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SAFETY DESIGN ANALYSES OF KOREA ADVANCED LIQUID METAL REACTOR

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Abstract

The national long-term R&D program updated in 1997 requires Korea Atomic Energy Research Institute(KAERI) to complete by the year 2006 the basic design of Korea Advanced Liquid Metal Reactor(KALIMER), along with supporting R&D work, with the capability of resolving the issue of spent fuel storage as well as with significantly enhanced safety. KALIMER is a 150 MWe pool-type sodium cooled prototype reactor that uses metallic fuel. The conceptual design is currently under way to establish a self consistent design meeting a set of the major safety design requirements for accident prevention. Some of current emphasis include those for inherent and passive means of negative reactivity insertion and decay heat removal, high shutdown reliability, prevention of and protection from sodium chemical reaction, and high seismic margin, among others. All of these requirements affect the reactor design significantly and involve supporting R&D programs of substance. This paper summarizes some of the results of engineering and design analyses performed for the safety of KALIMER.

1. Introduction

As of the end of 1997, Korea's total nuclear capacity was more than 10 GWe, with 12 units in operation. In addition, 8 units are currently under construction. It is expected that the country's present nuclear capacity will be more than doubled by the year 2010, by which time nuclear generation will account for 40 % of total electric power production. Nuclear generation currently stands at 35 % of the total. The heavy dependence on nuclear energy raises the issue of spent nuclear fuel storage or disposal as well as that of utilization of uranium resources. To date, more than 3,000 MTU of spent fuels have been stored in At-Reactor(AR) pools of the 12 operating nuclear power plants. Taking only nuclear power plants currently in operation or under construction into account, the cumulative amount of spent fuels is estimated to reach up to about 26,000 MTU by 2030.

From the viewpoint that liquid metal reactors(LMRs) have the potential of enhanced safety utilizing inherent safety characteristics and of resolving spent fuel storage problems through proliferation-resistant actinide recycling, LMRs appear to be the most promising nuclear power option of the future. In this context, the KALIMER development program was launched as a national long-term R&D program in 1992 and has been carried out by Korea Atomic Energy Research Institute(KAERI) since then. As such, the objective of the KALIMER Program was set to develop an inherently and ultimately safe, environmentally friendly, proliferation-resistant and economically viable fast reactor concept.

Up until July 1997, efforts had been concentrated on the development of basic sodium technologies and design methodologies unique to the LMR design and operating characteristics. An initial design concept also was proposed through the feasibility study of a number of innovative design features as well as various proven design features. As a result , KALIMER was defined to be a 150 Mwe pool-type sodium cooled prototype reactor that uses metallic fuels. In 1997, the KALIMER program plan was updated to call for the completion of the basic design and supporting R&D work by 2006. An effort is being made to establish ,by early 2000, not only a self-consistent conceptual design of system configuration, arrangement and key features satisfying design requirements, but more importantly computer codes and methods specific for KALIMER engineering and design analyses[1].

At early phase of the conceptual design, an emphasis has been made to come up with the self-consistent design meeting a set of the major safety design requirements to avoid "unusual occurrences", or arrest them. One of the major requirements of current emphasis is that KALIMER shall be of inherent passive means of negative reactivity insertion and decay heat removal, sufficient to place the reactor system in a safe stable state for bounding ATWS events without significant damage to the core or reactor system structure. Even with the inherent reactor shutdown requirement, the reactivity control and shutdown systems are required to result in extremely high shutdown reliability. As for all the other sodium cooled reactors, the structures, systems, and components of KALIMER are to be designed and located to minimize the probability and consequences of sodium chemical reactions. Seismic isolation is also required to achieve high seismic margins. All these safety design requirements affect the design significantly and demand supporting R&D programs of substance.

For the analysis of KALIMER's inherent safety, a plant-wide transient analysis code SSC-K is being developed. Models for reactivity feedback effects and pool thermal-hydraulics have been developed into the code and a preliminary analysis of UTOP and ULOF/LOHS performance has been attempted. Design alternatives have been investigated to improve decay heat removal capability by passive means, for which functional testings are to be done. Seismic base isolation is shown to reduce seismic response of building and structures significantly and ,therefore, provides a great advantage in safety as well as economy for the structural design of nuclear power plants. Substantial progress has been made in developing and validating the methodologies, and engineering analyses for the structural design of the KALIMER are under way. An investment is also being made on the other key design features testing, such as electromagnetic pump , self-actuated shutdown system, and fuelling machine in reactor vessel. Effort continues to be made on the development of basic sodium technologies, such as measurement or detection technique as well as the investigation on thermal-hydraulic and chemical behavior. Engineering and design analyses are also being made to improve IHTS configuration against sodium chemical reaction.

In the following sections, the major design features of KALIMER are briefly described, and some of results from the safety design analyses and supporting R&D programs are summarized.

2. Major Design Features of KALIMER

Table 1 summarizes some of the major design parameters of KALIMER, which is currently under the conceptual design phase. A salient feature of its key system designs is briefly described in the following[2].

Table 1. KALIMER Key Design Parameters

OVERALL		**PHTS**	
Net plant Power, Mwe	150	Reactor Core I/O Temp, ^{o}C	386.2 / 530.0
Core Power, MWt	392	Total PHTS Flow Rate, kg/s	2143.1
Gross Plant Efficiency, %	41.5	Primary Pump Type	electromagnetic
Net Plant Efficiency, %	38.2	Number of Primary Pumps	4
Reactor Pool Type			
Number of IHTS Loops	2		
Safety Shutdown Heat Removal	PSDRS		
Seismic Design	Seismic Isolation Bearing		
		IHTS	
CORE		IHX I/O temp., ^{o}C	339.7 / 511.0
Core Configuration	Radially Homogeneous	IHTS Total Flow Rate, kg/s	1803.6
Core Height, mm	1000	IHTS Pump Type	Electromagnetic
Axial Blanket Thickness, mm	0	Number of IHXs	4
Maximum Core Diameter, mm	3447	Number of SGs	2
Fuel Form	U-10% Zr Alloy		
Enrichments (IC/OC) for	14.4 / 20.0		
Equilibrium Core, %		**Steam System**	
Assembly Pitch, mm	161.2	Steam Flow Rate, kg/s	175.5
Fuel/Blanket Pins per Assembly	271 / 127	Steam Temperature., ^{o}C	483.2
Cladding Material	HT9	Steam Pressure, MPa	15.50
Refueling Interval, months	12		

Core and Fuel Assembly

The KALIMER core system is designed to generate 392 MWt of power. The reference core utilizes a homogeneous core configuration in radial direction with two driver fuel enrichment zones, surrounded by a layer of blanket assemblies. The core layout, shown in Figure 1, consists of 96 driver fuel assemblies, 42 radial blanket assemblies, 6 control rods, 1 ultimate shutdown system(USS) assembly self-actuated by a Curie point electromagnet,6 gas expansion modules(GEMs), 48 reflector assemblies, 54 B_4C shield assemblies, 72 shield assemblies, and 54 in-vessel storages(IVSs) in an annular configuration. The in-vessel storages(IVSs) are located between the stainless steel shielding zones. There are no upper or lower axial blankets surrounding the core. The reference core has an active core height of 100 cm and a radial equivalent diameter (including control rods) of 172 cm; the height-to-diameter ratio (H/D) for the active core becomes 0.581. The physically outermost core diameter of all assemblies is 344.7 cm. The core structural material is HT9. It's low irradiation swelling characteristics permits adequate nuclear performance in a physically small core. The fuel pin is made of sealed HT-9 tubing containing metal fuel slug in columns. The fuel is immersed in sodium for thermal bonding with the cladding. A fission gas plenum is located above the fuel slug and sodium bond. The bottom of each fuel pin is a solid rod end plug for axial shielding. The driver fuel, blanket fuel, reflector, and shield assemblies use identical structural components with only the bundle and its mounting grid changing from one assembly type to the other. The control assemblies use outer hardware (nosepiece, duct and handling socket) that is identical to that in the other assemblies. Reflector assemblies contain solid HT9 rods. The absorber assemblies use a sliding bundle and a dashpot

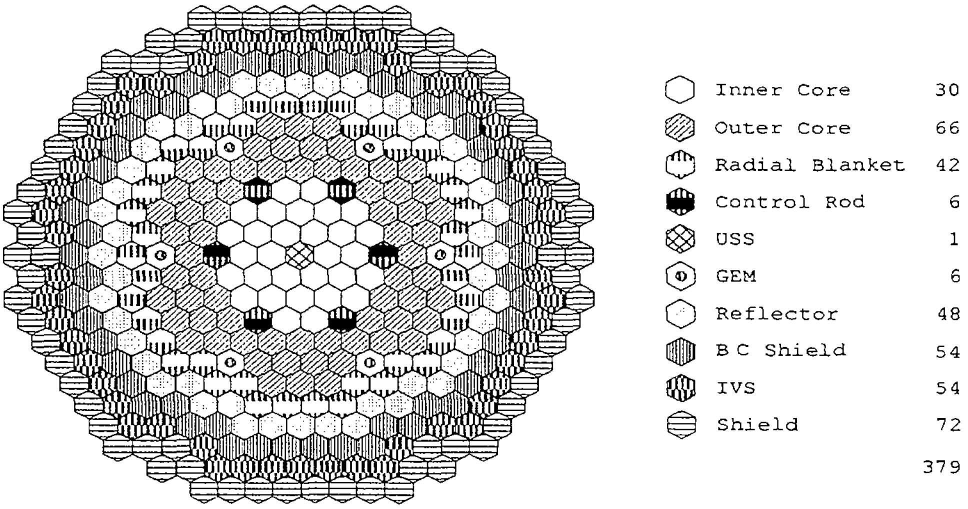


Fig.1. KALIMER Core Layout

assembly within the same outer assembly structure as the other assembly types. In all assemblies, the pins are in a triangular pitch array. The bottom end of each assembly is formed by the nosepiece which provides the lower restraint function and the coolant inlet[3].

Reactivity Control and Reactor Shutdown

Reactivity and power are controlled by means of the control rod system in the driver fuel region of the core. The control rod design satisfies both the one rod stuck condition and the unit control rod worth condition against the unprotected transient over-power(UTOP) event. The gas expansion modules(GEMs) are passive reactivity feedback assemblies that insert negative reactivity into the core during a loss of flow. The Self-Actuated Shutdown System(SASS) located at the center of the core is designed as an ultimate shutdown system by using a Curie point electromagnet which loses its magnetic force holding the shutoff rod when the temperature of the primary sodium reaches the curie point, hence a passive shutdown can be achieved.

Residual Heat Removal System

In KALIMER, the shutdown heat removal system is designed with the emphasis on system reliability to achieve a higher level of plant safety. Safety grade heat removal is achieved by the Passive Safety Decay Heat Removal System(PSDRS), which consists of the air path around the containment vessel and takes the decay heat from the reactor pool and discharges the heat to the atmosphere. Normally the decay heat is removed by steam generators and the condenser. During the maintenance of any IHTS, heat is removed by the remaining IHTS loop. Also there is the Steam Generator Auxiliary Cooling System(SGACS) to aid the decay heat removal. SGACS induces natural or forced circulation of atmospheric air past the shell side of steam generator. Intensive analysis on the system performance and design parameters is under progress for system level design optimization.

Reactor Structure

The reactor vessel has overall dimensions of 17.6m height, 7.02m diameter, and 5cm thickness in preliminary concept design and is composed of a cylindrical shell with an integral hemispherical shell bottom head. The structural integrity and safety of the reactor vessel has been achieved by providing no penetration nozzle and no attachments other than the core support structure. The shape of the core support structure is skirt-type. All equipment like IHX, EM Pump, IVTM, and UIS are supported by a reactor head and a rotating plug is adopted for the refueling operation. The support barrel, which is a major component of reactor internal structures, serves as a redan to separate the hot sodium pool and cold sodium pool and as a support of internal structures including the reactor core. The containment vessel, which encloses the reactor vessel, is easy to access from the reactor vault so that the inspection and maintenance of the vessel can be easily accomplished. General arrangements for NSSS and reactor building are tentatively developed as shown in Fig.2&3.

The seismic base isolation for the rector building using high damping rubber bearings has been adopted to achieve sufficient structural integrity and economic design of KALIMER, when subjected to the design basis earthquake such as a horizontal Safe Shutdown Earthquake of 0.3g. The development of a design concept adopting 3 dimensional seismic base isolation is under consideration to reduce both horizontal and vertical seismic responses.

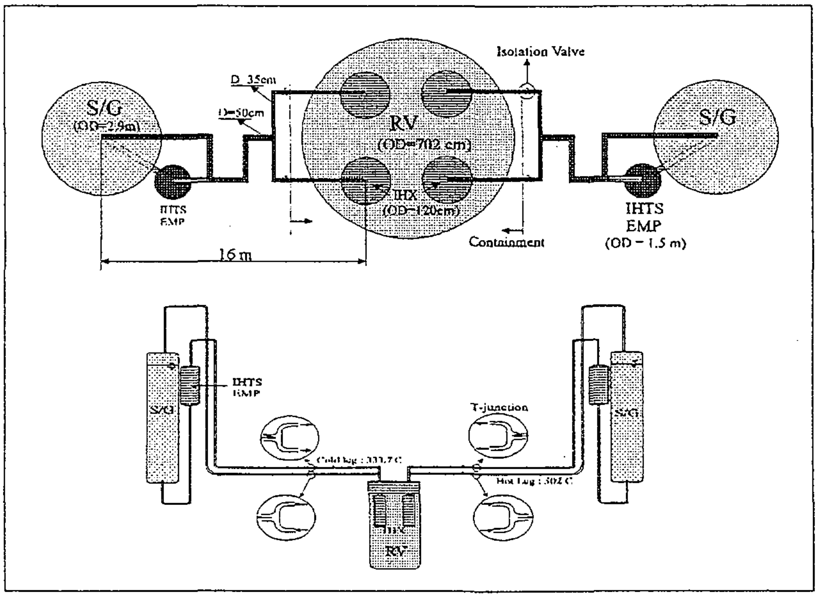


Fig. 2. General Arrangements of NSSS

Heat Transport System

A superheat steam cycle is implemented to have a high plant efficiency noting that high thermal efficiency reduces the heat discharge from the plant, resulting in less impact to the environment. IHTS

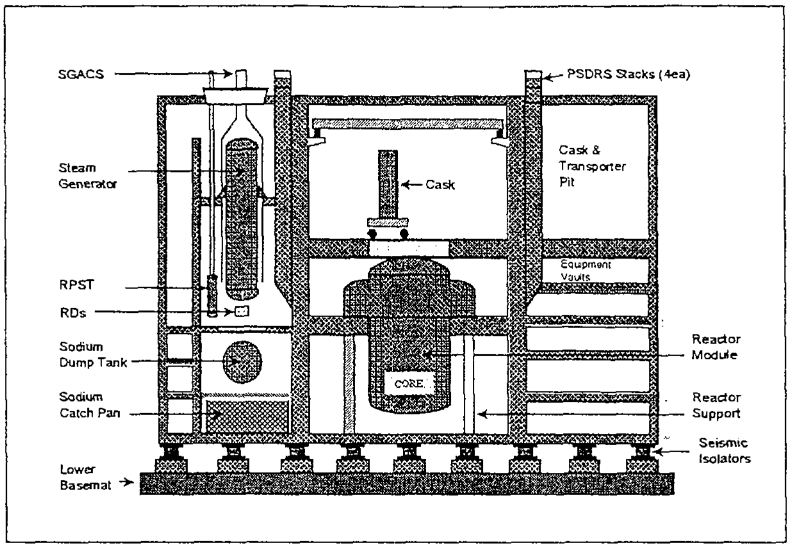


Fig.3. General Arrangement of Reactor Building

consists of two loops and each loop is equipped with one steam generator unit to simplify the system design and increase the plant operation flexibility. For safety, large system thermal inertia is achieved by using a pool based primary system. Strong emphasis has been given to the prevention and mitigation of possible sodium-water reaction events for the IHTS piping routing. Valves for isolation of IHX from the sodium-water reaction products are installed at each IHTS piping penetrating the containment. The system reliability is improved by using electromagnetic (EM) pumps, which do not have moving parts, for both of the primary and intermediate coolant pumping. The low momentum inertia of the EM pump is compensated for by using an auxiliary device which keeps a certain amount of rotating kinetic energy when the EM pump runs normally but supplies electricity from the rotating kinetic energy to the EM pumps when the electricity supply to the pumps is interrupted. The operating temperature and component size were determined to make the net plant thermal efficiency higher than 38%. Preliminary analysis on economic effects was made in setting up the plant heat balance, as shown in Figure 4, for system design optimization.

3. Safety Design Analyses and Supporting R&D Programs

3.1 Inherent and Passive Safety Design Analyses

Inherent Safety Analysis

A plant-wide transient analysis code is being developed for the analysis of KALIMER's inherent safety and for the assistance in the development of design, where new design features will frequently demand not just new data but new models. Transient and safety analysis code SSC-K is under development based upon the SSC-L code which was developed by BNL for the analysis of loop type

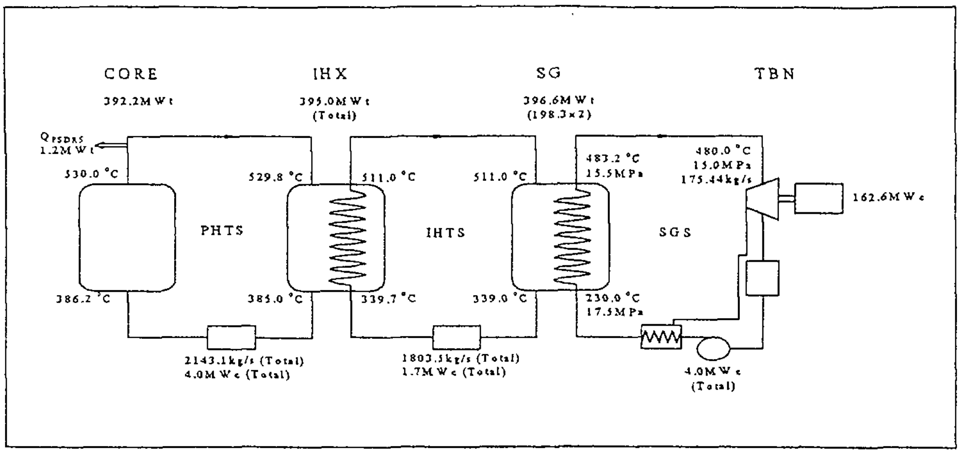


Fig.4. KALIMER Plant Heat Balance

LMRs with oxide-fueled core. Models modified and newly developed into the code so far include models for reactivity feedback effects and pool thermal-hydraulics. In order to verify the logic of the models developed, and to assess the effectiveness of the inherent safety features based upon the negative reactivity feedbacks in achieving the safety design objectives of passive safety, a preliminary analysis of UTOP and ULOF/LOHS performance has been attempted.

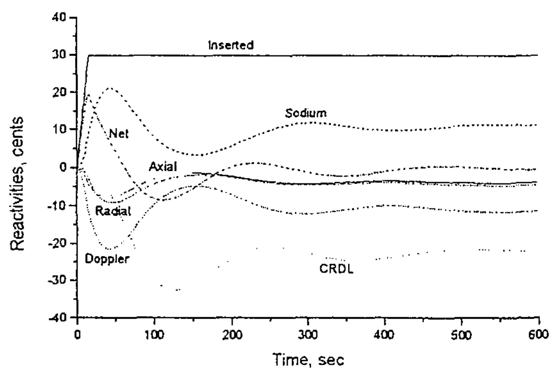


Fig.5..Reactivities during UTOP Event

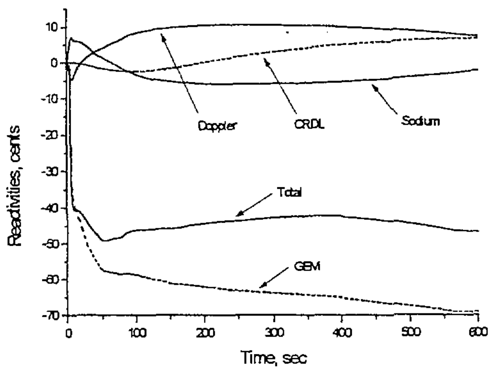


Fig.6. Reactivities during ULOF/LOHS Event

Inadvertent withdrawal of the control rod at reactivity insertion rate of 2 cents/second was assumed for the simulation of UTOP. As expected, the reactor power reaches an asymptotic level higher than that of the initial steady state due to negative feedback effects. As shown in Figure 5, the Doppler effect is an instantaneous and important feedback for UTOP and the net reactivity increases initially and then decreases to negative values due to feedback effects.

Trip of all primary pumps with coastdown and the loss of IHX heat removal capability due to sodium water reaction in the steam generator is assumed for the ULOF combined with LOHS event. Reduction of the core flow is due to the coastdown of primary electromagnetic pumps, and the reactor power decreases to about 6% of the rated power due to negative reactivities. When there were no

GEMs in the core, there occurred a sodium boiling since the reactor power decreases rather slowly and power-to-flow ratio increases. As shown in the Figure 6, the net reactivity is always negative during the course of the transient due mainly to the largest contribution from GEMs[4].

According to the preliminary evaluation of the inherent safety characteristics, there is a large safety margin even under severe unprotected event conditions. In order to validate the SSC-K code for safety analysis, code-to-code comparison calculations and/or calculation against experimental data need to be performed. Potential safety concerns of KALIMER need to be resolved as well. Even though EBR-II experiments have shown the possibility of inherent safety of small metallic cores, there need to be an investigation in extending the result to larger cores. Coastdown characteristics of electromagnetic pumps has a significant effect on the core safety under loss of flow events, and the performance of synchronous machine for inertia need to be evaluated. Effect of the fluctuating sodium level inside GEM on reactivity, and the effect of GEM reactivity insertion due to the restart of pumps at low power operation need also to be investigated.

Probability of HCDA occurrence is extremely low due to inherent safety characteristics of KALIMER, and mechanistic analysis is not planned during the conceptual design stage. However, depending upon the decision of the licensing authority, there may be a developmental effort for the mechanistic approach in the future. A simple model, based upon Modified Bethe-Tait model, is being developed for the estimation of energy release and available work under HCDA for the analysis of ultimate safety.

Passive Decay Heat Improvement Analysis

To increase the capacity of decay heat removal of a LMR system that uses a natural air circulation cooling, feasibility of heat transfer enhancement has been studied for a planar air channel by introducing a new channel configuration using radiation-convection structures of compact heat transfer surface. For the new channel configuration, the heat transfer mechanism has been investigated and design guides for the radiation-convection structure have been developed based on the investigation results. Following the developed design guides, a new radiation-convection structure has been also devised. Analysis of the air channel cooling with the new radiation structures revealed substantial heat transfer enhancement and the feasibility of the heat transfer enhancement with the new channel configuration design has been confirmed[5].

In the operation of PSDRS, core decay heat is transferred to the containment vessel, as shown in Fig. 7, and the heat from the containment vessel is dissipated to the air flow which is generated by the natural circulation from the density difference between the air channel and the environment. The heat dissipation to the air flow is made of two paths. One is the direct convection heat transfer from the containment wall surface and the other is an indirect path to the air. In the indirect path, heat is first transported from the containment vessel surface by radiation to the air separator which separates the hot air from the incoming cold air. Then the heat is dissipated to the air flow by convection.

The main resistance in the heat transfer from the core to the air in a system like PSDRS is at the path from the containment vessel to the air [5]. The improvement of the heat removal capacity of the system comes to heavily depend on the improvement of the heat transfer in the air channel. Two types of works have been made to improve the heat removal capacity. One is the modification of the wall surface to enhance the convection heat transfer coefficient and the other is modification of the air channel configuration itself. In this study, a new channel configuration is introduced and the feasibility of the heat transfer enhancement of the new channel configuration is examined for black body surfaces. The new channel configuration is shown in Fig. 8 and is provided with lateral compact heat transfer surface structures. The new channel configuration is different from the conventional configurations in that it uses compact heat transfer surface and the surface is located across the channel. Since the configuration is different, the heat transfer mechanism becomes different from that of previous studies.

By introducing the lateral structures to the air channel, the radiation heat transfer from the containment vessel is redistributed. The high heat transfer performance of the radiation-convection structure (hereafter called as radiation structure) effectively dissipate the heat received by radiation to the air and the overall heat transfer capacity can be increased depending on the channel system design. For the geometry of the air channel of black surface and fixed wall temperature condition, the overall heat transfer is predicted to increase up to 6 times than the heat transfer rate of the same gap size , and up to about two times than the rate at the optimum gap size without radiation structures

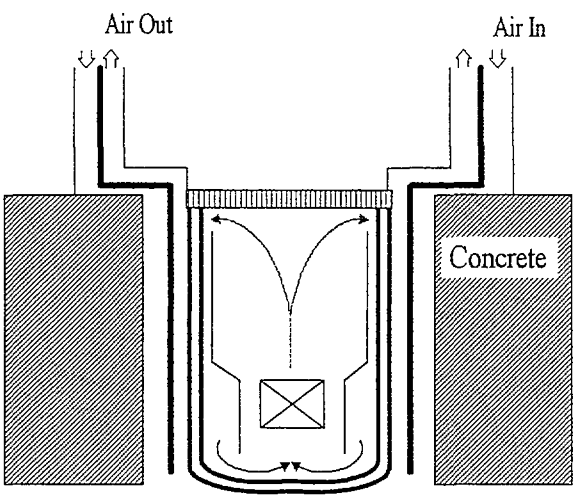


Fig. 7. Analysis domain & Heat Transfer Path Network

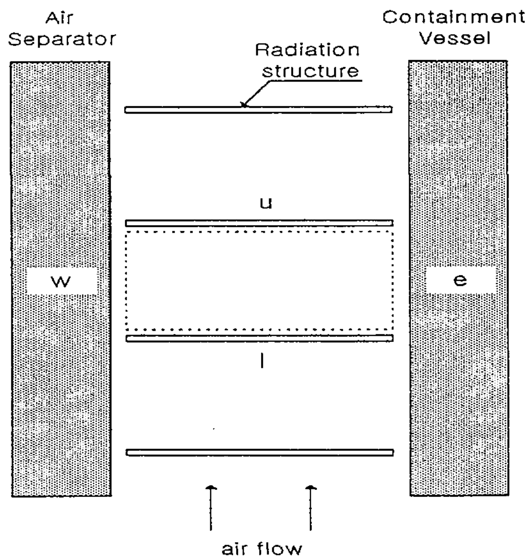


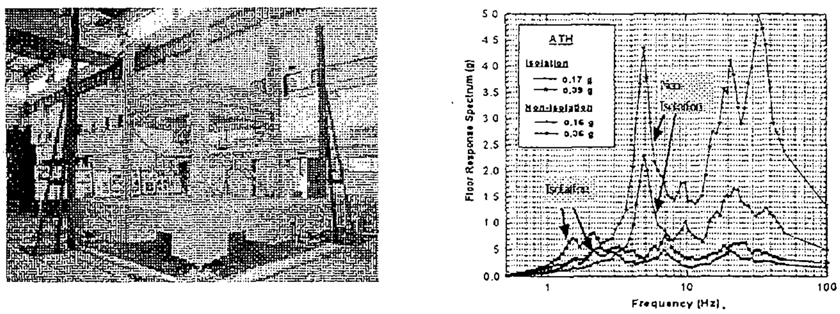
Fig.8. Radiation Structure

3.2 Seismic Isolation Study

Some essential results of the seismic base isolation studies for KALIMER are summarized in this section.

LRB and Shake Table Test

For the rubber specimen and laminated rubber bearing(LRB) tests, various effects such as the shear strain, the loading rate, the cyclic loading, and so on are investigated. In these tests, the LRB being developed in KAERI shows good mechanical characteristics applicable to KALIMER. In the shaking table tests for the seismically isolated structure, it is confirmed that the seismically isolated structure produces significant reductions of the seismic responses compared with the case of non-isolated structure. Structural dynamic test for base isolated structure equipped with 2 dimensional 4-1/8 scale high damping rubber bearings were performed using 30 ton-6 dof shaker. Fig. 9 shows test model structure and seismic response results at upper slab of the test model to artificial time history input of SSE 0.3g[6].



Test Model

Test Results of Isolated and Non-isolated Test Model to Artificial Time History 0.3g & 0.15g

Fig.9. KALIMER Seismic Isolation Test Program

Reactor Building Analyses

To obtain the time history of the seismic responses of reactor building, a lumped-mass beam model is developed. The model is composed of two sticks; the one is for the reactor building and the other is for the reactor support structure. The time history responses for the non-isolated and isolated reactor buildings are calculated for an artificial time history earthquake generated by using the seismic design spectrum curve of US NRC RG1.60. Design basis earthquakes for KALIMER are SSE 0.3g for horizontal and 0.2g for vertical direction, and OBE 0.15g for horizontal and 0.1g for vertical direction respectively. The isolation frequency of reactor building is 0.5 Hz and the equivalent damping of LRB is 12%. The lumped-mass model of the reactor building is presented in Fig. 10.

The total weight is about 68,000 tons. The 9 beam elements for the reactor building and the 3 beam elements for the reactor support structure are used. The maximum acceleration responses of the non-isolated and isolated reactor buildings for the horizontal and vertical earthquake data are shown in Table 2.

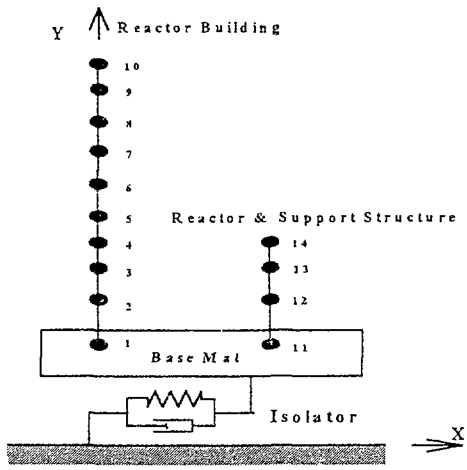


Fig.10. Lumped mass-beam models of KALIMER building

Table 2. Accerations and Displacements of Reactor Building Under ATH Earthquake

Location	X-Direction(g)		Y-Direction(g)		Z-Vertical (g)	
	Non-isolated	Isolated	Non-isolated	Isolated	Non-isolated	2D isolator
Base	0.30	0.175	0.30	0.177	0.205	0.321
Top	**1.461**	**0.177**	**1.609**	**0.179**	**0.577**	**0.848**
RV support	**0.583**	**0.173**	**0.676**	**0.175**	**0.362**	**0.558**

The time history responses for x-direction displacement are presented in Fig. 11 and the response spectra at major locations represented in Fig. 12.

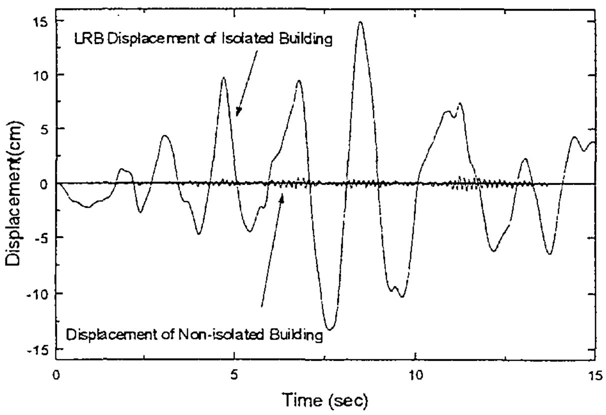


Fig.11. Displacement Responses of Reactor Building

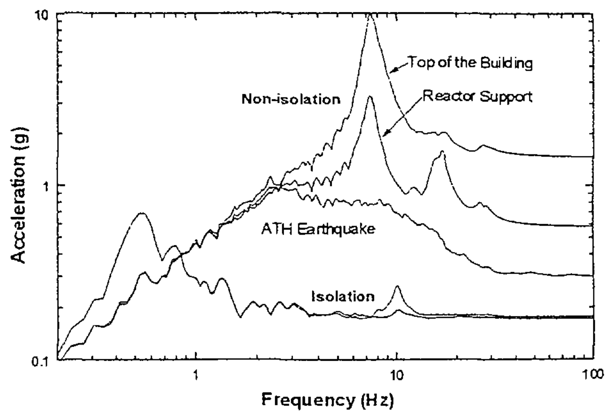


Fig.12. Comparison of Acceration Reponse Spectra of Reactor Building(ATH,X-dir. 0.3g)

The maximum peak acceleration is reduced to 0.177g for isolated condition, while it is 1.46g for non-isolated condition. The maximum displacement becomes larger to 15.0cm for the isolated condition. The maximum acceleration for the vertical earthquake of 0.208g ZPA is amplified to 0.848g for isolated condition, while the maximum acceleration is amplified to 0.577g for non-isolated condition. This agrees with the general trend that the horizontal isolation of structure can amplify the vertical responses[7].

Reactor internal structures and components

To produce the seismic analysis model for the reactor internal structures, the lumped-mass modeling technique is used. From the 3-dimensional finite element model of KALIMER reactor internal structures, the detail local stiffness analyses are performed to construct the lumped-mass seismic analysis model. The seismic analysis and evaluation of KALIMER are presented through the modal analysis, the seismic time history analysis, and the equivalent seismic stress analysis. Table 3 shows the natural frequencies of the reactor structures resulted from the modal analysis for the seismic analysis model shown in Fig. 13.

Table 3. Results of Modal Analyses of KALIMER

Mode	Horizontal (Hz)		Vertical (Hz)	
	Isolation	**Non-isolation**	**Isolation**	**Non-isolation**
1	0.70	8.11	1.87	1.87
2	11.51	11.88	8.09	8.25
3	13.69	18.81	17.77	17.94
4	21.04	27.85	23.08	34.26
5	27.90	27.97	34.85	36.59
6	31.29	33.13	36.60	36.71
7	35.54	36.95	37.01	37.15
8	38.19	39.77	62.10	78.16
9	39.78	53.00	86.14	91.53
10	53.29	58.07	95.24	98.22

The seismic responses of reactor structures of seismically isolated KALIMER are significantly reduced for accelerations and relative displacements in horizontal direction. For the isolation case, the maximum peak acceleration in horizontal direction is same in all structures and components; i.e., 0.11g for OBE and 0.22g for SSE. The responses are reduced about 14 times in IHX, 9 times in EMP and 8 times in reactor vessel liner, support barrel, and core compared with those in non-isolated case. However, for the vertical direction, significant response amplifications occur in whole structures. This is due to the vertical structural frequency of 8.1Hz located in dominant excitation frequency band of input motion.

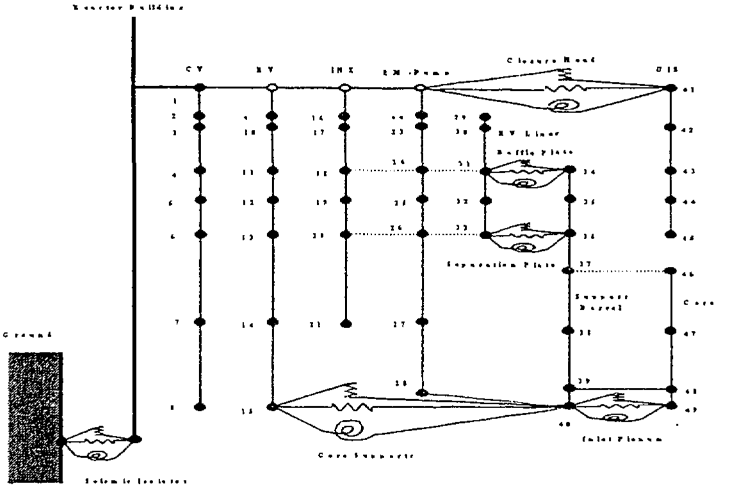


Fig.13. Seismic Analysis Model of Reactor Structures

Table 4 shows the results of the seismic margin evaluations and the seismic capacity of KALIMER reactor internal structures including the reactor vessel and containment vessel. From the results, the containment vessel, reactor vessel, inlet plenum, and core support have large seismic stress margins but the reactor vessel liner, support barrel, separation plate, and baffle plate have small margins. The maximum stress occurs in reactor vessel liner parts connected with the separation plate due to the vertical seismic loads.

Table 4. Accerations & Displacements of Reactor Building Under ATH Earthquake

Items	**σ_{SSE} * (MPa)**	**P_{L+b}* (MPa)**	**Margins***	**Minimum Seismic Capacity***
Containment Vessel	21.4	401.9	17.78	
Reactor Vessel	39.6	401.9	9.15	
RV Liner	340.0	401.9	*0.18*	0.354g
Support Barrel	113.0	382.4	*2.38*	
Inlet Plenum	20.8	401.9	18.32	
Separation Plate	188.0	401.9	*1.14*	
Baffle Plate	193.0	382.4	*0.98*	
Core Supports	72.1	401.9	4.57	

□□σ_{SSE} = Total stress intensity for horizontal and vertical SSE loads

* P_{L+b} = 1.5 x Min [2.4 S_m , 0.7 S_u], ASME Code Sec.III App.F.

* Margin = (P_{L+b} / σ_{SSE}) - 1

* Seismic Capacity = Min[Seismic Margin +1] x SSE

To evaluate the maximum seismic resistance in preliminary designed KALIMER reactor internal structures, the index of seismic capability(SC) is defined in this paper as follows;

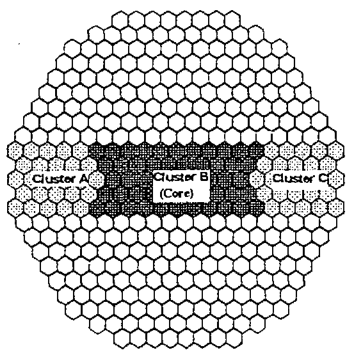
SC = Minimum [seismic stress margins +1] x SSE

Using above equation, the seismic capability of KALIMER is preliminary calculated as 0.354g. When the vertical stiffness of the support barrel/separation plate/reactor vessel liner region increases by the design change, this index value is expected to be significantly increased[8].

Core Seismic Response

The seismic analysis of LMR core structures is a complex problem involving the dynamic interaction of many hundreds of individual fuel, blanket, and shield assemblies in a sodium environment. To simplify the core seismic problem, the cluster modeling technique shown in Fig.14 for a diametral row of the core is used. The clusters of assemblies are assumed to have no relative motion between the assemblies within a cluster. The diametral row modeling approach gives conservative results and it is easier to evaluate the core seismic behavior compared to a full core model using the cluster technique.

In the present analyses, 3-clusters row model, in which cluster B represents fuel assemblies and clusters A and C represent the shield, blanket, reflector, and etc. as shown in Fig.14, is used to simplify the core seismic problem. The clusters A and C have 26 assemblies in each and cluster B has 51 assemblies. Fig.15 shows the core seismic model used in analysis.



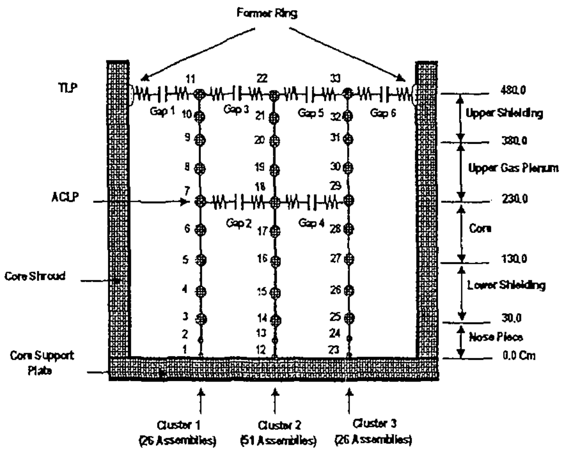


Fig.14. Clustering of LMR Core Assemblies *Fig.15. Simplified Core Seismic Analysis Model*

To investigate the dynamic characteristics of LMR core seismic analysis model shown in Fig.15, the modal analysis is carried out. To generate the linear model used in modal analysis, all the gap stiffness shown in Fig.4 are eliminated. The results of modal analysis show that the fundamental frequency of LMR core is 4.3 Hz and the second natural frequency is 24.3Hz. These natural frequencies of core will show non-linear behavior during impacts at load pads.

For the general investigation of core seismic responses, the harmonic excitations subjected to rigid core shroud and core support plate are used in the analyses considering conservative excitation conditions. Table 1 shows the input loading conditions.

Table 5. Results of Modal Analyses of KALIMER

Load Case	Core Support Excitation for SSE Conditions (0.3g)		
	Acc.	Freq.	Remarks
1	1.28g	8.1 Hz	Non-Iso, RI Freq.
2	1.28g	4.3 Hz	Non-Iso, Core Freq.
3	0.22g	4.3 Hz	Iso., Core Freq.
4	0.22g	0.7 Hz	Isolation Freq.

The results of the core seismic response analyses show that, the load case 4, which is the case of a seismically isolated LMR, gives significantly reduced seismic responses compared with those of the load cases 1 and 2, which are for the cases of non-isolated LMR. The seismic responses for the load case 3, which may give the limit design case of the seismic isolation frequency for core, show little reduction in seismic responses(Fig.16). When the seismic isolation frequency(0.7Hz) is much lower than the core fundamental frequency(4.3Hz), a good isolation performance is observed in terms of core seismic responses. Fig.17 illustrates the impact load at the gap 3(TLP).

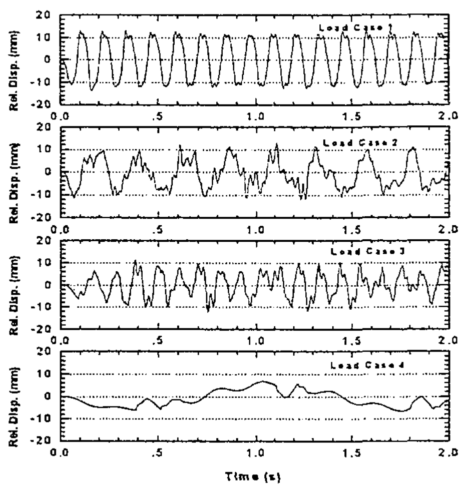


Fig.16 .Relative displacement at node 22(TLP)

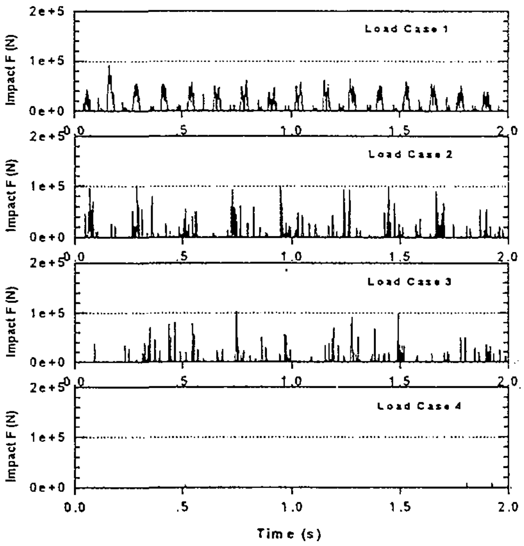


Fig.17. Impact Loads at Gap3 (TLP)

From these results, we can conclude that the seismic isolation provides great reductions of the impact loads as well as the number of contacts at the load pads of core assemblies at the former ring. This can allow the simple design of a core control system. And it is expected that the requirements of the core compaction and reactivity insertion problem can be easily satisfied when an efficient seismic isolation is adapted for the LMR design[9].

3.3 Sodium Technology Development

Sodium Water Reaction Analysis

Large scale water leakage into the sodium side due to the failure of tubes in LMR steam generators leads to an increase in the pressure and temperature by hydrogen and the heat of reaction, and may give significant effects on the structural integrity of the intermediate heat transport system(IHTS). Prior to designing IHTS and steam generator, a pre-estimate of the pressure effects for this system should be conducted. As a general trend of pressure change, when water leakage occurs, a relatively high pressure is formed within milliseconds and is called the initial spike pressure. After this peak pressure, a lower secondary pressure follows and decreases slowly because pressure change is not sensitive to time. This step is called the quasi-steady state. The intensity of the initial spike pressure depends on the internal structure of the steam generator and the transient characteristics of the sonic waves. The intensity of the pressure depends on the inertia constraints of the IHTS.

A computer code, SPIKE, has been developed for analyzing the various characteristics of IHTS resulting from initial spike pressure. Briefly, the sodium flow in the IHTS is assumed to be a compressible, one dimensional, unsteady viscous flow. From these assumptions and equations of continuity, momentum and energy, the governing equations were developed.

A comparison of the calculated results using the SPIKE code with the experimental value is shown in Fig. 18, for an experimental IHX model of a 1/12.5 scale. The figure shows that the calculated results are consistent with the experimental values in the IHX inlet[10]. The code will be further verified by simulation experiments at KAERI's test facility, which is scaled down from KALIMER in the ratio of 1/256 (the heat load scale-down ratio, about 1/6 of the linear scale-down ratio). The SG-model has a diameter of 420mm (O.D.) and length of 2750mm with 5 layer helical coil tubes of which the total length is about 280m and the material is stainless steel 304 without welding. To assure the safety from accidents caused by large water leakages in KALIMER steam generators, studies on leak propagation, their simulation, and a pressure change estimation by computer codes have been carried out. The computer codes, HOPRE and DIPRE , are being developed to analyze the quasi-steady-state pressure.

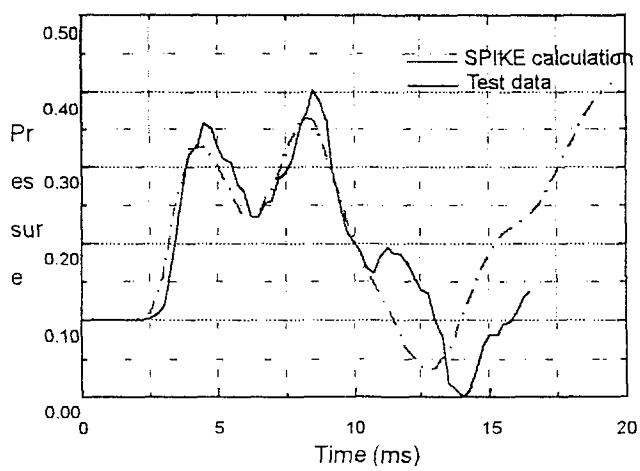


Fig.18. Comparison of pressure changes

The SPIKE code has been applied to investigate the pressure transients at various points of the IHTS of KALIMER. As shown in Figure 2, KALIMER is of two IHTS loops, each loop consisting of a steam generator, two intermediate heat exchangers, a pump and pipes which are connected with several fittings. The IHTS of KALIMER was modeled as a network having 40 branches and 39 junctions for the analyses. The results show that pressure transients or peak pressures are rather sensitive to such design parameters as leak rate, distance between the lower plenum of steam generator and rupture disc, and distance between steam generator and IHX. Figure 19 shows the pressure transients at various points of the IHTS with the rupture disk intact. It is noted that pressures tend to be monotonically increasing but heavily oscillating at some points. It was also observed that pressure transient behavior was quite sensitive to the size of sodium expansion tank[11].

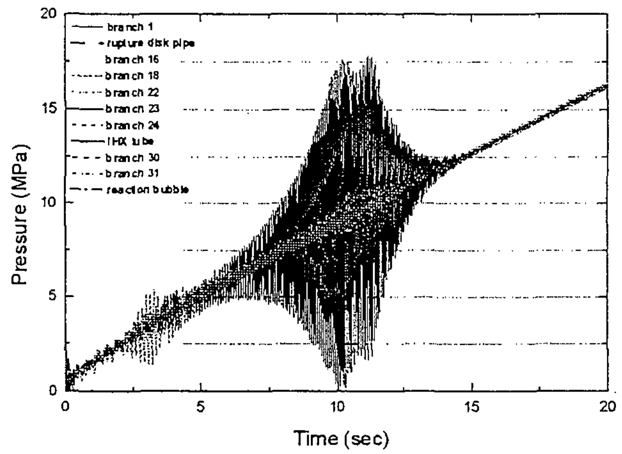


Fig.19.IHTS pressure transients

Sodium Thermal hydraulics and Component Development Testings

Small-scale sodium experiments have been performed to investigate the coolant thermal-hydraulic behavior, such as turbulent mixing in compact reactor space, flow reversal by natural circulation with
an electromagnetic pump operation, and decay heat removal by wall cooling, among others. Sodium experiments continue to be performed to develop the technologies to measure such parameters as differential pressure, local flow rate, and void fraction.

In addition to the safety evaluation analyses of the IHTS for large leaks, R&D work on sodium water reaction carried out to date includes small water leak experiments for the determination of a design base leak rate, development of reliable and real time detection system of water leaks using the acoustic signal as well as hydrogen detection, among others. Sodium fire characteristics and

phenomena are also being investigated with $48m^3$ of rectangular type fire cell. Analyses of various types of sodium fire phenomena, development of sodium leak detection system, and fire extinguishment, prevention and mitigation, aerosol filter and scrubbing devices will be carried out.
In the area of key component development, the submersible-in-pool type electromagnetic pump of operating temperature of 600° C and 200 l/min maximum flow rate were developed using the theory of magneto-hydraulics and the equivalent circuit analysis and its prototype was manufactured and its operation tests were performed. The SASS and IVTM were developed and their mockups are manufactured and their theoretical validation tests were performed.

6. Conclusion

An effort has been made to establish by early 2000 the conceptual design of KALIMER with system configuration, arrangement and key features satisfying design requirements. Emphasis is currently placed upon coming up with the design features meeting a set of the major safety design requirements for accident prevention, which include those for inherent and passive characteristics of negative reactivity insertion and decay heat removal, high shutdown reliability, high seismic margin, and prevention of sodium chemical reaction, among others.

For the analysis of the KALIMER's inherent safety, a plant-wide transient analysis code SSC-K is being developed. Models for reactivity feedback effects and pool thermal-hydraulics have been developed into the code and a preliminary analysis of UTOP and ULOF/LOHS performance has been attempted. The results show that net reactivity stays negative during the transients analyzed. Design alternatives have been investigated to improve decay heat removal capability by passive means, for which functional testings are to be done. Seismic base isolation is shown to reduce seismic response of building and structures significantly and, therefore, provides a great advantage in safety for the structural design of nuclear power plants. Engineering and design analyses are also being made to improve the IHTS configuration against sodium chemical reaction. An investment is also being made on the other key design features testing, such as electromagnetic pump, self-actuated shutdown system, and fuelling machine in reactor vessel.

Substantial progress has been made in developing and validating the methodologies, and engineering analyses for the conceptual design of KALIMER. However, we still have a long way to go down the road to accomplish the mandate; that is, to complete the basic design of KALIMER as well as supporting R&D work.

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