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Technical Evaluation of Corium Cooling at the Reactor Cavity

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ABSTRACT

To terminate the progression of the severe accident and mitigate the accident consequences, corium cooling has been suggested as one of most important design features considered in the severe accident mitigation. Till now, some kinds of cooling methodologies have been identified and, specially, the corium cooling at the reactor cavity has been considered as one of the most promising cooling methodologies. Moreover, several design requirements related to the corium cooling at the reactor cavity have been also suggested and applied to the design of the next generation reactor. In this study, technical descriptions are briefly described for the important issues related to the corium cooling at the reactor cavity, i.e. cavity area, cavity flooding system, etc., and simple evaluations for those items have been performed considering present technical levels including the experiment and analytical works.

1. Introduction

In the case of the severe accident, the molten core can directly threaten the integrity of the reactor vessel and induce the failure of the reactor vessel without suitable cooling means to the molten core. If the failure of reactor vessel is occurred at the high pressure condition of reactor coolant system (RCS), the corium can move to and heat up the containment atmosphere and contact with the containment inner wall inducing the phenomena called direct containment heating (DCH). In contrary, under the depressurized condition of RCS, molten core ejected from the failure location of the reactor vessel and relocated at the reactor cavity can induce the variable kinds of phenomena, which threaten the containment integrity, if the corium cannot be maintained as coolable condition. To remove this kind of threaten elements to the integrity of the reactor vessel and containment, it is necessary to provide the cooling methodologies to the molten corium. One of these cooling methodologies is corium cooling at the reactor cavity through the flooding cavity with water.

Relating to this cooling methodology, several design requirements have been suggested in Electric Power Research Institute Utility Requirement Document (EPRI URD) [1], European Utility Requirement (EUR) [2] and Korea Electric Power Research Institute (KEPRI) [3]. Specially, for the evolutionary nuclear power plant, important items can be summarized as following:

- Provision of cavity area to enhance the spreading of the corium;
- Provision of cavity flooding system;
- Inventory of water in containment, ...

In this paper, state of the art related to above raised issues for the corium cooling at the reactor cavity are briefly described and simple evaluation for those items have been performed considering present technical levels including the experiment and analytical works.

2. Technical Evaluation

2.1 Features for the retention of core debris

In the case of the reactor vessel failure under high RCS pressure condition, molten core ejected from the failure position can induce the containment atmosphere heating and DCH. To possibly reduce those phenomena, nuclear regulatory commission (NRC) and EPRI have suggested the features for the retention of the core debris. Specially, EPRI have conducted detail study for the limitation of the corium amounts, which are moved to containment atmosphere, using the modification of the cavity design and suggested that the capture volume of the reactor cavity effectively decrease the amounts of the corium moved to containment atmosphere.

- Through industry degraded core rulemaking (IDCOR) program, EPRI assessed the ejection characteristics on the various cavities categorizing the cavities of current operating nuclear power plants (NPPs) into 14 cavity types [4]. According to the assessment, the cavity type of the Millstone NPP is the effective type in the point of the ejection amount of core material. Moreover, EPRI suggested the installation of the capture volume at the reactor cavity to maximize the capture effect for the molten core.
- Small scale experiments (1/30 scale of the UCN 3&4 and YGN 3&4) related to the capture volume have been accomplished to identify the effect of the capture volume [5]. According to experimental results, the capture volume is helpful to decrease the moving corium amounts to containment atmosphere and decrease the pressure and temperature of containment atmosphere. In addition, application of the cavity volume, which are larger than 5 times of corium volume, sufficiently is possibly to decrease the pressure and temperature of the containment.

2.2 Reactor cavity flooding system

Without the adequate cooling of the corium relocated at the reactor cavity, the corium continuously erodes the cavity floor and directly threatens the containment boundary. In addition, the non-condensable gases, the steam and aerosol resulted from corium-concrete interaction (CCI) can pressurize and threaten the containment. Therefore, it is important to provide cooling methodology for the corium relocated at the reactor cavity. Cavity flooding system is consist of water injection system, water source for cavity flooding and water flow path. Generally, in-containment refueling water storage tank (IRWST) and passive system are suggested as the water source for cavity flooding and passive methodology. It is also suggested that, considering the possibility of the damage and plugging for water flow path, the cavity flooding system should be designed to operate under severe accident condition.

Coolant inventory

Necessary water inventory for the flooding of the reactor cavity is only suggested in the EPRI URD. In EPRI URD, considering the decay heat, 100 % zirconium reaction and water to quench and cover the core debris with an overlying pool of water about 3 ft (0.91 m) deep, delivery of approximately 60,000 gallons (227.1 m^3) of water in first hour is estimated to be sufficient volume for initial flooding. However, it is difficult to evaluate whether or not suggested inventory is sufficient to cool the corium. Therefore, using simple calculations, the effectiveness of suggested water inventory is assessed.

- Considering the requirement of cavity floor area suggested by EPRI, the necessary cavity area for KNGR is calculated to be 76 m^2 (3800 $MW_{th} \times 0.02\ m^2/MW_{th}$). The coolant inventory to cover this area with an overlying pool of water with 1.5 m is calculated to be about 114 m^3.
- To calculate the water inventory to cool the decay heat, it is necessary to identify the total decay from the corium. For the simple calculation, it is assumed that the level of decay heat is maintained

at 1% for 1 hr. Based on this assumption, the water inventory is calculated to be about 60.58 m^3 considering total heat generated from the corium, 1.38×10^8 kJ/kg. In this calculation, the heat is only removed by the vaporization of the water.

- To calculate the water inventory to cool the total heat generated from zirconium, the heat from the reaction and zirconium amounts are identified. Steam-zirconium reaction is exothermic reaction and emits about 6430 kJ/kg. Using the core parameters of System 80+, the amounts of zirconium is calculated to be 24817 kg [6]. Therefore, total energy to be removed is about 1.59×10^8 kJ/kg and necessary water inventory is calculated to be about 70.6 m^3.

Using above calculation results, the necessary water inventory for 1 hr is calculated to be 244.6 m^3, which are slightly larger than that suggested by EPRI. However, considering some assumptions, i.e. 1% of decay heat and 1% maintenance for 1 hr, 1.5 m cavity flooding level and cooling by only the vaporization of the water, the water inventory suggested by EPRI is seemed to be reasonable. In addition, covering core debris with an overlying pool of water about 1.5 m deep is seemed to be good measure in the point of the scrubbing of the corium [4]. According to the EPRI work related to the decontamination, the water height from the upper part of the corium is suggested as very important parameter (the decontamination coefficient considerably increase between 1 m and 2 m water height).

Coolant injection timing

In KNGR, pre-flooding strategy using active and passive systems is accepted as the accident management strategy for corium cooling at the reactor cavity during the severe accident. However, it is difficult to suggest the flooding timing for cavity flooding due to the insufficient information. According to the general accident management guidance, cavity flooding will be started when the core is start to be melted or core is melting. The instruments for identifying the situations are also suggested in the guidance.

- Core exit thermocouple (CET): Generally, it is suggested that cavity flooding will be started when the CET is larger than 650°C. The CET measurement capability installed in YGN 3&4 is up to 1260°C, therefore, the CET can provide useful information for flooding timing.
- Reactor vessel level monitoring system (RVLMS): It is suggested that if the indication (there is no water above the plate of fuel alignment) is happened, the cavity flooding will be started. However, RVLMS has considerable uncertainty measuring the water level.
- Self powered neutron detector (SPND)

2.3 Cavity floor area

In addition to cavity flooding system, cavity floor area is suggested as one of important items due to its relation to corium spreading. Considering the 1 % decay power level, maximum heat flux removed from the debris bed, 1MW/m^2, and design factor of 2 for conservatism, the cavity floor area, 0.02 m^2/MWth, is suggested for the cooling of the corium at the cavity in EPRI URD. In this part, the effectiveness of the level of decay heat and maximum heat flux, which are important parameters to calculate the cavity floor area, are briefly investigated. Specially, as the maximum heat flux is very important item to calculate the cavity floor area and to determine the cooling possibility of the molten corium, the details related to the maximum heat flux are described.

Cavity floor area

- Level of decay heat: To calculate the decay heat removed from the debris bed, it is important to identify the relocation time of the corium at the reactor cavity. However, it is very difficult to get information related to relocation time. Generally, it is possible for the use of the severe accident analysis code, i.e. MAAP or MELCOR, to calculate the relocation time. Next table shows the relocation time of the corium at the lower head of reactor vessel and reactor cavity for the YGN 3&4 NPP [7]. According to the analysis results, the relocation of corium at the reactor cavity may be happened at about 2.73 hr after the initiation of the accident in the case of LBLOCA. Therefore, the level of decay heat at about 1 hr used in EPRI URD seems to be conservative.

Accident Name	Descriptions	Actual Vessel Failure Time (s)
LB LOCA	Cold leg break, Break Size = 0.16 m^2	9,827 (2.73 hr)
SB LOCA 1	Intermediate leg break, Break Size = 0.00218 m^2	23,626 (6.56 hr)
TMLB	Power, Main feed water and Aux. Feed water fail	13,613 (3.78 hr)

- Maximum heat flux: 1MW/m^2 of the maximum heat flux, which can be removed from the debris bed, is used in EPRI URD. The value is less than the critical heat flux at infinite upward-facing plate under saturation water condition, nearly 1.3MW/m^2, and similar to dryout heat flux of debris bed which consists of uniform diameter of 2 or 3 mm. However, according to related experimental results, this level of heat flux cannot be maintained through the overall accident situations and debris bed is not consist of uniform particle diameter, but consisted of distributed particle diameters. Therefore, additional works should be prepared for the detail evaluation.

	Initial time	Mediate time	Final time
MACE experiment Performed at Aug. 1989	2.4~3.5 MW/m^2	0.6 MW/m^2	150 kW/m^2
MACE experiment Performed at 1991	1 MW/m^2	-	30~60 kW/m^2
SWISS experiment	0.8 MW/m^2	0.8 MW/m^2	0.8 MW/m^2

Debris bed coolability

The possibility of the corium cooling is dependent on severe accident progression situation, the relocation time of the corium and corium mass relocated at the reactor cavity, size distribution of particles in core debris and accumulation type of the corium at the cavity. Moreover, it is affected by the noncondensable gases and aerosol resulted from the CCI, it is very difficult to suggest the quantitative evaluation methodology for the possibility of the corium cooling.

In OECD, based on the available literatures related to the corium cooling, critical pool depth (CPD) is suggested for the quantitative evaluation and is described as following equation [8]:

$$Critical\ Pool\ Depth = \sqrt{(T_{dc} - T_{dw})\frac{k}{2q}}$$

Here, CPD is the maximum depth of the solidified debris layer for which all internally generated can be transported to the debris-water interface by the conduction. In addition, T_{dc} and T_{dw} represent the temperatures of the concrete decomposition (~1600K) and interaction point between upper debris and overlying water (~400K), respectively. Using the properties of totally oxidized core debris (k = 3W/mK, q = 0.8 MW/m^3), the CPD is calculated to about 10 cm. This value is similar to that predicted by the CORCON code.

To predict maximum heat flux, which can be removed from the debris bed, several experimental works have been performed. In addition, based on the experimental results, dryout heat flux correlations have been suggested and details are shown in Ref. [9]. The suggested correlations have been developed only for the debris, which have uniform particle diameter, however, according to TMI-2 vessel investigation program, the debris bed has distribution like next table. As shown in table, the ratio of particle diameter between 2 and 3 mm is about 30 % and that of particle diameter less than 2 mm is about 70 %. Therefore, to evaluate the core debris coolability with dryout heat flux correlation, further studies will be performed, especially on the effect of particle distribution on dryout heat flux.

Diameter range (μm)	Mass fraction	Accumulated ratio
0.28 – 52.0	0.0254	0.0254
52.0 – 294	0.0916	0.1170
294 – 1665	0.394	0.5100
1665 – 2354	0.145	0.6560
2354 – 3321	0.148	0.8040
3321 – 4676	0.126	0.9300
4676 – 6600	0.070	1.0000

2.4 Interaction of the corium and cavity floor area

Corium-concrete interaction can threaten the containment integrity through next phenomena: 1) containment overpressurization due to the noncondensable gases and aerosol resulted from the CCI, 2) containment basemat melt-through due to the noncoolable corium.

In the viewpoint of containment overpressurization, the usage the material which generates small amounts of noncondensable gases, i.e. CO, CO_2, etc., as basemat material seems to be promising strategy Therefore, the basaltic concrete has been suggested, but the erosion rate for the basaltic concrete is much higher than that for the limestone concrete. Special attention should be paid to this point. Recently, to avoid the CCI, core catcher concepts have been provided and some of them are shown in next table.

Type of core catcher	Name of core catcher	Research institute
No Flooding & Vertical Type	Multi-Crucibles Core Catcher	CEA
No Flooding & Horizontal Type	Flat Core Catcher with Enhanced Radiative Heat Transfer Multi-Layer Core Catcher COMSORS	CEA ENEL ORNL
Flooding & Horizontal Type	COMET Staggered-Pans Core Catcher SCORE3	KfK KfK ENEL

The erosion rate is also important for the maintaining of the integrity of the containment basemat. Therefore, considerable works have been conducted to resolve this issue, specially related to boiling water reactor (BWR). In NUREG-1079 [10], the liner erosion rates have been calculated based on the convection of the molten corium considering the basaltic and limestone concrete. As shown in table, the erosion rate for the basaltic concrete is much higher than that for the limestone concrete, however, the failure of the liner is always occurred in the case of limestone concrete.

Run	Concrete	Corium temperature (K)	Core mass (%)	Erosion depth of the concrete (vertical, cm)	Eroded liner depth (cm)
1	Basaltic	1775	80	3.3	0.1 (no liner failure)
2	Limestone	1775	80	1.2	3.0
3	Basaltic	1900	80	7.4	0.3 (no liner failure)
4	Limestone	1900	80	1.5	3.0
5	Basaltic	2550	80	4.0	3.0
6	Limestone	2550	80	1.6	3.0
7	Basaltic	2550	80	3.6	3.0
8	Limestone	2550	80	1.6	3.0

3. Summary

In this study, investigation of recent status and technical evaluation on corium cooling at the reactor cavity have been performed, especially on the cavity floor area, cavity flooding system and CCI etc. Identified important items are as follows:

- The capture volume installed at the reactor seems to be effective measure to decrease the corium amounts, which move to the containment atmosphere.
- Necessary water inventory for flooding suggested in EPRI URD seems to be reasonable according to the present evaluation. In addition, the water height, which is considered in the water inventory, is effective in the viewpoint of the corium scrubbing. However, there is no clear criterion for the coolant injection timing, therefore, further investigation related to the injection timing should be performed.
- It is very difficult to judge the cavity floor area for the corium spreading and debris coolability. However, decay heat level seems to be conservative considering the relocation time predicted by severe accident analysis code. On the other hand, there are considerable uncertainties related to the maximum heat flux removed from the debris bed. Therefore, to evaluate the adequacy of the cavity floor area, more researches should be accomplished.
- To decrease the noncondensible gases resulted from the CCI, the usage of basaltic concrete as basemat material can be suggested. However, the erosion rate of basaltic concrete is much higher than that of limestone concrete. Therefore, in a cautious manner, the selection of the basemat material should be established.

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Reference

1. *Advanced Light Water Reactor Utility Requirement Document*, Vol. 2, Chapter 5 & 6, Electric Power Research Institute, Revision 7, 1995.
2. *European Utility Requirement for LWR Nuclear Power Plants*, Vol. 1& 2, Revision, 1994.
3. KRC-92N-J11, *Research & Development on Next Generation Reactor (Phase I): Development of Evaluation Technology for Severe Accident*, KEPRI, 1994.
4. *Severe Accident Management Guidance Technical Basis Report*, Vol. 1 & 2, EPRI/TR-101869, 1992.
5. *2nd Nuclear Safety Information Conference*, KINS, 1996.
6. *System 80+: Standard Design CESSAR Design Certification*, Combustion Engineering.
7. C.H. Roh et al., *Identification of Reactor Vessel Failures Using Spatiotemporal Neural Networks*, IEEE Nuclear Science, Vol. 43(6), pp. 3223-3229, 1996.
8. N. Yamano et al., *Technical Note on Ex-Vessel Core Melt Debris Coolability and Steam Explosions*, NEA/SEN/SIN(96)4, OECD/NEA, 1996.
9. Y.H. Jeong et al, *Assessment of DHF Correlations for Particle Beds*, KNS Spring Meeting, Kwang-ju, pp. 362-367, 1997.
10. Draft Report NUREG-1079, *Estimates of Early Containment Loads from Core Melt Accidents*, NRC Containment Loads Working Group, 1985.