Proceedings of the Korean Nuclear Society Autumn Meeting
Taegu, Korea, October 1997

Advanced In-Vessel Retention Design for Next Generation Risk Management

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Abstract

In the TMI-2 accident, approximately twenty (20) tons of molten core material drained into the lower plenum. Early advanced light water reactor (LWR) designs assumed a lower head failure and incorporated various measures for ex-vessel accident mitigation. However, one of the major findings from the TMI-2 Vessel Investigation Project was that one part of the reactor lower head wall estimated to have attained a temperature of 1100° C for about 30 minutes has seemingly experienced a comparatively rapid cooldown with no major threat to the vessel integrity. In this regard, recent empirical and analytical studies have shifted interests to such in-vessel retention designs or strategies as reactor cavity flooding, in-vessel flooding and engineered gap cooling of the vessel. Accurate thermohydrodynamic and creep deformation modeling and rupture prediction are the key to the success in developing practically useful in-vessel accident/risk management strategies. As an advanced in-vessel design concept, this work presents the COrium Attack Syndrome Immunization Structures (COASIS) that are being developed as prospective in-vessel retention devices for a next-generation LWR in concert with existing ex-vessel management measures. Both the engineered gap structures in-vessel (COASISI) and ex-vessel (COASISO) are demonstrated to maintain effective heat transfer geometry during molten core debris attack when applied to the Korean Standard Nuclear Power Plant (KSNPP) reactor. The likelihood of lower head creep rupture during a severe accident is found to be significantly suppressed by the COASIS options.

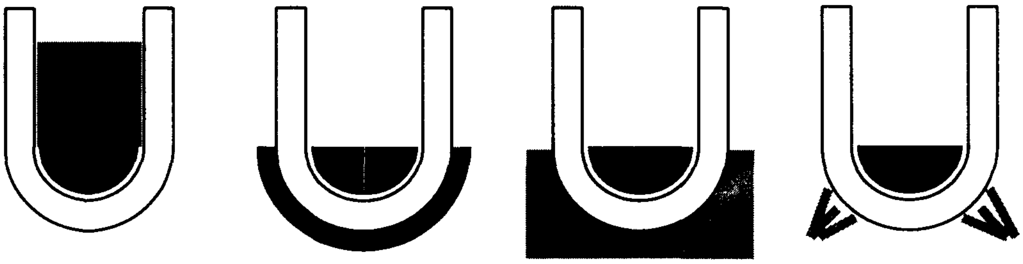
I. INTRODUCTION

Metallographic studies in the TMI-2 Vessel Investigation Project [1] determined that a significant part of the reactor vessel lower head was substantially overheated. Specifically, one part of the vessel wall is estimated to have reached a temperature of at least 1100 °C for about 30 minutes and then experienced a comparatively rapid cooldown. The cause and nature of this rapid cooling are of considerable importance since the TMI-2 vessel was at a pressure of 11 MPa during this time. With this internal pressure, the vessel wall would have undergone significant creep and perhaps eventual rupture, had it been sustained at 1100 °C for an extensive interval. Consequently, this rapid cooling of the vessel at some time after four hours into the accident may have been responsible for maintaining the vessel integrity. Major research programs [2,3,4] have recently been developed to investigate this inherent nature of degraded core coolability inside the lower head due to boiling in a narrow gap between the debris crust and the vessel wall [5,6,7] coupled with the primary system heatup and degradation models [8,9].

The TMI-2 findings [10,11] have led to a nuclear industry standard for advanced LWR development to add measures to mitigate the progression of severe accidents. The first kind of severe accident management strategy was developed in mid 1980's assuming the lower head failure focusing on the capture and cooling of the escaped core debris which otherwise would react with concrete floor to generate additional heat and pressure [12]. The reactor cavity flooding, but not wetting the lower head, has been introduced as a mitigative measure to core debris-concrete reaction.

This so-called ex-vessel management approach, however, has to cope with outstanding severe accident issues ranging from core debris induced steam explosion to containment direct heating.

In early 1990's, the lower head protection methods were sought aiming at the retention of core debris within the vessel. Varying methods of the proposed in-vessel retention design are portrayed in Figure 1. Several investigators have suggested that ex-vessel flooding combined with reactor depressurization is adequate to maintain the lower head integrity [13]. The in-vessel management approach is now seen as a key safety feature of recent advanced LWR designs, such as AP-600 [14].



(a) in-vessel flooding (b) engineered gap cooling (c) ex-vessel flooding (d) external spraying

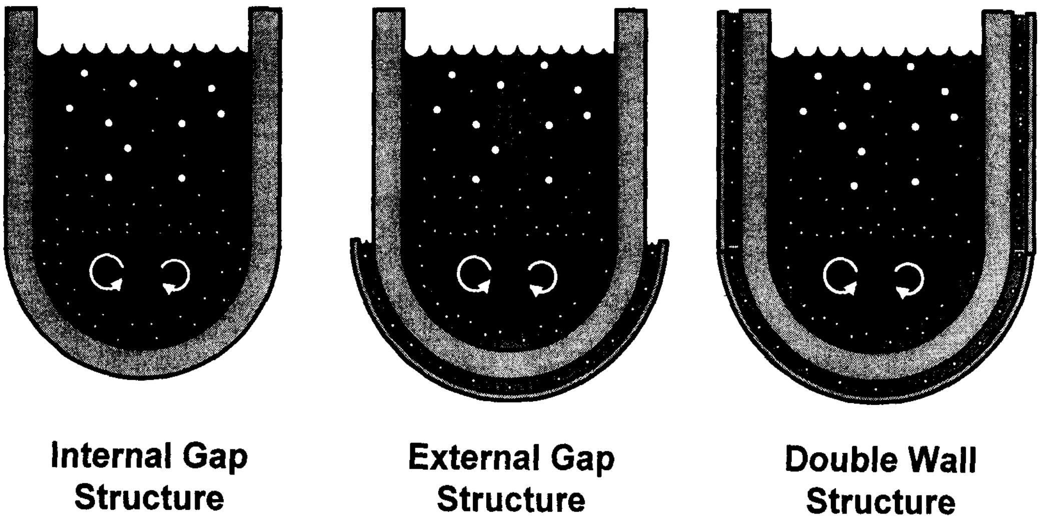
Figure 1. In-Vessel Retention Strategies for LWRs

The Korean Next Generation Reactor (KNGR) development has been undertaken with the initiative of the Korea Electric Power Corporation since early 1990's. The principal objective of the KNGR development is to significantly improve the safety and economy over those of current LWRs. Construction of the first KNGR is expected in early 2000's. In order to take advantage of existing foundation with the KSNPP technology, a reference design for the KNGR was designated to be System 80+ of ABB-CE [15] which had adopted the ex-vessel management approach. The reactor cavity flooding is deliberately limited to keep the outer wall of lower head dry for the sake of investment protection. Reactor cavity and containment structures are designed to withstand potential steam explosion in the flooded cavity in the event of core debris falling.

Although System 80+ design is the current baseline of severe accident management strategy for the KNGR, in-vessel management strategies are being pursued in parallel. Options for the latter avenue may include ex-vessel flooding to wetting and engineered gap cooling techniques, as will be described in this paper. Development of in-vessel management strategies presents nuclear materials challenges in that understanding of high temperature behavior of core debris, core structural materials and lower head has to be improved significantly, as illustrated in the Vessel Investigation Program (VIP) for TMI-2 accident by disagreement between creep analysis results [11]. The creep suppression options for the in-vessel management for KNGR and their effectiveness in the lower head protection are evaluated from the thermomechanical standpoint.

II. ENGINEERED GAP STRUCTURES FOR ADVANCED IN-VESSEL RETENTION

We have developed a range of creep suppression options for advanced in-vessel retention design. The bottomline idea centers about the structural designs that would help maintain coolable geometry even under massive core debris relocation to the lower plenum. The structures designated as COrium Attack Syndrome Immunization Structures (COASIS) are made of metallic hemispherical shells with joints that form gaps toward either the inner wall (COASISI) or the outer wall (COASISO) of the lower head or extended up to the beltline (COASISX), as sketched in Figure 2. Cooling water to the gap can be supplied from the safety injection lines or the water tanks in the containment for the COASISI, COASISO and COASISX engineered systems, respectively. The COASISO nozzle protection design is presented in Figure 3 against the possible thermal shock with ensuing quench crack that may be caused by the emergency coolant being injected into the gap during a severe accident as mitigative measures. This is perhaps the most salient feature of the COASISO design that distances itself from the ex-vessel flooding approach that may in cases run into severe vessel outer surface and nozzle weld damage by the quench crack during the submergence of the reactor. Heat transfer coefficients applicable in the accompanying thermal hydraulic boundary conditions analysis are collected in Figure 4 compared against the classical Rohsenow correlation [5,6,7] for nucleate boiling.



(a) COASISI (b) COASISO (c) COASISX

Figure 2. Engineered Gap Structures for High Temperature Creep Suppression of the Vessel

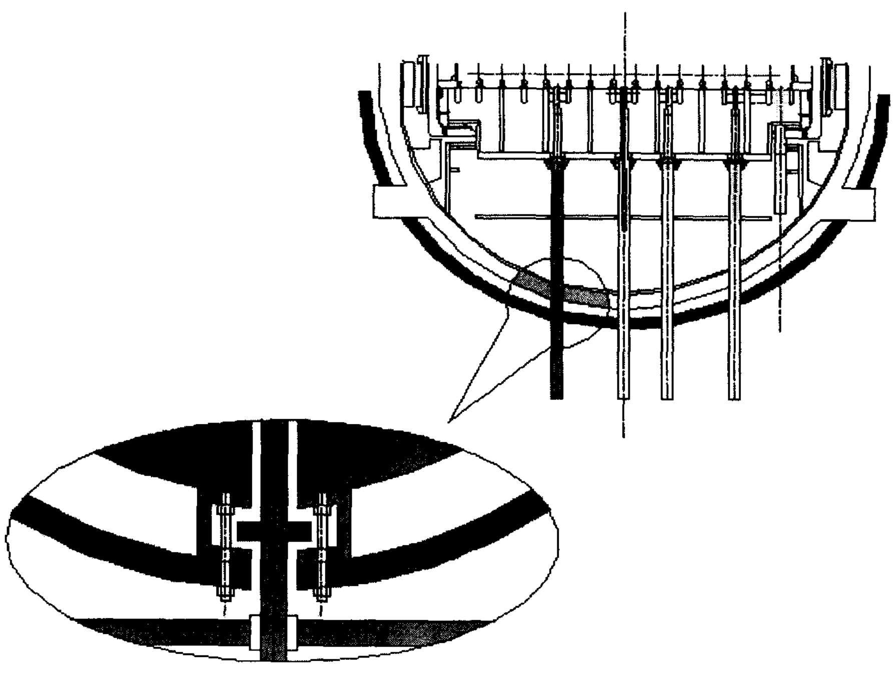


Figure 3. Nozzle Protection Against Thermal Shock by Incoming Emergency Coolant

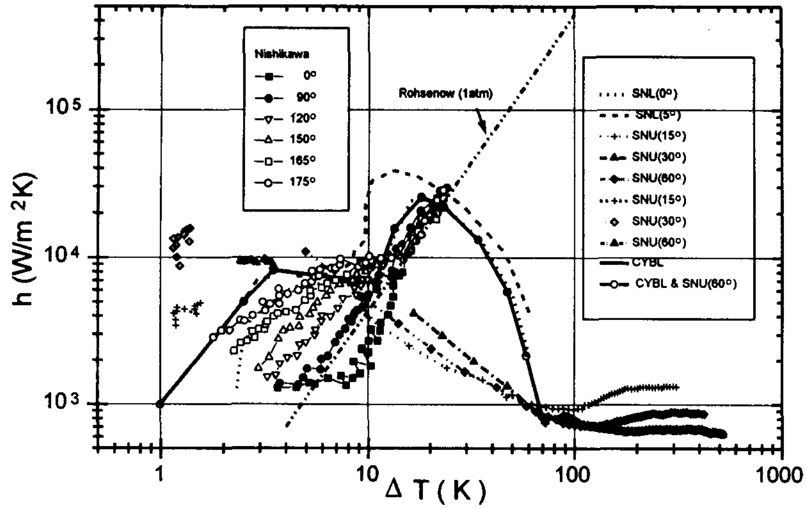


Figure 4. Comparison of Heat Transfer Coefficients for Vessel Cooling

III. REACTOR APPLICATION FOR SEVERE ACCIDENT MANAGEMENT

As described earlier the debris thermal and mechanical attack of the reactor pressure vessel is an urgent issue from the severe accident management point of view. The gap cooling strategies are being pioneered in Korea as part of the SONATA-IV program [4]. This paper concentrates on the COASISI and COASISO structures for practical applications.

The accident/risk management may now be pursued along the line of in-vessel melt retention in concert with existing ex-vessel management measures for the KNGR. The dual defense-in-depth strategy may be summarized as in Table 1.

Table 1. Dual Defense-in-Depth Accident/Risk Management Strategies for the KNGR

In-Vessel Management	Ex-Vessel Management
1) Hardware: **COASISI** Procedure: Partial Depressurization if Necessary DVI (HPSIT and SIT) 2) Hardware: **COASISO** Dedicated Water Supply Valve and Controller Procedure: Complementary and Prior to COASISI (minimize thermal shock) Water Injection to Bottom Sparging from Top Annulus Flow Rate Control	Hardware: IRWST Ex-Vessel Debris Catcher Capture Volume Hydrogen Igniters/Recombiners Containment Spray Containment Cooling Procedure: Similar to System 80+ SAMG

The benefit of having COASISI and/or COASISO is to be able to deal with the late phase of the melt progression in much more an efficient manner than with flooding the whole reactor cavity. Be aware that the ex-vessel flooding ought to be executed at the cost of time and water resources, and that with potential for jeopardizing the vessel integrity itself via thermal shock to the lower head penetrations with ensuing quench crack at the time of submergence. The influence of quenching may differ by medium, specimen size and geometry. In general, the more rapid the quench, the more severe the impact. Relatively large pieces that are rapidly quenched may crack as a result of internal stresses. This becomes a problem especially when the carbon content in the vessel steel exceeds 0.5 % by weight. For higher carbon-content steels, a water quench may be too severe because of resultant cracking and warping.

On the other hand, the COASISO design can ensure prompt delivery and highly effective utilization of the emergency cooling water for only the part of the vessel that needs to be cooled at the time of accident. Furthermore, should it turn out to be an inadvertent action to have initiated the COASISO injection system, the operator should easily be able to immediately drain the water from the gap thus protecting the reactor vessel investment. In contrast, it'll be impractical to drain the cavity once it has been flooded, and that by mistake not to mention the potential disaster of under-water steam explosion induced by the draining molten debris from the vessel rupture. Also, when considering ex-vessel flooding, an account must be taken of newly surfacing technical issues such as the reactor vessel insulator design and impacts of inadvertent flooding during otherwise normal operation on the reactor vessel material properties. The cavity flooding system (CFS) should also be designed with additional water source. If the CFS is placed external to the containment, its reliability should be ensured, else if incorporated into the containment, structural loads on the CFS should be evaluated.

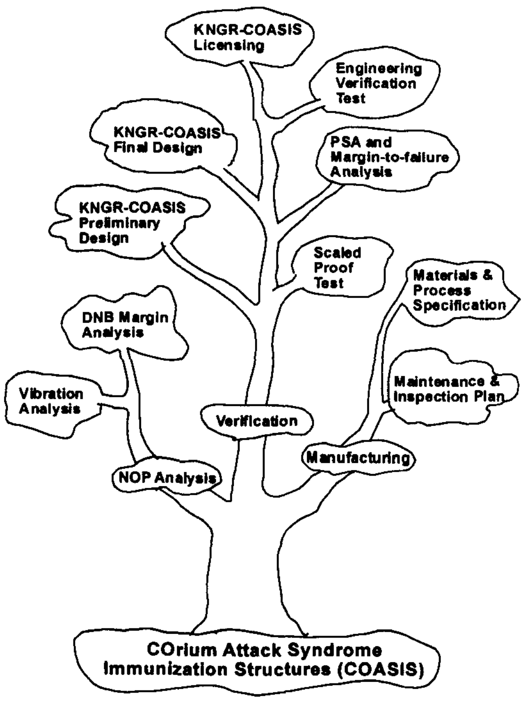


Figure 5. Roadmap to COASIS Licensing

The roadmap to design certification and licensing of the COASIS is shown in the tree of Figure 5. The process may be segmented into three principal routes involving a number of nuclear organizations with varying tasks. The first one id of course the design verification and validation through extensive and thorough testing and analysis in combination of probabilistic and deterministic approaches. The safety analyses and tests must also be accompanied by the normal operation, thermohydraulic design and mechanical component design analyses to secure proper margins during the plant lifetime. The manufacturing sector shall concentrate on maintenance and inspection plan and on materials and process specification. The specification shall not only consider the expected cost-benefit but also any undue risk to plant safety. To summarize, both design basis and severe accident evaluations ought to be performed in tandem when considering actual implementation of the COASIS structures for retaining the molten core debris within the reactor vessel during and after the accident

IV. CONCLUSIONS AND FUTURE WORK

Severe accident management strategies for advanced LWRs are being shifted from ex-vessel to in-vessel retention of molten core debris. Possible in-vessel management options have been explored for the KNGR with its baseline design of ex-vessel management strategy.

The COASIS structures have been developed as a potential in-vessel management option for the KNGR. Both the gap structures for in-vessel (COASISI) and ex-vessel (COASISO) were shown to maintain effective heat transfer geometry during core debris attack when applied to the KSNPP case studies. The likelihood of lower head creep rupture during a severe accident is found to be effectively suppressed. Further analysis for COASIS effectiveness in KNGR is in progress.

COASIS can thus protect the lower head without thermal shock and direct water resource to the hot spot with efficiency. Synergism of COASIS with existing ex-vessel management can be utilized to free KNGR from emergency evacuation requirement

ACKNOWLEDGMENT

The authors would like to express their sincerest gratitude to KEPRI and KAERI for their support during the course of this work.

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