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# A New LMR SG with a Double Tube Bundle Free from SWR

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## Abstract

To resolve the concern of the SWR possibility in LMR and improve the economic feature of LMR, relative performance of various SG designs using a double tube bundle configuration is evaluated and a new SG design concept is proposed. The new steam generator design houses two tube bundles that are functionally different and its tube bundle region is radially divided into two. It prevents the occurrence of sodium water reaction while sodium is still used as the coolant for the primary heat transport system. The feasibility of the SG with a double tube bundle for actual use in an LMR plant is evaluated by setting up the skeleton of the NSSS for various possible configurations of the SG tube bundles. The evaluation revealed the relative advantages and disadvantages of the configurations and the new SG design concept performs good and can be actually used in an LMR plant.

**Key Words** : LMR, SWR, SG, tube bundle configuration, double, performance, evaluation

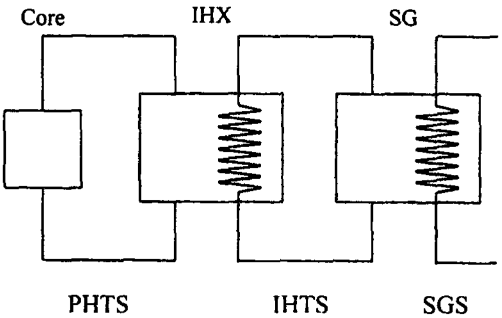
## 1. Introduction

LMR can make the utilization of uranium resource very efficient and also reduce transuranics substantially. These desirable features make LMR (Liquid Metal reactor) highly promising for solving the energy resource problem and the spent fuel storage problem. However, the relatively high construction cost and concern on the possibility of the violent SWR (Sodium Water Reaction) have been the difficulties against wide use of LMR.

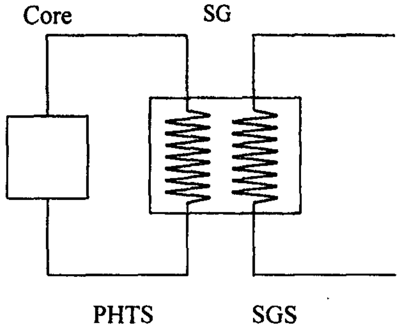
To resolve the difficulties in deploying LMR for power generation, various efforts are being undertaken in many countries[1,2]. The efforts are generally in the direction to eliminate the intermediate heat transport system (IHTS), which is an unique system of LMR and conventionally required for LMR using sodium to protect the nuclear core in an SWR event, by using a coolant other than sodium or using a steam generator design which can prevent the occurrence of SWR.

Elimination of IHTS by using a new SG (Steam Generator) was suggested by various researchers such as ANL[2], Kinoshita[3] and Miyazaki[4]. Recent evaluation [5] on the suggestions showed that their performance is not practical or they introduce new difficulties. One of the suggestions made in literature is the double installation of the heat transfer tube bundles in SG and was suggested by Miyazaki, et al[4]. Evaluation on the suggested idea showed the required SG size is not practical because of the poor heat transfer performance of the concept. Quite recently there was a report on the work for a SG with a double bundle[6] and results of the study on the SG with a bundle configuration in vertical separation were presented. They also suggested use of forced circulation as suggested in this paper to remedy the poor heat transfer of the natural circulation. Their work and the work of this paper were carried out independently from each other.

In this paper, the SG idea of using a double heat transfer tube bundle is improved by the study on the tube bundle configuration effects and use of a forced convection. Feasibility of the SG with a double tube bundle for actual use in an LMR plant is evaluated by setting up the skeleton of the NSSS (Nuclear Steam Supply System) for the various possible configurations of the tube bundles, and a SG design with a new bundle configuration is proposed.



(a) Reference design



(b) Design of this study

**Fig. 1. Comparison of the Functional Structures of NSSS**

## 2. The SG Structures for Evaluation

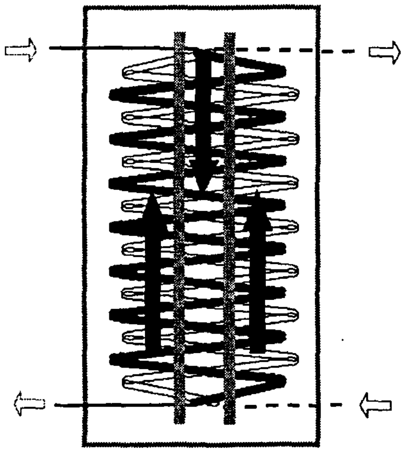
The steam generator structures for the performance evaluation have the following common features.

- The SG shell is filled with a medium fluid which is chemically stable with water and sodium.
- Two different kinds of heat transfer tubes are installed in the shell. One for the heat transfer from the PHTS(Primary Heat Transport System) sodium to the medium fluid and the other is for that from the medium fluid to the feedwater. The first tubes are denoted as PM(Primary and Medium) and the second as MH (Medium and Water) in this paper.
- The medium fluid is circulated by a pump.

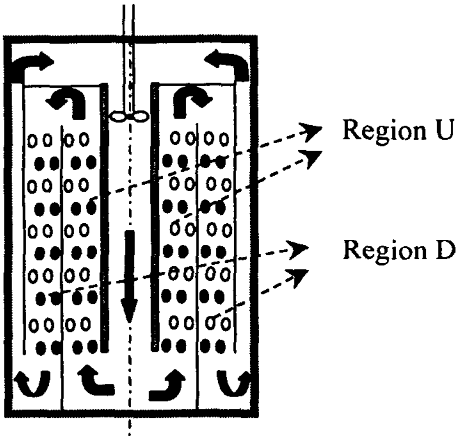
Figure 1 compares the functional structures of the NSSS of the current SG design such as that in KALIMER[7] and the NSSS with the new SG design of the double tube bundle in this study.

In the configuration of the heat transfer bundles of PM and MH, there are several alternatives and the configurations studied are the integrated and separated types. Also two variations were considered for the integrated type. Fig. 2 shows the configurations.

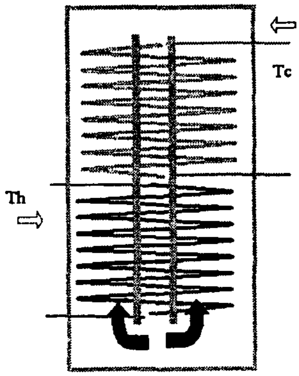
The configurations of Figs. 2-a and -c are the configurations studied in the previous works of References 3, 4 and 5. The Integrated double-region type shown in Fig. 2-b, is newly introduced in this work. In the figures, all of the tubes are helical and the colors black, white and gray denote the type of heat transfer tubes. For example, the black and white in Fig 3.a represent cold fluid tube



(a) Integrated single-region type



(b) Integrated double-region type



(c) Separated Type

Fig. 2. Heat Transfer Tube Bundle Configurations

and hot fluid tube respectively. Fig. 3b shows the cross section of the tube bundle configuration.

In the integrated configurations, the tubes of PM and MH are installed alternatively and the two tubes which are functionally different from each other make a single integrated bundle in space. The tubes of each type, however, construct its own tube bundle functionally. In the separated type configuration, the bundles are functionally and also physically clearly separated. The integrated double-region type of Fig. 2-b is a variation of the integrated-single region type of Fig.2-a and the bundle region is radially divided into two regions and the medium fluid flows up and down in the bundle. The region where the medium flows upward is called, hereafter, Region U and the region downward Region D as shown in the figure.

There is a big difference in the role of the medium fluid in the heat transfer between the integrated and separated configurations. In the separated configuration, the heat from the hot fluid to the cold fluid is carried by the medium fluid in a total basis but the heat transfer in the integrated type is made locally. More explanation on this difference will be provided later.

## 3. Quantitative Evaluation

The quantitative evaluation on the performance of the SG designs with various bundle configurations is made utilizing the design data set of KALIMER[7] of which conceptual design was recently completed in KAERI(Korea Atomic Energy Research Institute) by the LMR technology development program supported by MOST (Ministry of Science and Technology). Specifically speaking, the evaluation is made by evaluating the effects of the design difference between the new SG design and reference SG design on the required NSSS equipment sizes and thermal efficiency instead of directly analyzing the plant system with development of a NSSS design for each SG design. This approach saves efforts and makes the work more efficient compared to the direct approach.

The assessment is made mainly by the following steps.

1. Deriving the expression for the ratio of heat transfer resistances between the new design and reference design.
2. Deriving the expression for the ratio of the heat transfer rate as a function of the bundle configuration, heat transfer resistances and operation parameters.
3. Calculating the required equipment size and electric power for pumping fluids to meet assigned NSSS performance

The conditions and targets used in the assessment are as follows.

1. The highest and lowest temperatures of NSSS are maintained the same between the new and reference designs
2. The net electricity generation rate and thermal efficiency of the plant with the new design NSSS need to be no less than the reference design plant.
3. The heat transfer area adjustment required to meet the plant performance target in the new design is made by changing the number of heat transfer tubes while keeping the tube length the same for simplicity of the assessment work.

## 3.1. Expression for the Heat Transfer Resistances

### 3.1.1. Basic Expression

Considering that the analysis of this work is to find out approximate NSSS features with new SG designs, the concept of heat transfer resistance is used to simplify the analysis.

The heat transfer resistance is defined by Eq. (1) for the heat transfer between two locations of different temperatures.

$$R \equiv \frac{\Delta T}{Q} = \frac{1}{UA} \quad (1)$$

where ΔT is the temperature difference and Q is

**Table 1. Structure of the Heat Transfer Resistance**

| | The first path | | The second path | |
|---|---|---|---|---|
| | Region | Composition | Region | Composition |
| Reference Design | IHX | $R_{CVe} + R_{CD} + R_{CVi}$ | SG | $R_{CVe} + R_{CD} + R_{CVi}$ |
| New Design | PM | $R_{CVi} + R_{CD} + R_{CVe}$ | MH | $R_{CVe} + R_{CD} + R_{CVi}$ |

**Table 2. Basic Features of the Resistances in the New Design**

| | Region PM | | | Region MH | | |
|---|---|---|---|---|---|---|
| | $R_{CVi}$ | $R_{CD}$ | $R_{CVe}$ | $R_{CVe}$ | $R_{CD}$ | $R_{CVi}$ |
| material | Sodium | *1 | Lead-Bismuth | Lead-Bismuth | *2 | $H_2O$ |
| flow rate | $m_p$ | | $m_M$ | $m_M$ | | $m_H$ |
| pressure | $P_P$ | | $P_M$ | $P_M$ | | $P_H$ |

*1 : same as the material of the IHX tube in the reference design

*2 : same as the material of the SG tube in the reference design the heat transfer rate. $U$ and A are respectively the overall heat transfer coefficient and heat transfer area.

In the new concept, the heat is transferred first from the PHTS fluid to the medium fluid and then transferred again to the feedwater as shown in Fig. 1-b. In other words, the first heat transfer path is 'fluid(PHTS)-solid(tube wall)-fluid(medium)' and the second path is 'fluid(medium)-solid(tube wall)-fluid(feedwater)'. The structure of the resistance in the heat transfer path is shown in Table 1 with that of the reference design. The region of the first path in the new steam generator, which is indicated by PM in this paper, corresponds to the IHX (Intermediate Heat Exchanger) of the reference design and the region of the second path, which is indicated by MH, corresponds to the SG in the reference design as shown in Fig. 1

In the table, the subscripts $CV$, $CD$, e and i mean convection, conduction, external and internal, respectively.

The physical features of the resistance components of the new design is shown in Table 2. The subscripts $P$, $M$, and H respectively mean PHTS, medium and $H_2O$(feedwater and steam).

From the basic features of the resistances and heat transfer physics, the resistances in the PM region are written as below.

$$R_{CVi}^{PM} = R_{CVi}^{IHX}\left(\frac{\dot{m}_{KP}}{\dot{m}_{NP}}\right)^{0.8}\left(\frac{A_{fi}^{P}}{A_{fi}^{IHX}}\right)^{0.8}\left(\frac{A_{IHX}}{A_{PM}}\right) \tag{2}$$

$$R_{CD}^{PM} = R_{CD}^{IHX}\left(\frac{t_{PM}}{t_{IHX}}\right)\left(\frac{A_{IHX}}{A_{PM}}\right) \tag{3}$$

In the equations, the scripts $KP$, $NP$, $IHX$ and $t$ respectively mean the property of KALIMER PHTS, new design PHTS, KALIMER IHX and thickness. $A_{fi}$ is for the internal flow area and A is the heat transfer area. For considering the effects of the flow rate, the Dittus-Boelter's correlation for forced convection [8] was used.

Similarly in the MH region,

$$R_{CD}^{MH} = R_{CD}^{SG}\left(\frac{t_{MH}}{t_{SG}}\right)\left(\frac{A_{SG}}{A_{MH}}\right) = R_{CD}^{SG}\left(\frac{A_{SG}}{A_{MH}}\right) \tag{4}$$

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$$R_{CVi}^{MH} = R_{CVi}^{SG}\left(\frac{\dot{m}_{KH}}{\dot{m}_{NH}}\right)^{0.8}\left(\frac{A_{fi}^{H}}{A_{fi}^{SG}}\right)^{0.8}\left(\frac{A_{SG}}{A_{MH}}\right) \tag{5}$$

The scripts KH, NH and SG respectively mean the property of KALIMER feewater, new design feedwater and KALIMER SG.

The external convection resistance $R_{CVe}$ needs to consider also the property and geometry differences and their effects are considered by the Reynolds number.

$$R_{CVe} = \frac{1}{(hA)_{CVe}} \sim \left(\frac{1}{k\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}\,A_{fe}/L_e}\right)_{CVe} \tag{6}$$

$$\mathrm{Re} = \frac{\rho VD}{\mu} = \frac{\dot{m}L_e}{A_{fe}\mu} \tag{7}$$

$$R_{CVe} \sim \left(\frac{A_{fe}\mu}{\dot{m}}\right)^{0.8}\frac{1}{k}\frac{1}{\mathrm{Pr}^{0.4}}\frac{L_e^{0.2}}{A} \tag{8}$$

where $A_{fe}$ and $L_e$ are respectively the flow area and length scale for the external convection. A is the heat transfer area.

Equation (8) is applied to the regions PM and MH.

$$R_{CVe}^{PM} = R_{CVe}^{IHX}\left(\frac{A_{fe}^{PM}}{A_{fe}^{IHX}}\right)^{0.8}\left(\frac{L_e^{PM}}{L_e^{IHX}}\right)^{0.2}\left(\frac{\mu_M}{\mu_I}\right)^{0.8}\left(\frac{\dot{m}_I}{\dot{m}_M}\right)^{0.8}\left(\frac{\mathrm{Pr}_P}{\mathrm{Pr}_M}\right)^{0.4}\left(\frac{A_{IHX}}{A_{PM}}\right)\left(\frac{k_I}{k_M}\right) \tag{9}$$

$$R_{CVe}^{MH} = R_{CVe}^{SG}\left(\frac{A_{fe}^{MH}}{A_{fe}^{SG}}\right)^{0.8}\left(\frac{L_e^{MH}}{L_e^{SG}}\right)^{0.2}\left(\frac{\mu_M}{\mu_I}\right)^{0.8}\left(\frac{\dot{m}_I}{\dot{m}_M}\right)^{0.8}\left(\frac{\mathrm{Pr}_I}{\mathrm{Pr}_M}\right)^{0.4}\left(\frac{A_{SG}}{A_{MH}}\right)\left(\frac{k_I}{k_M}\right) \tag{10}$$

where $P$ and $I$ mean respectively the property of the PHTS and IHTS of KALIMER. In other sections of this paper, $P$ is used to denote PHTS regardless of the design type when that use does not cause ambiguity. However, *I* always denotes the KALIMER IHTS.

Inserting Eqs. (2), (3) and (9) into $R^{PM}$ in Table 1,

$$\begin{aligned} R^{PM} &= R^{PM}_{CVi} + R^{PM}_{CD} + R^{PM}_{CVe} \\ &= \left\{ R^{IHX}_{CVi}\left(\frac{\dot{m}_{KP}}{\dot{m}_{NP}}\frac{A^{P}_{fi}}{A^{IHX}_{fi}}\right)^{0.8} + R^{IHX}_{CD}\left(\frac{t_{PM}}{t_{IHX}}\right) + R^{IHX}_{CVe}\frac{k_P}{k_M}\left(\frac{A^{PM}_{fe}}{A^{IHX}_{fe}}\right)^{0.8} \right. \\ &\qquad \left. \left(\frac{L^{PM}_{e}}{L^{IHX}_{e}}\right)^{0.2}\left(\frac{\mu_M}{\mu_P}\cdot\frac{\dot{m}_I}{\dot{m}_M}\right)^{0.8}\left(\frac{\Pr_P}{\Pr_M}\right)^{0.4} \right\} \\ &\cdot\frac{A_{IHX}}{A_{PM}} \end{aligned} \tag{11}$$

Now, the ratio of the property between the medium fluid of this study and the fluid of the reference design are inserted into the derived expression. For this, the properties of lead are used for the medium fluid and the ratios used for conductivity *k*, specific heat $C_p$, density ρ, viscosity μ, Prandtl number *Pr* are as following.

$$\begin{aligned} &\frac{k_L}{k_{Na}} =\sim 0.22, \quad \frac{Cp_L}{Cp_{Na}} =\sim \frac{1}{8}, \quad \frac{\rho_L}{\rho_{Na}} =\sim 10 \\ &\frac{\mu_L}{\mu_{Na}} =\sim 5.3, \quad \frac{\Pr_L}{\Pr_{Na}} =\sim 3.3 \end{aligned} \tag{12}$$

The thickness ratio $\frac{t_{PM}}{t_{IHX}}$ is set to 1 as done for the SG tube thickness since the system operation pressures are kept the same between the new design and reference design.

Before inserting the ratios into the derived expression, the ratio of the medium mass flow rate to the IHTS flow rate of the reference design $K^{MI}_{m}$ is substituted by that of the product of flow rate and *Cp* as shown in Eq. (13)

$$K^{MI}_{\dot{m}} \equiv \frac{\dot{m}_M}{\dot{m}_I} = \frac{Cp_{Na}}{Cp_L}K^{MI}_{\dot{m}Cp} \text{ where, } K^{MI}_{\dot{m}Cp} \equiv \frac{(\dot{m}C_P)_M}{(\dot{m}C_P)_I} \tag{13}$$

Equations (12) and (13) are inserted to Eq. (11).

$$\begin{aligned} \frac{R^{PM}}{\left(\frac{A_{IHX}}{A_{PM}}\right)} &= R^{IHX}_{CVi}\left(\frac{\dot{m}_{KP}}{\dot{m}_{NP}}\frac{A^{P}_{fi}}{A^{IHX}_{fi}}\right)^{0.8} + R^{IHX}_{CD} \\ &+ \left\{2.027\left(K^{PM}_{Afe}\right)^{0.8}\left(K^{PM}_{Le}\right)^{0.2}\left(K^{MI}_{\dot{m}Cp}\right)^{-0.8}\right\}R^{IHX}_{CVe} \end{aligned} \tag{14}$$

where $K_{Afe}$ and $K_{Le}$ are respectively the ratios of the flow area and the representative length in the external convection for the new design and to those for the reference design. In this paper, K generally means a ratio of its subscript property between the new and reference designs.

Consideration of the weighting of each resistance in the overall resistance is made by assuming that the weighting distribution is the same as that in the reference design. Since the ratios are mainly decided by the operation temperatures and the heat transfer mechanism of each heat transfer component and the operation temperatures and heat transfer mechanism are basically the same between the reference and new designs, the assumption does not cause significant error. The weightings, i.e., ratios of the resistance components to the overall resistance are shown in Table 3.

**Table 3. Distribution of Resistances**

| Path | $R_{CVe}$ | $R_{CD}$ | $R_{CVi}$ |
|---|---|---|---|
| PM | 0.16 | 0.55 | 0.29 |
| MH | 0.17 | 0.45 | 0.38* |

* 0. 38 consists of the portions for pure convection 0.17 and fouling consideration 0.21. (The IHX fouling allowance in the reference design was considered in setting the operation point and heat transfer area.)

Dividing Eq. (14) by $R^{PI}$ (= the overall resistance in the reference design IHX heat transfer) and inserting the weightings in Table 3 to the resulting equation produces Eq. (15).

$$\begin{aligned} K^{PM}_{R} \equiv \frac{R^{PM}}{R^{PI}} &= \left\{0.29\left(K^{P}_{\dot{m}}\right)^{-0.8}\left(K^{P}_{Afi}\right)^{0.8} + 0.55 \right. \\ &\left. + 0.324\left(K^{PM}_{Afe}\right)^{0.8}\left(K^{PM}_{Le}\right)^{0.2}\left(K^{MI}_{\dot{m}Cp}\right)^{-0.8}\right\}\frac{1}{K^{PM}_{A}} \end{aligned} \tag{15}$$

where $K^{PM}_{A}$ is the ratio of APM to $A_{IHX}$.

Similar work is performed for the MH region. The external convection resistance is derived as Eq. (16).

$$R_{CVe}^{MH} = 10.7\left(K_{iii}^{MI}\right)^{-0.8}\left(K_{Afe}^{MH}\right)^{0.8}\left(K_{Le}^{MH}\right)^{0.2} \cdot \left(K_{A}^{MH}\right)^{-1} \cdot R_{CVe}^{SG} \tag{16}$$

where $K_A^{MH}$ is the ratio of AMH to ASG.

The values of the tube thickness of the MH region and flow rate are set as those of the reference design.

Finally the expression for the ratio of overall heat transfer resistance in MH to the corresponding part in the reference design $K_R^{MH}$ is derived as Eq. (17)

$$K_R^{MH} \equiv \frac{R^{MH}}{R^{IH}} = \frac{1}{K_A^{MH}}\Big[0.17\left(K_{iii}^{H}\right)^{-0.8}\left(K_{Afi}^{H}\right)^{0.8} + 0.66 + 0.0586\left(K_{Afe}^{MH}\right)^{0.8}\left(K_{Le}^{MH}\right)^{0.2}\left(K_{iiiCp}^{MI}\right)^{-0.8}\Big] \tag{17}$$

In the expressions for the total resistance Eqs. (15) and (17), the external flow area ratiodepends on the tube bundle geometry. Since the bundle geometry of the new design is the same as that of the reference design except the number of tubes, the ratio becomes a function of the bundle diameters as shown in Eq. (18)

$$K_{AFe} = \frac{K_n}{1 + \dfrac{2D_{C0}}{(D - D_C)_0}}\left(K_n + \frac{2D_{C0}}{(D - D_C)_0}\right) \tag{18}$$

where $D$, $D_c$ and $K_n$ respectively represent the outer and inner diameters of the bundle and the ratio of the number of tubes between the new and reference designs. The subscript 0 means a property of the reference design.

### 3.1.2. Treatment for the Division of the Bundle Region

In the integrated double-region configuration, the bundle is radially divided into two regions $U$ and $D$ as shown in Fig. 2-b and additional treatment needs be made to the resistance equations.

In this configuration, the fluid velocities of the PHTS and feedwater fluid do not change by the division but the velocity of the medium fluid changes since the flow area decreases while the flow rate remains same by the division.

- external flow area $A_{fe}$

$$\frac{A_{fe}^x}{A_{fe}^T} = \frac{A_{fi}^x}{A_{fi}^T} = R_A^{xT}\left(\equiv \frac{A_{fe}^x}{A_{fe}^U + A_{fe}^D}\right), \quad x = U, D \tag{19}$$

where the superscript T means the property of the total bundle, that is, of the bundle without the division. $R_A^{xT}$ is the ratio of the external flow area at the flow direction $\chi$ to the total external flow area for the medium fluid.

The flow rates in the regions U and D become proportional to their flow areas since the tube bundle geometries are the same and the pressure loss in the flow regions need to be the same between the regions U and D. The rates for each fluid are expressed by Eqs. (20) and (21).

$$\frac{\overset{x}{\dot{m}_k}}{\overset{Tot}{\dot{m}_k}} = R_A^{xT}, \quad k = P, H \tag{20}$$

$$\overset{P}{\dot{m}_M} = \overset{Tot}{\dot{m}_M} = \overset{H}{\dot{m}_M} \tag{21}$$

The effects of the division on the UA are considered by the following equations.

$$\frac{(UA)_x}{(UA)_T} = \left(\frac{R_T}{R_x}\right)_N = \frac{\left(R^N / R^K\right)_T}{\left(R^N / R^K\right)_x} \equiv \frac{1}{K_R^{xT}} \tag{22}$$

where (UA)x is UA at region U or D, and (UA)T is the UA without the division.

The ratio is calculated from Eqs. (15) and (17) for the cases of =1 and .

$$K_R^{xT} = \frac{1}{K_A^{xT}} \frac{C_1\left(K_{Afi}\big/K_m\right)^{0.8} + C_2 + C_3\left(\dfrac{K_{Afe}R_A^{xT}}{K_{mCp}}\right)^{0.8}}{C_1\left(K_{Afi}\big/K_m\right)^{0.8} + C_2 + C_3\left(\dfrac{K_{Afe}}{K_{mCp}}\right)^{0.8}} \tag{23}$$

### 3.2. System Heat Transfer

The heat transfer rate from the hot fluid of PHTS to the cold fluid of the feedwater is determined by the heat transfer resistances and the system configuration effects.

#### 3.2.1. Integrated Configuration

The three fluids are involved in the heat transfer simultaneously and the heat transfer is expressed by Eqs. (24)~(26) when fluid properties are treated as uniform.

$$\frac{du}{dx} = au - av \quad u = T_p, v = T_m,\ a = \frac{-UA_{PM}}{(m\dot{C}p)_P}$$

$$\frac{dw}{dx} = bv - bw \quad w = T_H,\quad b = \frac{-UA_{MH}}{(m\dot{C}p)_H}$$

$$\frac{dv}{dx} = c(u - v) - d(v - w)$$

$$c = \frac{UA_{PM}}{(m\dot{C}p)_M},\ d = \frac{UA_{MH}}{(m\dot{C}p)_M},\quad x = \frac{s}{L} \tag{26}$$

where s is the vertical direction coordinate in the bundles and x=0 and x=L are respectively the bottom and the top of the tube bundle region. In the equations, the temperatures $T_M$, $T_M$ and $T_H$ were represented by u, v, and w respectively.

The solution to the set of the governing equations is found with appropriate boundary conditions at each fluid inlet and they are shown below.

$$T_P(x) = u(x) = C_1 - \frac{a}{\alpha - a}C_2e^{\alpha x} - \frac{a}{\beta - a}C_3e^{\beta x} \tag{27}$$

$$T_m(x) = v(x) = C_1 + C_2e^{\alpha x} + C_3e^{\beta x} \tag{28}$$

$$T_{C'}(x) = w(x) = C_1 + \frac{b}{\alpha + b}C_2e^{\alpha x} + \frac{b}{\beta + b}C_3e^{\beta x} \tag{29}$$

where the constants C, α and β are determined from the system operation conditions such as *UA*, flow rate and inlet conditions.

The specific temperature condition for the medium flow needs to be applied to the general solution of Eqs. (22)~(24).

- Integrated single-region configuration.

The temperature at the bottom is equal to the that at the top.

$$T_M(s=0) \quad = \quad T_M(s=L)) \tag{30}$$

- Integrated double-region configuration.

The temperatures defined at the U and D gions should be the same at the common cations of the top and bottom.

$$\begin{aligned} T_M^U(s=0) &= T_M^D(s=0) \\ T_M^U(s=L) &= T_M^D(s=L) \end{aligned} \tag{31}$$

The sign of the flow rate is decided by its direction.

- flow direction : Region U : $m_M>0$ , Region D : $m_M<0$

#### 3.2.2. Separated Configuration

In the separated configuration, the system temperature distribution is like the profile shown in

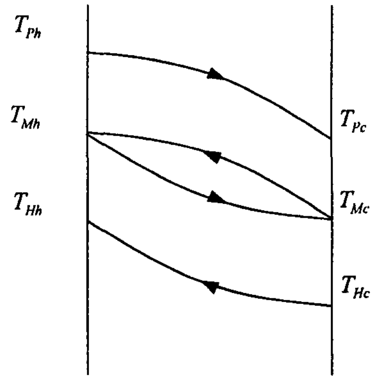


**Fig. 3. Temperature Profile in the Separated Configuration**

Fig. 3. The system can be considered as a serial coupling of PHTS-Medium heat transfer and Medium-Feedwater heat transfer and the heat transfer can be described by the equations for a counter-flow heat exchanger when the fluid property is considered uniform.

The exit temperatures are expressed by Eq. (32) and (33) of a counter-flow heat exchanger.

$$T_c(L) = T_c(0) + \left(T_h(L) - T_c(0)\right) \left( \frac{1 - \exp\left(-a_h(1 + R_{mc}^{HC})\right)}{1 + \exp\left(-a_h(1 + R_{mc}^{HC})\right)/R_{mc}^{HC}} \equiv \eta_{Mc} \right) \quad (32)$$

$$T_h(0) = T_c(0) + \left(T_h(L) - T_c(0)\right) \left( \frac{1 + 1/R_{mc}^{HC}}{1 + \exp\left(-a_h(1 + R_{mc}^{HC})\right)/R_{mc}^{HC}} \equiv \eta_{Mh} \right) \quad (33)$$

where the cold and hot fluids enter the heat exchanger respectively at s=0 and *L*. When a fluid flows in the direction same as that of the feedwater, its flow rate becomes positive. ah is the $a_h$ of Eq. (24) calculated for the hot fluid and $R_{mc}^{HC}$ is defined by the following equation.

$$R_{mc}^{HC} = \frac{\left(\dot{m}C_p\right)_{hot\ fluid}}{\left(\dot{m}C_p\right)_{cold\ fluid}} \quad (34)$$

From the configuration, the medium fluid temperature at *s*=*L* in the heat transfer with the PHTS fluid, $T_c^{PM}$ (L) is same as that at s=0 in the heat transfer with the feedwater fluid, $T_h^{MH}$ (0)

$$T_c^{PM}(L) = T_h^{MH}(0) \quad (35)$$

From Eqs. (32),(33) and (35), the cold temperature of the medium fluid TMc, which is the temperature when the medium fluid leaves the MH region and enters the PM region, is calculated as Eq. (36).

$$T_{Mc} = \frac{T_{Hc} + (T_{Ph}\eta_{Mh} - T_{Hc})\eta_{Mc}}{1 - \eta_{Mc} + \eta_{Mh}\eta_{Mc}} \quad (36)$$

where $T_{ph}$ and $T_{hc}$ correspond to the inlet temperatures of the PHTS and feedwater fluids.

One point to note on the difference between the two configurations is that the medium fluid temperature difference between the inlet and exit of the bundle region matches the overall heat transfer rate of the heat exchanger in the separated configuration but it does not in the integrated configuration as shown mathematically in Eq. (37)

$$\begin{aligned} Q_M^S &\equiv \left(\dot{m}C_p(T_{ex} - T_{in})\right)_M^S = Q_{HX} \\ Q_M^I &\equiv \left(\dot{m}C_p(T_{ex} - T_{in})\right)_M^I \neq Q_{HX} \end{aligned} \quad (37)$$

The reason for this is that the transferred heat from the hot fluid to the cold fluid is carried by the medium fluid in a total basis in the separated configuration while the heat transfer in the integrated type is made locally in the integrated type as mentioned previously.

### 3.2.3. Calibration of the Analysis Model

In using the NSSS heat transfer equations of Section 3.2.1 and 3.2.2, some errors are involved such as the error from the non-uniformity of the fluid property and existence of the saturation region in the water. To compensate the error effects, the analysis model was applied to the reference design and the calibration factors that make the IHTS cold temperature and steam temperature from the analysis model equal to the values of the reference design are found. Since the reference design values were decided by an analysis model fully considering the non-uniformity of the fluid property and existence of the saturation region, the error effects can be compensated by calibrating the model of this study to the reference design analysis with the use of the calibration factors. The calibration factors which calibrate the values of UA decided from the heat transfer rate and log-mean temperature difference are as follows.

- For $UA_{ihx}$ : 0.76
- For $UA_{sg}/UA_{ihx}$ : 1/0.73

### 3.3. Required Electric Power for Pumping

Since lead-bismuth is the candidate for the medium fluid and it generally requires much more power than sodium does for pumping, the change in plant efficiency can not be ignored and the expression for the change in the electric power required for pumping is derived.

From the basic relations of Eqs. (38) and (39),

$$P_{pp} = \dot{V}\Delta P \tag{38}$$

$$\Delta P \sim k\frac{1}{2\rho}\left(\frac{\dot{m}}{A}\right)^2 \tag{39}$$

the general expression for the ratio of the required pumping powers is derived as Eq (40).

$$K_{P_{pp}} \equiv \frac{P_{pp}^{N}}{P_{pp}^{KAL.}} = \frac{K_{\dot{m}}^{3}}{K_{\rho}^{2}} K_k \frac{1}{K_{Af}^{2}} \tag{40}$$

The nomenclature used in the equations is, $pp$ : pump, $P_{pp}$ : pumping power, $V$ : volume flow rate, $k$ : pressure loss coefficient.

Eq. (40) can be used for the PHTS pumping and feedwater pumping but additional treatments need be made for the medium fluid pumping because of the differences in the fluid property, flow circulation range and flow area configuration. Between the circulation flow of the new design and the IHTS flow of the reference design, the ratio of the pumping power $K_P^M$ is expressed by Eq. (41).

$$K_P^M \equiv \frac{\left(P^M\right)_N}{\left(P^I\right)_K} = \frac{P_K^{MH}}{P_K^I}\frac{\left(K_m^M\right)^3}{\left(K_\rho^{MI}\right)^2}\left(\frac{K_K^{PM}}{\left(K_{Afe}^{PM}\right)^2}+\frac{K_K^{MH}}{\left(K_{Afe}^{MH}\right)^2}\right) \tag*{41)}$$

where the superscript $I$ means the whole region of IHTS. Also $N$ and $K$ respectively mean the new design and KALIMER. $P_K^I$ is the pumping power for the whole IHTS region of the reference design and $P_K^{MH}$ is that corresponding only to the portion of the SG bundle region of the reference design.

In the integrated double-region configuration, the bundle consists of two regions, U and D and Eq.(41) becomes Eq. (42).

$$\begin{aligned} K_P^M = \frac{P_K^{MH}}{P_K^I}\frac{\left(K_m^M\right)^3}{\left(K_\rho^{MI}\right)^2}\Bigg\{ & K_K^{PM}\left(\frac{1}{\left(K_{Afe}^{PM.U}\right)^2}+\frac{1}{\left(K_{Afe}^{PM.D}\right)^2}\right) \\ & + K_K^{MH}\left(\frac{1}{\left(K_{Afe}^{MH.U}\right)^2}+\frac{1}{\left(K_{Afe}^{MH.D}\right)^2}\right)\Bigg\} \end{aligned} \tag{42}$$

### 3.4. Assessment of the NSSS Performance and the Required Heat Transfer Area

The NSSS heat transfer rate can be calculated by the developed equations and the required changes in the heat transfer area and flow rate are considered by the ratio factors $K_A$ and $K_{\dot{m}}$. From the ratios, the heat transfer rate is calculated by the developed temperature equations and the pumping powers are also calculated. Using the calculated steam temperature, the change of the gross thermal efficiency of the plant is calculated and the change in the pumping power electricity is also calculated. From these, the net electricity supply capacity at the same core thermal power and the net thermal efficiency are calculated. For the consideration of the steam temperature effect on the plant thermal efficiency, the sensitivity of 0.5%/20℃ [9] is used.

All the equations are solved together and the performance was assessed for various system design data sets. Table 4 shows the calculation results.

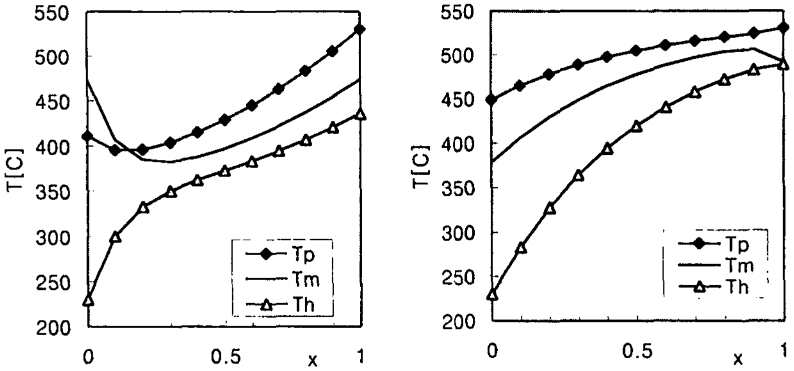
In the table, the columns of flow direction:+ and :- mean respectively the cases where the medium

**Table 4. Features of the NSSS with the New SG Design**

| | Ref. Design | Separated Conf. | Integrated Conf. | | |
|---|---|---|---|---|---|
| | | | Double Region | Single folw direction:+ | Region flow direction:- |
| • **Heat Transfer Area Ratio** | | | | | |
| kApm | | **1.28** | **1.36** | **1.5** | **1.72** |
| kApm | | **1.28** | **1.36** | **1.5** | **1.72** |
| • **Flow Rate Ratio** | | | | | |
| Kvf. PHTS | | **1.1** | **1.4** | **1.48** | **1.5** |
| Kvf. Feedwater | | **0.77** | **0.19** | **0.37** | **0.32** |
| Kvf. Feedwater | | **0.97** | **1.03** | **1.06** | **1.14** |
| • **Temperature, C** | | | | | |
| Tphts. exit. U | | | 398.8 | | |
| Tphts. exit. D | | | 448.9 | | |
| Tphts. exit. avg | 384.8 | 398.1 | 426.5 | 432.0 | 432.9 |
| Tm. c | 337.3 | 335.1 | 378.7 | 497.9 | 359.8 |
| Tm. h | 509.1 | 514.6 | 491.7 | 497.9 | 359.8 |
| Tsteam. U | | | 455.3 | | |
| Tsteam. D | | | 488.5 | | |
| Tsteam. avg | 481.4 | 488.2 | 473.6 | 467.7 | 452.1 |
| dTsteam | -1.8 | 50. | -9.6 | -15.5 | -31.1 |
| • **Pumpin Parameter Ratio** | | | | | |
| KDP. PHTS, pressure loss | 1 | 0.74 | 1.06 | 0.97 | 0.76 |
| KDP. Medium, pressure loss | 1 | 3.55 | 1.44 | 0.50 | 0.23 |
| KDP. Feedwater pressure loss | 1 | 0.58 | 0.58 | 0.50 | 0.44 |
| Kp. PHTS, pumping power | 1 | 0.81 | 1.48 | 1.44 | 1.14 |
| Kp. Feedwater, pumping power | 1 | 2.72 | 0.27 | 0.19 | 0.50 |
| • **Changes related to plant performance** | | | | | |
| pump electricity, MWe | 0 | 0.42 | -0.93 | -1.52 | -3.03 |
| NSSS Q, MWth | 0.46 | 0.33 | 0.23 | 0.25 | 1.95 |
| efficiency by steam T change, % | -0.04 | 0.13 | -0.24 | 0.00 | -0.01 |
| **Net electricity for supply, Mwe** | **0.0** | **0.2** | **0.1** | **0.1** | **0.8** |
| **Net thermal efficiency, %** | **0.0** | **0.0** | **0.0** | **0.0** | **0.0** |

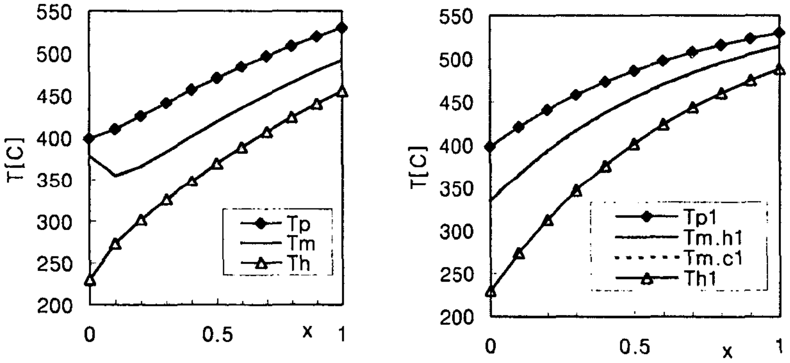
fluid flows upward and downward at the bundle region in the integrated single-region configuration. The ratios in the table generally mean the ratio of a new design value to a reference design value of the same parameter. The flow rate ratio Kvf is for the volumetric flow rate.

The table shows that the required heat transfer area to achieve the same plant performance as the reference design is the largest in the integrated single-region configuration. This comes from the poor temperature distribution in the configuration as shown in Fig. 4-a. Since the medium temperature is the same at $\chi=0$ and $\chi=1$, the medium temperature becomes higher than the PHTS fluid temperature at the region near $\chi=0$ and reverse heat transfer, i.e., from the medium fluid to the PHTS fluid, is made in that region and



a. Integrated Single-Region Configuration (flow direction:upwward)

b. Integrated Double-Region Configuration :Region D



c. Integrated Double-Region Configuration : Region U

d. separated configuration

**Fig. 4. Temperature Distributions at Each Configuration**

it produces poor overall heat transfer performance. By configuring the medium fluid flow path as that in the integrated double-region configuration, the poor temperature distribution disappeared as shown in Fig. 4-b and 4-c. In the separated and integrated double-region configurations, the required heat transfer area increase is about 30% and 40%, respectively. These increases can be relatively easily accommodated. The flow rate for the medium fluid at the integrated double-region configuration is about 20% of the reference design and this low flow rate requirement comes from that the heat transfer from the hot fluid to the cold fluid via the medium fluid in this configuration is mainly made in a local basis while that in the reference design configuration and also in the separated configuration is made in a bulk basis. In other words, the heat transfer can be basically made without medium fluid flow at all in the integrated type configurations. This feature of the integrated configurations requires the magnitude of the medium flow rate only for maintaining suitable convection heat transfer coefficients and a small flow rate suffices for the requirement. Also the flow velocity becomes double by the division of the

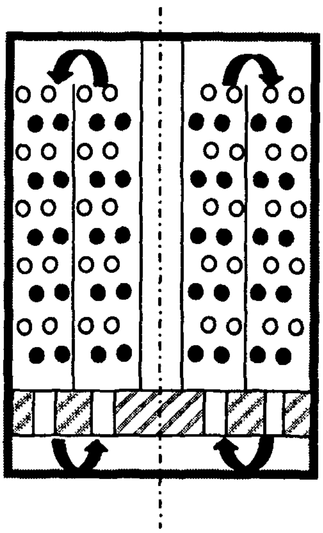


Fig. 5. The Simplified Structure with an EM Pump

tube bundle region into two. Consequently the integrated double-region configuration can be operated satisfactorily with a small flow rate and this feature is an advantage of this configuration since the low flow rate and low pumping power reduce the pump size and total weight of the SG unit. Also it introduces a possibility of using an EM (electro-magnetic) pump, which will simplify the internal structure of the SG. substantially as shown in Fig. 5. In the figure, the shaded area represents the EM pump.

In the separated configuration, the medium fluid pressure loss in the separated configuration is about four times that of the IHTS pressure loss of the reference design. This increase is relatively large but this increase can also be well accommodated since the flow rate is decreased by 20%, the pump motor can be installed outside the steam generator and/or further optimization can be made in the system parameters.

From the required heat transfer areas, flow rate and system pressure loss, it can be said that the new NSSS design concept with the separated and integrated double-region configurations are practically feasible.

## 4. Qualitative Evaluation

The qualitative features of the SG design concepts are as follows.

### 4.1. Manufacturability

The configurations studied were checked in their manufacturability and the separated configuration can have some difficulty in handling the nozzles when the configuration shown in Fig 3.c is used since at least two nozzles need to be installed in the vertical cylinder section and this installation process may need to cut the cylinder section into two parts and then weld them. The integrated double-region configuration can be manufactured by the same method for the reference design SG only with additional processes.

### 4.2. Elimination of the SWR Possibility

In the SG design with a double tube bundle, the water and sodium flow with the barriers of two tube walls and the medium fluid. For SWR to occur, the tube walls need to be simultaneously in a failed condition but the possibility of this occurrence is negligibly low since tube leak can be continuously and easily monitored by the current technology such as monitoring of a pressure change in a tank. It means the possibility of an SWR occurrence is practically eliminated in the new design concept.

By eliminating the SWR possibility, the IHTS system itself and the mitigation system for SWR such as an SWR product processing system can also be completely eliminated from NSSS. It will make the system design simpler, safer and improve the economic features of an LMR.

## 5. Conclusions

A new SG design with the tube bundle configuration of improved thermal performance has been proposed. Also the feasibilities of various SG tube bundle configurations have been evaluated by setting up the skeleton of the NSSS for each bundle configuration. The evaluation revealed the following features.

- The new SG design concept eliminates the SWR possibility in a practical sense without loosing practicality in actual use for an LMR plant.
- The effects of the SG tube bundle configuration on the temperature distribution and heat transfer performance have been found for various configurations. The integrated double-region configuration proposed in this study and the separated configuration are turned out to have satisfactory performance. They have the following relative advantages.
  - The integrated double-region configuration can be satisfactorily operated with a very low medium flow rate and manufactured with the current method without difficulty.
  - The separated configuration has the best heat transfer performance but it may require a new method for handling the tube nozzles for commercial manufacturing.

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This work has been carried out under the national nuclear long-term R&D program which is supported by MOST (Ministry of Science and Technology).

### Nomenclature

| | |
|---|---|
| A | area, flow or heat transfer |
| Cp | specific heat |
| D | diameter, region of downward fluid flow |
| H | feedwater/steam |
| h | convection heat transfer coefficient |
| K | ratio |
| k | conductivity, pressure loss coefficient |
| L | reference length |
| $\dot{m}$ | flow rate |
| P | PHTS, pressure |
| $P_{pp}$ | pumping power |
| Pr | Prandtl number |
| Q | heat transfer rate |
| R | thermal resistance, ratio |
| Re | Reynolds number |
| s | vertical direction coordinate in the bundles |
| T | temperature |
| t | thickness |
| U | overall heat transfer coefficient, region of upward fluid flow |

**Greek Letters**

| | |
|---|---|
| $\eta$ | coefficient in the temperature equations (32) and (33) |
| $\mu$ | viscosity |
| $\rho$ | density |

**Superscripts and Subscripts**

| | |
|---|---|
| 0 | reference |
| c | cold |
| CD | conduction |
| CV | convection |
| e | external of the tube |
| f | flow |
| H | feedwater/steam |
| h | hot |
| I | KALIMER IHTS, integrated type |
| i | internal of the tube |
| KAL | KALIMER |
| KP | KALIMER PHTS |
| L | lead |

| | |
|---|---|
| M | medium fluid of the new design |
| MH | medium-water/steam |
| MI | medium fluid versus KALIMER IHTS fluid |
| n | number of tubes |
| N | new design |
| Na | natrium |
| NH | new design feedwater/steam |
| NP | new design PHTS |
| P | PHTS |
| PI | PHTS-IHTS |
| PM | PHTS-medium |
| S | separated type |
| SG | steam generator |
| xT | region U or D versus total |

(Some of the letters explained in the regular nomenclature are also used as in sub- and superscripts without change of their meanings.)

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