Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 17-18, 2018

Sensitivity Analysis of Heat Load on Passive Molten Core Cooling System in iPOWER

Do Hyun Hwang[a]*, Keun Sung Lee[a] , Chang Hwan Park[b]
[a]KHNP-CRI, 70, 1312 Gil, Yuseong-daero Yuseong-gu, Daejeon 34101, Korea
[b]FNC Technology Co., Ltd., Main Building, Institute of Future Energy Technology, 46, Tapsil-ro, Giheung-gu, Yongin-si, Gyeonggi-do, 17084, Korea
**Corresponding author: crihwang@khnp.co.k*

1. Introduction

In Korea, an innovatively safe nuclear power plant, which is named iPOWER, is being developed to significantly enhance the safety, taking advantage of passive safety systems which are designed to operate without external power supply. As one of the safety systems, Passive Molten Core Cooling System (PMCCS) is being developed to mitigate a severe accident, reach a safe state, and finally maintain the containment integrity [1].

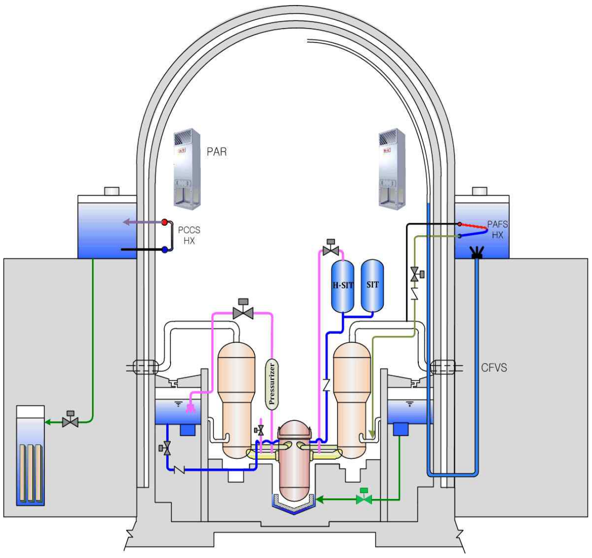

Fig.1. Conceptual Diagram for iPOWER

In this paper, sensitivity analysis of heat load on PMCCS located under Reactor Vessel (RV) is presented based on the results of reference plants, new safety system design and engineering judgment.

Table 1. Estimated properties for iPOWER and PMCCS

Property	Expected Value	Remark
Thermal Power	3,600 MW	Dependent on thermal efficiency of Passive Containment Cooling System in iPOWER
Electric Power	1,250 MW	Assumed thermal efficiency: 34.7%
Reactor Diameter	4.96 m	Estimated based on APR1400 and OPR1000
Cavity Diameter	6.6 m	RV support column to be removed
PMCCS Diameter	7.0 m	Hemisphere configuration assumed

2. of Passive Molten Core Cooling System for iPOWER

2.1 Evaluation Model

Evaluation model for the heat load on PMCCS with the configuration of hemisphere is determined as the VEssel Statistical Thermal Analysis (VESTA) code developed by Idaho National Engineering and Environmental Laboratory (INEEL) for the assessment of IVR in AP600 [2].

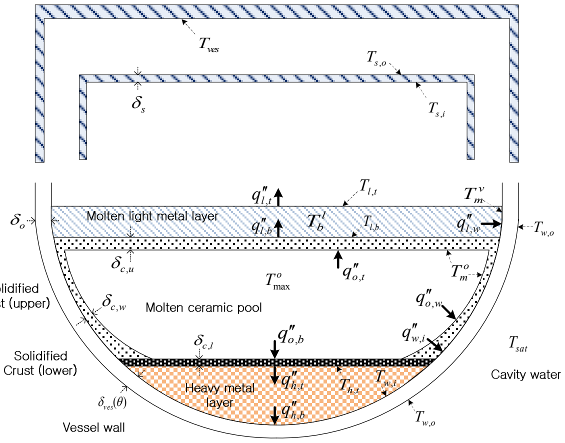

Fig.2. Heat load evaluation model developed by INEEL

2.2 Timing of Heat Load for PMCCS

The timing of heat load for PMCCS is defined as follows,

$$\mathrm{T_{ini} = T_{ref} + T_{SI} + T_{SM}}$$

Where, $\mathrm{T_{ini}}$: Time of heat load for PMCCS

$\mathrm{T_{ref}}$: Rector Vessel (RV)failure time in reference plants such as APR1400, APR+

$\mathrm{T_{SI}}$: Delayed time to RV failure by Passive Emergency Core Cooling System (PECCS) in iPOWER

$\mathrm{T_{SM}}$: Delayed time by the ablation of sacrificial materials in PMCCS

From the equation above, $\mathrm{T_{SM}}$ is not able to be estimated because sacrificial material is under development at the moment.

To obtain T_{ref}, the RV failure time of reference plants is reviewed based on results of severe accidents analysis with MAAP code for APR1400 and APR+. The minimum time of RV failure is 1.75 hour (6,365 sec) in case of LBLOCA for APR1400 and 3.5 hours in case of LOCV for APR+ respectively.

Table 2. RV failure results due to LBLOCA in APR1400

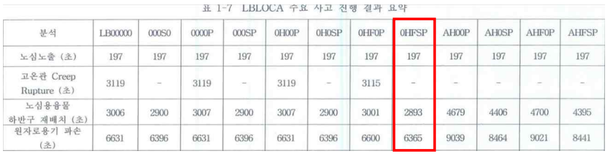

표 1-7 LBLOCA 주요 사고 진행 결과 요약

분석	LB00000	000S0	0000P	000SP	0H00P	0H0SP	0HF0P	0HFSP	AH00P	AH0SP	AHF0P	AHFSP
노심노출 (초)	197	197	197	197	197	197	197	197	197	197	197	197
고온관 Creep Rupture (초)	3119	-	3119	-	3119	-	3115	-	-	-	-	-
노심용융물 하반구 재배치 (초)	3006	2900	3007	2900	3007	2900	3001	2893	4679	4406	4700	4395
원자로용기 파손 (초)	6631	6396	6631	6396	6631	6396	6600	6365	9039	8464	9021	8441

Table 3. RV failure results in APR+

사고경위		원자로정지, hr	원자로용기 파손, hr	원자로정지후 RV 파손까지 경과시간,hr
TLOCCW003		0.001	11.008	11.007
SLOCA	**15**	0.154	15.213	15.059
SBO	**6**	0	19.072	19.072
LOOP	**6**	0	19.358	19.358
SGTR	**10**	0.303	35.794	35.491
LOOP	**11**	0	12.327	12.327
SLOCA 016	기본	0.154	4.441	4.287
	A	0.154	6.833	6.679
LOOP 012	기본	0	5.566	5.566
	A	0	6.887	6.887
LSSB-D 015	기본	0.107	4.863	4.756
	A	0.107	15.814	15.707
GTRN 018	기본	0	4.34	4.34
	A	0	8.236	8.236
MLOCA	**3**	0.003	7.015	7.012
LOFW 012	기본	0	3.711	3.711
	A	0	4.412	4.412
MLOCA	**4**	0.003	5.586	5.583
SGTR	**24**	0.303	6.125	5.822
PLOCCW014		0.001	39.864	39.863
SBO	**14**	0	13.474	13.474
LSSB-D 038	기본	0.107	5.128	5.021
	A	0.107	15.311	15.204
LLOCA	**5**	0.001	4.63	4.629
SBO 024	기본	0	5.566	5.566
	A	0	6.887	6.887
SGTR 032	기본	0.303	5.716	5.413
	A	0.303	9.444	9.141
LOFW	**11**	0.01	7.346	7.336
LOCV 034	기본	0.01	3.511	**3.501**
	A	0.01	3.877	3.867

For the evaluation of heat load of PMCCS, each mass of UO_2 and Zr is extrapolated based on the properties for APR1400 in consideration of thermal power difference.

Table 4. Corium mass for iPOWER

Property	APR1400	iPOWER
Thermal Power (MW_t)	3,983	3,600
UO_2 Mass (kg)	117,800	106,473
Zr Mass (kg)	29,511	26,673

Other properties are assumed based on engineering judgment as the mass of metallic corium is assumed about 30% of UO_2 mass, Zr oxidation rate is assumed 50%, and Emissivity is 0.430.

iPOWER adopted Passive Emergency Core Cooling System (PECCS) as safety injection system. PECCS consists of the three systems that are designed to be injected at high pressure, middle pressure and low pressure respectively as shown in Fig. 3.

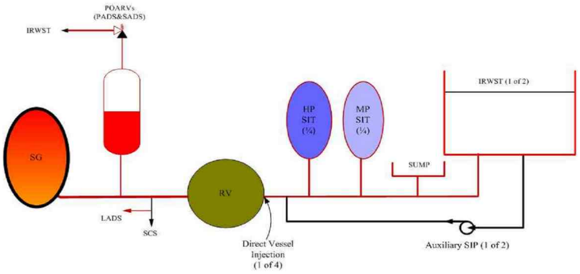

Fig.3. Conceptual diagram of PECCS

3. Results of Sensitivity Analysis

The sensitivity analysis on the heat load of PMCCS with hemisphere shape is performed for several cases.

As shown in three figures below, the ratio of heat flux to Critical Heat Flux (Y-axis) is evaluated based on the angle of lower head of Reactor Vessel (X-axis) with hemisphere shape as 0 degree is at the bottom of Reactor Vessel (RV) and 90 degree is at the location where the lower head of RV meets its cylindrical body.

The results show that heat load abruptly increases around the angle of 50 degree where metallic corium with so-called focusing effect of heat flux is located as it is assumed in 2-layer configuration that metallic corium layer is located above oxide corium pool because of density difference.

First, the ratio of heat flux to CHF is evaluated with several CHF correlations derived from the experiments for IVR. As shown in Fig. 4, the heat flux has a big deviation according to the selected CHF correlation. According to Yang correlation, the ratio of heat flux to CHF decreases (CHF increases) as an insulator is installed or the outside surface of RV is coated.

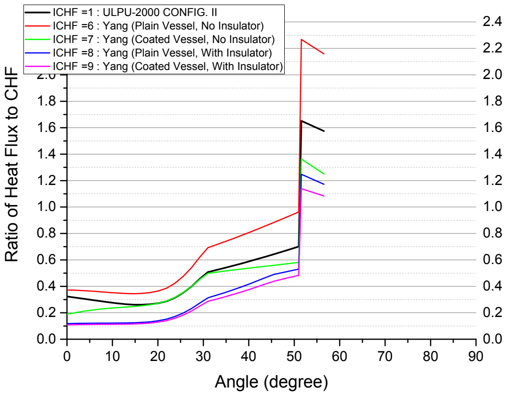

Fig.4. Heat flux to CHF correlations

Fig. 5 shows the ratio of heat flux to CHF according to RV failure time as the CHF correlation of ULPU-2000 configuration II is applied. The result shows that heat flux decreases by about 40% in case of 10 hours compared with 1.75 hour in RV failure time.

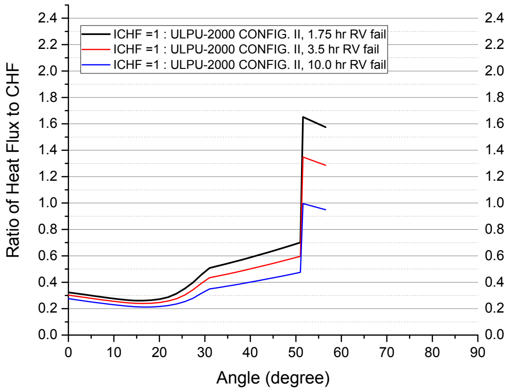

Fig.4. Heat flux according to RV failure times

Fig. 6 shows the ratio of heat flux to CHF according to the variation in amount of metallic and oxide corium as one case has two time's metallic corium and the other case has three time's oxide corium. The result shows the heat flux is more sensitive in metallic corium rather than oxide corium.

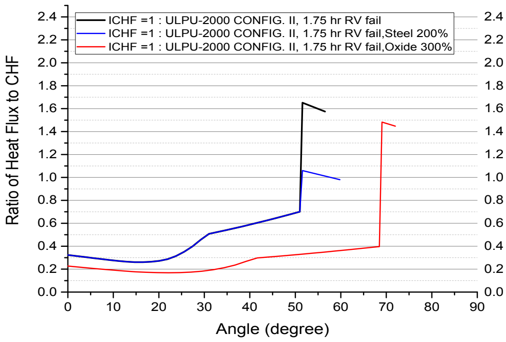

Fig.6. Heat flux according to amount of metal and oxide corium

4. Conclusions

In this paper, the sensitivity analysis on the heat load of PMCCS with hemisphere shape has been performed for several cases such as CHF correlation, RV failure time, and the amount of metallic and oxide corium.

In conclusion, key parameters for the heat flux of PMCCS are RV failure time and the amount of metallic corium. In order to reduce heat flux on PMCCS, it is crucial to delay the RV failure time and to increase the thickness of metallic layer.

It is expected to obtain more realistic results in the future as the designs of iPOWER and PMCCS make progress.

Acknowledgement

This paper was supported by the Development of Conceptual design for Passive Cooling System in Reactor Containment Building of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korean Ministry of Trade, Industry and Energy.

REFERENCES

[1] D. H. Hwang et al., “Conceptual Design of Passive Molten Core Cooling System for iPOWER”, KNS Spring Meeting, Jeju, Korea, May, 2017.
[2] J. L. Rempe et al., “Potential for In-Vessel Retention through Ex-vessel Flooding”, Proceeding of the OECD/CSNI Workshop on In-Vessel Core Debris Retention and Coolability, Garching, Germany, March, 1998.