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In-Vessel Melt Retention of Pressurized Water Reactors: Historical Review and Future Research Needs

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ABSTRACT

A historical review of in-vessel melt retention (IVR) is given, which is a severe accident mitigation measure extensively applied in Generation III pressurized water reactors (PWRs). The idea of IVR actually originated from the back-fitting of the Generation II reactor Loviisa VVER-440 in order to cope with the core-melt risk. It was then employed in the new deigns such as Westinghouse AP1000, the Korean APR1400 as well as Chinese advanced PWR designs HPR1000 and CAP1400. The most influential phenomena on the IVR strategy are in-vessel core melt evolution, the heat fluxes imposed on the vessel by the molten core, and the external cooling of the reactor pressure vessel (RPV). For in-vessel melt evolution, past focus has only been placed on the melt pool convection in the lower plenum of the RPV; however, through our review and analysis, we believe that other in-vessel phenomena, including core degradation and relocation, debris formation, and coolability and melt pool formation, may all contribute to the final state of the melt pool and its thermal loads on the lower head. By looking into previous research on relevant topics, we aim to identify the missing pieces in the picture. Based on the state of the art, we conclude by proposing future research needs.

1. Introduction

Nuclear power safety involves estimating the risks posed by one or more nuclear power plants (NPPs) to the public at large and the efforts to reduce these risks. The populace of most concern is that residing in the vicinity of an NPP; populations in other locations that could be affected by an accident in an NPP are also considered. The basic goal of nuclear power safety is to ensure that an NPP will not contribute significantly to individual and societal health risks. This goal translates to the prevention of the release of radioactivity into the environment from the power plant. A complementary aim is to prevent damage to the plant and to protect the personnel at the plant from injury or death in an accident.

To meet this safety goal, the general configuration of a pressurized water reactor (PWR) plant provides three important physical barriers to the release of fission products into the environment: the cladding on the fuel element, which contains the fission products generated in the fuel; the reactor vessel, which contains all the fuel elements forming a reactor core; and the leak-tight containment, which is intended to keep any fission products inside the containment from escaping to the environment. Assuring the integrity of each of these physical barriers in any accident scenario becomes the corner stone of the defense-in-depth approach which is extensively employed in nuclear safety against the release of radioactivity to the environment. During a severe accident, the occurrence of reactor core meltdown may cause the first one or two physical barriers to fail, leading to the release of a certain fraction of fission products (gaseous and solid in the form of aerosol) to the pressure-bearing containment. The fission products may leak into the environment if this last barrier also fails. Thus, one can say that the ultimate goal of nuclear power safety is

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to maintain the containment integrity.

According to the state-of-the-art understanding of severe accidents in a PWR [1], the main threats to containment integrity are as follows:

(1) Direct containment heating (DCH);
(2) Ex-vessel steam explosion (EVE);
(3) Hydrogen combustion (H2C);
(4) Containment long term over-pressurization (LOP);
(5) Containment bypass and leakage (CBL); and
(6) Basemat melt penetration (BMP).

For the Generation III PWR designs, the above items (1)–(5) are taken care mainly through careful design, construction, operation, and accident management, in order to let their risks to be reduced to as low as reasonably possible. The last item, BMP, concerns the thermo-chemical attack of the decay-heated core melt (corium), which may melt through the reactor pressure vessel (RPV) and then the containment basemat if melt coolability is not achieved. The corium coolability (i.e., preventing melt-through of physical barriers) has been recognized as the "Achilles-heel" of the Generation II or earlier PWR designs [2]. The solutions adopted by Generation III reactors are basically divided into two categories: in-vessel melt retention (IVR) or ex-vessel melt retention (EVR), corresponding to the termination of a severe accident in the RPV or in the containment, respectively. The key strategy of IVR is to arrest and confine the corium in the lower head of the RPV by flooding the reactor pit (cavity), while EVR collects and cools the corium ejected from the RPV in a core catcher placed in the containment. Well-known core catcher designs include the melt spreading and cooling compartment deployed in the containment of the European Pressurized Reactor (EPR) [3] of AREVA, and the crucible-like vessel installed under the RPV of the Russian VVER [4]. EPR plants are currently under construction in Finland, France, and China. The VVER-1000 plant with a core catcher (AES-91) was first built in China and came into operation in 2007.

IVR is preferred in Chinese designs of advanced PWRs: It is adopted in the Generation III and Generation III+ PWR designs, and it is also one of the important features of AP1000, which is under construction at two NPP sites in China, and intended to be intensively built in the near future. Therefore, this paper focuses a historical review of IVR development, and afterward provides a recommendation of future research needs in order to improve the credibility of IVR and enable its application in new PWR designs. This historical review of IVR along with state-of-the-art knowledge of severe accidents in PWRs, serves as a basis and rationale for identifying further research needs.

2. History of in-vessel melt retention (IVR)

It should be noted that in-vessel melt coolability and retention includes three general concepts: ① quenching of the core *in situ*; ② coolability of in-vessel particulate beds; and ③ coolability of the in-vessel melt pool. The first concept, which is the best opportunity to catch the core during its heating-up stage, refers to the introduction of water into the core as soon as the emergency core cooling system (ECCS) is recovered. Core quenching is not a straightforward management action since the steam formed may aggravate the accident by increasing the zircaloy oxidation (leading to the addition of oxidation heat to the core and the release of hydrogen). The key action to reduce the cladding temperature quickly and reduce hydrogen production is to add a large volume of water at a rapid rate. The addition of water to the very hot core can create a particulate debris bed due to the crumbling of some of the hot fuel rods that are chilled by cold water. A particulate debris bed is also formed when the melt from the core drops into the lower head full of water. The coolability of such debris beds provides the second best opportunity to terminate the accident, since the porous media is much more amenable to cooling than a molten pool. If reflooding the core is impossible, the last resort is to realize the coolability of a molten corium pool in the lower head through external cooling of the RPV. This is the IVR strategy to be discussed hereafter. It should be recognized that the water circuit required for the external cooling of the vessel should be separate from the water circuits that add water to the vessel, and that it must function even in the case of a station blackout.

2.1. Principle of IVR

Fig. 1 shows a conceptual picture of IVR, in which the core melt is finally relocated into the lower head and forms a pool of molten materials heated volumetrically by the decay heat, while the outer surface of the RPV is submerged either completely or at least to a level above the lower head. The coolant flow (normally driven by natural circulation) through the external surface of the RPV keeps the vessel wall cool enough to prevent it from creep failure.

The IVR strategy therefore requires that the decay heat of the melt pool be removed by coolant flow outside the vessel. This translates to the rationale that the angular heat flux (q_w) imposed by the melt pool to the vessel wall should not exceed the limit of the external cooling capacity, that is, the critical heat flux (CHF) of boiling at all points around the lower head, see Fig. 2. Otherwise the integrity of the vessel will be lost, sooner or later, due to a boiling crisis and subsequent escalation of vessel wall

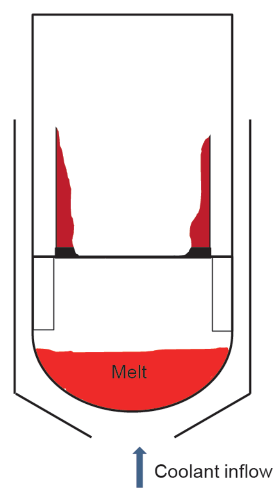

Fig. 1. Sketch of in-vessel melt retention (IVR) by external cooling.

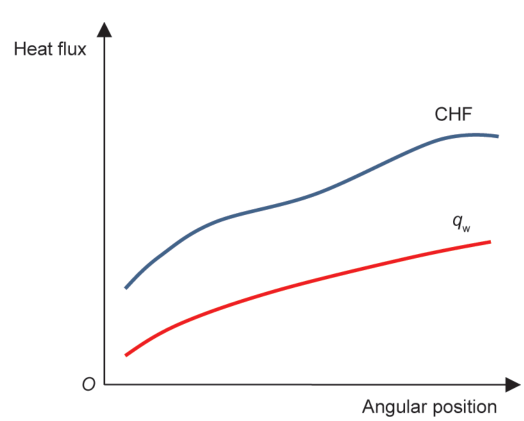

Fig. 2. A comparison of critical heat flux (CHF) and q_w in IVR.