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Corium Retention and Cooling by an Ex-vessel Core-catcher for Nuclear Power Plants

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1. Introduction

In the very unlikely event of a severe accident (SA), the reactor pressure vessel (RPV) could fail and molten corium could be released into the reactor cavity. Under such a condition, the basemat melt-through issue is a particular concern for light water reactors to prevent release of fission products out of the containment. There are several types of core-catcher design for retention and maintaining coolability of the molten corium [1, 2 and 3].

For the APR1400, a cavity flooding system is designed in accordance with the US NRC regulations and In-Vessel Retention with External Reactor Vessel Cooling (IVR-ERVC) is additionally adopted to enhance its SA mitigation capability. On the other hand, an ex-vessel core-catcher is required by European Utility Requirements (EUR). The purpose of this paper is to review the existing countermeasures and to suggest an optimal core catcher design for the APR1400 to comply with the EUR.

2. Existing Core-catcher Designs

The VVER-1000 design [1] employs a core-catcher consisting of a separate crucible installed under the RPV with an intake designed to cover almost the whole surface of the bottom head. The core-catcher is partly filled with oxide bricks acting as sacrificial materials to reduce the power density and the temperature of the discharged corium by mixing with them. In this concept, the necessary increase of the heat transfer surface is achieved by a volume increase of the corium through dissolution of the sacrificial material. The crucible is cooled externally by flooding of the reactor cavity.

In the EPR concept [2], the corium is first collected in the reactor cavity while mixing with the sacrificial concrete layer of the inner cavity wall. This process is used to pretreat the composition and temperature of the corium. After a melt plug is penetrated, the corium flows onto a large surface spreading area through an inclined melt discharge channel. Cooling of the corium is achieved by water flowing in cooling channels under the spreading area and top flooding. The horizontal cooling structure is provided consisting of an array of steel blocks which form parallel channels of rectangular cross-section.

The core-catcher of the ABWR [3] with inclined cooling channels is placed at the lower drywell floor. The core-catcher gathers the molten corium in a round basin covered with a refractory layer. After the corium drops in the core catcher, the molten corium is cooled by both the inclined channels under the basin and the flooded water over the corium by the flooding water supplied from the suppression pool. The bottom structure has cooling channels formed by embedded square tubes extending radially or by piping arranged in the same way.

The core-catcher systems of the EPR and the ABWR are protected by their patents for layout, concept of cooling, structure, and so on [4, 5, and 6]. Each concept involves passive safety features to increase reliability such as flooding by gravitation and cooling by natural convection, while the countermeasures depend on the specific reactor designs.

3. Development of Ex-vessel Core-catcher

3.1 Major Design Requirements

To retain and control the corium without endangering the integrity of the containment, the core-catcher must have the following attributes: heat removal capabilities in excess of decay heat generation, continuous and appropriate amounts of cooling water by passive injection, and minimizing the probability of the damaging steam explosion.

The application of the VVER-1000 type core-catcher is not practical for the APR1400 because it requires a large-scale reconstruction of the reactor cavity. In addition, we need to develop the core-catcher without infringement of the mentioned patents above: the EPR patent claims the concept of corium treatment by the pre-catcher, the melt discharge channel, and the spreading area; and the ABWR applied for a patent for the shape of the inclined cooling channels which are separated from each other.

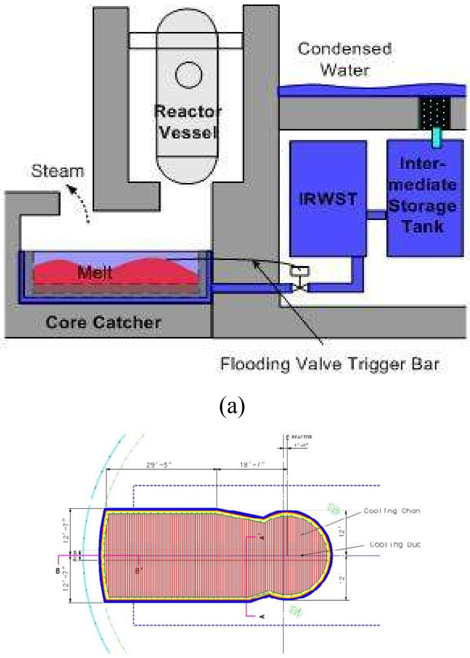
3.2 System Configuration and Cooling Structure

The core-catcher system is to be located in the reactor cavity under the reactor vessel, as shown in Fig.1. Its main functional principle is the increase of the surface-to-volume ratio of the molten corium to make the subsequent flooding, quenching and cooling more effectively. Considering the general arrangements of the APR1400, approximately 100m^2 of area is available for the spreading of the corium in a coolable configuration.

The mass of molten corium that could be discharged from the RPV during a severe accident was evaluated using the MAAP4 code. The heat removal requirement for the APR1400 core debris is about 32 MW corresponding to about 1% decay heat, 20% of which is released out as the volatile fission products and 80% is stored in the corium. An average downward heat flux is about 160~200kW/m². Transferring the heat to the water pools in the upward is not a problem as compared with the other core catcher designs, and the downward heat loads with a safety margin are reasonably handled by inclined cooling flow path because heat flux can be assumed to be at least 400kW/m².

After the corium drops in the core catcher, the In-containment Refueling Water Storage Tank (IRWST) water fills the central supply duct underneath the bottom structure and the water enters the unified cooling channel. Finally the water pours onto the surface of the molten corium and overflow will continue until the hydrostatic pressures in the IRWST and the reactor cavity are equal. According to the previous tests [7 and 8], spreading performance and problems of energetic corium-water reaction are not our present concern assuming the spreading for high pour rate melt discharges and top flooding after spreading.

Fig. 2 shows the schematic diagram of the core catcher with unified cooling flow path. The core-catcher consists of inversed pent-roof type crucible, Pilotis evenly distributed to support the crucible, and the bottom structure. The inclined cooling channel is formed by the Pilotis between the crucible and the bottom structure so that the main stream of the channel is formed in the direction from center to sides with mixing effect. This also contributes to increase the heat transfer area between the crucible and water and efficiency of the cooling. It was determined that either of a co-current flow with a downcomer system or a countercurrent flow in the water flow path would be capable of removing the downward heat transfer of the crucible.



(a)

(b)

Figure 1 Configuration of the core-catcher system: (a) layout and (b) general arrangement of the reactor cavity

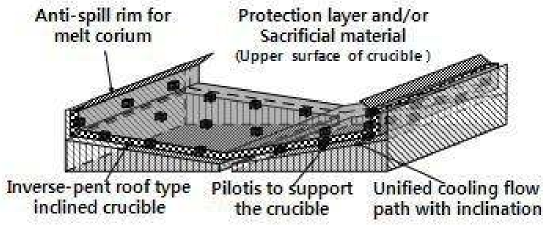


Figure 2 Cross-sectional diagram of the cooling structure with unified cooling flow path

The results of CFD analyses showed that measures to prevent spill over of the melt are rather to be supposed because of high fluidity of molten corium. Therefore, the side wall of the crucible has an overhang to prevent the corium from spill over. If necessary, the crucible can be protected from the jet impingement of the corium by a refractory layer and sacrificial materials on the upper surface.

4. Conclusions

We have successfully developed the conceptual design of an ex-vessel core-catcher with the consideration of the configuration, heat loads and coolability. The Korean specific design of core-catcher was applied for an international patent. As a further research, investigation on the spreading performance and development of the sacrificial materials will be implemented. This specific core-catcher design can be applied if the regulatory body of each country request.

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