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Preliminary Design Study of the KALIMER Containment Dome

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Abstract

KALIMER (Korea Advanced LIquid MEtal Reactor) is a pool type advanced liquid metal reactor which is being developed in KAERI (Korea Atomic Energy Research Institute). Advanced design features are incorporated into the conceptual design for the enhancement of its safety. The reactor core, which produces 392MWt, is loaded with a metallic fuel for the inherent negative reactivity feedback, and the residual heat is removed by the passive safety grade decay heat removal system (PSDRS). Due to the high degree of passive and inherent safety characteristics, the severe accident, such as hypothetical core disruptive accident (HCDA) and associated large release frequency is significantly low. However, in the aspect of defense-in-depth philosophy, the containment design is being studied to mitigate the consequence of radioactive material release by a HCDA. This paper summarizes the on-going study on the conceptual design of KALIMER containment dome.

I. Introduction

For the future reactor development program of Korea, KAERI is developing an advanced pool-type liquid metal reactor (Fig. 1), KALIMER[1]. Advanced design concepts are implemented in KALIMER for the enhancement of its safety. The reactor core, which produces 392MWt, is loaded with metallic fuel for the inherent negative reactivity feedback. The reactor can be shutdown safely in any condition by Self-Actuated Shutdown System (SASS) and Gas Expansion Module (GEM). After reactor shutdown, the passive safety decay heat removal system can remove core residual heat.

Due to the high degree inherent and passive safety features, KALIMER is expected to have very low severe accident (HCDA) occurrence frequency. However in order to satisfy the safety philosophy of nuclear power plant, defense-in-depth, and to overcome the uncertainties of newly incorporated systems and concepts, the containment design is being developed to mitigate the consequence of radioactive material release by a HCDA.

The containment concepts, design basis accidents, reactor source terms, and containment performance analysis methodologies of some LMRs have been investigated to determine the reference design and analysis methodology of KALIMER containment.

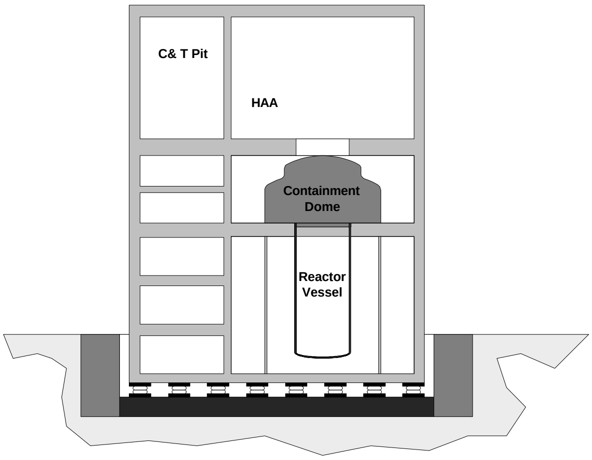

Fig. 1 Basic Diagram of KALIMER

In this paper, the containment design option available for KALIMER is proposed and analyzed through the sensitivity studies in the aspect of containment performance and radiological consequence.

II. Review of Existing LMR Containment Design

To propose the containment design for KALIMER, the containment design of existing LMRs have been reviewed. There are mainly four types of containment design used in existing LMRs[2].

Single containment is the simplest design, which has only one containment dome on the reactor vessel head. In double containment design, the inner barrier contains

Table 1 . Types of Containment Systems used in Current LMR[2]

Containment Type	Description	Reactors
Single containment	Open head compartment and low-leakage outer containment building	FFTF, EBR-II, JOYO, PRISM
Double containment	Sealed, inert high pressure inner containment barrier, surrounded by a low-leakage outer containment building	FERMI, SEFOR
Containment/Confinement	Sealed, low-leakage inner containment barrier, surrounded by a ventilated low pressure outer confinement building with discharge to stack via an air cleaning system	PFR, CRBRP, SUPER PHENIX, BN-350, BN-600
Multiple containment with pumpback	Sealed high pressure inner containment barrier, surrounded by one or more outer barriers, A negative pressure zone is maintained in the outer most space by pumping back leakage to the inner containment space. Eventual venting to a stack via the air cleaning system is provided.	SNR-300

inert gas such as He, to eliminate the probability of sodium fire during the vessel head breach accident. In containment/confinement system, the space between inner containment and outer containment systems has the ventilation system by which the air is filtered before being discharged to outer containment. As shown in Table 1, the containment/confinement system is the most preferable design out of four types. Another design is multiple containment system with pumpback. This design is similar to double containment, but the barrier may be more than two, and the outermost space is maintained at sub-atmospheric pressure by pumping back leakage to the inner-most containment space. Air cleaning system similar to that of containment/confinement system is also provided.

III. Preliminary Performance Analysis of KALIMER Containment

III.1 Containment Design

From the review of current LMR containment designs, the preliminary containment dome design concept of KALIMER has been determined to be the single containment dome due to the significantly low frequency of HCDA and sufficient margin to accommodate the consequence of HCDA within the reactor vessel without breaching the reactor closure[3].

The containment system consists of two sections. One is containment vessel around the reactor vessel, with agron-filled annular space, which can accommodate the spilled sodium from reactor vessel without core and associated systems uncovery if there the reactor vessel break occurs. The other is containment dome located on the reactor vessel head. The design pressure of the containment dome is 134.4kPa (25psig) at 645K (371°C). The leakage rate is 1% of the containment volume per day at design condition. Since the reactor vessel is designed such that the vessel can maintain its integrity under HCDA, the reactor closure is the potential structure which can yield to mechanical work produced by HCDA. Thus the role of containment dome becomes important and Table 2 shows the preliminary design parameters for the dome.

III.2 Accident Scenario and Source Terms for Analysis

The design basis accident for containment performance analysis is sodium pool fire under HCDA condition.

A relatively large breach in the reactor closure has been created by a HCDA. Then, 100% of the noble gases (Xe, Kr), 0.1% of the halogens (Br, I), 0.1% of the alkali metals (Cs, Rb), 0.1% of Te and Ru, and 0.01% of other fission products (Sr, Ba) and fuel are instantly released to the containment volume.

In addition, it is assumed that the breach in the reactor closure is large enough to allow the He cover gas to escape into the containment dome. And air is assumed to enter the reactor cover gas region, initiating a sodium pool fire, which continues until all the oxygen in the containment dome is consumed.

Burning of primary sodium within the reactor

Table 2 Prelimianry KALIMER Containment Design

Design Parameter		Description
Shape		Cylindrical + Torispherical
Type		Single containment
Material		Carbon steel (SA516 Grade 70)
Design pressure/temperature		134.4kPa/645K
Volume		1111.4 m^3
Design leakage rate		1%(vol.)/day at design condition
Upper Dome	Height	3.67m
	Diameter	7.32m
	Thickness	3.81cm
Lower Dome	Height	3.67m
	Diameter	14.63m
	Thickness	2.54cm

vessel results in release of radioactive isotopes that are carried with the sodium combustion products, such as sodium aerosols and hot air, into the containment dome atmosphere. It has been conservatively assumed that the complete core melts, and all the fission products are uniformly distributed in the primary sodium before burning initiates. From the assumption, additional release of radioactive material can be estimated as 0.8% of halogens, 1.6% of the alkali metals, 0.004% of Te and Ru, 0.0016% of Sr and Ba, and 0.0008% of the fuel. In addition, 0.4% of the radioactive sodium isotopes, Na-22 and Na-24, contained in the primary sodium inventory, are assumed to be released into the containment dome atmosphere. The accident source terms are summarized in Table 3.

Table 3 Source Term used for Design-Basis Analysis

Item	Magnitude	
	Early phase (0~10sec)	**Sodium fire phase (10sec~6hr)**
Material released to containment through reactor closure		
Noble gas (Xe, Kr)	100%	0%
Halogens (Br, I)	0.1%	0.8%
Alkali metals (Cs, Rb)	0.1%	1.6%
Te, Ru	0.1%	0.004%
Sr, Ba	0.01%	0.0016%
Fuel & other fission products	0.01%	0.0008%
Na22, Na24	None	0.4%

III.3 Containment Performance Analysis for KALIMER

With containment dome design, accident scenario, source terms described above, the base case for the sensitivity study has been determined. The analysis condition of base case is listed in Table 4.

The containment thermal-hydraulic conditions, aerosol behavior and containment leak rate have been calculated with CONTAIN-LMR code[4], which is the LMR version of containment analysis code that can cope with severe accident condition. The exposure dose rate at the plant site boundary has been estimated with MACCS code[5], which is environmental consequence calculation code.

The nodalization of KALIMER containment dome for CONTAIN-LMR analysis is shown in Fig. 2. The containment dome is a right-circular cylinder, divided into cells to allow establishment of convective air currents within the structure. A hot sodium is assumed to be in direct contact with the air in the containment atmosphere. A leak path is provided between the containment and the environment to allow release of material present in the containment atmosphere. The containment structure is assumed to be a 2.54cm thick steel shell, and the floor outside of the sodium pool was assumed to be concrete about 1m thick. Heat transfer between the containment atmosphere and these structures is considered. The environment outside of the containment dome is assumed to be at a nominal temperature of 311K(38°C). And heat is assumed to be passively removed from the containment dome by natural convection of air.

From the base case, the sensitivity studies on the volume of containment dome have been performed. The containment dome size was changed from 80% to 120% of base case. Case 1 is the 80%, while case 2 is 120% of base case. The calculational results of CONTAIN-LMR and MACCS are as follows.

Containment Performance

Fig. 3 shows the pressure within the containment calculated by CONTAIN-LMR following the initiation of the sodium pool fire and introduction of the radioactive materials from the primary coolant. The peak of pressure is between 11 and 13psig depending upon the volume of containment. The pressure decreases to atmospheric pressure between 380 and 520 minutes following the

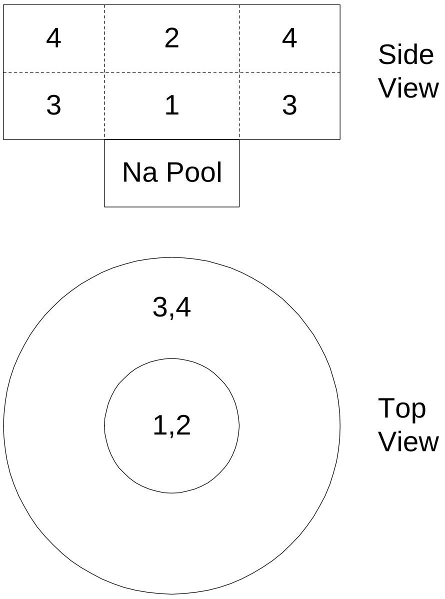

Fig. 2 Containment Dome Nodalization for CONTAIN-LMR

Table 4 Design Parameters of Base Case

Design Parameter	Value
Dome volume	1111.4m^3
Dome internal diameter	14.63m
Dome atmosphere initial temperature	38°C(311K)
Dome atmosphere initial pressure	1atm
Sodium pool diameter	6.92m
Sodium pool temperature	485°C(758K)
Dome leak area	0.003cm^2(0.0005in^2)

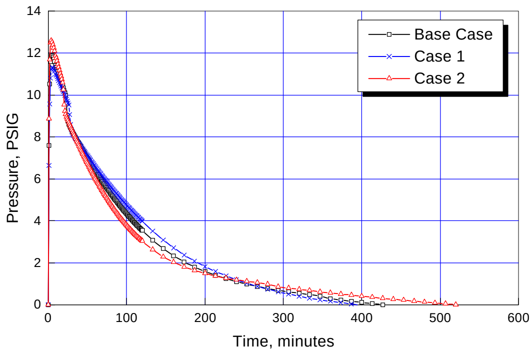

Fig. 5 Containment Pressure

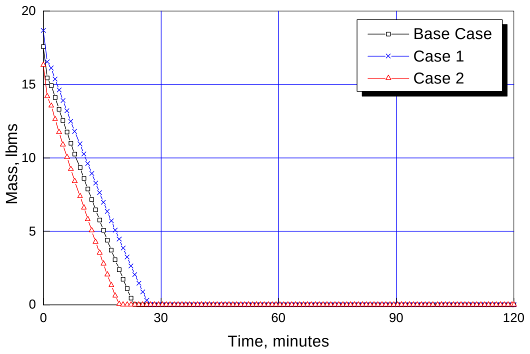

Fig. 4 Cell Water Vapor Mass

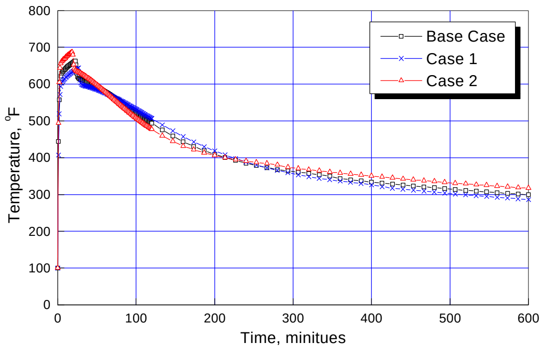

Fig. 3 Cell 1 Temperature

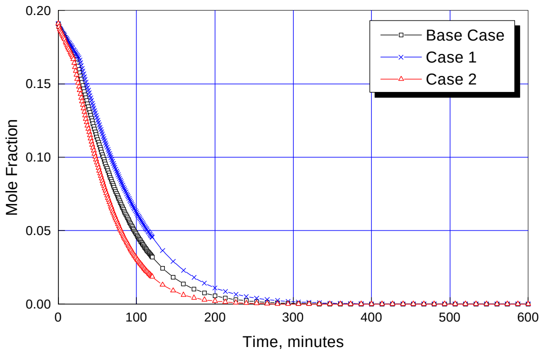

Fig. 6 Oxygen Mole Fraction

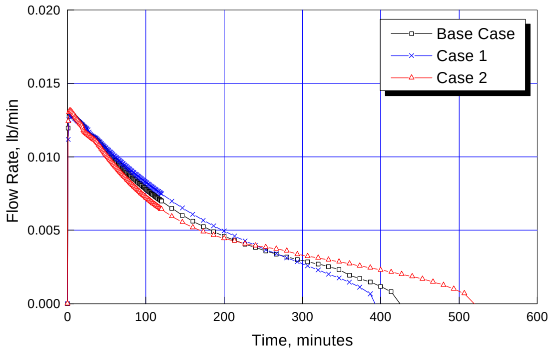

Fig. 7 Leak Flow to the Environment

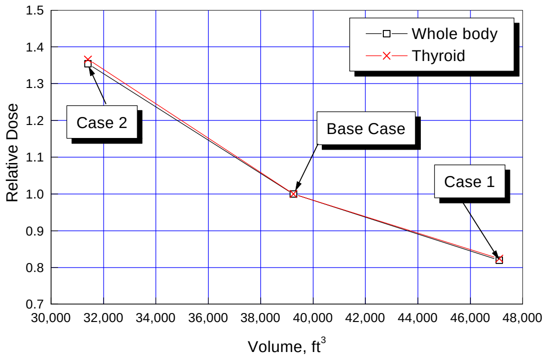

Fig. 8 Relative Dose Rate

pressure peak. The peak pressure is proportional to the containment dome volume, and the time for the peak is delayed as the containment volume increases. The perturbation shown in pressure curve is caused by termination of the reaction between water vapor (100% humidity assumed) to be present in the containment atmosphere and sodium oxide produced by the pool fire. This termination (Fig. 4) eliminates one of the energy generation sources to the containment atmosphere, causing the effects seen in the containment pressure and temperature calculations.

The containment atmosphere temperature (Cell 1) shows similar trends. Cell 1 is immediately adjacent to the sodium pool and located where the fission products are introduced.

Fig. 6 shows the containment oxygen mole fractions, which continually decreases due to the sodium pool fire. The containment oxygen is consumed about 220~320minutes into the transient depending upon the containment volume. Depletion of the oxygen within the containment also contributes to the decreasing trend in the containment pressure.

The peak pressure and temperature of containment dome is well below the design limits for all cases.

The leakage flow from the containment to the environment is shown in Fig. 7. As expected, the leak flow follows the trend similar to that of the containment pressure.

Consequence Evaluation

From the CONTAIN-LMR analysis results, the amount of each radionuclide leaked to environment can be obtained. After processing the raw data into the form suitable to MACCS code, the exposure dose rate outside containment can be calculated.

Fig. 8 shows the relative dose for whole body and thyroid as the containment dome volume changes. It is apparent that as containment volume increases, the exposure dose rate decreases. The relative dose decreases rapidly as the volume increase from case 2 to base case, while the decreasing rate is relatively insensitive to the volume when the volume increases from base case to case 1. From this, it can be thought that the base case is rather optimal in the aspect of containment dome volume.

IV. Conclusions and Recommendations

In this study, the preliminary design study on the KALIMER containment dome has been performed.

For the determination of preliminary design concept, the containment types of existing LMR have been reviewed. and, preliminary parametric study on the containment dome volume has been performed, which leads to the conclusions;

1. Preliminary KALIMER containment dome design can be chosen to be the single containment system considering the following. First, the HCDA occurrence frequency is significantly low due to the inherent and passive safety features incorporated in KALIMER. Next, KALIMER containment vessel has sufficient margin to accommodate work energy resulting from HCDA within it without reactor closure breach. Finally, even if the HCDA take place, the containment thermal-hydraulic condition is well below the design limits.
2. The preliminary sensitivity studies with containment dome volume as a sensitivity parameter have shown that the containment dome volume is somewhat insensitive to main design requirement such as containment pressure within the analysis range.
3. The exposure dose rate at the site boundary is decreasing function of the containment volume. But the decreasing slope becomes smooth as the containment volume increases. That is, the containment volume of base case is somewhat optimized in the aspect of containment performance.

Based on the conclusions, some recommendations for future work can be derived.

To certain weather the selected sensitivity parameter is important in safety or containment performance, more sensitivity study on the selected parameter should be performed. And more design parameters should be considered in the design study, such as break area, leakage area, reactor source terms, accident and associated scenario, and passive heat removal capability in sensitivity study. Evaluation of the consequence from long term exposure dose rate also should be performed to identify the ultimate safety of containment design.

Acknowledgements

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