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Overview of Ex-Vessel Cooling Strategies and Perspectives

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1. Introduction

The Nuclear Safety Act of Korea has been amended requiring the applicant or utility to submit the Accident Management Programs (AMPs) including the severe accidents as a licensing document [1]. The Korea Institute of Nuclear Safety (KINS) has been preparing the corresponding safety review guides in which the detailed acceptance criteria should be addressed [2].

Meanwhile, in the progress of a severe accident in nuclear power plants (NPPs), insufficient cooling of a damaged core could result in the failure of the reactor pressure vessel (RPV) followed by melt pouring and relocation to the reactor cavity area. If the ex-vessel cooling for the melt or debris fails in the reactor cavity, however, the core debris with decay heat generation might contact the concrete floor of the reactor cavity that could lead to a molten core-concrete interaction (MCCI) to challenge the containment integrity by basemat concrete erosion or massive generation of steam and non-condensable gases.

The authors have comprehensively reviewed not only the status of experimental and analytical research works completed worldwide so far regarding the ex-vessel coolability, but also the strategies or designs actually applied in operating and newly developed NPPs [3], in order to update the corresponding knowledge base. Based on the review work, this paper shortly describes the state of the art of the ex-vessel cooling strategies applied both in new and old NPPs and takes a view of the near future regulation in Korea following the amended act.

2. Strategies Applied in New Plants

In this section some of the strategies for debris cooling with related designs applied in new plants that are called as the Generation-3/-3+ plants are introduced. Strategies are categorized into dry cavity and wet cavity, according to the timing to inject cooling water to the reactor cavity area. Some plants adopted the 'dry cavity' to enhance the spreading of the core melt on the cavity floor as well as to remove the steam explosion risk, while other plants use pre-flooding strategy to make the 'wet cavity' in order to enhance the coolability after RPV failure or to reduce the RPV failure probability.

2.1 Dry Cavity Strategy

Dry cavity strategies are used in EPR, ESBWR, VVER, EU-APR1400, and so on. These NPPs have specialized engineered feature, that is, the 'core catcher' at the cavity area or at the reactor pit. In these plants, the core melt released from PRV is collected in specified area and intentionally interacted with sacrificial materials to lose its energy. The major advantage of this strategy is to remove the risk of steam explosion.

In the EPR of Areva, the Core Melt Stabilization System (CMSS) was adopted using initially dry cavity concept. During a severe accident, the core melt is released after the RPV failure and collected in the reactor pit. An intentional MCCI might occur at this stage resulting in failure of the melt plug and then the melt would move to the spreading compartment with reduced viscosity. The core melt is finally quenched by the indirect cooling by the water injected from the In-containment Refueling Water Storage Tank (IRWST) through the piping under the floor and then direct cooling by this water overflowed through the side wall of spreading compartment. Fig. 1 shows the schematic of the core catcher concept of the EPR.

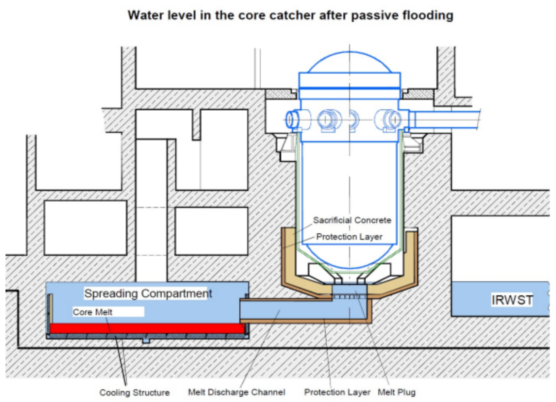


Fig. 1. Core catcher concept in EPR [4].

The ESBWR of GE Hitachi Nuclear Energy, also adopted a core catcher concept named Basemat Internal Melt Arrest and Coolability (BiMAC). The BiMAC core catcher installed at the bottom of circular lower drywell (LDW) as shown in Fig. 2. The melt cooling concept is similar to that of the EPR core catcher. There is a sacrificial layer made of ceramic material over the cooling jacket. The water of the Gravity Driven Cooling System (GDCS) is injected to the cooling jacket through two vertical downcomers (LDW deluge lines), and then overflows to directly quench the melt by top flooding.

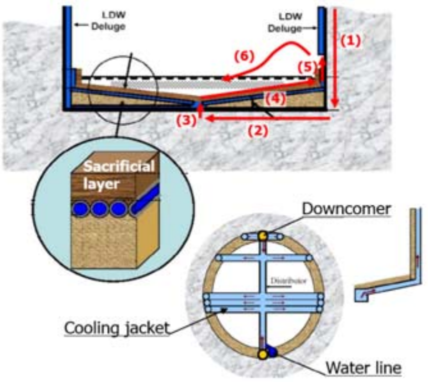


Fig. 2. BiMAC core catcher in ESBWR. The numbers describe the flow direction of water [5].

VVER-1000 and VVER-1200 of Russia adopted different type of core catcher concept at the below of the RPV as depicted in Fig. 3. The core catcher is a corn-shaped metal structure that contains sacrificial materials made of ceramic mixture. The gap region of the double-barrier outer walls is filled with the ferric and aluminium oxide granules (FAOG). At the outer region of the metal structure, the coolant can be supplied to remove heat from the melt inside by external cooling. Thus VVER core catcher concept uses indirect cooling of the melt with multiple barrier.

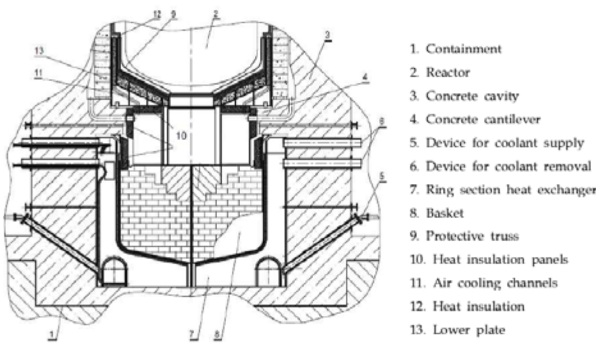


Fig. 3. Core catcher concept of VVER-1200 (AES-2006 model) [6].

EU-APR1400 of Korea changed and improved several safety features from the original version of APR1400 to meet the requirement of European countries, and one of the changed design feature is the consideration of the core catcher. The reactor cavity was changed to a rectangular-shaped area with inclined sacrificial concrete layers. The cooling water is injected from the IRWST and heat transfer is expected to be enhanced with the metal layer under the sacrificial layer and recirculation flow paths. Fig. 4 shows the core catcher concept applied in EU-APR1400.

2.2 Wet Cavity Strategy

Wet cavity strategies are adopted in AP1000, APWR, APR1400, APR+, etc. Large amount of cooling water

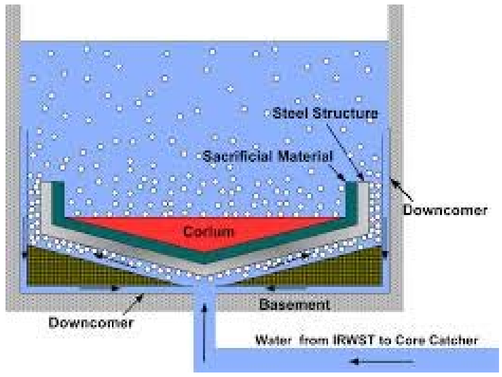


Fig. 4. Core catcher concept of EU-APR1400 [7].

can be supplied into the cavity area to cool down or to quench the melt. Some plants utilize the In-Vessel Retention of core melt through External Reactor Vessel Cooling (IVR-ERVC) to arrest the melt inside RPV and to delay the failure of RPV. From the viewpoint of defense-in-depth (DID) philosophy, the IVR-ERVC strategy can be a good measure to provide another barrier against the fission products release. In this case, however, an increased level of steam explosion risk can be a drawback that should be properly estimated.

AP1000 and AP600 of Westinghouse applied the IVR-ERVC strategy as major countermeasure for cooling of the melt in RPV. The conceptual diagram of ERVC situation is depicted in Fig. 5. The configuration of RPV and reactor cavity was optimized to maximize the boiling heat transfer around the vessel wall and natural circulation of the water by adopting engineered vessel insulation. The cooling water is supplied from the IRWST with passive manner.

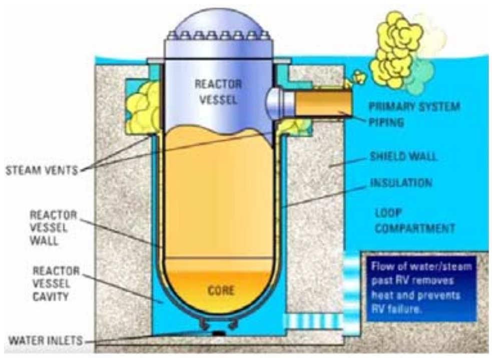


Fig. 5. IVR-ERVC concept of AP1000 [8].

APWR of Mitsubishi Heavy Industry, Ltd. and APR1400 of Korea have very similar strategies to cool down or quench the core melt. These plants adopted high-level cavity flooding before the RPV breach. In APWR the water in IRWST can be delivered through the containment spray system operation and outer water source from the fire protection system can be supplied directly to the cavity. For APR1400 and APR+, they also use IRWST water to directly fill the cavity using gravitational force by opening the dedicated valves of the cavity flooding system. This water can also be injected into the cavity with active manner using a corresponding system pump. The strategy of APR1400 is shown in Fig. 6.

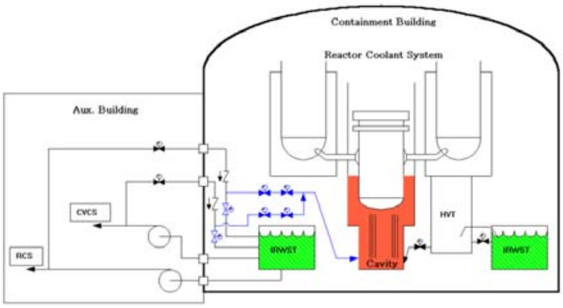


Fig. 6. Cavity flooding strategy adopted in APR1400 [9].

These plant designs (APWR and APR1400) are also considering the IVR-ERVC as a severe accident management (SAM) strategy. This approach will surely enhance the DID level for fission products release to the environment unless the steam explosion risk greatly increases. Since the possibility of successful IVR-ERVC is getting lower with increase of thermal power of reactor, the ERVC strategies in these plants are considered as an optional strategy that can be taken by technical support center, and are not treated as reliable strategy in the probabilistic safety assessments (PSAs).

For both plant designs, they tried to enhance the coolability of the melt or debris bed on the cavity floor by introducing large cavity floor area which design feature is more effective when large amount of core melt is released in short period, as conservative assumption.

3. Strategies for Operating Plants

The first part of this section introduces the ex-vessel cooling strategies applied in operating plants of Korea described in SAM guidelines (SAMGs). In order to assess the feasibility of the strategies, the cavity design of each plant has been investigated.

Meanwhile, the importance of ex-vessel cooling was estimated based on the results of Level 2 PSA of each plant, by comparing the frequency of basemat melt-through (BMT) against the total containment failure frequency (CFF). The second part of this section describes the review results in this point of view.

In the last part of the section, some examples of measures to improve the ex-vessel coolability for operating plants are introduced. These examples can be referred to as design improvement of operating plants, if needed.

3.1 Ex-Vessel Cooling Strategies

For all plants in Korea, the development of SAMGs was fulfilled in compliance with the Policy on Severe Accident of NPPs [10]. A SAMG consists of several guidelines to stabilize the degraded core and to cope with the challenges threatening the integrity of containment. One of them is the strategy to flood the reactor cavity with water to remove heat from the degraded core or the melt and to prevent the MCCI that could result in BMT. Decision of water injection to reactor cavity is made by the Technical Support Center (TSC) when the water level is lower than the specific level following the corresponding guideline.

A study has been conducted by KINS to investigate the possibility to flood cavity by reviewing design features and SAMGs of operating plants. In spite of the accident management strategy regarding the cavity flooding in SAMGs, it was found that some plants have limitation to achieve a successful water injection into reactor cavity because of their own design characteristics. For example, there are very limited water piping or penetrations to the cavity to timely flood it with enough amount of water. This problem should be properly resolved.

Fortunately, parts of this problem has been treated within the follow-up actions derived from the special safety inspection conducted by the Korean Government supported by KINS in 2011 in the light of the Fukushima Daiichi accident. The action item number 4-5 recommended the revision of SAMGs to enhance the effectiveness. This item concerned the ex-vessel coolability from the view point of the effectiveness of the strategy. Following this action, the utility examined the possibility of water injection into the reactor cavity with seeking alternative paths to achieve the aim of the strategy, while the reliability might be one thing.

3.2 Insights from Level 2 PSA Results

Regarding the importance of ex-vessel coolability in Level 2 PSA, the role of ex-vessel coolability to the containment failure was estimated by comparing CFF by BMT with total CFF for each plant. This can give a good simple estimation of the relative vulnerability induced from BMT in comparative manner. Here, we do not discuss the validity of the containment event tree (CET) modelings and its quantitative estimation in Level 2 PSA, while those could affect the results of Level 2 PSA in some degree.

Fig. 7 comparatively indicates the importance of ex-vessel coolability to the containment failure. The alphabetic characters A to H represent the types of NPPs of Korea in operation. As shown in the graph, plant types B and F were ranked highest among all plant types. This means that these type of plants have some drawbacks in ex-vessel cooling and it might be due to the physical limitations in carrying out the SAM strategy to flood cavity with water. This is a consistent result with that of review on SAMGs described in the former section.

3.3 Experience on Improvement of Ex-Vessel Coolability

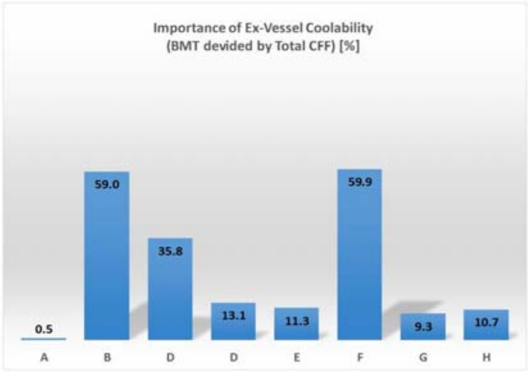


Fig. 7. Importance of BMT to the containment failure [3]. The values of corresponding plant type were taken from CFF of BMT divided by total CFF for each plant type.

As mentioned in Sections 3.1 and 3.2, some operating plants need to supplement their weakness in the ex-vessel coolability and this situation is similar for some plant designs in other countries as well as those in Korea. With regard to this problem, several efforts have been made mainly in some European countries to enhance the ex-vessel coolability for their operating plants. It is true that the design change or modification for reactor cavity of operating plant is very difficult because of high level of radioactivity. However, more serious discussion about it may be needed for practical improvement of the nuclear safety regarding severe accidents, especially after the recent accident occurred in Fukushima. This section, therefore, introduces some examples on the improvement of ex-vessel coolability and each of them can be referred to as a good precedent for Korean plants.

French Backfitting Strategy for Operating Plants

The Electricity of France (EDF), a French electric utility company, started a project to extend the lifetime of their operating Generation 2 NPPs to 40 years. In this project one of safety issues was the BMT after a severe accident, in the light of the Fukushima accident.

To resolve this problem, the EDF finally decided to modify the cavity design for operating plants by extension of the cavity floor to secure enough area for melt spreading after the RPV breach. An additional concrete layer is installed over the original cavity floor. The idea of EDF for this backfitting is consistent with the strategy of initially dry core catcher of EPR where the melt is distributed to the spreading area first and then the water is flooded onto the top of spread melt layer. The conceptual drawing for this backfitting is shown in Fig. 8.

Finnish Application of IVR-ERVC to the Loviisa NPP

The application of the IVR-ERVC strategy to the Loviisa NPP which is a VVER-440/213 was proposed in late 1980s, and several experiments such as COPO, ACOPO, ULPU, etc. were performed to study the feasibility of the application and/or to verify it.

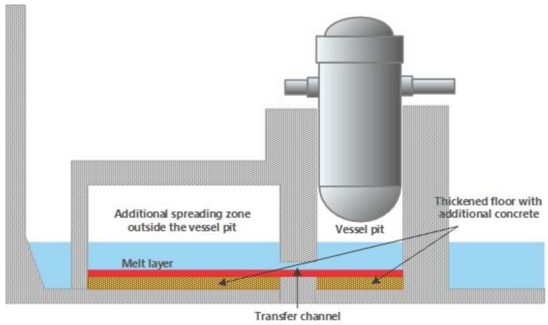


Fig. 8. Configuration of extended spreading area planned by EDF for French operating reactors [11].

Throughout these programs, it was found that the heat flux at the surface of RPV is lower than the critical heat flux. The Finnish regulatory body finally approved the strategy at 1995 and related design improvement was finished in 2002.

Main reasons how they could apply the IVR-ERVC to the Loviisa NPP are related to the design characteristics of the VVER-440 plant and the several additional design improvement regarding the strategy as follows: relatively low reactor thermal power of about 1,500 MWt; no penetration at the lower head; high RPV level to support the natural circulation with design change for thermal insulation; large amount of water; installation of evaporated steam outlet valve and water inlet valve; and installation of a screen mesh at water inlet.

The COMET Core Catcher Concept

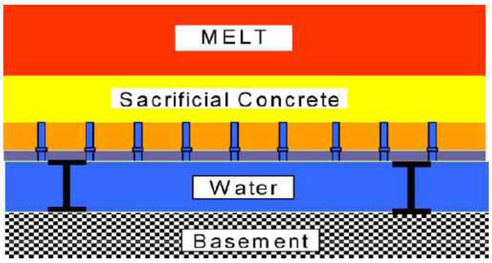
This core catcher concept has been studied initially by KIT (former FzK) using COMET test facility, as an alternative measure to stabilize the core melt in cavity floor. Fig. 9(a) shows the schematic of COMET concept. The idea is to utilize the natural buoyancy force of the steam of which upward flow would be generated when the sacrificial concrete is eroded by the melt up to the water piping location.

The COMET concept was initially considered as an alternative measure to arrest the melt in the spreading compartment of EPR. Now the developers believe the simple version of this concept, that is the CometPCA in which the water piping and water channel were replaced by a water-filled porous concrete layer as shown in Fig. 9(b), can be applied to the current operating plants.

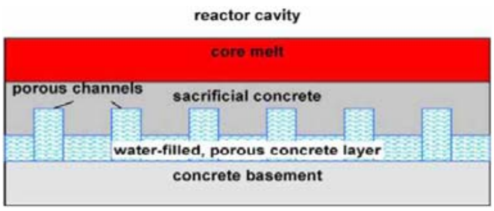
The design concept has continuedly been upgraded with several versions by research groups in KIT, KTH, Stuttgart University, and so on. Recent research of KIT showed that an optimized design using this concept can be applied to cool down the 50 cm-thick melt.

4. Perspectives with New Regulation

As described in Section 1, the utility has to submit the AMPs as legal licensing documents for all NPPs of



(a) COMET concept



(b) CometPCA concept

Fig. 9. Configurations of the COMET core catcher [12].

Korea soon, including the assessment for the ex-vessel coolability to show the containment integrity under severe accident conditions. However, it might be challenging to successfully meet this deterministic performance goal with current cavity designs and measures as shown in Section 3.

An alternative measure, therefore, at least the water injection to the cavity should be provided in each plant. This can be achieved by considering the lesson learned from the special safety inspection of 2011. As one of the follow-up actions the utility's examinations on the water injection possibility of each plant were done. With this information the deterministic analyses on MCCI, with related to FCI if needed, are expected to be carried out to realistically estimate the ex-vessel coolability.

If the results do not show the coolability of the melt or the containment integrity cannot be secured, an alternative measure should be provided to meet the regulation. In this process, the most feasible and effective method, including the examples introduced in Section 3.2, might need to be considered based on a consensus reached after enough discussion among the experts group. The most important things would be the treatment of the uncertainties as well as the reliability of the strategies. Another important point might be the provision of the effective SAMGs properly considering the corresponding strategies with support of analytical or experimental proofs.

5. Conclusions

New regulation of Korea requires for the utility to show that the containment integrity can be secured from the challenges under severe accident conditions. Because of the uncertainties existing in phenomena in the progression of the accident, however, it would be challenging to show the acceptance of the strategies and corresponding designs. Among various phenomena related to severe accidents, the MCCI is the most uncertain one and, therefore, the appropriate measure and strategy to stabilize and/or cool down the melt or debris at reactor cavity might be needed. Nevertheless, the proper efforts for the improvement of ex-vessel coolability will play an important role to achieve the safe NPPs even under the severe accidents.

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