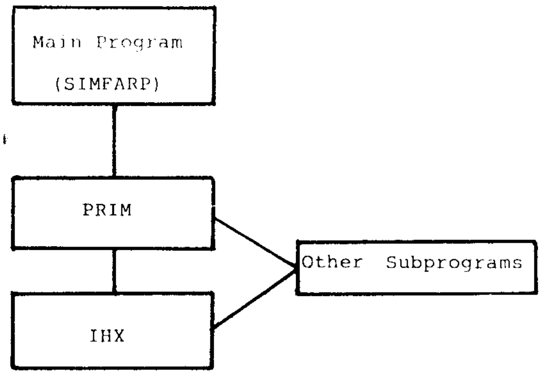

Fig. 6. Interconnections between Subprograms

fluid properties varying with temperature[3] are introduced as functions of temperature into our subprograms:

III. Sample Calculation

In order to examine the performance of developed computer program, it is tested on two sample cases. Input data[4], shown in Table 2,

Table 2. Input Parameters for Sample Calculation[4]

Parameters	Input Values
thermohydraulic diameter of fuel cell	6.315×10^{-3}m
core inlet temperature	395°C
core outlet temperature	545°C
incore thermal power	2,990MW$_{th}$
number of primary pump	4
primary sodium flow rate	15,810kg/sec
inventory of primary sodium	3,250ton
number of intermediate heat exchanger	8
number of tubes per unit	5380
heat transfer surface area per unit	1,300m^2
secondary side inlet temperature	345°C
secondary side outlet temperature	525°C
secondary side sodium flow rate	1,633kg/sec
volume of core	24.25m^3
volume of chimney	4.490m^3
volume of hot pool	3,000m^3
volume of cold pool	1,000m^3
volume of IHX shell side	26.76m^3
reactor pressure drop	4.508×10^{5}kg/msec^2
primary pump half-time	50.0sec
secondary pump half-time	10.0sec

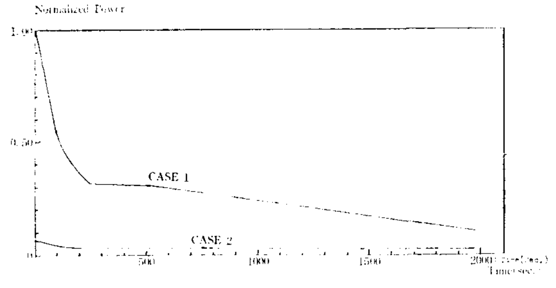

Fig. 7. Incore Thermal Power for Input
Case 1) Loss of electric supply power without scram
Case 2) Loss of off site electric power with scram

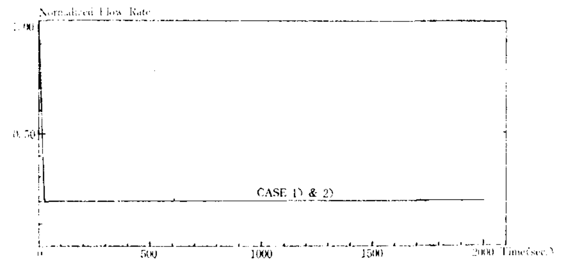

Fig. 8. Secondary Side Flow Rate for Input
Case 1) Loss of electric supply power without scram
Case 2) Loss of off site electric power with scram

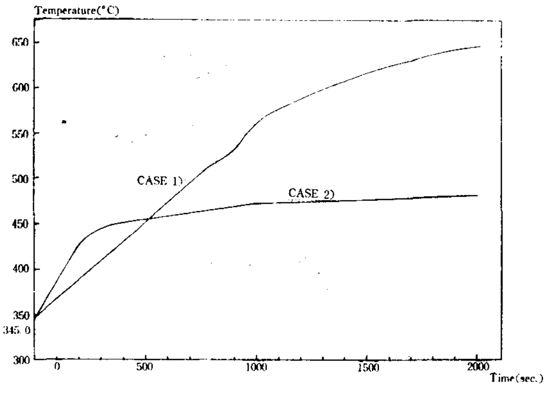

Fig. 9. Secondary Side Inlet Temperature for Input
Case 1) Loss of electric supply power without scram
Case 2) Loss of off site electric power with scram

are based on the Super-Phenix-I design. Attention should be paid to the selection of time int erval, Δt, and it is taken as 0.5 seconds in this

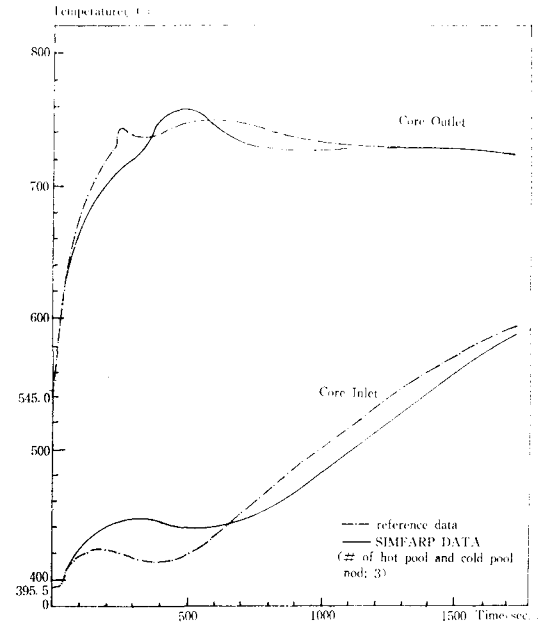

Fig. 10. Core Outlet and Inlet Temperature (Loss of electric supply power without scram)

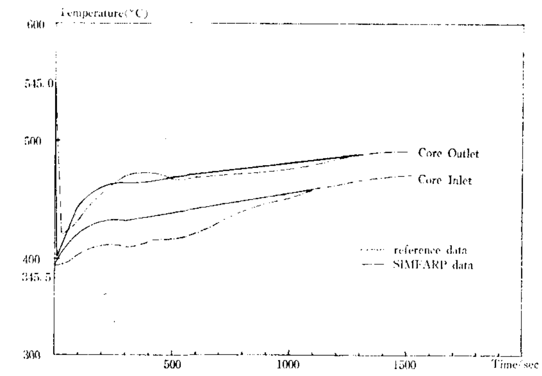

Fig. 11. Core Inlet and Outlet Temperature (Loss of off site electric power with scram)

present calculation.

Two examples are treated in this work;

i) loss of electric supply power without scram.

ii) loss of off site electric power with scram.

Since only primary circuit is modeled in SIM FARP, secondary side conditions including flow rate and inlet tempearture are given as input in Fig. 7, 8 and 9 which are from the literature [6, 7]. Computational results are shown in

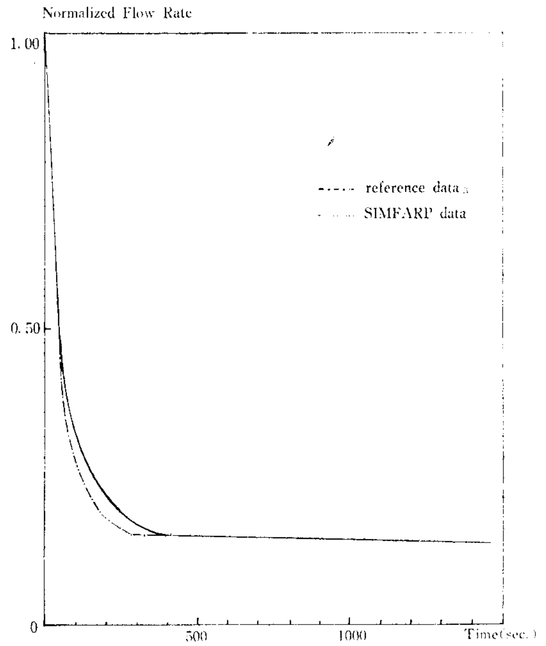

Fig. 12. Primary Flow Rate (Loss of electric supply power without scram)

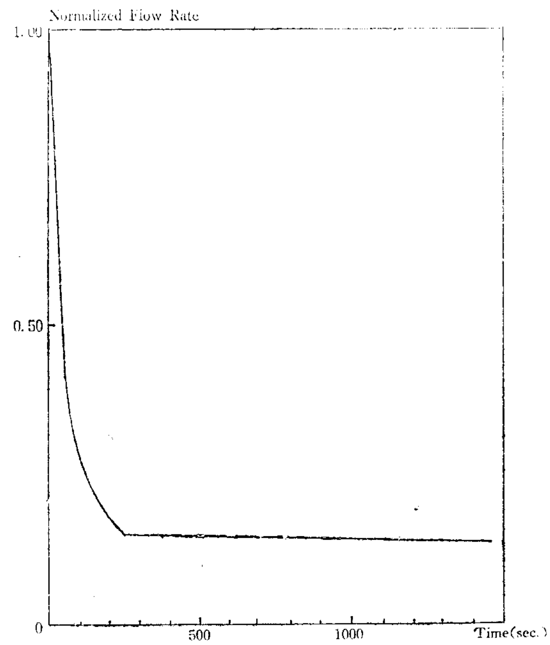

Fig. 13. Predicted Primary Flow Rate (Loss of off site electric power with scram)

Fig. 10, 11 and 12 and compared with the French reference data [6, 7].

CASE 1 Loss of electric supply power without scram[6]

The procedures of loss of electric supply power without scram accident are as follows; The four primary pumps coast down with half-speed after 50 seconds and recovered by the auxiliary motor when their speed reaches 15% of the rated speed after about 30 seconds. The eight secondary pumps coast down with half-speed after 10 seconds and recovered by the auxiliary motor when their speed reaches 20% of the rated speed after about 30 seconds as shown in Fig. 8. The power is given as input in Fig. 7 and the results are presented in Fig. 10 and 12.

CASE 2 Loss of off site electric power with scram[7]

The loss of off site electric power results in:

—scram which produces only decay power as shown in Fig. 7,

—tripping of main primary and secondary pumps which coast down gradually,

—startup of the four diesel generator,

—primary pumps coast down with half-time after 50 seconds and with recovery on the auxiliary motor when their speed reaches 20% of the rated speed after about 30 seconds.

The results are shown in Fig. 11 and 13.

IV. Discussion and Conclusions

Derivation and discussion of the governing equations, computer program and sample calculatins are described in previous sections.Results can be summarized as follows.

(i) It takes about 25 seconds in CYBER to simulate 2000 second transient with the time interval of 0.5 second.

(ii) From the Fig. 7, 8 and 9 it is overestimated in earlier time less than 1000 seconds, but its trend is similar with the reference results [6, 7]. Although there is good agreement between this results and reference results in long time (>1000 sec), there is still a vital need

Table 3. Impact of Integration Time Interval on Core Outlet Temperature in Sample Calculation Case I

Time interval \ Time	100 sec	200 sec	300 sec	500 sec	1,000 sec	2,000 sec
0.1sec	635.44	755.96	764.10	758.50	744.03	719.77
0.2sec	635.34	755.94	764.11	758.50	743.16	715.56
0.5sec	635.03	755.91	764.19	758.21	741.57	714.05

for more experimental data to test the validity of the models employed.

(iii) Since primary circuit is modeled only in SIMFARP, secondary side conditions (secondary side inlet flow and temperature) are given as input as a function of time. Therefore, it is needed to model the secondary and tertiary circuits to obtain more detail results.

(iv) At steady state the buoyancy force is about 3.19×10^4kg/msec^2 which is about 6.63% of the total circulation force at steady state (natural forced forces). After 260 seconds, the primary flow is maintained at 15%, but it decreases very slowly because the buoyancy force decreases very slowly.

(v) As shown in Table 3, it is found out that the suitable values of time interval, Δt, lie between 0.1 and 1.0 second. Attention should be paid to the selection of time interval, and it is taken as 0.5 second in this work.

In conclusion, the developed SIMFARP code predicts pretty well the general behavior of the pool type LMFBR although this code has several aspects to be improved.

And SIMFARP can be used for several purposes. Since it is not a detailed system code and fast running, it can be applied to the operational transient analysis for the real time basis as well as the conservative safety analysis for licensing. It can also be very useful for the educational purposes, of the pool type LMFBRs.

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