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A multi layer core catcher concept for future sodium cooled fast reactors

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ABSTRACT

Sodium cooled fast reactors (SFRs) have an in-vessel core catcher to collect, contain and cool the core debris settling upon it following a severe accident. Liquid sodium with its excellent heat transfer characteristics is able to cool the core debris by natural circulation, rejecting heat to the safety grade decay heat removal system. The core catchers for reactors like Superphenix-1 in France and Prototype Fast Breeder Reactor (PFBR) in India are designed to handle the core debris resulting from seven subassemblies melting. But for future reactors it would be desirable if the core catcher is able to accommodate and cool debris resulting from a whole core melt down. Such a design would enhance the safety of the reactor by maintaining the main vessel integrity even for the worst accident scenario. Several design options of core catchers for fast breeders are discussed in the present work with particular emphasis on a multi layer core catcher. A multi layer core catcher comprising of a sacrificial layer of Molybdenum, delay bed of thoria or magnesia and the bottom most base layer made of SS316LN is proposed and its adequacy is substantiated by heat transfer analysis. The heat transfer analysis which is aimed at optimizing the thickness of the delay bed layer reveals that, 4 cm thick thoria layer or 5 cm thick magnesia layer can serve as delay bed in order to restrict the temperature at the core catcher bottom within design safety limits for core debris spread evenly on the core catcher plate.

1. Introduction

The whole core melt down in a SFR is a low probability event with frequency of occurrence being $<10^{-6}$/RY. This is because of continuous monitoring of critical parameters such as power, flow, temperature etc., and highly reliable fast acting shut down systems and decay heat removal systems. Local melting of the fuel to the extent that it does not threaten clad integrity is considered as a design basis event. Engineered safeguards such as multiple radial entries for the coolant at the foot of each subassembly and a blockage adaptor that permits 40% sodium flow through an alternate path at the top are provided to categorize a Total Instantaneous Blockage (TIB) of the fuel subassembly as a beyond design basis event. However, in line with the defense-in-depth philosophy, a core catcher is provided below the grid plate to collect, disperse and safely cool the core debris resulting from melting of seven fuel subassemblies, in the event of total instantaneous blockage of a single fuel subassembly. For future reactors, a third passive shut down system is envisaged and the core catcher has to be designed to contain and cool core debris resulting from whole core damage, so that CDA can be categorized under the residual risk.

In general, for nuclear reactors including light water reactors, there are two approaches to permanent retention of core debris. The retention may be achieved either, in-vessel, within the primary system or, ex-vessel, external to the primary system but within the containment. The in-vessel core catchers are generally single or multiple plates with inclusion of sacrificial layers. Ex-vessel core catchers adopt large spreading compartment type catchers (e.g., EPR) or multiple crucible catchers (e.g. VVER). But in the case of fast breeders which are sodium cooled, because of hazardous reaction of sodium with air and water, main vessel has to be intact and in-vessel core catcher is the only option. Nevertheless, there are many possible design options which might enhance core debris retention. The choice of core catcher material and its configuration leading to its optimization is an important scientific task which needs to be addressed for future fast breeders and in particular SFRs.

2. Core catchers for SFRs

In the French sodium cooled reactors, Rapsodie had an external gas cooled outer vessel. Super Phenix-1 (SPX-1) had in-vessel catch trays which can accommodate only seven subassemblies. Heat transfer by natural convection in sodium pool above and below the internal core catcher in SPX-1 was evaluated by Le Rigoleur

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and Tenchine (1982). European Fast Reactor (EFR) has in-vessel catch trays, which can accommodate whole core debris. In the design of UK reactors, Dounreay Fast Reactor (DFR) had fuel dispersion cone to avoid lump formation and splash plates to direct the corium to core catcher plate to manage the thermal load, Prototype Fast Reactor (PFR) had a single layer of trays with retention capacity for entire core, with cooling provision underside of the plate. Commercial Demonstration Fast Reactor (CDFR) design had vertical standpipes attached to the core catcher plate to aid natural convection of sodium and avoid sodium dryout within the debris bed (Broadly, 1982; Waltar and Reynolds, 1980).

Ex-vessel core catcher can be considered as an additional provision only, apart from the in-vessel core catcher which serves to preserve the main vessel intact. Ex-vessel core catcher is generally added as an additional safety feature to prevent the reaction of sodium with concrete in the reactor vault but cannot replace the invessel core catcher in sodium cooled reactors. Main vessel integrity is mandatory for sodium cooled fast reactors unlike ALWRs where main vessel can be breached and core-melt allowed to fall into core catching crucibles or large spreading compartments. The idea of ex-vessel core catcher was tried for Fast Flux Test Facility (FFTF), in the design stage; but was later dropped due to space and other constraints. Forced cooling of the gap between main vessel and safety vessel is yet another viable additional safety option. KALIMER 150 which is a small metal fuelled Korean reactor is relying upon forced main vessel cooling for its decay heat removal. For larger reactors, forced air/nitrogen cooling may not be sufficient to cool the main vessel surface. In Phenix reactor, cooling pipes were wound around the safety vessel surface for forced convection heat removal (Mochizuki et al., 2013).

The in-vessel core catcher in the Indian PFBR consists of a heat shield plate and a core catcher plate made of SS316LN each of thickness 20 mm and separated by a sodium gap of 20 mm. It has a central chimney of diameter 500 mm and height 180 mm along with an inverted cone structure to aid the natural convection of liquid sodium from below the plate. The design safety limit is set at 923 K for the core catcher based upon creep considerations. (Sati et al., 2010). It was originally designed to withstand the thermal and heat load from a 7 subassemblies melting accident. Subsequent analysis predicts that it can contain the consequences of accident encompassing 19 subassemblies too (Roychowdhury, 2003). The vertical section of the main vessel with breached grid plate and core catcher containing the core debris, following a core melt down accident is illustrated in Fig. 1.

For future Indian SFRs, a core catcher which is capable of retaining, dispersing and cooling core debris from a whole core event is to be designed. Towards meeting this requirement, a multi layer core catcher is proposed. It is conceptualized based on the core catcher designs existing for ALWRs and modified to meet specific requirements of sodium cooled reactors.

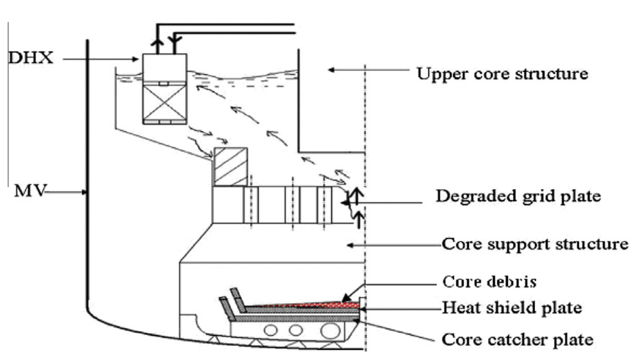

Fig. 1. Vertical section of PFBR main vessel with core catcher after a core melt down.

3. Performance enhancement of core catchers

There are several possible methods to improve the core catcher heat retaining capacity in SFRs. The performance of in-vessel core catcher can be enhanced by adopting new techniques such as

- Refractory coating on the core catcher plate.
- Multi tray concept.
- Multi layer concept.

Multi tray concept is planned to be adopted for the upcoming Japanese reactor JSFR, which is a loop type reactor. The other two concepts are still in nascent stage for SFRs and need rigorous analysis and careful evaluation of the material choice, to be of practical use in the future reactors. A passive ex-vessel core catcher can be additionally housed in the reactor cavity/vault as a diverse safety measure.

3.1. Refractory coating on catcher plate

This concept has been adopted for high power APRs (Kanga et al., 2007). A joint U.S.–Korean effort to design and evaluate the feasibility of an enhanced in-vessel core catcher for APR-1000 has been reported in literature (Condie et al., 2004). The core catcher consists of two material layers with an option to add a third layer, if deemed necessary: (i) a base material, which has the capability to support and contain the mass of core materials that may relocate during a severe accident; (ii) an insulator coating material on top of the base material, which resists interactions with high temperature core materials; and (iii)an optional coating on the bottom side of the base material to prevent any potential oxidation of the base material during the lifetime of the reactor. Results from scoping thermal and structural analyses suggest that an in-vessel core catcher is feasible with stainless steel as base material, MgO or ZrO with thickness up to 1 mm as the coating material with a 100 micron of bond coating with Nickel based alloy. This concept has not been tried with SFRs due to vulnerability of the coating peeling off because of corrosion in sodium environment. Experimental studies in liquid sodium could throw more light on the feasibility of such a core catcher for SFRs.

3.2. Multi tray core catcher concept for SFRs

The option to use multiple trays stems from the fact that if the total heat load can be distributed to several trays, it is easy to maintain plate temperatures within design safety limits. Sharma et al. (2008) have discussed the option of using a set of three trays. They have established that triple tray can dissipate a heat load of 25 MW without tray temperatures exceeding 923 K. Multi tray core catchers promise scope for invessel retention, but the height of the lower plenum may have to be increased which would entail more cost. Ensuring equal distribution of the core debris to all the plates too is a challenging task.

In JSFR which is a loop type reactor, it is proposed to use a multi tray core catcher (Sato et al., 2011). In order to facilitate tray-to-tray debris transfer, "debris guide tubes" are adopted. This structure consists of a hole surrounded by a vertical collar and allows pouring off of the excess debris above this collar. Precise design of this multi tray core catcher is underway for JSFR. Preliminary analysis showed that the decay heat from the100% fuel inventory would be transported successfully to the heat sink by natural circulation.

3.3. Ex-vessel core catcher

Several preliminary concepts for an Ex-Vessel Core catcher (EVCC) were evaluated for FFTF including a completely passive