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Discussion on the In-Vessel Retention Feasibility with respect to Reactor Internal Design in a Large Evolutionary Advanced Light Water Reactor

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Abstract

Feasibility of In-vessel retention (IVR) of molten core through external reactor vessel cooling (ERVC) of a two-loop 1300 MWe evolutionary advanced light water reactor (ALWR) design is discussed with respect to focusing effect due to thin metallic debris layer in the reactor vessel lower plenum. Core melt progression of 1300 MWe ALWR suggests that parameters such as shutdown time and steel mass molten from the reactor internal structures are crucial for the feasibility of IVR in this type of reactors. In this paper, with the objective of giving insights on the feasibility of IVR for the Korea Next Generation Reactor (KNGR) design, the steel mass required to demonstrate, using ROAAM (Risk-Oriented Accident Analysis Methodology) approach, that reactor vessel thermal failure is "physically unreasonable" for the typical two-loop 1300 MWe ALWR is calculated using appropriate lower plenum debris heat transfer model.

1. Introduction

Since the TMI-2 incident, there have been extensive studies to support severe accident management and mitigation. One of the severe accident mitigation concepts is the In-Vessel Retention (IVR) of corium through external reactor vessel cooling (ERVC). This concept involves flooding the reactor cavity to submerge the reactor vessel and cool the core debris within the lower plenum. IVR is being considered as an effective severe accident management strategy for advanced and existing light water reactors, and has been successfully implemented in AP600 and Loviisa (VVER-440) power plant designs. [1]

One of necessary conditions of IVR is that the heat flux from the molten debris relocated to RPV lower plenum should be less than the critical heat flux on the outer surface of reactor pressure vessel (RPV) lower head in order to prevent vessel thermal failure. Recent RASPLAV experiment [2] shows a stratification of the core melt into two layers: a heavy, mainly oxidic, pool, and lighter, mainly metallic, layer. The separation seems attributed to density effects and this stratification, even though the reason is not well understood, tends to simplify the problem of the molten debris behavior in the lower plenum. Each layer would have its own melting temperature considered as a boundary temperature for thermal-hydraulic calculations.

The heat flux from the molten metal layer floating above the oxidic pool is a concern since in this layer heat transferred from the oxide pool could be focused (and peaked) into RPV wall when the depth of the layer is very thin (called "*focusing effect*"). Key parameters with respect to the focusing effect are core thermal power which determines decay power, and the amount of molten steel heat sink generated by the melting of reactor internal structures.

The focusing effect is one of important issues for AP600-like reactor [1,3]. For the higher-powered (1300 MWe) ALWR designs, this effect becomes even more important due to high power density and can be an issue both during the formation of the corium pool and final quasi-steady state.

In the process of Risk Oriented Accident Analysis Methodology (ROAAM), based on the appropriate severe accident management window identified by a consistent integration of stochastic and deterministic elements, a screening frequency is employed to discard remote and speculative sequences. And for those that cannot be so discarded, a bounding (*scenario independent*) physics-based approach is used to render the failure in question “physically unreasonable”. [1]

To apply the ROAAM to the focusing effect, one needs to show that there is enough metal layer for all the plausible core melt scenarios. One approach to simplify the problem is to place enough steel mass in the lower plenum. In this paper, steel mass required in the reactor vessel lower plenum needed to prevent the focusing effect is calculated for the typical 1300 MWe ALWR design.

2. Structural Mass Needed to Prevent Focusing Effect

2.1 Scenario Aspects of Core Melt Progression

Under severe accident condition when core is melting and relocating to lower plenum, the amount of oxide melt and metallic layer in the lower plenum increases as accident progresses. As discussed in the previous section, the important parameters determining focusing effect is the decay power (shutdown time) and steel mass involved in the lower plenum molten debris. The accident progression described in terms of decay power and reactor internals melting behavior depends on the type of accident (LOCA and Non-LOCA, Break Size, and Engineered Safety Features Status, etc.). In this section, we reviewed the plausible accident sequences based on the recent PSA (Probabilistic Safety Assessment) result of KNGR.

Among the PSA scenarios leading to core melt, we chose two different cases for further investigation. The first scenario, large loss of coolant accident (LOCA) with safety injection failure (break size is 0.5 ft^2), is chosen due to its rapid core melt progression though its contribution to core damage frequency (CDF) is very low. The second scenario, steam generator tube rupture (SGTR) accompanied by successive failures of aggressive secondary cooling (ASC) and safety injection (one tube), is chosen because of its high contribution to the CDF.

For the typical two-loop 1300 MWe ALWR design, we analyzed above two scenarios using MAAP4 computer code [4] but without considering external reactor vessel cooling. The core melt progression timing and condition of interest before vessel failure estimated are shown in Table 1.

Table 1. Core melt progression for a typical 1300 MWe Evolutionary ALWR

Variables	Large LOCA with Safety Injection Failure	SGTR with ASC* and Safety Injection Failures
Rapid Oxidation Time	1.9 hr	2.1 hr
First Relocation Time	2.6 hr	3.5 hr
Reactor Vessel Breach (VB) Time	4.1 hr	6.7 hr
Metallic Mass at VB	52 tons (72%**)	53 tons (71%)
Oxide Pool Mass at VB	92 tons (30%)	53 tons (52%)

* Aggressive Secondary Cooling

** fractional mass of the full core

Table 1 shows that large LOCA is rapidly progressing and only about 30% of core is molten and relocated to lower plenum before vessel breach (VB). On the other hand, progression of SGTR is slower and about 52% of core is molten and relocated to lower plenum before VB.

For a 1300 MWe ALWR, large LOCA with safety injection failure is most rapidly progressing and the first core melt relocation time estimated is 2.6 hr as shown in Table 1. However, considering that small amount of core melt would not challenge the integrity of reactor vessel due to cooling by residual water in the lower plenum, we chose 3 hour as a best bounding estimation of core melt relocation condition which gives a potential threat to reactor vessel.

2.2 Metal Mass Needed to Prevent Focusing Effect

In order to show that vessel failure is physically unreasonable based on ROAAM approach, focusing effect should be prevented from the rapidly progressing sequences with partial core melt relocation stage as stated in the previous section. In this section, the amount of metallic (steel) mass required to keep the focusing heat flux to RPV wall below CHF is evaluated. The amount of corium mass in the lower plenum is varied to bound all the expected intermediate states of core melt progression of 1300 MWe ALWR design.

The necessary condition is that the heat flux from the metallic layer should not exceed the critical heat flux on the outer surface of RPV lower head. This determines the necessary metal mass for a given oxidic mass. Once the oxidic melt pool touches the lower support structure, the focusing effect can be alleviated due to heat sink effect of steel structure. The steel mass satisfying these two conditions can be represented as oxidic (core) melt fraction relocated to lower plenum given shutdown time.

The simulation results using MAAP4 discussed in section 3.1 shows that 3 hour could be the reasonable bounding time of molten core relocation. The decay power at this time is about 27 MW and the intangible is the amount of core melt existing in the lower plenum. Thus regardless of how much molten core is in the RPV lower plenum, the decay power density could be assumed constant as 1.4 MW/M^3. This is obtained by dividing 27 MW with full oxidic core melt (UO_2 + ZrO_2) volume. Two thermal success criteria are considered: q''/q''_{CHF} =1.0 and q''/q''_{CHF} (to include uncertainty in CHF correlation)

Steel mass required is estimated using the analytical model of core debris and reactor vessel heat transfer in the RPV lower plenum used for AP600 [1]. The natural convection correlation for oxide pool used is from ACOPO test [5] and the critical heat flux correlation based on the ULPU-Configuration II [6] is also applied. There is some limitation in the ULPU-II correlation since it does not account for the effect of in-core instrument (ICI) nozzles which is present in the 1300 MWe ALWR. Also, there is an issue of two-dimensional (2-D) scale effect. However, it is reasonable in this study since the ICI nozzle would enhance the lower head cooling effect. The 2-D system of ULPU-II is known to be conservative compared to 3-D system because divergence effect is not reflected.

Other assumptions used are:

1) Decay power is calculated at the core melt relocation time which is fixed as 3 hr as stated above, and the contribution from non-volatile fission products is considered only.

2) Fraction of Zircaloy oxidation is constant as 75%.

3) Emissivity on the top of metallic layer is 0.4.

4) The height of lower support structure bottom necessary to be touched by core melt in the lower plenum is 1.6 m and the diameter of lower head hemisphere is 2.37 m.

5) The fraction of core melt considered ranges from 20% to full (100%) condition since smaller amount of melt can be cooled by the residual water in the lower plenum.

Figure 1 shows the resulting curves representing steel mass required to meet the heat flux required as a function of partial core melt fraction (solid and dashed lines). Also, we calculated additional mass necessary to reach the lower support structure (dotted line).

The smaller the core melt fraction is in the lower plenum, the smaller mass of steel is required for the heat flux from the metallic layer to be smaller than CHF. The solid and dashed lines in Fig. 1 show the cases that q''/q''_{CHF} =1.0 and q''/q''_{CHF} =0.8, respectively. The difference is about 10 tons of steel mass. The minimal mass of steel to compensate and displace the oxide pool volume to touch the lower plenum heat sink, lower support structure (LSS), is represented by the dotted line in Fig. 1.

When about 77% of oxide pool exists in the lower plenum, it nearly touches the LSS bottom, and the mass needed to displace the oxide pool increases as the melt fraction decreases. When the oxidic melt mass fraction is in the range of 77-55 %, and take the first condition with q''/q''_{CHF} =1.0, the required steel mass is at most 30 tons (the crossing point of solid and dotted lines). When the fraction is below 55%, the mass to meet the first condition is below 30 tons, and thus when this amount of steel is available to displace the oxide pool to touch the LSS, thermal failure due to focusing effect can be excluded. In case that q''/q''_{CHF} =0.8, about 40 tons of steel is necessary using the same procedure (dashed and dotted lines)

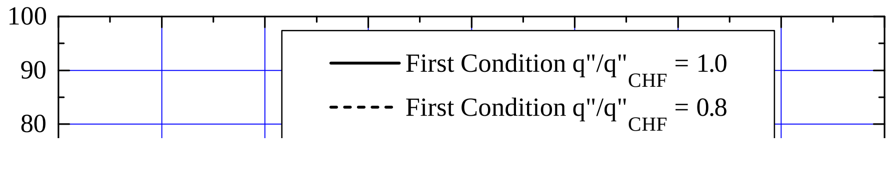


Fig. 1. Steel mass needed to prevent focusing effect as a function of core melt fraction in the lower plenum for 1300 MWe ALWR reactor internals design

3. Conclusion

Feasibility of In-Vessel Retention (IVR) for 1300 MWe Evolutionary ALWR with respect to metallic layer focusing effect is discussed with respect to scenario aspects, success criterion (thermal point of view) and crucial parameters such as shutdown time and reactor internal steel mass involved in the metallic layer.

As a part of ROAAM process, one of the issues is that adequate metal layer should be formed to avoid the focusing effect. In order to get an insight on the state where reactor vessel thermal failure is physically unreasonable through IVR for KNGR geometry, reactor vessel internal steel mass necessary to avoid the focusing effect in the bounding accident sequence is derived.

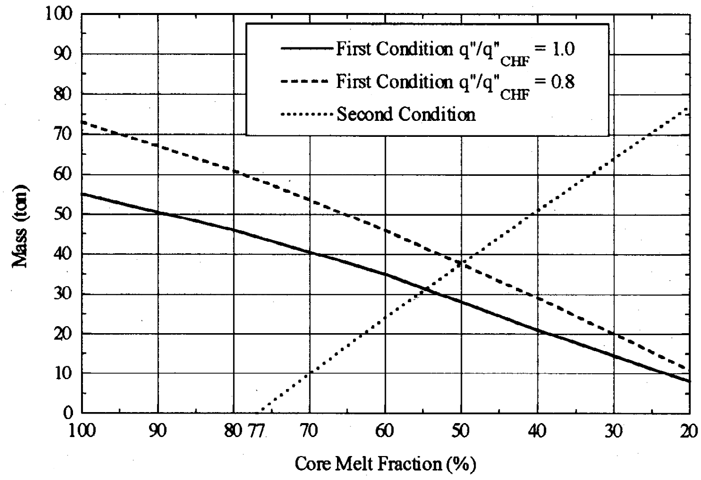
Two conditions that should be met are imposed based on the feature of core melt progression of 1300 MWe ALWR: (1) the heat flux from the metal layer shall be less than the external critical heat flux and (2) the partial core relocated to lower plenum shall reach the lower support structure to make use of heat sink effect.

It is estimated that about 30 to 40 tons of steel mass in the lower plenum would make thermal failure of reactor pressure vessel under external reactor vessel cooling condition physically unreasonable by IVR for the typical two-loop 1300 MWe ALWR design.

References

1. T.G. Theofanous et al., *In-Vessel Coolability and Retention of a Core Melt,* DOE/ID-10460, 1995.

2. Asmolov, et al., “Latest Findings of RASPLAV Project”, Workshop on In-Vessel Core Debris Retention and Coolability, Gaeshing, Germany, March 1998.
3. T.G. Theofanous et al, *Lower Head Integrity Under In-Vessel Steam Explosion Loads*, DOE/ID-10541, 1996.
4. R.E. Henry et al., *MAAP 4 - Modular Accident Analysis Program for LWR Power Plants*, Vol. 1-4, Fauske & Associates, Inc., 1994.
5. T.G. Theofanous et al., “In-Vessel Retention as a Severe Accident Management Strategy”, Workshop on In-Vessel Core Debris Retention and Coolability, Garching, Germany, March 1998.
6. T.G. Theofanous et al., “Critical Heat Flux through Curved, Downward Facing Thick Walls”, *Nuclear Engineering and Design*, Vol. 151, pp.247-258, 1994.



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