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A Study on Natural Circulation of Primary Pb-Bi Coolant and Decay Heat Removal System for ENHS

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ABSTRACT

The feasibility study has been carried out for verifying the feasibility of the ENHS (Encapsulated Nuclear Heat Source) concept with 100% - natural circulation of primary Pb-Bi coolant. However, the heat transfer characteristics of Pb-Bi heavy liquid metal were not quantified. This problem leads to the uncertainty of accuracy of the ENHS module scale and layout. In addition, the most accident scenarios were not simulated through the detailed analysis code.

Therefore, this paper presents the heat transfer characteristics of Pb-Bi coolant and the optimized ENHS design. The other is decay heat removal system, which is proper to Pb-Bi eutectic pool of ENHS secondary system, which is simulated through the detailed code – DSNP (Dynamic Simulator for Nuclear Power Plant). In addition, as the validation of the ENHS stability, the LOHS (Loss of Heat Sink) and reactivity insertion are simulated through the DSNP code. Results illustrate that the performance of the ENHS module is reasonable.

I. Introduction

One of the unique features of the ENHS is that the fission-generated heat is transferred from the primary coolant to the secondary coolant through the reactor vessel wall. This enables the reactor module to have a very simple design and to be free of any mechanical connections to the power plant components. The ENHS coolant need have a low vapor pressure at operating temperatures. Pb or Pb-Bi eutectic appear to be the most promising.

A schematic vertical cut through an ENHS concept is shown in Figure 1. This concept features 100% natural circulation. It uses a cover-gas lift-pump that circulates the cover gas from the plenum above the primary coolant level and injects it into the coolant in the riser through nozzles located at a certain level above the core. The cover gas bubbles reduce the effective density of coolant in the riser, thus increasing the head for coolant circulation.

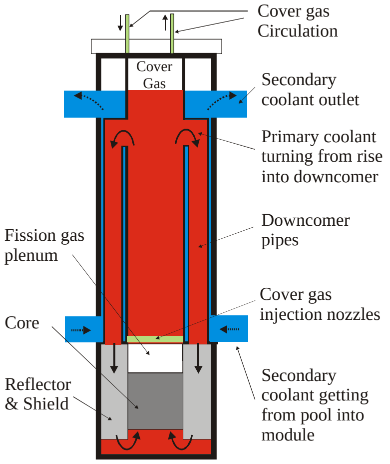

Fig. 1 A schematic vertical cut of ENHS

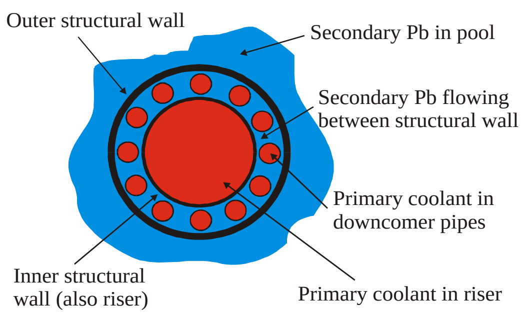

Fig. 2 A schematic horizontal cut of ENHS

There are three walls to the ENHS reactor vessel – two structural walls and a confinement wall in between. A schematic horizontal cut through an ENHS concept is shown in Figure 2. The confinement wall provides the barrier between the primary and the secondary coolants. The primary coolant gets from the riser into the downcomer pipes that are formed between two structural walls. The downcomer pipes start from the level 2m-above the top of the core. The secondary coolant gets from the pool into the ENHS module. In order to keep the primary-to-secondary temperature drop at a reasonable value – taken to be 50ºC, the surface area of the downcomer pipe is increased by using the narrower pipes.

The ENHS will be manufactured and fuelled in the factory and shipped to the site as a sealed unit with solidified Pb or Pb-Bi filling the vessel up to the upper level of the fuel rods.

The path for decay heat removal is from the primary coolant through the downcomer pipes into the secondary coolant and through the pool wall into a passive air-cooled RVACS. The ENHS is characterized by a very large area per MWth of decay heat removal from both the primary to the secondary and from secondary to the RVACS. In addition, the ENHS is characterized by a large thermal inertia due to the large heat capacity of the primary and the secondary coolants. Both features are expected to make the ENHS highly and transparently safe.

So far, the feasibility study has been carried out by being based on the general heat transfer correlations, which were developed using the experimental data of Sodium and Sodium Alkaline. Therefore, the detailed study on the heat transfer characteristics of Pb-Bi liquid metal is required and quantified with the proper accuracy.

The purpose of this paper is to illustrate the acceptability of the general heat transfer correlations and to suggest the proper heat transfer correlation (or graphic curve) of Pb-Bi liquid metal. And then, the alternative ENHS design is represented and simulated on basis of the principal design basis accident scenarios.

II. Design Goal for ENHS Module

A preliminary study was performed to determine the required dimensions of the ENHS modules for 125MWth and its corresponding weight. The design goal of this study is to get a primary-to-secondary coolant temperature drop (LMTD) of approximately 50ºC with cover-gas lift-pump @90% density.

Following is a list assumptions used for this optimization study[3][9]:

1. Thermal power is 125MWth
2. Average heat rate is 80W/cm
3. Core support plate thickness is 0.3m
4. Cavity height below core support plate is 1m
5. Fission gas plenum length above fuel is 50% of fuel rod length
6. Cover gas cavity height is 1m
7. Vessel bottom and top base thickness is 0.5m
8. Effective coolant layer around the core is 3cm
9. Core barrel thickness is 1cm
10. Coolant layer outside of core barrel is 1cm
11. Reflector thickness is 15cm
12. Reflector drive guide wall thickness is 2cm
13. Assumptions “5” and “8” through “12” are based on the 4S reactor design by Toshiba
14. Outer structural wall thickness is 3cm
15. Core coolant inlet/outlet temperature is 400/560ºC
16. The effect of lift-pump on generating head for Pb circulation is accounted for parametrically by assuming an effective reduction in the Pb density above the gas injection level
17. The confinement wall thickness is 4mm. This thickness appears adequate for 15 years of operation
18. Module weight for transportation, when loaded with fuel and solidified Pb is less than 200tons.
19. p/d of downcomer pipes is 1.5.

The neutronic feasibility of designing small and simple Pb-Bi cooled and reflected cores to operate up to the metallurgical limit with nearly zero burnup reactivity swing was investigated by E. Greenspan et al.[4]. They suggested the core height of 1.5m and p/d of 1.34 with zero burnup reactivity swing.

III. Natural Circulation Optimization

1. Model

Since the ENHS is on the possibility study stage, the acceptable design domain should be evaluated. A parametric study is employed for the optimization study based on a simple program, which uses the following formulations:

This program is an one-dimensional analysis tool. Basic equations are momentum, energy conservation equations and constitutive geometric formulations[5].

- momentum equation:

$$\rho_o g \frac{dm_p}{dt} = -g\oint \rho dz - \frac{1}{2\rho_o} R m^2 \tag{1}$$

- energy equation:

$$\rho_o c_p A_i \frac{\partial T}{\partial t} + c_p m \frac{\partial T}{\partial s} - k A_i \frac{\partial^2 T}{\partial s^2} = \Phi_i \tag{2}$$

- constitutive equation[10]:

$$D_{core} = \sqrt{\frac{4}{\pi} \times N_{ass} \times p^2 \times \sin\frac{\pi}{3}} \tag{3}$$

$$N_{ass} = \frac{Q}{\frac{q'_{max}}{PF} \times N_{rod/ass} \times H_{core}}$$

In this formulation, equivalent geometric parameters are evaluated for dimension calculation. PF is the peaking factor $q'_{max}/\langle q' \rangle$. The steady-state condition is considered for natural circulation simulation. R in Eq. (1) is flow resistance, including the friction and form resistances. For friction resistance, Vijayan & Austregesilo' s form[1] was selected for natural circulation simulation of single-phase liquid metal.

$$f = \frac{22.26}{\mathrm{Re}^{0.6744}} \tag{4}$$

For form loss calculation, K-values are obtained from the other references[5]. Geometric formulations are included to calculate the parameters in these basic equations.

Finally, simple program consist of the following 5-formulations;

$$D_{core} = \sqrt{\frac{4}{\pi} \times N_{ass} \times p^2 \times \sin\frac{\pi}{3}} \tag{5}$$

$$\frac{1}{2\rho_o^2 g \beta} R m^2 = \oint T dz \tag{6}$$

$$Q = U \Delta A \Delta T_{\ln} \tag{7}$$

$$Q = m_p c_{pp} (T_{po} - T_{pi}) \tag{8}$$

$$Q = m_s c_{ps} (T_{so} - T_{si}) \tag{9}$$

For design optimization of the ENHS with Pb (or Pb-Bi) coolant, material properties of heavy liquid metal Pb should be verified[6][8]. Especially, the heat transfer characteristics are very important. The heat transfer of Pb is a very complicated problem, which has been studied for many decades. However, heat transfer phenomena are far from being quantified with sufficient accuracy for design work. Heat transfer coefficient of Pb is smaller than that of Na. This results from two obstacles; (1) poor wetting with stainless steel structure, (2) erosion-corrosion problem. Basic phenomena of two obstacles are known but are far from being quantified with sufficient accuracy. In addition, heat transfer coefficient is then lowered again by the fact that the necessity to reduce pressure drop requires to reduce the velocity of primary Pb coolant and to increase the hydraulic diameter.

To investigate the effect of heat transfer coefficient on the ENHS design, a number of the predicted models for heat transfer coefficient were considered.

Heat transfer coefficient for primary Pb coolant in downcomer pipes is considered like the following.

- for circular tube with constant heat flux

$$Nu = 7 + 0.025 Pe^{0.8} \quad (10)$$

- for parallel plate with constant heat flux

$$Nu = 5.8 + 0.02 Pe^{0.8} \quad (11)$$

- Dwyer

$$Nu = 4.82 + 0.697(r_o / r_i) + 0.0222 Pe^{0.758(r_o / r_i)^{0.053}} \quad (12)$$

- Kirillov[7]

$$Nu = \left[\frac{1}{5 + 0.025 Pe^{0.8}} + \frac{200}{\mathrm{Re}^{0.75}} \right]^{-1} \quad (13)$$

In case of rod bundles, the following correlations are considered for heat transfer coefficient.

- Westinghouse

$$Nu = 4 + 0.33(p/d)^{3.8}(Pe/100)^{0.86} + 0.16(p/d)^5 \ (1.1 \le p/d \le 1.5, 10 \le Pe \le 5000) \quad (14)$$

- Schad-modified

$$Nu = \left[-16.15 + 24.96(p/d) - 8.55(p/d)^2\right] Pe^{0.3}$$

$$(1.1 \le p/d \le 1.5, 150 \le Pe \le 1000)] \quad (15)$$

- Borishanskii

$$Nu = 24.15 \log 10[-8.12 + 12.76(p/d) - 3.65 (p/d)^2] + 0.017[1 - \exp(6 - 6(p/d))] \times [Pe - 200]^{0.9}$$

$$(1.1 \le p/d \le 1.5, 200 \le Pe \le 2000) \quad (16)$$

- Graber & Rieger

$$Nu = \left[0.25 + 6.2(p/d) + 0.32(p/d)^2\right] - 0.007(Pe)^{0.8 - 0.024(p/d)}$$

$$(1.25 \le p/d \le 1.95, 150 \le Pe \le 3000) \quad (17)$$

Pb-Bi liquid metal has not be experimented to be enough quantified with the proper accuracy. Therefore, the material properties as well as the heat transfer characteristics are not verified with the reasonable criteria. The obstacles are two uncertainty; (1) poor wetting problem and (2) aggressive erosion-corrosion problem. So far, the detailed papers had not be presented for these problem, Kirillov said that Nu number of Pb-Bi in the operating condition is lower by 20% than that in the well-conditioned environment.

2. Results

Simple program with variant predicted models have generated the quantified results of heat transfer coefficients.

Table 1 represents heat transfer coefficients and thermal resistances in case of downcomer pipes. Thermal resistance R is

$$R = \frac{1}{hA} \tag{18}$$

Table 1. Heat transfer coefficients in pipes-region

(a) Primary side heat transfer

	Heat transfer coefficient, H (W/m^2K)	Thermal resistance, R (mK/W)
Seban	13231	0.00756
Lyon	10741	0.00931
Dwyer	10600	0.00943
Kirillov	7537	0.0133

(b) Secondary side heat transfer

	Heat transfer coefficient, H (W/m^2K)	Thermal resistance, R (mK/W)
Westinghouse	6517	0.01096
Schad – Modified	7610	0.009386
Borishanskii	7832	0.00912
Graber & Rieger	5462	0.013

Table 2. Heat transfer coefficients in core-region

	Heat transfer Coefficient, H (W/m^2K)	Nominal rate
Westinghouse	16161	72.5 %
Schad – Modified	22283	100 %
Borishanskii	21472	96.4 %
Graber & Rieger	12876	57.8 %

In case of downcomer pipes, the predicted models of Kirillov and Graber & Rieger generate the smallest heat transfer coefficients and lead to conduct the more conventional design.

Table 2 represents heat transfer coefficients in case of fuel rod bundles. In case of fuel region, the predicted model of Graber & Rieger generates the smallest heat transfer coefficient. This obliges to increase the p/d of fuel rods. In this study the wall thickness of downcomer pipe is 4mm. Therefore, wall thermal conductivity is the fixed 21.634 W/mK.

To investigate the sensitivity of heat transfer coefficients on the ENHS design specification, four sets of thermal resistances are used;

1. Smallest thermal resistance:
   Circular tube (General correlation) and Borishanskii correlations
2. Medium thermal resistance:
   Dwyer and Westinghouse correlations
3. Largest thermal resistance:
   Kirillov and Graber & Rieger correlations
4. The Alternative Heat Transfer Models

Since the variant models of heat transfer coefficients had been developed by using the other liquid metals, the heat transfer coefficient of Pb-Bi coolant should be verified and quantified. Most of the predicted models were developed using the Sodium Alkaline. And the experimental range is limited into the low Pe number – 100 to 1,000 of Pe. The followings are the some heat transfer correlations.

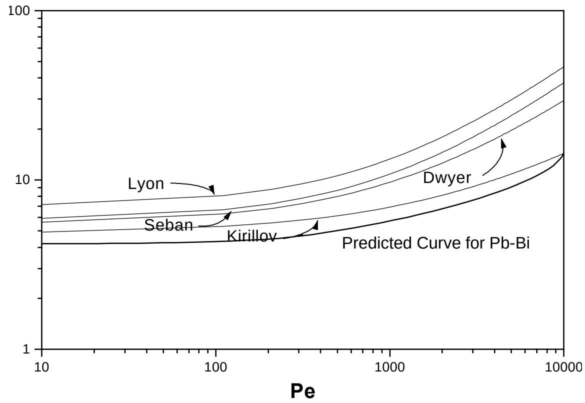

Fig. 3 Heat Transfer Correlations Inside Tubes

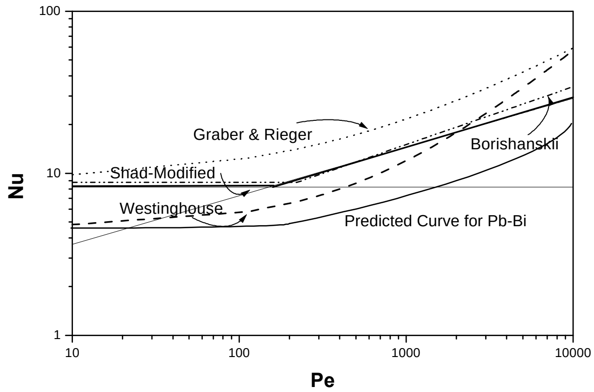

Fig. 4 Heat Transfer Correlations in Rod Bundles

Figs. 3and 4 are heat transfer correlations of the predicted models of Sodium Alkaline. In addition, using the rare experimental data the alternative heat transfer correlation is displayed.

Table 3. Effect on total weight of ENHS module

	Case 1	Case 2	Case 3	Case 4
Secondary inlet/outlet temperature (ºC)	359/510	361/511	360/510	361/512
Primary-to-secondary temperature drop (ºC)	47.64	44.27	44.19	42.833
Total thermal resistance (mK/W)	0.03218	0.03589	0.0418	0.0522
Vessel height/diameter (m)	15.0/2.4	16.6/2.4	19.6/2.4	22.6/2.4
Total Pb coolant weight (ton)	314	352	412	489

Table 4. Conceptual Design Specification

Module Height / Diameter (m)	22.6/2.5	Cover-gas Lift Pump (%)	90
Core Height / Diameter (m)	2 / 1.42	Linear Heat Rate (W/cm)	80
No. of Assemblies (217 fuels)	36	p/d (1cm – diameter fuel)	1.34
Vessel Wall Thickness (mm)	45	Reflector Wall Thickness (cm)	15
Rise Length (m)	14.5	Riser Diameter (m)	1.87
No. of Downcomer Pipes	1200	Downcomer Pipe Diameter (cm)	3.2
No. of Rows of Pipes	6	Pipe Thickness (mm)	7
Radial Space of Pipes (cm)	3.5	Circumferential Space (cm)	4.05
Annular Space for Pipes (cm)	22.5	LMTD (ºC)	48.7
Total Coolant Weight (tons)	489	Total SS Weight (tons)	72.5

Using the above predicted models and the alternative model of liquid metals, two results were developed like Tables 3 and 4. Table 3 illustrates the effect on total weight of ENHS module and Table 4 illustrates the conceptual design specifications of the ENHS module with the alternative heat transfer correlation of Pb-Bi liquid metal.

Table 3 is design specification of the ENHS module, which was evaluated through four cases of thermal resistances. Case 1 is the smallest thermal resistance, case 2 is medium thermal resistance, case 3 is the largest thermal resistance, and case 4 is the alternative heat transfer for Pb-Bi liquid metal.

In Table 4, the optimum dimension of the ENHS vessel is 22.6m-height and 2.5m-outer diameter. Downcomer region needs 1200 downcomer pipes with 3.2cm-diameter. The overall weight of the ENHS module is nearly 561 tons. This overweight is not prior to that of the ENHS module with the predicted heat transfer correlation of general Sodium Alkaline.

IV. Decay Heat Removal System

Most of liquid metal cooled-reactors employ the passive RVACS, which was suggested in the conceptual design of ALMR. RVACS is considered as the only passive decay heat removal system, especially for liquid metal reactors. However, heavy liquid metal such as Pb or Pb-Bi has very large material density. Therefore, static pressure of heavy liquid metal is also very large. This is obstacle on the development of heavy liquid metal cooled-reactors with RVACS. In this study, we has investigated the alternative RVACS concept. Therefore, ordinary RVACS and alternative RVACS are, together, investigated to evaluate the feasibilities and possibilities.

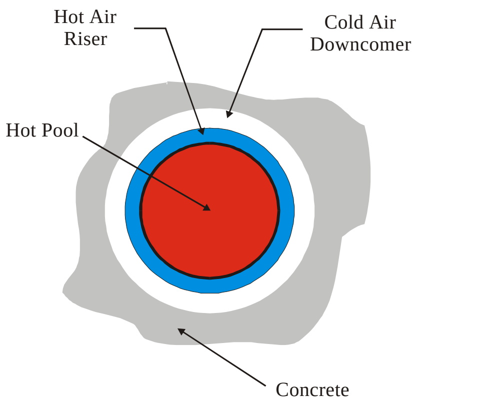

Fig. 5 Horizontal cut with ordinary RVACS

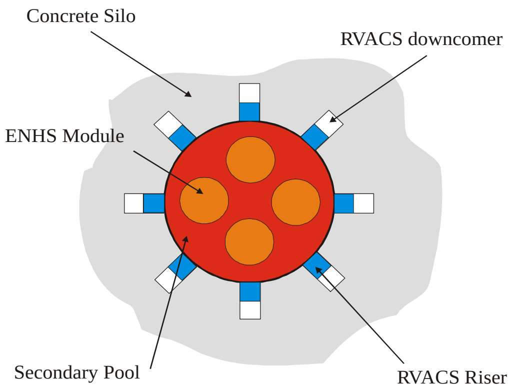

Fig. 6 Horizontal cut with alternative RVACS

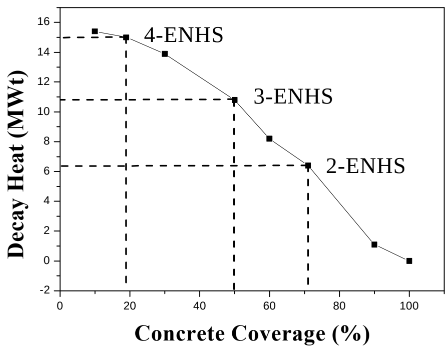

Fig. 7 Concrete coverage of alternative RVACS

Some assumptions are employed for the clear simulation of each RVACS concept.

(1) 4-ENHS modules are implemented inside the secondary pool system
(2) Air chimney inside the air circulating-duct is assumed to be 30m
(3) Secondary pool diameter is assumed to be 9m, considering the 2.5m-diameter of ENHS module
(4) Inlet cold air is assumed that its temperature is 25°C
(5) Thickness of pool structure is 7cm
(6) It is assumed that 3%-decay heat removal is the most optimal

For each RVACS concept, some additional features are necessary: (1) triggering temperatures are, respectively, 500 °C, 600 °C, and 700 °C. (2) Concrete coverage is considered in case of alternative RVACS simulation.

Table 5 is the results of the ordinary RVACS. Decay heat is therefore extracted by a simultaneous process of internal Pb and external air natural convection, conduction, and radiation. These affects are considered in this result.

18cm-riser channel gap width is the most optimal for our ENHS secondary pool. In case of 500 °C--vessel temperature, drag time-time to maximum temperature rise- was the largest. However, it has the smallest decay heat removal rate of 4.45%-rated power. In comparison with ordinary 2.5%-rated power, 4.45%-rated power is very large rate. Therefore, we can deduce that ordinary RVACS has very large surface area per MWth of decay heat removal. In addition, large thermal inertia was verified by the long time to maximum vessel temperature rise.

Figure 7 is illustration of concrete-coverage of alternative RVACS. Concrete coverage is percentage of the concrete-covered area on the pool outer area.

In this study, several cases of ENHS implementation have investigated to evaluate the optimal decay heat removal capability. From Figure 7, concrete coverage should be approximately 20% with 4-ENHS implemented. For 3-ENHS, concrete coverage is about 50% and for 2-ENHS it is about 70%. To implement more ENHS modules within the secondary pool, concrete coverage should be reduced. However, concrete coverage may mean the structural integrity. Therefore, in case of more ENHS modules the structural integrity is degraded.

Table 5.Performance characteristics of ordinary RVACS

Riser Channel Gap Width (cm)	18		
Downcomer Channel Gap Width (cm)	57		
Trigger temperature (°C)	500	600	700
Maximum Vessel Temperature Rise (°C)	105	84.1	66.7
Time to Max. Temperature Rise (°C)	23.2	16.6	13.2
Outlet Air Temperature (°C)	323	356.2	387.2
Decay Heat Removal Rate (%)	4.45	4.92	5.42

V. Accident Analysis

The ENHS module was developed with the alternative heat transfer model of Pb-Bi. Therefore, this ENHS design should be validated on basis of design basis accidents. Analysis scenarios are LOHS and reactivity insertion accidents. In advance, the ENHS schematics should be considered to be modeled by DSNP (Dynamic Simulator for Nuclear Power Plant) code. The ENHS module is Fig. 1. The overall plant layout is based on 1 ENHS module plant. In these analyses, core, riser and upper plenum with free level, downcomer with circular pipe, hydraulic pipe segments, steam generator, Pb-Bi cavity pool, and decay heat removal path are included in the modeling. In addition, neutronics and thermodynamics, feedback reactivity, and decay heat are used in the core module. Fig. 8 is the simulation model for ENHS of DSNP code.

This simulation model can cover the whole plant layout of the ENHS. Most of design parameters are lumped and steam generator is represented by intermediate heat exchange module. RVACS is represented by simple heat removal path. In this simulation model, heat transfer characteristics are used by the previously verified model of Pb-Bi liquid metal. First, LOHS is represented like the following.

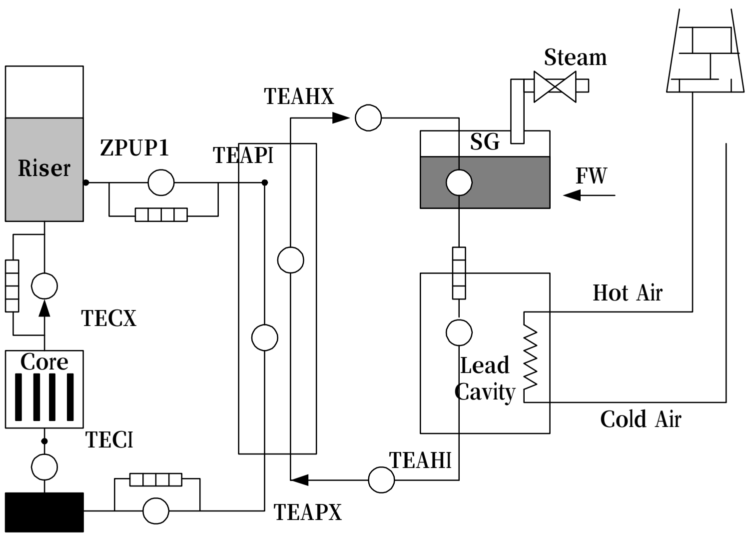

Fig. 8 Simulation Model of DSNP

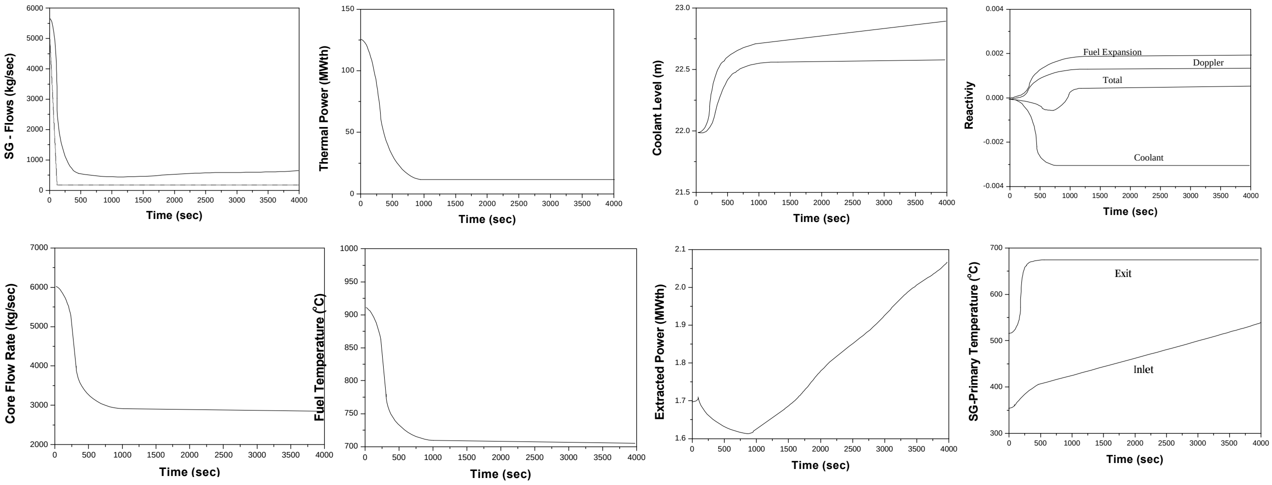

Fig. 9 ENHS Response of LOHS

From these Figs., one can know that the flow transients rapidly propagate with time goes on. And temperature changes very slowly propagates as time goes on.

The following Fig. 10 is the DSNP nodalization diagram in case of reactivity insertion. In this accident scenario, initiating events are occurred at 1 and 3 seconds. At 1 second goes on, reactivity change is positively 7e-3, and at 3 seconds go on the reactivity change is negatively 5e-3.

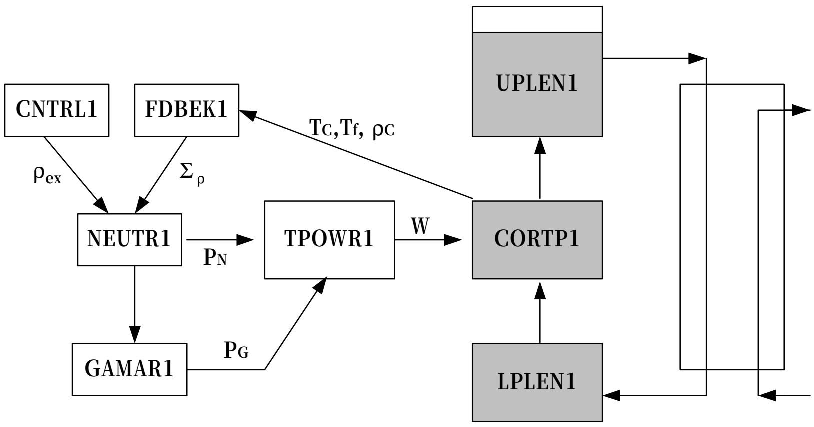

Fig. 10 DSNP Nodalization of Reactivity Insertion

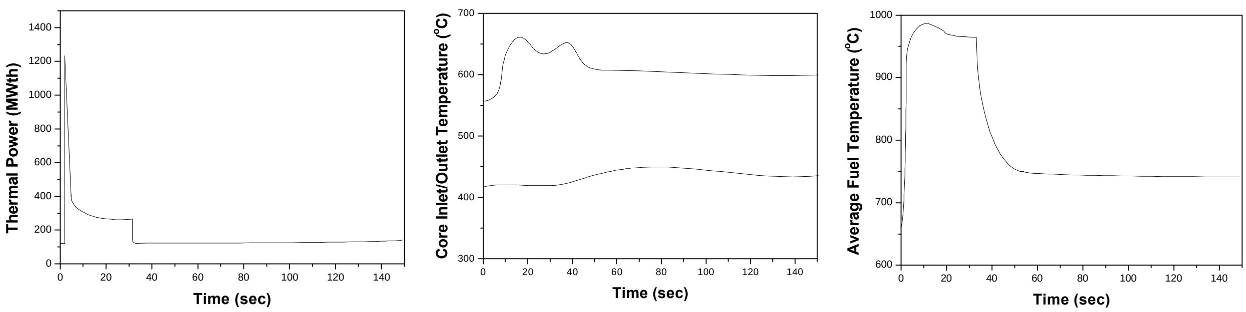

Fig. 11 ENHS Response of Reactivity Insertion

From these Figs., the power transient is around 1000%. The normal power is 125MWth. However, At 3 seconds, power transient reaches the peak of 1245MWth. However, one can observe that there is no damage to core or other components.

VI. Conclusions and Remarks

Using Pb-Bi coolant, an ENHS concept has been developed to have 100%-natural circulation and deliver 125MWth to secondary coolant through a 7mm-thick pipe with no more than 50ºC temperature drop. In addition, alternative RVACS concept was proposed for Pb cooled pool system. In addition, LOSH and reactivity insertion are simulated for accident scenarios.

Conclusions are like followings:

(1) In case 1, which is circular tube (general correlation) and Borishanskii correlations, dimension of the ENHS module is the smallest.
(2) In case 4, which is the alternative heat transfer characteristics, dimension of the ENHS module is the largest.
(3) The alternative ENHS concept with Pb-Bi heat transfer correlation is not prior to that with the predicted heat transfer correlations of general Sodium Alkaline.
(4) Ordinary RVACS has a large surface area per MWth of decay heat removal.
(5) Alternative RVACS is proposed for structural integrity.
(6) LOHS and reactivity insertion are simulated for validation of the alternative ENHS concept with the heat transfer characteristics of Pb-Bi liquid metal.
(7) From these accident scenarios, no damage to core or other components is observed.

In further study, the more experimental data of such heavy liquid metal as Pb (or Pb-Bi) will be collected and be compared with the predicted correlations for variant heavy liquid metals. In addition, DSNP code will be upgraded by adding the detailed TH and flow correlations and by recoding the node configuration schemes of reactor components.

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