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Evaluation of New Design Concepts for Steam Generators in Sodium Cooled Liquid Metal Reactors

Seong-O.Kim, Sim Yoonsub, Eui-kwang.Kim, Myung-Hwan.Wi, and Dohee.Han
Korea Atomic Energy Research Institute
150 Dukjin-dong, Yuseung-gu, Daejeon 305-353, Korea
sokim@kaeri.re.kr

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Abstract

To reduce the construction cost and enhance the safety of sodium cooled liquid metal reactors, various kinds of new design concepts were evaluated using the KALIMER operation condition. The required equipment sizes were set for plant electricity output to be similar to that of KALIMER. The evaluations were made focusing on the plant performance and implementation practicality. Each design concept was evaluated for the concept itself and design impacts to interfacing systems. Through the evaluation of the concepts, it was found that the most favorable design concept is the integrated steam generator with forced convection using lead bismuth as the intermediate heat transfer fluid between the primary sodium tube and feed water/steam tube in the steam generator.

Key Words : LMR, steam generator, new design concepts, evaluation

1 Introduction

LMR(=Liquid Metal Reactor) can make the utilization of a uranium resource very efficiently and also reduce transuranics substantially compared with LWR(= Light Water Reactor). However, the commercial operations of the LMR are postponed because of the relatively high construction cost and the possibility of SWR (=Sodium Water Reaction). The major causes of the construction cost of a sodium cooled LMR come from installing the facilities to mitigate the effects of SWR. As a typical example, KALIMER(=Korea Advanced LIquid MEtal Reactor) uses IHTS(=Intermediate Heat Transport System) as shown Fig.1 to prevent the propagation of SWR effects to the reactor core and to exclude radioactive material release to environment from SWR. Sodium and steam dump systems and rupture disks are also equipped to prevent over-pressurization of IHTS and to terminate SWR events.

As an effort to resolve the problem in a sodium cooled LMR, new reactor system concepts are developed and evaluated. The evaluated design concepts are those proposed in literature and the new concepts in this study. The concepts from literature are DCSG(=Direct Contact Steam

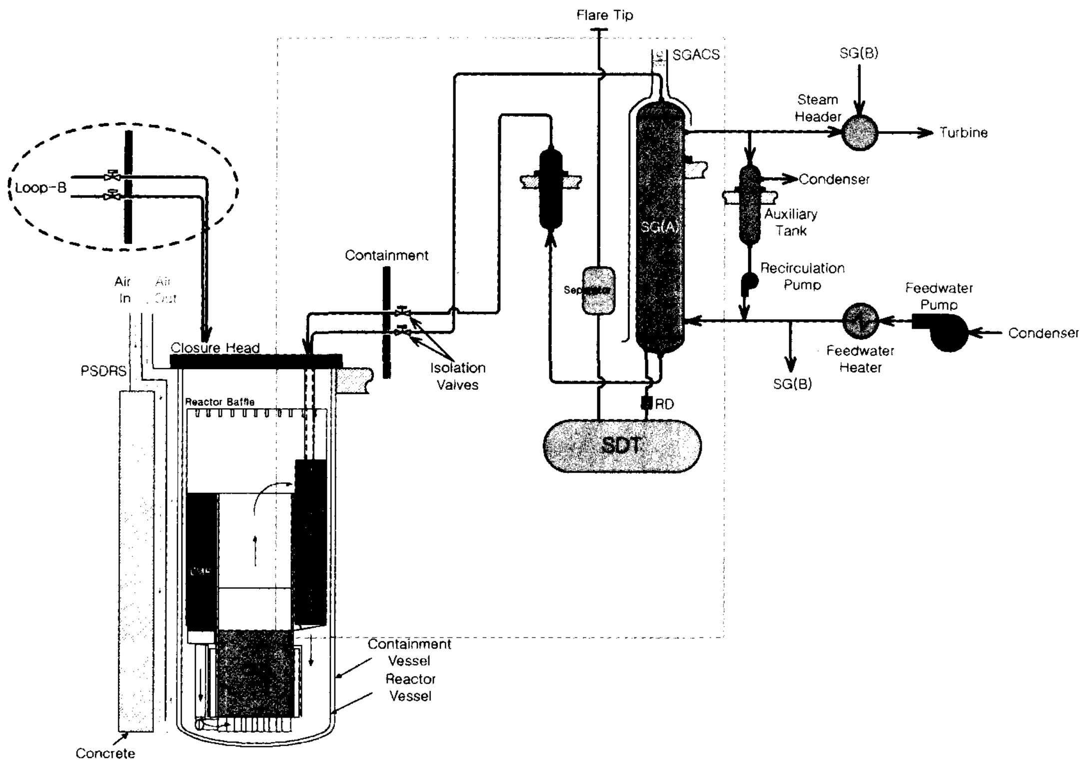

Fig. 1. Overall System Design Concepts of KALIMER

Generator), CBSG(=Copper Bonded SG) in GEN-IV design concept report[1] and ISG(=Integral SG) with natural circulation of media fluid proposed by Miyazaki[2]. The concepts devised in this study are LB-IHTS(=Lead Bismuth Intermediate Heat Transport System)[3,4] and ISG with forced convection of media fluid[5].

The LB-IHTS is a design concept to use LB(=Lead Bismuth) as the IHTS coolant instead of sodium. The LB is chemically non-reactive with water. The ISG is a concept to combine a steam generator and IHX(=Intermediate Heat Exchanger) without using IHTS.

To evaluate heat transfer of the concepts, the boundary conditions such as the maximum system temperature of the core exit and the feed water inlet temperature were set identically to those of KALIMER.

2. Lead Bismuth-IHTS

2.1. Design Concept

The LB-IHTS is a design concept which uses LB as the IHTS coolant to exclude SWR in the steam generator tube area.

2.2. Heat Transfer Evaluation

The density of LB is about 11 times and the specific heat is about 1/9 times as big as sodium. The product of density and specific heat is almost similar to that of a sodium system. From the relations, if the temperature difference between the hot and cold side is the same as the one of KALIMER, it is expected that the volume flow rate of LB in IHTS would be almost similar to the sodium volume rate of KALIMER IHTS.

However, since the thermal conductivity of LB is about 1/4 times that of sodium, the heat transfer resistance of LB convection in a steam generator and IHX is higher than the case of sodium and the heat transfer area is increased so as to transfer the same amount of heat as that of the sodium system.

By use of a computer code for the design of a once-through type helical tube steam generator, the required heat transfer area of a steam generator for LBIHTS were calculated[3] and the area turned out to be more than the value of KALIMER by 30%. The required value for IHX is more than that of KALIMER IHX by 50%.

Maintaining the SG tube diameter, array shape and pitch to be identical to those of KALIMER, the steam generator outer diameter and height of LBIHTS were calculated to be bigger than that of KALIMER by 10% respectively. The IHX outer diameter and height also increased by 10% and 20% respectively.

The required pumping power for the circulation of LB is 2.5 times more than that of KALIMER from the high density and viscosity of LB. The net efficiency of LB-IHTS design is 0.4% below KALIMER which is from the loss of pumping power.

2.3. Design Impacts

The LBIHTS design concept is completely identical to the KALIMER system except for the increase of the heat transfer area from the difference of coolant conductivities. The LB-IHTS can eliminate the possibility of SWR by using LB as the IHTS coolant because LB is chemically stable with steam/water. On the contrary, to the benefits of LBIHTS, the high density of LB needs lots of support for the IHTS piping, steam generators and seismic devices such as seismic isolation bearings. Furthermore, the leakage of LB may impact environmentally from the point of harmful heavy metal leakage. These kinds of design features are expected to increase construction costs. The leakage of LB through IHX into the primary system also may impact on reactivity control and corrosion of the fuel assembly.

3. Integral Type Steam Generator

Integral type steam generator concept is to combine the separated steam generator and all the components of IHTS as marked by a square box in Fig.1 into a single integral steam generator. The design concepts treated in this study are DCSG(=Direct Contact Steam Generator), CBSG(=Copper Bonded Steam Generator), ISG with natural circulation and ISG with forced convection. The detailed evaluations are discussed in separate sections respectively.

3.1. Direct Contact Steam Generator

3.1.1. Design Concept

DCSG concept was proposed in JAPAN at first and developed for the application to the reactor afterwards in MIT of USA[1]. The design concept developed in MIT is to use LB as the primary coolant to remove heat from the core. Feed water is injected into the coolant directly and steam is generated from the direct contact of feed water and LB. In this study, the DCSG concept is applied to the steam generator where LB is heated by a sodium tube as shown Fig.2. The shell side of the DCSG is filled with LB and primary sodium tubes, with a helical type, which are installed at the lower part of the DCSG. The feed water of 230℃ is injected into the middle part of the DCSG through the feed water injection nozzles which are

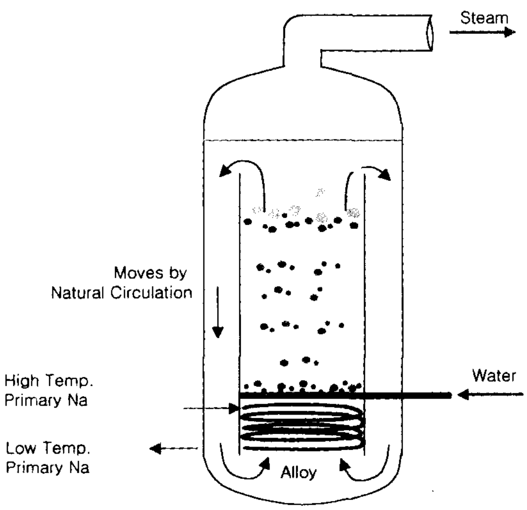

Fig. 2. Design Concepts of Direct Contact Steam Generator

arranged to supply feed water evenly. In the upper part of DCSG, flow guides are installed to separate the steam flumes of each nozzle. The steam is gathered in the plenum of the upper region of the DCSG and are provided to the turbine generator. During the steam generating process, LB is circulated by a buoyant force of density difference of LB and steam/LB mixtures. Since the steam density is negligibly small compared to LB, high natural circulation head can be developed.

3.1.2. Heat Transfer Evaluation [4]

The heat transfer phenomenon of DCSG between primary sodium and feed water is a function of the elevation of each component, temperature and flow rate of the primary sodium and feed water because the major heat transfer occurs through natural circulation of the intermediate media LB. As shown in the figure, the flow direction of the primary sodium is in the opposite direction to the LB flow. The opposite flow direction increases the efficiency of the heat transfer in general as known in the heat exchanger design. However, the flow direction of the feed water and steam is the same as that of the LB flow. The heat transfer efficiency of parallel flows is lower than that of counter flows. The design parameters of DCSG are set as shown in Table 1[4] to have maximum efficiency on the boundary conditions of KALIMER such as the hot pool and feed water temperatures and thermal power[5].

Table 1. Major Design Parameters for Direct Contact Steam Generator

	Inlet Temp. (℃)	Outlet Temp. (℃)	Mass flowrate (kg/sec)	Operating Pressure (MPa)
Primary system	530	445	1837	Atmos. pressure
Feed water /Steam system	230	408	92.94	10.0

The net efficiency of the DCSG design were estimated to be 2% below the KALIMER 38.5%. The dimensions of DCSG were arranged such that the height of DCSG is almost similar to the KALIMER steam generator but the diameter is about 6.0m which is around twice that of the KALIMER design. Since the DCSG includes IHX, however, the overall dimensions of DCSG is larger than KALIMER by a 30~40% increase.

3.1.3. Design Impacts

The design impacts of DCSG to the neighboring system are described bellow.

First, the possibility of over-pressurization of the primary system: The operating pressure of the DCSG shell side is about 10MPa as delineated in Table.1 but the operating and design pressures of the primary system are near the atmospheric pressure[5]. The large pressure difference of the two neighboring systems may threaten the pressure boundary of the primary system.

Second, embrittlement of the turbine blade: the separation of LB and steam in the steam dryer of the DCSG is not perfect. A small amount of LB aerosol remains entrained in the steam stream and is carried over to the turbine causing liquid metal embrittlement on stressed parts of the turbine. Possible solutions to this problem are coating of the turbine blade casing, employment of alternative turbine materials that are not susceptible to LB embrittlement, electrostatic precipitation and/or oxidation of the LB droplets prior to impact with the turbine blades.

Third, increase of size and design pressure of the containment dome: Since the primary sodium gets into the DCSG, the steam generator needs to be installed in a containment dome in order to satisfy the requirements of the design code. From the location of SG in a containment, the internal volume of the containment dome needs to be increased to incorporate the large size of the steam generators. The most extreme design basis event considered in KALIMER is sodium fire leaked from a IHTS pipe or the reactor head. From the evaluation results[7], the expected peak pressure of the containment dome in KALIMER by sodium fire is ceased by exhaustion of oxygen in the containment dome. However if the internal volume of containment increases, the duration of sodium fire increases and the peak pressure from the sodium fire may increase.

Apart from the sodium fire, SLB(=Steam Line Break) events need to be considered as a design basis event for containment dome design for DCSG. Since the isolation valve of a feed water system is not a safety grade component, in case of a SLB event, feed water would be provided to the steam generator and the pressure of the containment dome would increase until the containment pressure is equivalent to the pressure of the steam generator.

3.2. Copper Bonded Steam Generator

3.2.1. Design Concept

CBSG is a design concept proposed by UK NNC[1]. As shown in Fig.3, the CBSG is a kind of ISG where primary sodium tubes and feed water/steam tubes are arranged in uniform intervals alternatively and its shell side is filled with a solid copper matrix.

3.2.2 Heat Transfer Evaluation[8]

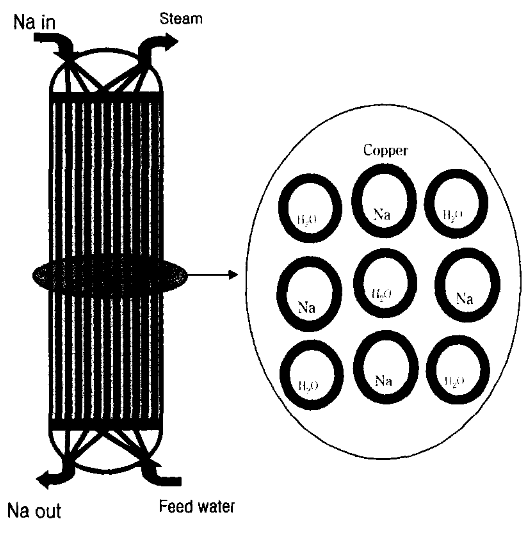

Fig. 3. Design Concept of Copper Bonded Steam Generator

The design concept of CBSG is to use high thermal conductivity of a copper matrix. The conduction heat transfer through the copper matrix is almost equivalent to the convection of the sodium of IHTS in KALIMER. Through it's design concept, SWR could be eliminated by a

Table 2. Major Design Parameters for Copper Bonded Steam Generator

	Inlet Temp. (℃)	Outlet Temp. (℃)	Mass flowrate (kg/sec)	Operating Pressure (MPa)
Primary system	530	386.2	1071.6	Atmos. pressure
Feed water /Steam system	230	483.2	87.74	15.5

thick wall of CBSG as well as reducing construction cost by eliminating IHTS.

In order to evaluate heat transfer characteristics of CBSG and generate design parameters for KALIMER conditions, numerical analyses were done on the boundary conditions as delineated in Table 2[6].

The shape of sodium and steam tubes were selected to have a straight type and the same tube diameter as the that of KALIMER. The thickness of the copper matrix between the sodium and steam tubes were selected such that P/D is 1.6 to prevent from SWR in the case of steam/water leakage.

After evaluations for the conditions, the relation between the heat transfer area and tube length of the CBSG data with respect to the number of sodium/steam tube was obtained as shown in Fig.4. In the figure, the increase in the number of the tubes brings an increase in the heat transfer area and a decrease of the tube length. The reason seems to be that if tube length increases, the length for the phase change from water to steam increases and the heat transfer efficiency increases. From the figure, an appropriate steam generator size could be selected. In considering the height of the KALIMER steam generator, the tube length of CBSG was selected as 10m. For this length, the total heat transfer area is 1450m^2 and

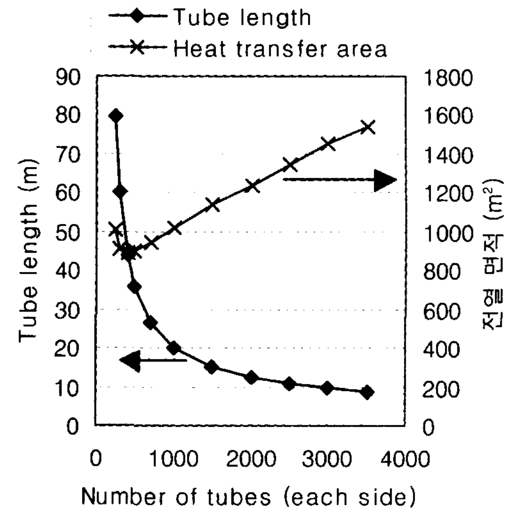

Fig. 4. Tube Length and Heat Transfer Area with Respect to Number of Tubes

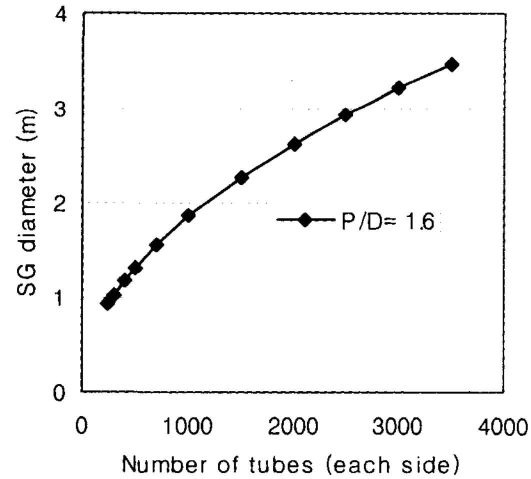

Fig. 5. Steam Generator Outer Diameter with Respect to Number of Tubes

the number of tubes is estimated to be 3000. Based on this data and design experiences of KALIMER, the outside diameter of CBSG is 3.3m in Fig.5 which is bigger than that of KALIMER by 18% and the length of CBSG is around 24m which is longer than that of KALIMER by 25%.

From the above evaluations, it is known that the possibility of SWR can be eliminated with a slight increase in the steam generator size while eliminating IHTS.

3.2.3. Design Impacts

As described above, the CBSG design concept is able to eliminate the SWR event and it also could prevent from over-pressurization of the primary system by a tripple wall of steam and sodium tubes and a copper matrix.

However, the tubes and copper matrix of CBSG should be designed to be tightly fixed so as to reduce heat transfer resistance in the gap between the structures but the tight fixture of the tube and copper matrix can bring in thermal stress during transient operations such as the heat up and cool-down process of the plant. The thermal stress may deteriorate the integrity of the steam generator itself as well as primary pressure boundaries. Furthermore, maintaining the tight fixture between the tubes for sodium and steam/water and the copper matrix is required for the life time of the plant because it is expected that it will be hard to do inservice inspection and maintenance.

The CBSG is also a kind of ISG and similar consideration should be paid to the design of the containment dome as in the DCSG.

3.3. ISG with Natural Circulations of LB

3.3.1. Design Concept

ISG with natural circulations of LB was proposed by MIYAZAKI[2]. The concept is evaluated by classifying it into two models. The first one is a separated type as shown in Fig.6 where sodium tubes of a straight type are installed in a cylindrical structure and helical type steam tubes are installed outside the cylindrical structure.

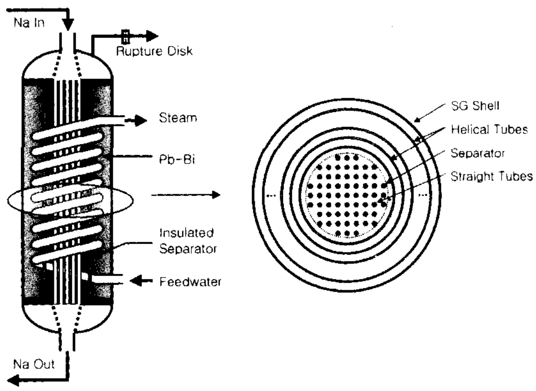

Fig. 6. Design Concept of Separated Type of Integrated Steam Generator with Natural Circulations of Lead Bismuth

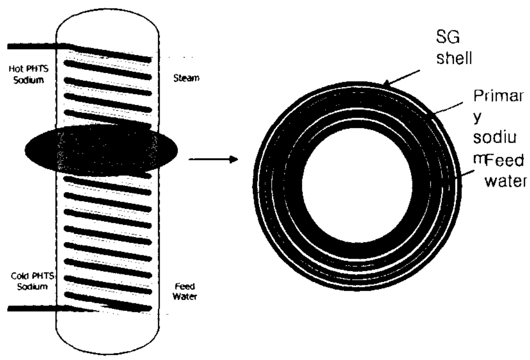

Fig. 7. Design Concept of Accumulated Type of Integrated Steam Generator with Natural Circulations of Lead Bismuth

The whole volume of the tube region is filled with LB to transfer heat from primary sodium to steam/water by natural circulation of the LB. The benefit of the separated type is to prevent tube failure of the sodium tube from the steam jet of the helical tube by the cylindrical structure.

The other one is an accumulated type as shown Fig.7, where both of the sodium and steam tubes are in a helical shape of regular arrangements. The accumulated type is to use a local natural circulation of intermediate media LB rather than the global type of natural circulation. The accumulated one is expected to get better heat transfer efficiency than the global type as reported in MIYAZAKI[2].

3.3.2. Heat Transfer Evaluation[4]

The evaluation of ISG with natural circulation of LB was done by use of the calculation methodology for the KALIMER steam generator. The local heat transfer between the tubes and LB were evaluated by a general purpose fluid analysis code CFX4[9].

The geometry for the CFX calculation is depicted in Fig.8 and the temperature and the velocity fields are shown in Fig.9. The Nusselt number were evaluated as 2.6 between the tube surface and the bulk LB temperatures.

The total heat transfer was assessed by use of the calculated data and related experimental correlations. The heat transfer area of the accumulated type was calculated to be 6 times bigger than that of KALIMER. The separated type also gave very similar results. From the evaluations, the design concept of ISG with natural circulation does not seem to be realistic.

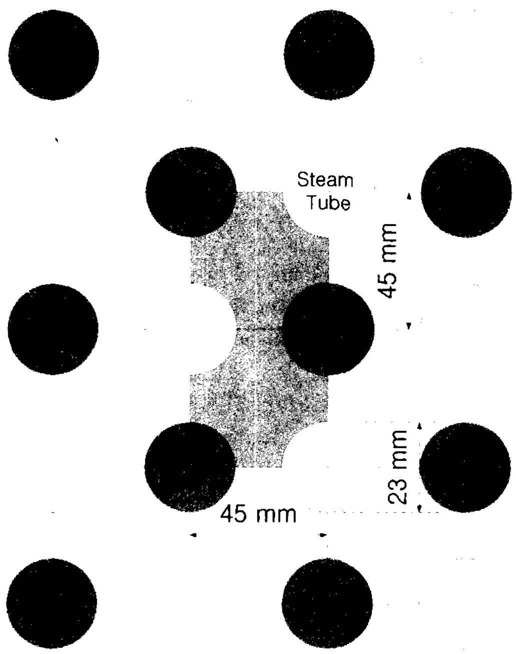

Fig. 8. Cross-sections of Accumulated Type Integral Steam Generator with Natural Circulating Lead Bismuth

3.3.3. Design Impacts

The ISG with natural circulation of LB is able to eliminate SWR but the size is unrealistically large compared with other concepts. Also, similar consideration should be paid, just like other ISG concepts, to the design of the containment dome as discussed for the DCSG.

3.4. ISG with Forced Convection of LB

3.4.1. Design Concept

The design concept of ISG with forced convection of LB is to circulate the intermediate media LB by using a pump instead of natural

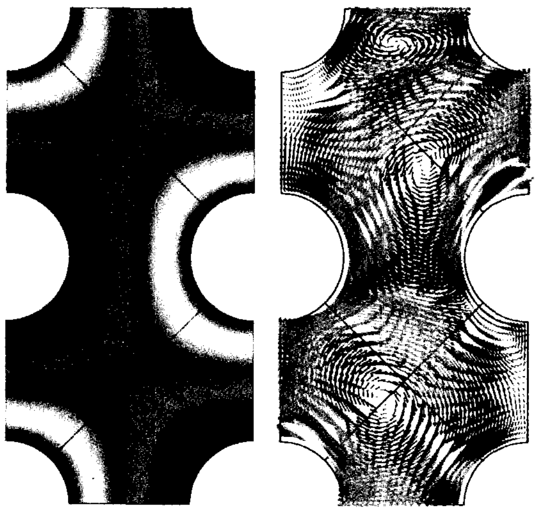

Fig. 9. Temperature(left) and Velocity Field of Accumulated Type Integral Steam Generator with Natural Circulating Lead Bismuth

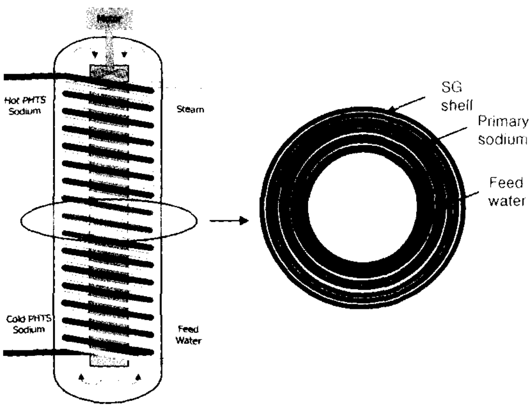

Fig. 10. Temperature(left) and Velocity Field of Accumulated Type Integral Steam Generator with Natural Circulating Lead Bismuth

circulation in the IGS of Section 3.3 as shown in Fig.10. This design concept is to prevent SWR and remove IHTS with a practical size of steam generator.

3.4.2. Heat Transfer Evaluation[10]

The evaluation and system design for ISG with forced convection of LB were done to have an optimum design between the plant efficiency and size of the steam generator using the procedures described below.

- Establish correlations for calculation of heat transfer rate with respect to the variation of design parameters using the KALIMER design and analysis data
- Selection of an arrangement for the sodium and steam tubes based on the evaluation of heat transfer characteristics with respect to the tube arrangement difference
- Calculation of the mass flow rate and heat transfer resistance to satisfy the required NSSS (=Nuclear Steam Supply System) performance by use of analytic solutions for a cross flow heat exchanger
- Calculation of the heat transfer area for the steam generator to have the required heat transfer resistance
- Calculation of plant efficiency from the calculation results of SG thermal power, electric power and house load
- Establish design parameters through iterative calculations for optimization of the efficiency and SG size.

Table 3. Major Design Parameters for Integral Steam Generator with Forced Convection of Lead Bismuth

	Inlet Temp. (℃)	Outlet Temp. (℃)	Mass flowrate (kg/sec)	Operating Pressure (MPa)
Primary system	530	384	1837	Atmos. pressure
Feed water /Steam system	230	483.2	92.94	15.5

Through the evaluations using the procedures described above, the optimum design parameters were selected as delineated in Table 3[10]. As the length of sodium and steam tubes are set to be the same as those of KALIMER, the required heat transfer area is about 1.25 times as large as the total heat transfer area of the sum of the steam generator and IHX of KALIMER. The outer diameter is about 3.9m which is bigger than that of KALIMER 2.8m.

Though the SG dimensions themselves are bigger than KALIMER the dimensions need to be compared to the sum of IHX and SG dimensions of KALIMER which requires IHX.

The circulation flow rate is about 40% of the KALIMER design and the required pump head for LB circulation is about 1.8 times that of KALIMER IHTS. The required pumping power is less than

Table 2. Integrated Evaluation Table for New Design Concepts of LMR

	KALIMER	LB IHTS	Direct contact steam generator	Copper bonded steam generator	Integral steam generator with LB natural circulation	Integral steam generator with LB forced circulation
Sodium-water reaction prevention	No	Yes	Yes	Yes	Yes	Yes
Steam generator size	N/A	10% increase of SG and 15% incerase of IHX to KALIMER	2 times of diameter to KALIMER	20% increase to KALIMER design	6 times of SG size to KALIMER	30~40% increase to KALIMER design
Steam generator location	Outside of containment	Inside of containment	Inside of containment	Inside of containment	Inside of containment	Inside of containment
Containment dome size and pressure	Small/Low pressure	Same as KALIMER	Large/High pressure	Large/High pressure	Large/High pressure	Large/High pressure
Manufacturing and maintenance	N/A	Same as KALIMER	Usual	Difficult	Usual	Usual
Originality	None	None	None	None	None	Yes
The others	N/A	Heavy weight of IHTS system	Embrittlement of turbine bladeby contact of LB aerosols, potential for overpressurization of primary system	Thermal stress by the difference of thermal expansion	Low efficiency of heat transfer by natural circulation	No big problems Synthetic Evaluations Reference design
Synthetic Evaluations	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Potential candidate

the KALIMER design by 30% and thus the overall efficiency increases slightly by 0.4%.

3.4.3. Design Impacts

The ISG with forced convection of LB is a kind of ISG and it leads to an increase in the size of the containment dome when installing steam generators in the containment dome. Similar consideration should be paid to the design of the containment dome as discussed for the DCSG, just like other ISG concepts.

4. Discusion of Evaluations

Summary of evaluations for all the design concepts are delineated in Table.4. As shown in the table, the efficiency of heat transfer of all the designs does not show big differences except the concept of ISG with natural circulation of LB. However some designs have critical problems for implementation using current technology.

The DCSG has a possibility of over-pressurization of the primary pressure boundary(~0.03MPa) from a breach of the barrier between high pressure of the steam system(>10MPa). Also, the DCSG concept needs to be able to cope with the embrittlement of turbine blades by the entrainment of LB aerosol in the steam stream.

The CBSG needs to be able to cope with thermal stress. The thermal stress comes from the tight fixture of the tubes and copper matrix which is necessary to enhance heat transfer.

The LB-IHTS and ISG with forced convection of LB are very similar design concepts from the point of using the same intermediate media LB and circulating the media using a pump.

The former has benefits of using the same design concept of the pool type NSSS as KALIMER and it can eliminate the increase in the containment dome size. However, the LB-IHTS concept needs lots of supports and structures from its heavy weight and it needs lots of facilities to collect LB to prevent from pollution of heavy metal to the environment.

However, the later can reduce reactor diameter by eliminating IHTS and IHX and reduce costs by reducing a number of components.

5. Conclusions and Further Study

Various kinds of new design concepts for eliminating the SWR possibility and reducing construction costs of sodium cooled LMR were reviewed and evaluated.

From the evaluation results, the ISG with forced convection of LB is the most favorable candidate to implement in KALIMER.

However, the concept also needs further research to be actually adopted into the KALIMER design.

Acknowledgement

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