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Study on heat removal capability of calandria vault water from molten corium in calandria vessel during severe accident of a PHWR

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HIGHLIGHTS

- Scaled test set up simulating the calandria vessel and calandria vault water of PHWR.
- Experiments conducted with simulant material at 1100 °C.
- Investigation of heat transfer from the melt pool to the outside vault water through calandria vessel.
- Numerical analysis to study the capability of calandria vault to remove decay heat from molten pool in calandria vessel.

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ABSTRACT

Recent Fukushima nuclear accident has triggered further awareness amongst reactor designers regarding enhancing the safety measures in a nuclear reactor. It has become important to analyse the capability of decay heat removal in a reactor to avoid radioactivity releases to the environment. Such a study has been carried out for an Indian PHWR. In a hypothetical severe core damage accident in PHWR, multiple failure of the core cooling system may lead to collapse of pressure tubes and calandria tubes, which may ultimately relocate inside the calandria vessel forming a debris bed. Due to decay heat generation, the debris ultimately melts down forming a molten pool inside calandria vessel. Calandria vessel is surrounded by calandria vault water that acts as heat sink. In order to study the extent of heat transfer from molten pool to surrounding water under severe accident condition, an experiment was carried out wherein a simulant material was poured inside a simulated calandria vessel immersed in the simulated calandria vault water. The amount of melt and water present in calandria vault scaled proportionately with regard to an Indian 700 MWe PHWR. Results show that as soon as the melt was poured in the vessel, a thick crust was formed on the inner calandria vessel, which reduced the heat transfer from the melt pool to vault water resulting high temperature gradient in melt. Even though the cylindrical vessel inner temperature was found to be very high, the water outside the vessel never boiled. When the cylindrical vessel was opened after the experiment, there was no gap observed between the vessel and crust. Numerical analysis was carried out to predict the temperature profile of the molten pool and the vessel which were in good agreement with experimental results. Results were compared for the crust growth rate and temperature profiles in the melt pool considering the decay heat and without decay heat. Results show that with no decay heat consideration, the crust thickness continuously increases with time and in case of decay heat generation, crust thickness is found to be a function of decay heat. The melt temperature is found to increase above a decay heat of 1%.

Abbreviations: BWR, boiling water reactor; CANDU, CANada Deuterium Uranium; CHF, critical heat flux; CV, cylindrical vessel; FE, finite element; FEM, finite element method; FOREVER, Failure Of REactor VEssel Retention; IAEA, International Atomic Energy Agency; LHF, lower head failure; LIVE, late in-vessel phase experiments; LWR, light water reactor; OLHF, OECD lower head failure; OECD, Organisation for Economic Co-operation and Development; PHWR, pressurized heavy water reactor; PWR, pressurized water reactor; RASPLAV, means "melt" in Russian; RPV, reactor pressure vessel; SBO, station blackout accident.

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1. Introduction

The severe accidents at Three Mile Island (Broughton et al., 1989), Chernobyl (IAEA, 1986) and Fukushima (Tokyo Electric report, 2012), illustrate that despite having the accidental preventive measures in nuclear power plants, still a very low probability remains which may develop into a severe accident with melting of core.

One of the accident management measures is cooling of the melt inside the vessel or in-vessel retention. In this concept, the core melt relocates to the bottom of the vessel and a molten pool is formed inside the lower head. Cooling water is circulated through outer surface of the vessel in order to remove decay heat and maintain integrity of vessel. Experiments have been performed at various facilities to study the physical phenomenon of in-vessel retention. These experiments were dedicated to the studies for coolability of the melt pool, failure of the vessel wall under the thermal loading, the pressure bearing capability of the vessel wall having large thermal gradient across the thickness, vessel failure time, etc. (Sehgal et al., 2005).

There are only a few tests conducted in the past for in-vessel retention. Experiments in LIVE (Gaus-Liu et al., 2010) were performed in a 1:5 scaled semi-spherical lower head for PWR. The objective was to investigate the melt pool coolability behaviour under different conditions like initial melt temperature (maximum 350 °C), initial external air/water cooling, central melt pouring, non-eutectic and eutectic melts, etc., for in-vessel retention. Comprehensive experimental results have been acquired regarding the melt pool temperature, heat flux distribution on the vessel sidewall and the crust thickness profiles and crust properties. Asmolov et al. (2000) conducted experiments in RASPLAV to study the behaviour of molten core on the RPV lower head and to assess the possible physico-chemical interactions between molten corium and the vessel wall. Tests were conducted in LHF (Chu et al., 1998) and OLHF (Humphries et al., 2002) to examine the lower vessel deformation and failure behaviour due to corium relocation and pool formation. It may be noted that the OLHF integral experiments were performed using scaled models of a typical lower head of a PWR. The vessel was internally heated with an induction-heater. Large temperature difference was induced across thickness of vessel wall. These tests were extensively instrumented to provide temperature, pressure, and displacement data. Two types of thermocouples (K and C types) were employed to measure the temperature of the inner and outer surface of vessel. The vessel surfaces were mapped both, before and after the test to provide measurements of pre-test thickness, post-test thickness, and cumulative vessel deformation. In FOREVER (Sehgal et al., 2003), tests were carried out on scaled vessels lower head to understand the molten pool convection, the timing and mode of the vessel failure. The vessel instrumentation included thermocouples measuring the temperatures at inner wall, outer wall and inside melt pool, a pressure transducer and a set of linear position transducers. Caroli et al. (1999) investigated the thermal and mechanical behaviour of a PWR vessel in consequence of a severe accident with core melt and flooding of the reactor pit by refined finite element analyses. Willschütz et al. (2001) estimated the failure time of the RPV of a LWR by numerical analysis during severe accident scenarios and validated the predictions with FOREVER results. Mathew (2004) studied the progression of a severe core damage accident in a CANDU 6 calandria vessel. Small-scale core disassembly tests were conducted with single and multiple channels to understand the behaviour of channels during moderator boil-off. The calandria vessel response to a SBO sequence resulting in severe core damage was estimated by numerical analysis by Mathew et al. (2009).

The above literature review suggests that though there have been a few experimental studies for melt coolability in PWR/BWR lower head of the vessel under severe accident conditions, however, experimental investigation on the melt coolability behaviour in calandria vessel of a PHWR by the calandria vault water is still lacking. The heat transfer behaviour of the molten corium to surrounding vault water in a PHWR is very crucial for maintaining the calandria vessel integrity. Prolonged exposure to high temperature melt on one side and low temperature water on the other side can generate excessive thermal stresses in the calandria vessel. If heat removal is very low, the CHF limit may also be reached and subsequently, it can cause early degradation of the vessel. Therefore, experiments simulating the PHWR calandria vessel containing molten corium and cooled by simulated calandria vault water is essential to establish the in-calandria corium retention capability of PHWRs.

In the present study, experiments were conducted in a scaled facility of an Indian PHWR to investigate the extent of heat transfer from the molten pool located in the calandria vessel to the outside vault water through the wall of calandria vessel. The temperature distributions inside the molten pool and across the wall thickness of the simulated calandria vessel were measured. Numerical analysis was carried out to validate the FEM model with the test data. The model was also applied to predict the heat transfer behaviour from the molten corium pool to the outside calandria vault water considering decay heat in the melt.

2. Severe accident scenario in pressurized heavy water reactor

Indian PHWR core consists of several horizontal channels in a large cylindrical calandria vessel. Each channel consists of a pressure tube which contains the fuel with hot pressurized heavy water as primary coolant and an external calandria tube separated from the pressure tube by an insulating gas-filled annulus. The fuel is natural UO_2 in the form of bundles of about 0.5 m length. The heavy-water moderator is contained within calandria vessel and each channel is submerged in it. The calandria vessel has rupture discs, which open and release the pressure in case of pressure increase in the calandria vessel due to unlikely events. The calandria vessel is surrounded by a calandria vault, which contains a large volume of

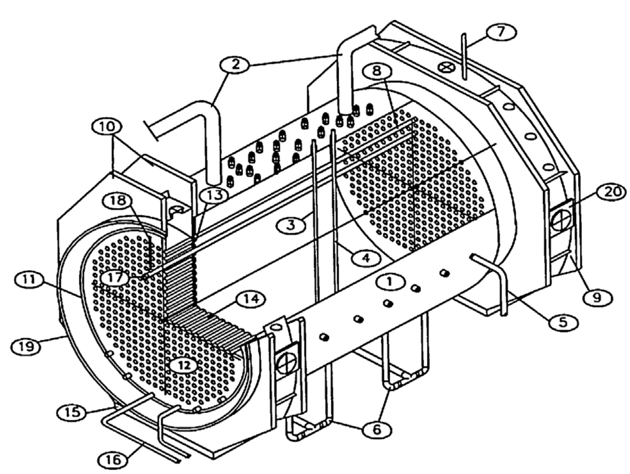

Fig. 1. PHWR core assembly.