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DEVELOPMENT OF KOREA ADVANCED LIQUID METAL REACTOR

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ABSTRACT

Future nuclear power plants should not only have the features of improved safety and economic competitiveness but also provide a means to resolve spent fuel storage problems by minimizing volume of high level wastes. It is widely believed that liquid metal reactors (LMRs) have the highest potential of meeting these requirements. In this context, the LMR development program was launched as a national long-term R&D program in 1992, with a target to introduce a commercial LMR around 2030. Korea Advanced Liquid Metal Reactor(KALIMER), a 150 MWe pool-type sodium cooled prototype reactor, is currently under the conceptual design study with the target schedule to complete its construction by the mid-2010s. This paper summarizes the KALIMER development program and major technical features of the reactor system.

1. Introduction

Korea has continued its quest to develop nuclear power since the introduction of its first nuclear unit Kori-1,a 600 MWe PWR, in 1978. In the mid-1980s, the country started to develop Korea Standard Nuclear Power Plant (KSNPP), a 1000MWe PWR plant. The two lead units of KSNPP are presently in operation and another six units are under construction. Along with the construction of KSNPP, Korea Next Generation Reactor (KNGR), an evolutionary 1300MWe PWR, is being developed to deliver a safer, more economical and more environmentally friendly energy source for the early 21st century. 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.

The objective of the KALIMER Program is to develop an inherently and ultimately safe, environmentally friendly, proliferation-resistant and economically viable fast reactor concept. The KALIMER core is initially designed with 20% enriched uranium metallic fuels, which generates a net negative reactivity with an inherent safety characteristics. KALIMER also has 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. The reactivity control and shutdown systems result in extremely high shutdown reliability. High seismic margins are achieved by a simple horizontal seismic isolation system. Recycling of transuranic elements by the pyroprocessing process would avoid the expense and potential long-term risk of their disposal in a geological repository, and would provide increased proliferation resistance.

2. KALIMER Development Schedule

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 various innovative design features. Based on the insight and results from the previous work, the KALIMER program plan was updated to call for the completion of the basic design and supporting R&D work by 2006. The program is to be carried out in three distinctive phases as follows :

- Phase 1(July 1997–March 2000): Conceptual design and design&analysis methods development
- Phase 2 (April 2000 – March 2002) : Optimized conceptual design and key feature evaluation
- Phase 3(April 2002-March 2006) : Basic design and validation of the design and methods

In Phase 1, an effort is being made to establish a self-consistent conceptual design of system configuration, arrangement and key features satisfying design requirements. In parallel, computer codes and methods for engineering design and analyses are being developed or updated all along. An investment is also being made on the key design features testing, such as electromagnetic pump and self-actuated shutdown system. Effort continues to be made on the development of sodium technologies, such as measurement or detection technique as well as the investigation on thermal-hydraulic and chemical behavior.

Phase 2 is a two-year program to evaluate alternative design features to optimize the reference design formulated in Phase 1 in terms of plant performance, safety and economics. A comprehensive set of computer codes and design methodologies should be developed in Phase 2.

Phase 3 covers a five-year period from 2002 to 2006. The focus of the KALIMER basic design is to produce the specific information required in the preliminary safety analysis report(PSAR) and preliminary cost estimate. Engineering and design tasks to be included are system performance analysis under normal, transient, and faulted conditions, specifications of major component and equipments, safety margin analysis, and probabilistic safety assessment(PSA), among others. Supporting R&D will be carried out to validate design codes and methods along with the performance testing of the major components or equipments.

3. 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.

Table 1. KALIMER Key Design Parameters

OVERALL		**PHTS**	
Net plant Power, MWe	150	Reactor Core I/O Temp., °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., °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 Equilibrium Core, %	14.4 / 20.0		
		Steam System	
Assembly Pitch, mm	161.2	Steam Flow Rate, kg/s	175.5
Fuel/Blanket Pins per Assembly	271 / 127	Steam Temperature., °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. Table 2 shows major nuclear design parameters for an equilibrium core with a cycle length of 12 months.

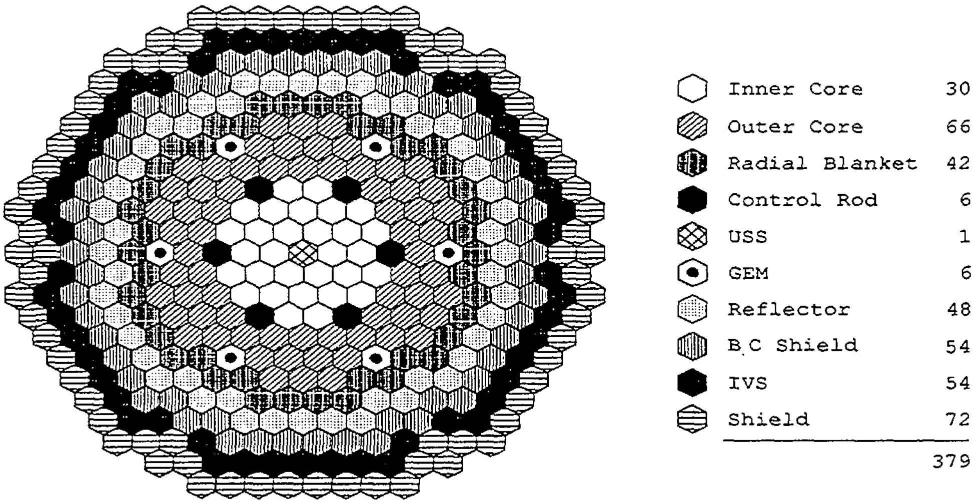

Fig 1. KALIMER Core Layout

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 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.

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.

Table 2. Major Nuclear Design Parameters for an Equilibrium Core

Average Breeding Ratio	0.669
Burnup Reactivity Swing (delta k/k_{boc})	1.150
Average Fuel Burnup (MWD/kg)	
Driver Fuel(Inner/Outer)	25.35/22.82
Radial Blanket	2.31
Peak Fuel Discharge Burnup (MWD/kg)	
Driver Fuel(Inner/Outer)	39.67/42.67
Radial Blanket	6.27
Feed Enrichment (Inner/Outer) (%)	14.41/20.00
Fissile Inventory at BOC (kg/cycle)	1715.15
Total Fissile Gain (kg/cycle)	-63.99
Average Power Density (W/cc)	160.2
For Driver Fuel at BOC	
Peak Linear Power (W/cm)	208.5
Power Peaking Factor for Driver Fuel(BOC/EOC)	1.603/1.569
Peak Neutron Flux (x 10^{15} n/cm^2 s)	2.304
Peak Fast Fluence, MOEX (x 10^{23} n/cm^2)	1.399

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.

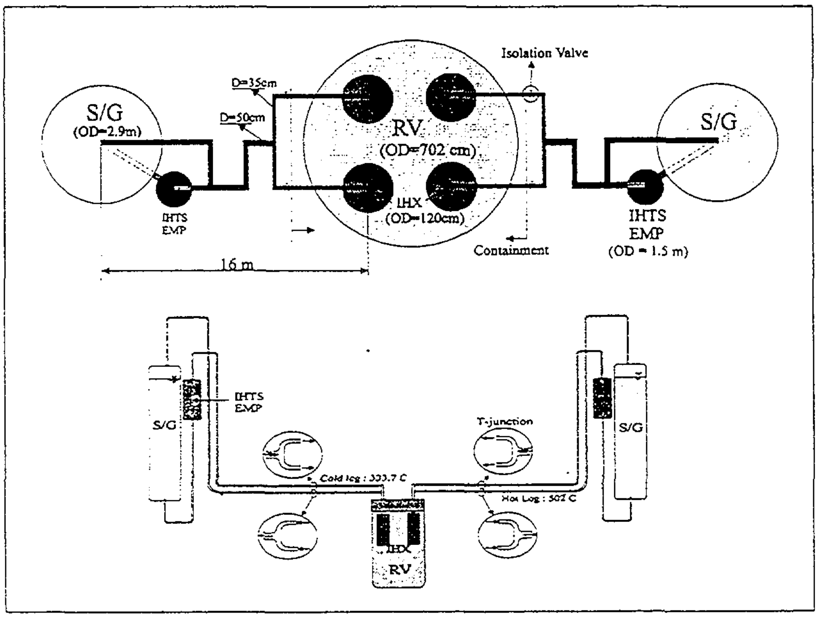

Fig 2. General Arrangements of NSSS

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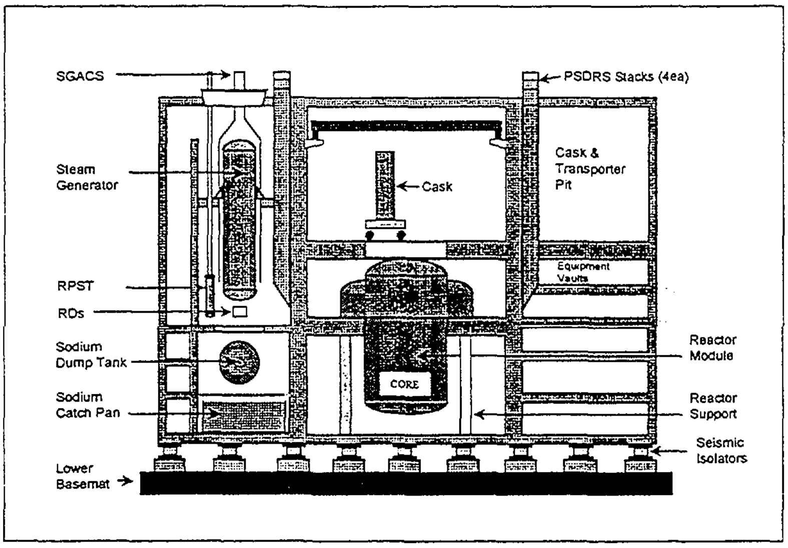

Fig 3. General Arrangement of Reactor Building

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 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.

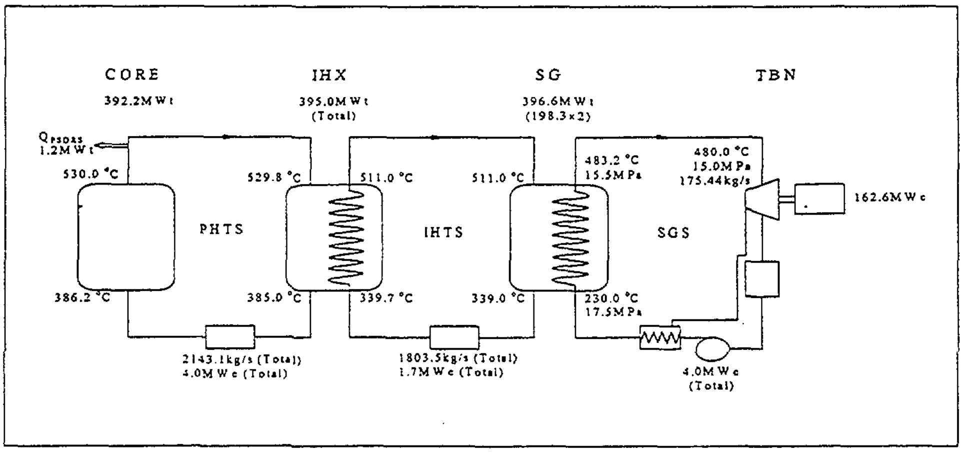

Fig 4. KALIMER Plant Heat Balance

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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 parameter changes is under progress for system level design optimization.

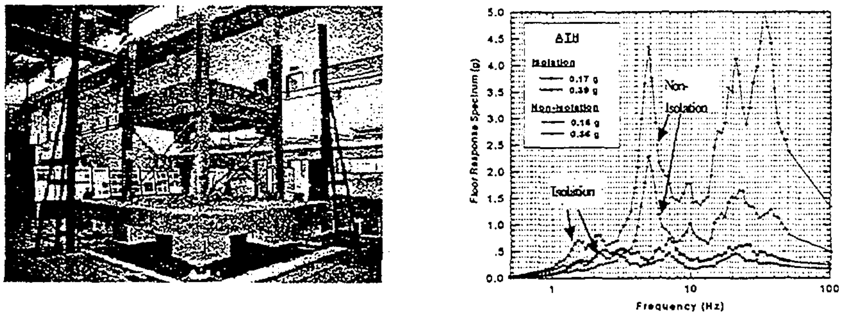
4. R&D Program Status and Plan

Core Design & Safety Analysis
The K-CORE system, an integrated system of KALIMER physics calculation modules, has been under development to provide major data links among the principal core design modules. The present works in progress include the developments of cross-section generation methodologies, a perturbation theory module and a reactivity feedback modeling in the kinetics module for coupled transient calculations. The benchmark experiment for uranium metallic fueled core having similar KALIMER core characteristics were performed jointly with Russia in 1997 and an extensive analysis on the experimental data is now being carried out to produce backup data for the verification and validation of the K-CORE system. Some of modelings employed in flow grouping and core temperature distribution modules have been improved, and core thermal-hydraulic subchannel analysis code is being developed

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. A simple model for the scoping analysis of HCDA energetics is also being developed for the analysis of ultimate safety.

Fluid System Design and Analysis
Various computer codes have been under development for thermal hydraulic design of the KALIMER system. The code development has been so far focused on the support of the initial stage of the system design. The codes for equipment sizing, HSGSA, 2DHX, and ASTEEPL, and the code for preliminary system analysis, LSYS and PARS have been developed. An analysis code system is also being setup for detailed three dimensional analysis of the thermal hydraulic behaviour of the reactor pool using the codes CFX-4 and COMMIX-1AR/P which are supplied by foreign organizations. The code system development efforts are now being shifted to verification of the developed codes and setting of the additional code systems for the support of the main phase work of the conceptual system design. For the verification, experimental data are planned to be generated within the KALIMER development program but international cooperation for the code verification data is also sought. The additional code systems for the development are for the analyses of steam generator stability, plant operation and performance, and free surface behaviour of the pool sodium.

Structural Analysis & Component Development
Structural R&Ds for KALIMER are mainly seismic base isolation and high temperature structural design technology. 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-5 shows test model structure and seismic response results at upper slab of the test model to artificial time history input of SSE 0.3g. Development and tests of 3D isolators to identify the performance by using shear compression tests and shaker tests are in progress. Methodology development for high temperature structures such as thermal striping and ratcheting is focused to evaluate thermomechanical fatigue, creep, and crack damages. 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 is developed using the theory of magneto-hydraulics and the equivalent circuit analysis. Its prototype was manufactured and its operation tests were performed. SASS and IVTM were developed and their mock-ups are manufactured and their theoretical validation tests were performed.



Test Model

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

Fig 5. KALIMER Seismic Isolation Test Program

Sodium Technology

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. The effect of the magnetic field on pressure drop is currently being investigated. Sodium experiments continue to be performed to develop the technologies to measure such parameters as differential pressure, local flow rate, and void fraction.

R&D work on sodium - water reaction has been carried out in the areas such as small water leak experiments for the determination of a design base leak rate, safety evaluation of the heat transport system in case of large leaks, development of reliable and real time detection system of water leaks using the acoustic signal as well as hydrogen detection. Additionally, sodium fire characteristics and phenomena are investigated with about 50m^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.

5. International Cooperation

KAERI has been in international collaboration with a number of organizations having LMR experiences, such as General Electric(GE) in US, AEA Technology in UK, IPPE in Russia, among others. Briefly described in the following are some of the recent international cooperation works.

As part of the partnership agreement between GE and KAERI(1995-1997), a number of KAERI staff had been assigned to GE to work together for the evaluation of design concepts of KALIMER over the two years in 1995 and 1996. GE also evaluated design options of the KALIMER in-vessel transfer machine(IVTM) and supported KAERI on the baseline schedule of the KALIMER program in 1997.

More recently, AEA Technology and KAERI put in place the 'Agreement relating to Joint R&D for the KALIMER Project' early this year and ,as a first-year cooperation part of it, collaborated on the computer progams for the KALIMER core design and safety analysis and discussed various topics to collaborate in the following years.

KAERI has been collaborating with IPPE in Russia since 1995 in carrying out critical experiments with uranium metallic fuels at the BFS facility, to secure core physics experiment data representing KALIMER core concept so as to verify and validate, to greatest extent possible, the design concepts as well as core physics design methodologies. Early this year, both organizations reached an agreement on collaborating in data acquisition, computer code development and validation for sodium-water reaction.

KAERI has been participating in multinational cooperation programs; OECD/NEA program for the measurement of effective delayed neutron fraction at the FCA in Japan, OECD Halden Reactor Project in Norway, and the IWGLMFR sponsored by IAEA.

The KALIMER development program requires that the conceptual design of KALIMER be done by March 2000. KAERI plans to collaborate with one of the major organizations having LMR experiences and expertise for engineering reviews and consultations on the evolving details of the conceptual design of KALIMER ,and for the support on developing and validating the design methods, computer codes and database, as well.

6. Conclusion

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 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. We realize that it is quite a task to achieve the requirements all by ourselves, with a limited program budget and LMR experiences. We believe, however, that we can make it through international cooperation with the countries having LMR experiences and their moral support on the program.