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ORIGINAL ARTICLE

Technology Development of Core Catcher for Indian Advanced Nuclear Reactors

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Abstract

Considering the carbon footprint and demand for electricity for a growing population of India, nuclear energy has to play a major role in the energy mix. Currently, India produces just around 3% of electricity from nuclear in the energy mix, which has to multiply by several folds in near future. Of course, the safety of current fleet of nuclear reactors are excellent; however, the core melt accidents at TMI-2, Chernobyl and the recent Fukushima have raised concerns on the safety of nuclear reactors. Soon after the TMI-2 and chernobyl accidents, advanced nuclear reactors (Gen III and III^{+}) were designed with innovative safety systems to practically eliminate core melt accidents, and some are being built with mitigatory features against core melt accidents such that the impact in public is minimum. In the Indian context, PHWRs are the main workhorse of the nuclear power at present. These reactors have several tons of cold water in calandria vault which can cool the corium debris by in-vessel retention in case of a very low probable severe accident. Passive safety systems have been designed in other advanced nuclear reactors which are robust enough against occurrence of core melt accidents. For further enhancement in safety in these advanced nuclear reactors, a core catcher is required to contain and cool the core melt for extended period and reduce the radioactivity release to public domain substantially, so that the public is not affected. The core melt is a complex mixture of nuclear fuel, clad material, structural material, control rod materials, etc. (also known as corium) and the corium forms at very elevated temperature (more than 3000 K). Retention and cooling of several tons of this aggressive material to very low temperature is technologically challenging and scientifically complex. The objective of this paper is to present technology of an innovative core catcher with the sacrificial material which can cool and absorb the enthalpy of high temperature corium and facilitate density inversion to cause low density oxide material to move to the top and high density metallic components to remain at bottom of core catcher, known as "density inversion". The density inversion is very important from undesirable hydrogen generation point of view. In addition, the melt forms a stable crust enveloping the heat generating high temperature melt like a "capsule", so that when water is added to the top of melt to cool it, the stable crust prevents water ingression into the bottom of core catcher and eliminates metal water interaction to cause hydrogen generation and create eruptions for aerosols to leave. The phenomenology of crust formation, growth and its stability by cooling the melt from top and side of core catcher, and elimination of water ingression is difficult to predict and scientifically unresolved. The geometry of the core catcher and cooling strategy directly affect the performance of core catcher. To address it, several simulated tests have been conducted to understand the physics of corium coolability, water ingression, and melt inversion. These tests helped to optimize the design of the core catcher to accomplish the objectives of (1) containing and localizing 100% core melt inside the core catcher, (2) to prevent the re-criticality of molten core, (3) to quench the melt within stipulated time, and (4) to stabilize the melt inside core catcher for sufficiently long time (several months). This paper provides a review of the series of tests done for core catcher design optimization and validation.

Keywords Core catcher · Severe accidents · Advanced reactors

Introduction

In design of nuclear power plants, safety is the primary consideration. To accomplish safety, the nuclear power plants are designed with multiple layers of

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defence-in-depth (DiD) (IAEA 1996) with different levels from 1 to 5. One of the objectives of DiD is to provide a series of multiple physical barriers to retain radioactivity if released due to failure of previous barrier. Furthermore, if the provisions dealing with safety at a given level fail to control the evolution of a sequence of events, the subsequent level will come into play. Therefore, the strategy of the DiD is based on the principle of reduction and limitation of consequences of incidents and accidents. The different levels are mutually independent, the general objective is to ensure that a single failure at one level of defence, and even combinations of failures at more than one level of defence, do not propagate to jeopardize DiD at subsequent levels. The DiD thus consists of a hierarchical deployment at different levels of provisions (equipment and procedures) to maintain the effectiveness of physical barriers placed between radioactive materials and the public or the environment, in normal operation, anticipated operational occurrences and in case of accidents.

In view of the above, the engineered and inherent safety features of the nuclear reactors do not allow the incidents to progress into accidental domain. However, in spite of these robust safety features, extremely low probability severe accidents may occur which result in significant core degradation and melting of core. Whatever could be the initiating events, a severe accident occurs only when the ratio of heat generation rate exceeds that of heat removal rate and is unable to be controlled by safety systems. The nuclear fuel is unable to get cooled and gets damaged leading to its melt down. The severe accident phenomena are complex due to the interactions of core-melt with structures, the coolant (water); fission products release, their transport and deposition on reactor structures. The molten core (corium) can cause large ablation of structures, vapour explosions having potential to damage the structures, structural concrete melting and gas generation, containment pressurization, dispersion of hot melt debris, early containment failure, etc.

In the history of nuclear reactors, three major accidents leading to core melt down has occurred so far; the first one occurred in TMI-2 in 1979, the second one occurred in Chernobyl in 1986 and the last one occurred in Fukushima in 2011.

The TMI-2 gave a serious blow to nuclear industry; it was unbelievable that a minor event could lead to a major accident resulting in significant core damage and melt down in less than 130 min just due to a valve failure, faulty operators' actions resulting in no water injection to vessel to cool the fuel. The nuclear-business suffered a lot; 129 plants were approved before TMI-2 accident, only 53 were completed, orders of51 US nuclear plants were cancelled from 1980 to 1984. No new nuclear plant projects were started in the US between the 1979 and 2012, a period of 33 years (Sehgal 2011).

Chernobyl was the worst ever severe accident that has occurred so far. The accident impact was so large that most of radioactivity could move far away and got deposited in Ukraine, Belarus, Russia and even to far away European nations like to Sweden. Magnitude of fission product release was higher than Hiroshima bomb. Accident was terminated by covering the core region with 5000 tons of sand, clay and boron bearing material. Clean-up was performed with help of scientific, civilian and military personnel. Costs of clean-up were around 7 billion rubles (that time rubble was more expensive than dollar). Concerns developed in general public that a nuclear reactor can explode. Legal cases increased the capital cost of plants; rigorous inspection and review on operating plants were taken. All these reduced capacity factor of plants to 50–70%; and resulted in high cost of N-electricity (Sehgal 2011).

In Fukushima accident, 3 on-site workers died following the earthquake and tsunami and several more were injured. No fatalities were reported from exposure to radiation. By 23 May, 2011, almost 7800 workers were deployed and received an average dose of 7.7 mSv, 30 had doses more than 100 mSv and some of the latter might have exceeded doses of 250 mSv (Povinec et al. 2013). More than 200,000 inhabitants from the vicinity of the site and potentially affected areas were forced to evacuate. Tens of thousands of people were staying in temporary residences even after several months, without knowing when they can return, because there was no clear plan yet for allowing displaced residents to go their homes. There were nearly 600 non-radiological deaths that were indirectly caused by fatigue or aggravation of chronic illness due to the disaster and mandatory evacuation (Hoeve and Jacobson 2012). According to TEPCO, the cost of clean-up including compensation to victims and resettlement may reach up to a colossal figure of US$ 125 billion. Other sources' estimates even as high as US$ 250 billion including US$ 54 billion to buy up and decontaminate all land within 20 km of the Fukushima plant, US$ 8 billion for compensation payments to local residents whose jobs or home lives have been affected, and up to US$ 188 billion to scrap the plant's reactors (Koo et al. 2014).

In summary, the consequences of severe accident in nuclear power plants are:

- Risks to life is quite small, in fact negligible as compared to any industrial accidents or even road accidents;
- Large financial risk;
- Psychological risk—difficult to quantify.

In view of the above, management of core melt accidents has become an integral part of advanced nuclear reactor designs as a safety measure towards minimum impact to the public, which can be accomplished using dedicated core catchers to cool and retain the molten core for extended period. Initially, for low power reactors (less than 600 MWe), the idea of in vessel melt retention, i.e., to retain the molten corium within the reactor vessel by cooling the vessel externally was proposed in early nineties (Tuomisto and Theofanous 1994). However, this was found to be infeasible for large size reactors due to the limitations of natural convection cooling to remove high thermal flux. Some of the advanced reactors were proposed to have in-vessel core catchers. However, due to the complexities in the cooling strategies of the molten corium inside the reactor vessel, distribution of various components in the vessel and the distribution of the heat flux over the boundaries of the melt pool, it was impossible to incorporate the core catcher in the reactor vessel of the high capacity reactors. This gave rise to the concept of the ex-vessel core catcher. Kukhtevich et al. (2001) presented an ex-vessel core catcher for the VVER. It consists of a large crucible placed beneath the reactor pressure vessel to collect the relocated molten corium in case of the failure of reactor pressure vessel. The crucible is cooled externally by flooding the reactor cavity with water injected passively. The crucible is partly filled with the sacrificial material, which melts and mixes with the corium, thus reducing the enthalpy in the melt and yielding heat fluxes at the surface of the crucible below the critical heat flux, which can be removed by the external cooling.

Similar concept is adopted for core melt cooling of a BWR proposed by Hamazaki (2009). Based on this concept, in ESBWR, a core catcher, called Basemat Internal Melt Arrest and Coolability device (BiMAC) is used to cool the melt is case of a severe accident (Kamei et al. 2014). This system consists of flooding lines from Gravity Driven Cooling System (GDCS) which feeds water to main header in the cavity. Water is distributed through several inclined pipes. A refractory material is laid on top of the BiMAC pipes so as to protect against melt impingement during the initial melt relocation.

A different approach to increase the heat transfer area is used in the European Pressurized Reactor (EPR) (Fischer 2004). The corium melt is collected in the reactor pit, pre-conditioned with sacrificial concrete and subsequently spread onto a large surface (e.g., 170 m^2) of a special compartment to obtain a thin layer that can be cooled by addition of water from the top.

Another core-catcher concept based on the fragmentation of corium and porosity formation has been developed at Forschungs Zentrum Karlsruhe (FZK) (Tromm et al. 1992) and was investigated further within the COMET project (Alsmeyer and Tromm 1995; Tromm et al. 1992, 2001; Alsmeyer et al. 2000). After erosion of a sacrificial concrete layer, the melt is passively flooded from the bottom by injection of coolant water. The water is forced up through the melt, the resulting evaporation process of the coolant water breaks up the melt and creates a porously solidified structure from which the heat is easily removed.

The core catcher technology is proprietary, so limited scientific information is available in open literature with regard to composition of sacrificial material, geometry of core catcher, experimental data and scientific insights.

In view of this, a new core catcher has been developed by the authors, which has following unique features as compared to other existing concepts:

- Optimized geometry for effective cooling, elimination of water ingression, minimum core catcher wall temperature.
- Unique sacrificial material which has been optimized based on extensive experiments to achieve density inversion.
- Passive water recirculation system enabling natural circulation with the use of downcomers to cool the corium for extended period.

The details of the core catcher are explained in following sections.

Objectives of the Core Catcher

The objectives of core catcher are:

- To contain and localize 100% core melt inside the core catcher.
- To prevent the re-criticality of molten core.
- To quench the melt within stipulated time.
- To stabilize the melt inside core catcher for sufficiently long time (several months).
- To minimize further generation of hydrogen.

Science and Technology Behind Core Catcher

How a Core Catcher Works?

A core catcher consists of mainly a vessel placed below the core. The vessel has a cavity which is lined with a material which is commonly termed as sacrificial material. The molten core (corium) falls on the sacrificial material and causes its ablation. Mixing of sacrificial material in the melt brings down the enthalpy of corium and assists in spreading and coolability. The melting of a large volume of the sacrificial material in the corium reduces the specific volumetric heat release. The endothermic interaction between the corium melt and the sacrificial material reduces the general temperature level in the terminal melt.

Corium is then flooded with water to achieve its coolability (Kukhtevich 2001).

The core catcher requires in-depth understanding of physics behind core melt interactions with sacrificial material (SM), the ablation behavior of SM, and the coolability of the mixture. This enables development of technology of core catcher for management of core melt accidents. The technology development road map for core catcher is represented in Fig. 1.

For Indian Advanced Heavy Water Reactor, an innovative core catcher based on the above philosophy has been developed. To arrive at the final design, several studies have been performed which are discussed below.

Selection of Flooding Strategy

To device effective strategy for cooling of corium inside core catcher, several studies were performed:

1. Top flooding
2. Bottom flooding
3. External vessel cooling with top flooding

1. **Top flooding:** Top flooding is one of the simplest approach in which the corium collected in the core catcher is cooled only from the top by flooding it with water. To ensure the coolability of several tons of molten corium, the cold water must ingress into the meltpool to take the heat away and cool it. The experiments showed that a layer of crust is formed at the top of corium pool on contact with cold water thereby limiting the heat transfer to the top water pool (Kulkarni and Nayak 2014). Coolability of corium thus is limited by the extent of water ingression in melt pool.

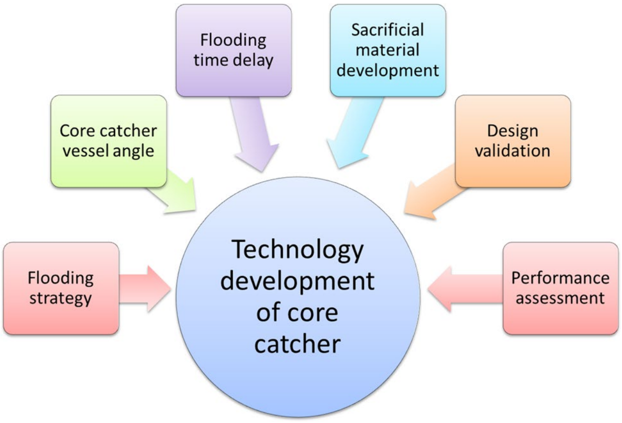


Fig. 1 Technology development roadmap for core catcher

Science behind water ingression (Nayak et al. 2009)

During top flooding, when water is flooded on the top of corium, a crust is formed. This crust is subjected to thermal and mechanical stresses due to differential temperature and its own weight. When the stresses exceed the strength, the crust breaks and forms a debris bed. The water ingresses into the debris by gravity and quenches it. During this process, the water boils and steam moves up through the debris. The upgoing steam encounters the down coming water in counter-current directions. The experiments have shown that, the water ingression, in fact, stopped after some depth and did not progress till bottom resulting the large fraction of melt to remain uncooled.

Why Water Ingression Stops?

As depth of water ingression increases, it means depth of debris flooded with water increases. This water takes the heat produced in the debris, i.e., stored heat and decay heat. However, due to increased debris depth as disintegration of crust proceeds, the path resistance increases for water to ingress further down to cool the top of the crust which is at the bottom of debris. Therefore, the crust top surface temperature progressively increases as time proceeds. Since bottom part of crust is always at liquidus temperature of melt, the thermal gradient inside the crust becomes lower and lower with time, which reduces the thermal stresses inside the crust. After some time, the stresses become so low to disintegrate the crust further. That is why water ingression stops after some depth.

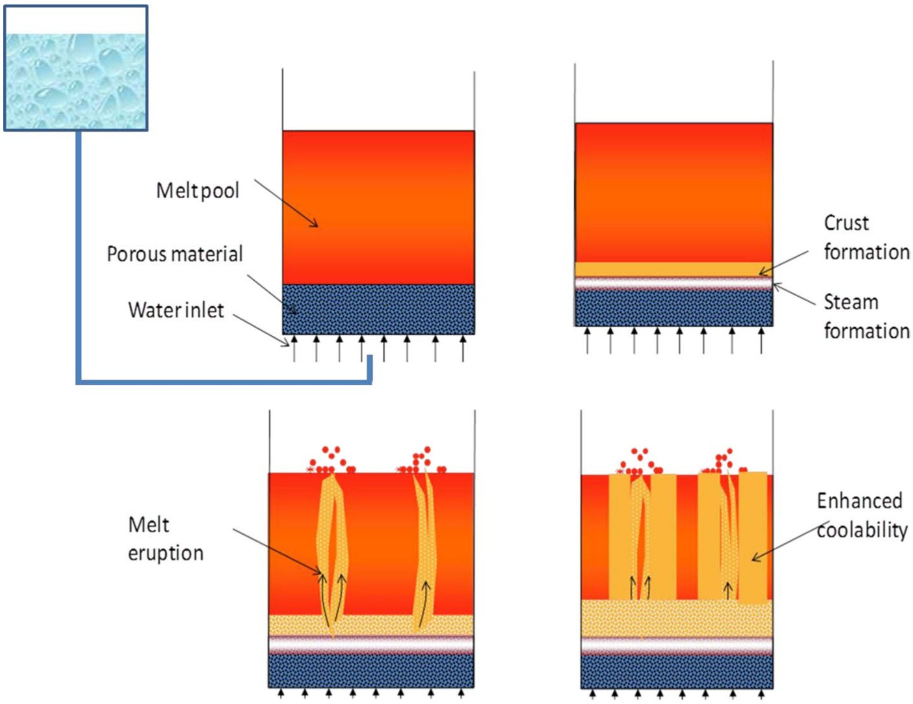
On What Parameters does Water Ingression Depends?

Through extensive experimentation and model development (Kulkarni et al. 2011), it has been demonstrated that, the coolability is influenced by a parameter $E\alpha/\sigma$ called as “Crust Break Parameter”. Where, E is Young’s modulus, α is thermal expansion coefficient and σ is strength of the material. Higher is the parameter, better is the coolability. Thus, it can be stated that corium coolability in top flooding is a material dependent phenomenon.

In addition, there is no guaranteed coolability under top flooding alone. Hence, this is not a reliable strategy for corium coolability

2. **Bottom flooding:** Bottom-flooding is another approach used for ensuring melt coolability. In this approach, the water is introduced into the melt from the bottom using nozzles as shown in Fig. 2.

Fig. 2 Corium coolability under bottom flooding



Science Behind Bottom Flooding

Introduction of water below the melt forms steam due to heat transfer between melt and water at the bottom of the melt. Due to steam pressure, the steam erupts through the melt making it a porous structure. The consequent porous debris formation and co-current flow between steam and water enhances the coolability of the melt. Several experiments have been conducted in this regard (Kulkarni and Nayak 2013; Singh et al. 2015) and it has been demonstrated that, the bottom flooding approach is the most effective technique for quenching and cooling the melt. It has also been demonstrated that, coolability under bottom flooding depends upon thermal–hydraulic parameters like inlet water velocity, pressure, nozzle diameter and melt temperature etc.

However, the enhanced coolability in case of bottom flooding leads to larger steam generation rate that is an order of magnitude higher than that observed in top flooding. This may result in high rate of pressurization of containment. Moreover, the formation of channels inside the molten pool increases the contact area between un-oxidised metal and steam, which may lead to exothermic metal–water reaction and hydrogen production. Hence, this cooling strategy was not pursued.

3. **External vessel cooling with top flooding:** Consequently, an approach is needed which ensures controlled rate of coolability while minimizing metal–water reaction to eliminate hydrogen generation. This is accomplished by indirect cooling of vessel with delayed top flooding.

For this an innovative core catcher has been developed, a schematic of which is shown in Fig. 3. The core catcher consists of a vessel having inclined plates at the centre. The inner walls of core catcher are lined with a special material called as sacrificial material. The corium is contained in the cavity of the core catcher. The water supply to the core catcher is provided by in-containment water storage tank (ICWST). A line from ICWST injects water from the bottom of the core catcher. The water rises along the sides of the core catcher from bottom as shown in figure. Two shrouds are provided which allow the passage of water from bottom to the top of the core catcher. Several downcomers are provided which allow continuous natural circulation of the water.

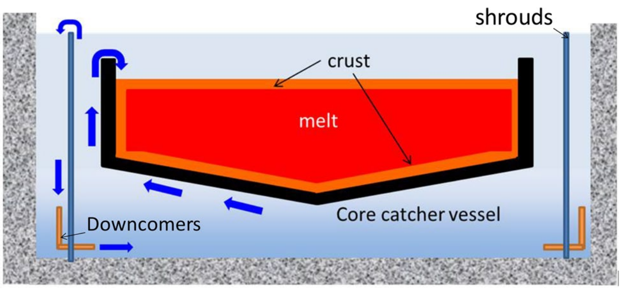


Fig. 3 Corium coolability with indirect cooling

This strategy ensures that a low temperature crust is formed all around the melt to encapsulate the molten corium, and thereby minimizing the chances of vessel failure due to low temperature crust in contact with the vessel, as shown in Fig. 3. The top flooding of water is typically done to ensure that the radiation heat load to containment from the top of corium pool is minimized. Besides, the stable crust so formed does not allow the water to ingress inside the bulk of melt.

Issues in External Vessel Cooling with Top Flooding

After top flooding, due to differential thermal expansion of core catcher vessel and crust, a crust-vessel gap may be created. Water ingression through this gap may lead to formation of steam which can puncture through the crust formed around the melt. This results in formation of channels inside the bulk of the melt similar to bottom flooding. This leads to enhanced coolability, enhanced steam production rate and a greater likelihood of metal–water reaction. To avoid this deleterious scenario, water ingression is to be avoided. This requires optimization of bottom angle of vessel.

In addition, corium contains both metallic as well as ceramic components. When corium falls on sacrificial material, the interaction products form low density oxidic compounds. These compounds rise at the top and metallic components sink at the bottom which is termed as “density inversion” (Munot et al. 2019). This is very important phenomenon as when water is flooded on the top, there should not be any metallic components at the top to avoid metal water reaction. Hence, it is necessary to ensure density inversion takes place before water is flooded. This is achieved by proper composition of sacrificial material and allowing sufficient time of interaction by delaying the flooding. Table 1 gives the summary of outcomes of flooding strategies.

Table 1 Summary of different flooding strategies

Strategy	Simple design	Complete coolability	Avoiding containment pressurization
Top flooding	☑	☒	☑
Bottom flooding	☒	☑	☒
Top flooding with external vessel cooling	☑	☑	☑

Hence, top flooding with external vessel cooling was selected as flooding strategy in our core catcher design.

Optimization of Bottom Angle of Core Catcher

After finalizing the flooding strategy, the external vessel is designed in such a way that, the bottom plates are inclined from the centre to enhance the buoyancy driven flow at the bottom of vessel. The angle between bottom plates of the core catcher plays an important role in elimination of water ingression and melt eruption.

To determine the optimum angle, several experiments were conducted with a corium stimulant material (Ganesh et al. 2020), i.e., $CaO–B_2O_3$ in the ratio of 70:30 by weight to understand the phenomena of water ingression by varying the bottom angle of the core catcher vessel. During these experiments, several corium simulants were used. A summary of simulant materials is given in Table 2. As seen from Table 2, it is seen that, the most important property, the thermal diffusivity of the simulant materials is similar to the actual corium. Hence, the transient temperature response of the simulant is similar to corium. The inclination angles considered for this study were 10°, 20° and 30° with the horizontal. Schematic of test section is shown in Fig. 4.

The experimental test facility consisted of a furnace, a test section assembly, heater for simulating decay heat and sensors for measurement of temperature, inlet water flow, level and steam flow rate. The melt is delivered to the test section at around 1200 °C through a funnel. Three different test sections were fabricated, each with a different bottom plate angle, viz.: 10°, 20°, and 30°. The capacity of all the three test sections was about 4 L. The schematic of the experimental facility is shown in Fig. 5.

It is seen that, at 10° angle, there is no water ingression, whereas at 20°, water ingression from the sides were observed characterized by sharp drop in melt temperatures. Similar behavior is observed at 30°.

Table 2 Properties of corium simulant materials

Property	Corium	Sodium borosilicate glass	$CaO + B_2O_3$	$ZrO_2 + CeO_2 + Fe + Al_2O_3$
Density (kg/m^3)	8800	2400	2500	5074
k (W/mk)	2.88	1	2.0	2.3
Cp (J/kg K)	565	730	1530	700
Volumetric expansion coefficient β (/K)	1.05×10^{-4}	1.03×10^{-4}	1.03×10^{-4}	1.04×10^{-4}
Thermal diffusivity α	5.79×10^{-7}	5.71×10^{-7}	5.22×10^{-7}	6.4×10^{-7}

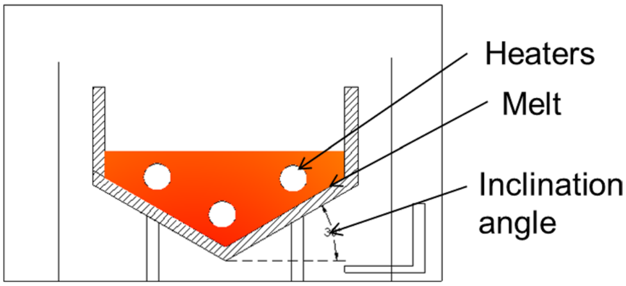


Fig. 4 Schematic of the test section

On the basis of experiments conducted on the three test sections with varying bottom plate angle, following conclusions were drawn:

- Melt coolability is ensured in all the three cases.
- Outside core catcher vessel surface temperature never exceeds 100 °C in any of the three cases in presence of water.
- The ingression is observed in the case of 20° and 30° test section. Water ingression is not observed in the case of 10° test section.
- Post-test examination also confirmed the water ingression with presence of melt globules in 20° and 30° test section and presence of widespread debris at the top and localized debris through the depth.
- Post-test examination of 10° test section revealed the presence of hard crust at the bottom and top, indicating that ingression did not take place.

It was thus concluded that the core catcher with 10° as the inclination angle of the bottom surface leads to no ingression of water while maintaining the coolability of the melt.

Evaluation of Flooding Time Delay for Stable Crust Formation

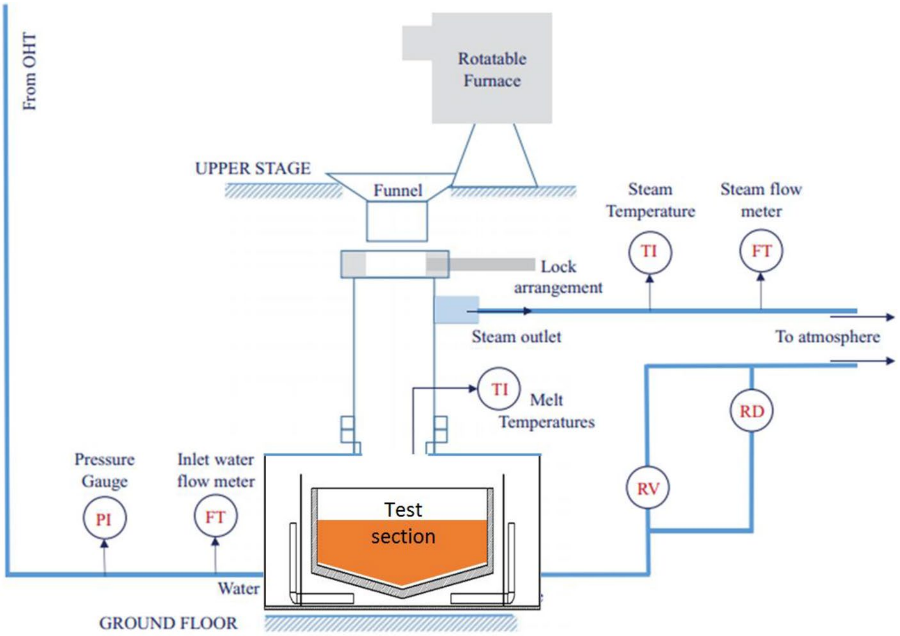
To study the effect of flooding delay on stable crust formation, experiments were conducted in the same facility as described in "Optimization of Bottom Angle of Core Catcher". The onset of flooding was done immediately, with 15 and 30 min delay after pouring of the melt to allow the melt inversion and formation of stable crust.

Following points are concluded from the study (Ganesh et al. 2020):

- Immediate flooding of water in the cavity after melt pouring causes melt eruption and rapid quenching of melt, both of which are undesirable due to high hydrogen and pressure loads that will be imposed on the containment.
- Delayed flooding (after 30 min) of water enables the development of stable crust enclosing the melt and consequently, a controlled coolability of melt can be achieved without direct melt–water contact.
- The water ingression into the bulk of the melt changes the mode of heat transfer from indirect contact heat transfer through the vessel wall to direct contact heat transfer between the melt and water.

The results of this study help in refining the severe accident management guidelines for core catcher in a way to make informed operator decisions so as to avoid extra

Fig. 5 Schematic of the experimental test facility



hydrogen and pressure loads in the containment while at the same time ensuring melt coolability. This study also helps to understand the significant role played by crust in controlled melt coolability. It establishes that melt coolability even if achieved without presence of crust can be deleterious to the containment due to the pressure loads imposed, thus emphasizing the necessity of ensuring the stable crust around the sides of the melt in all possible conditions under top flooding. For the top crust, even if its integrity cannot be ensured due to high surface area and the bending moments imposed on it, the counter current flow limitation ensures that water does not ingress deep into the bulk of the melt (Fig. 6).

Development of Sacrificial Material for Core Catcher

Sacrificial material plays very important role in the core catcher. The melt is initially relocated on the sacrificial material itself. The characteristics of sacrificial material required are as follows:

- High specific heat capacity and latent heat of fusion than corium so as to absorb the large heat content of the corium. Typically, 50 tons of sacrificial material should be able to absorb heat from 100 tons of corium and bring down its temperature to about 1700 °C. (Which requires specific heat of ~ 750 J/kgC and latent heat of the order of ~ 450 kJ/kg).
- It should have much lower thermal conductivity than structural material so as to prevent thermal shock on the core catcher structures
- Higher thermal diffusivity so as to diffuse heat from corium.
- It should be miscible with corium melts.
- Should form lower density components which will stratify at the top and cause the metallic components of the mixture to settle at bottom.
    - This will avoid the metal water interaction at the top when water is flooded on top of core catcher.
    - The mixture compound should be structurally stable, so that it will form a stable crust at the top and contain the corium inside.
- The sacrificial material should be able to oxidize the metallic zirconium so as to reduce the hydrogen generation potential.
- The sacrificial material should be thermally, chemically and radiologically stable during normal operation.

Considering all these factors, the composition of sacrificial material was worked out as given in Table 3.

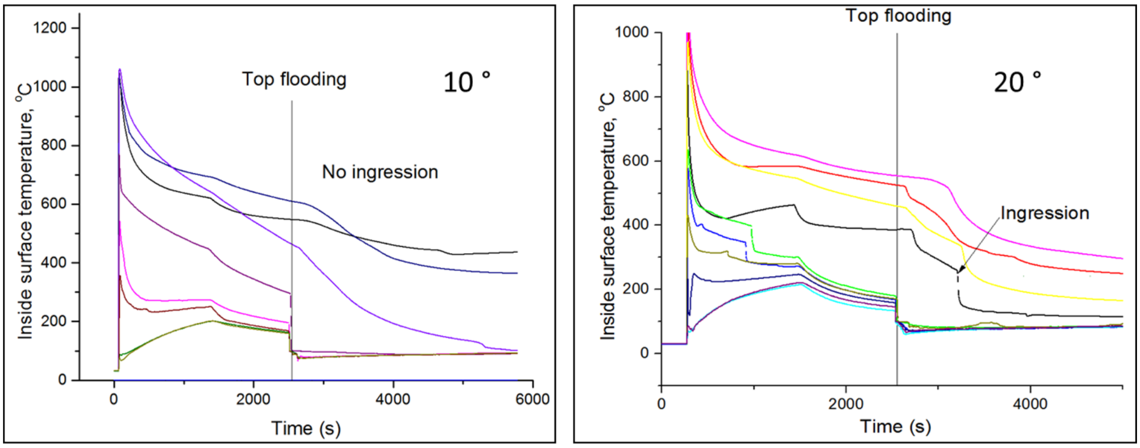
A sample sacrificial material brick is shown in Fig. 7.

Design Validation of the Core Catcher

The molten corium contains both stored heat (due to its high temperature) and decay heat. The stored heat is primarily dominant when the melt temperatures are very high (more than 1800 K). At relatively lower temperatures the decay heat becomes dominant. This happens after the ablation

Table 3 Sacrificial material composition

Oxide	Weight %
Fe_2O_3	57–58
Al_2O_3	17–20
SiO_2	4–6
Boron oxide	~ 1



(a) (b)

Fig. 6 Temperature history in **a** 10° and **b** 20° bottom angle

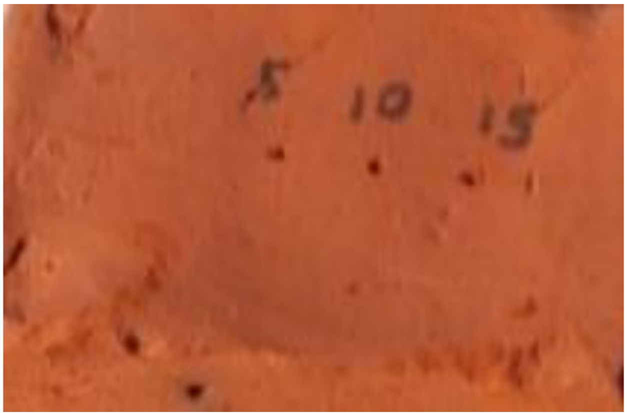


Fig. 7 Sacrificial material brick

of sacrificial material is complete; the sacrificial material absorbs the heat content of the corium resulting in reduction in its temperature.

Integral experiments were conducted for demonstrating corium coolability in core catcher for both the regimes as mentioned above. The details are explained below.

Corium Coolability in Stored Heat Dominated Regime at Prototypic Condition (Munot et al. 2019)

The objectives of these integral experiments were mainly to:

- Demonstrate the corium–sacrificial material interaction and density inversion.
- Demonstration of corium coolability at prototypic condition with flooding strategy as envisaged with 550 kg prototypic melt at above 2500 °C.

The test section consists of scaled down core catcher situated inside a water tank, delivery port and a water inlet. The test section is situated below the melt delivery vessel. Figure 8 shows the schematic of the experimental setup and actual test setup. The scaled core catcher schematic including the core catcher vessel, shroud plate and downcomer are shown in Fig. 9a and the thermocouple location is shown in Fig. 9b.

Sacrificial material is arranged inside the core catcher vessel in the form of bricks. The arrangement of bricks is shown in Fig. 10.

The test section is instrumented using K-type and C-type thermocouples to measure the temperature at various locations. A molybdenum wire was placed in the delivery port of the melt delivery system. In addition, 32 K-type thermocouples were also embedded in bricks at different depths from which the ablation and progression of melt front was tracked.

The thermite reaction was initiated remotely by electrically heating. Once started, the thermite reaction is self-sustaining. Water is pre-filled in the core catcher tank to a

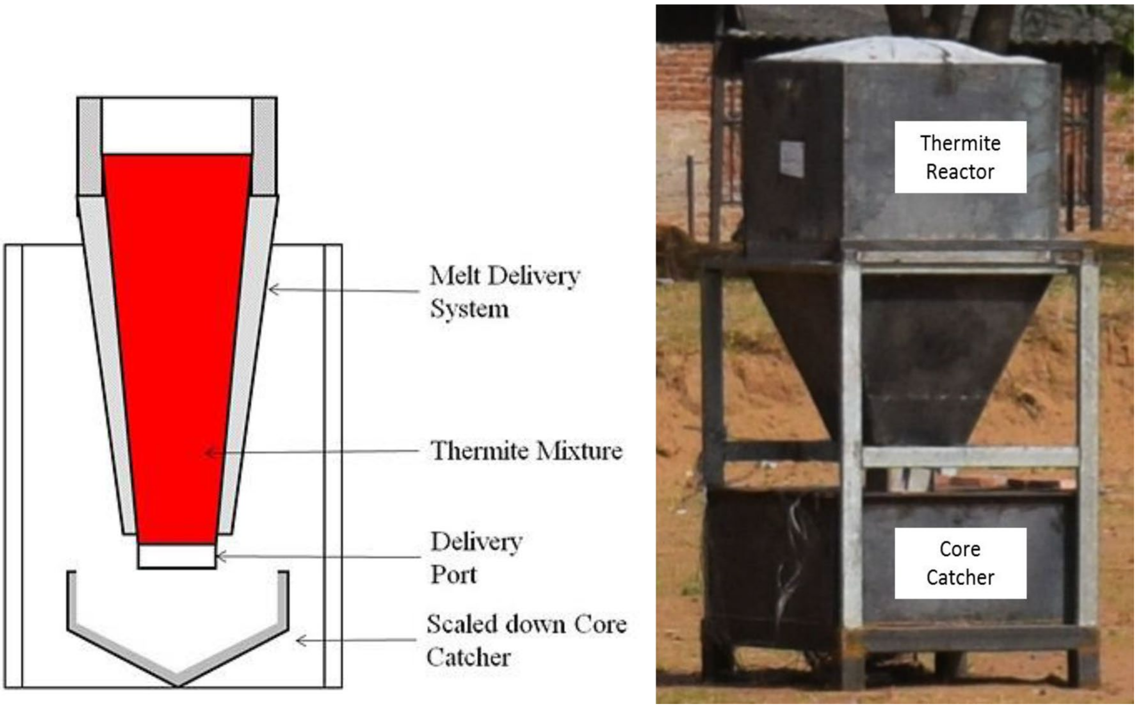
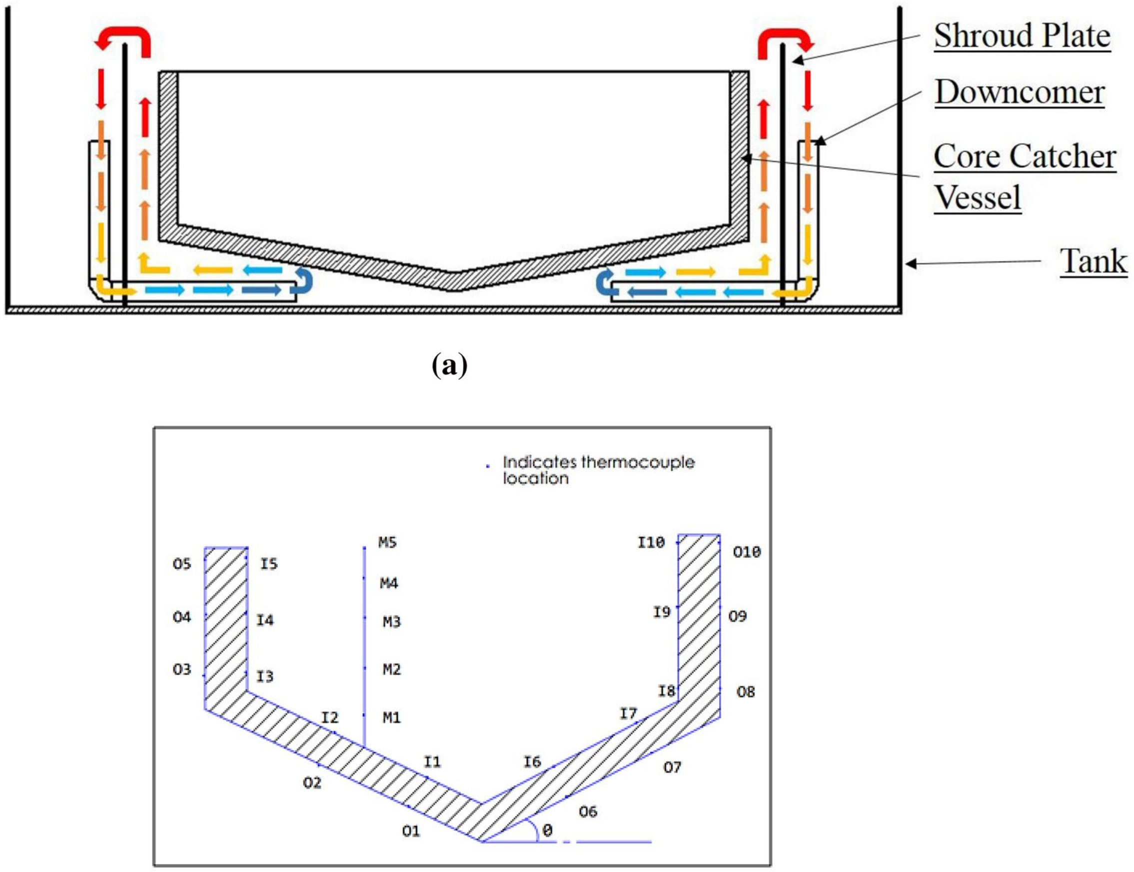


Fig. 8 Schematic and actual test sections



(a)

(b)

Fig. 9 **a** Schematic of the core catcher vessel and the test section assembly. **b** Schematic of arrangement of instruments

Fig. 10 Arrangement of the arrangement of sacrificial material in the core catcher cavity

set level, about 100 mm from the top which is the melt level in the simulated core catcher.

The melt delivery to the test section occurs through a delivery port. A C-type thermocouple was located just at the end of the delivery port to indicate the onset of melt delivery to the test section. After about half an hour from melt pouring, water is flooded into the cavity such that the core catcher is flooded from the top. This time delay is required for the simulated corium to interact with sacrificial material and undergo melt inversion. The water is continuously replenished as the level drops due to boiling.

The melt poured in the test section was indicated by a rise in temperature of C-type thermocouples located in the melt cavity, with the readings reaching the saturation value of 2500 °C in after few seconds, as shown in Fig. 11. In addition, the molybdenum placed in the delivery port melted indicating that the minimum temperature of the thermite melt was more than 2500 °C.

Figure 12 shows vessel outer surface temperatures. In this integral experiment, as a part of severe accident management strategy, water was initially filled up to the level of O3. Thus,

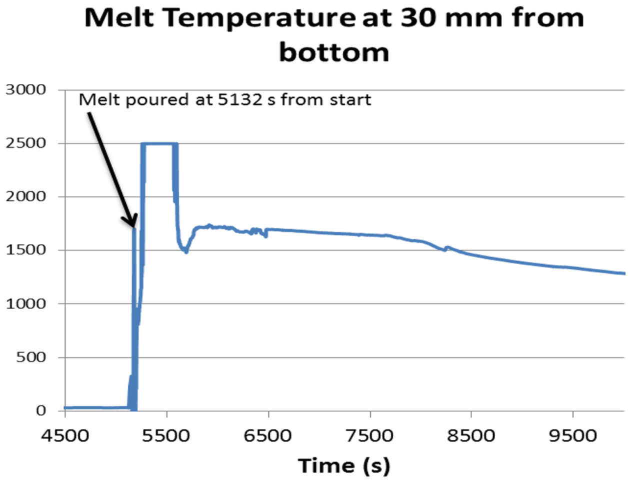


Fig. 11 Measured melt temperature in the core catcher

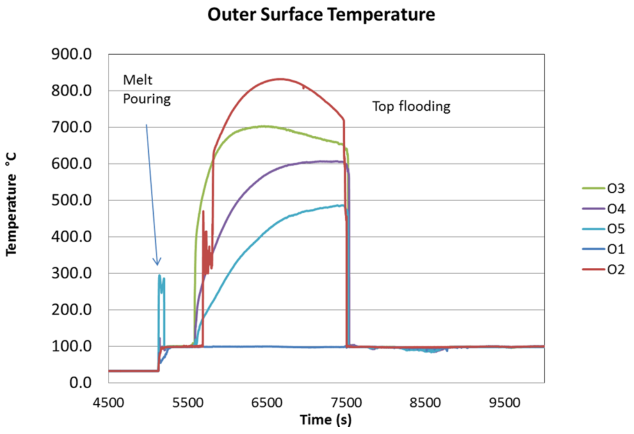


Fig. 12 Temperature of outer core catcher vessel wall

initially, the temperature of thermocouples O1 and O2 are found to be within 100 °C. After the boiling off of water, the water level drops below the level of O2 thermocouples leading to rise in temperature. The thermocouples O2–O5 show temperature more than 100 °C as they are uncovered. The thermocouple O2 shows highest rise as it is in close proximity of the melt. The thermocouple at O1 is submerged and shows temperature near to water surface temperature.

Flooding to the top of melt was initiated after 30 min of melt pouring. Subsequently, at 2300 s, drop in all outer vessel surface temperatures was observed. After the completion of top flooding, the water level was kept constant in the test section. The vessel outer surface temperatures were found just above 100 °C.

Ablation Rate of Sacrificial Material The rate of ablation of sacrificial material and the depth of ablation was interpolated from the measured temperature data by thermocouples embedded at different depths in the sacrificial bricks. The K-type thermocouple reading reaching saturation value (1400 °C) is taken as an indication of melt front reaching that particular point. The melt front progression with time is given in a series of plots, as shown in Fig. 13.

It can be observed from the plots, the high temperature melt preferentially ablates the corners of the sacrificial material rapidly within the first 50 s. The rate of ablation is the highest at the bottom corner as compared to other points, with the melt front reaching the inner wall in about 300 s after ablating around 100 mm of sacrificial brick matrix at the left lower corner as compared to only 25 mm of bricks being ablated in the same time in other areas of the cavity.

At about 400 s, substantial ablation can be observed with only 20–25 mm of sacrificial material surviving in selected locations of the core catcher. Post test analysis showed that, at about 500 s from the pouring of melt, almost all the sacrificial material inside the core catcher cavity is ablated.

Post-test observations revealed the formation of ceramic hard crust at the top, as shown in Fig. 14. Multiple cavities were also observed at the top, where water had ingressed up to a depth of 20 mm on an average, as shown in Fig. 14. Cavities in some places were observed up to a depth of about 40 mm. No gap was observed between vessel inner wall and melt crust which avoided ingression of water via the gap into the bulk of the melt matrix.

Summary: Initial Corium Coolability and Role of Sacrificial Material Ablation Melt coolability and ablation experiment was carried out using 550 kg of corium simulants at 2500 °C with oxide sacrificial material in the form of bricks arranged in a step pattern in the core catcher cavity. Following insights were obtained from the study:

1. Boiling heat transfer is capable of removing heat from the outer vessel wall, with the temperature not exceeding 100 °C with external water cooling.
2. The entire sacrificial matrix is ablated in about 500 s, with the rate of ablation being the highest at the lower corners of the cavity. The highest ablation rate in depth was observed as 0.75 mm/s within 50 s of melt pour and an average ablation rate of 0.18 mm/s was observed.
3. Formation of stable ceramic crust at the top limits the water ingression at the top surface to a range of few centimetres, while the stable crust adherence to the side wall and absence of vessel wall-crust gap ensures that water does not ingress from the side to the bulk of the melt. This would aid in preventing water–metal reaction.
4. The entire melt is cooled within 3.5 h from the time of pouring of melt keeping the vessel wall temperature under 100 °C. This signifies the stable cooling of melt, thereby minimizing the rate of steam production and containing the melt in surrounding stable crust.

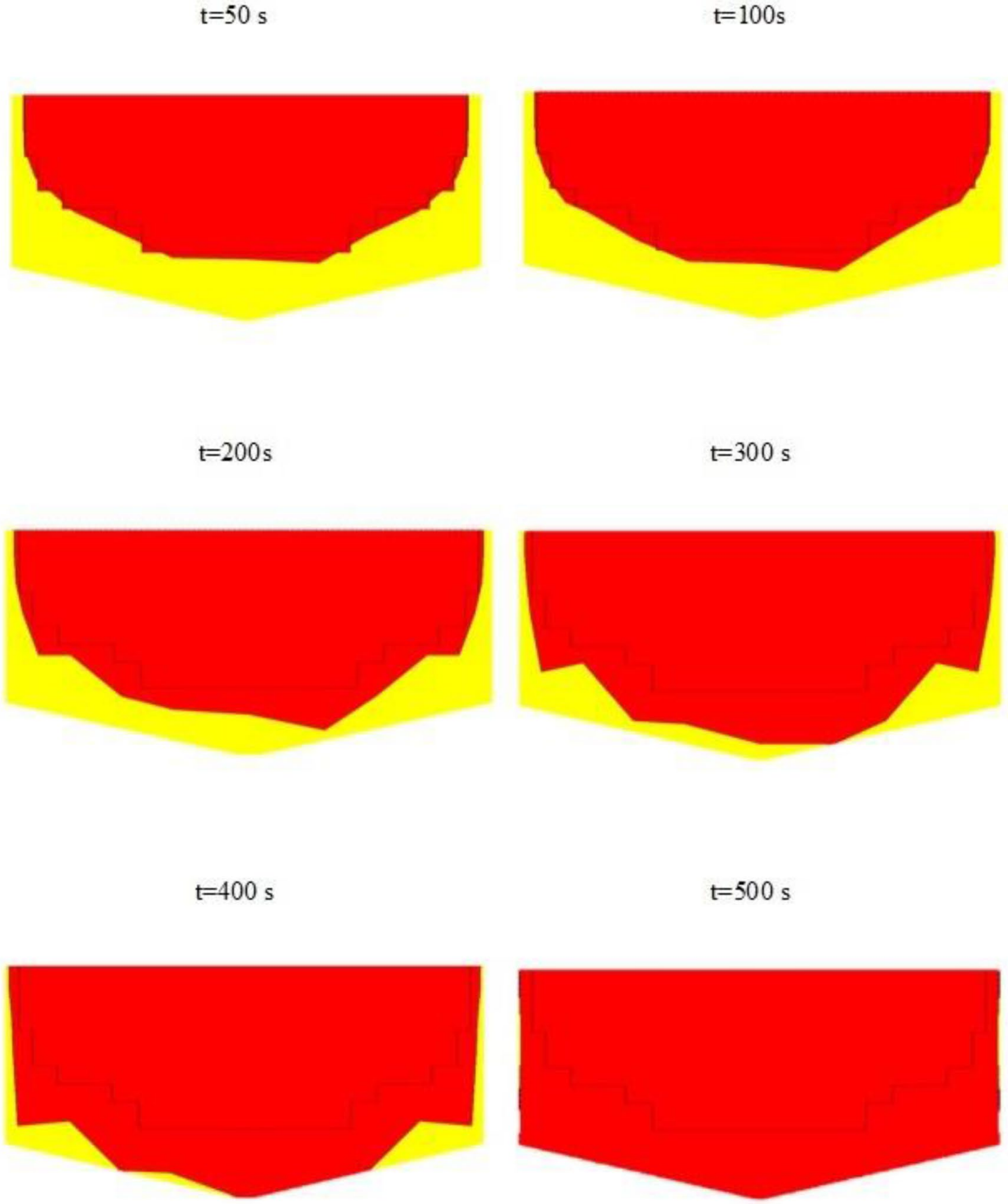


Fig. 13 Melt front progression inside the core catcher cavity with time

5. Post-test analysis confirms ceramic low density crust at the top.

This integral experiment established the efficacy of external vessel cooling with top flooding for quenching and stabilizing the molten pool in case of ex-vessel severe accident scenarios.

Corium Coolability in Decay Heat Dominated Regime—Demonstration of Long Term Corium Coolability and Decay Heat Removal

In the previous section, the ablation and initial coolability in the stored heat dominated regime was discussed. Once

Fig. 14 Ceramic crust at the top

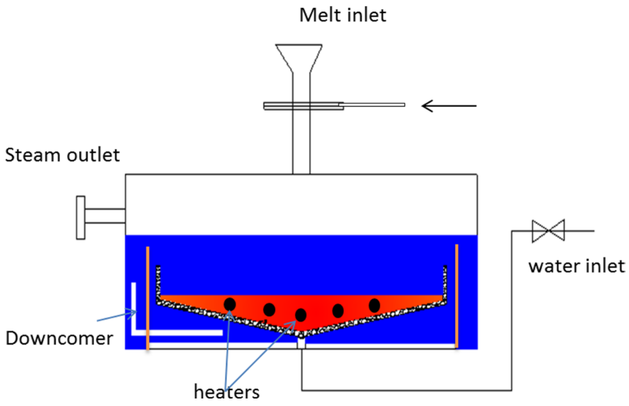


Fig. 15 Schematic of the test facility

the ablation is complete and the water has flooded on the core catcher, the further issues that remain are:

- Whether decay heat can be removed for prolonged period?
- Whether the crust remains stable and water ingression from sides is prevented?

To demonstrate these, another integral experiment was carried out with a melt simulant with decay heat simulation in the melt. The details of the experiment are as follows.

The experiment involved melting of sodium borosilicate glass in a cold crucible induction furnace. The glass was melted and the melt temperature was raised up to 1200 °C. The core catcher assembly, consisting of a simulated core catcher vessel placed in a water tank, shroud plates, downcomers, electrical heaters and enclosing box, was placed below the furnace and the melt was delivered in the test section by opening a solenoid valve below the furnace shown in Fig. 15. About 25 L of melt at 1200 °C was poured in the test section. After pouring was completed, the top flap of the test section was remotely closed which contained automatic sealing arrangement.

The test section consists of scaled down core catcher vessel, electrical heaters, shroud plate and downcomer, as shown in Fig. 16a and the thermocouple location is shown in Fig. 16b. The entire vessel assembly and the shroud plates are fabricated from carbon steel. The Core catcher vessel is made of Carbon steel having thickness of 30 mm. The core catcher vessel inner cavity has length 280 mm, depth 400 mm, maximum central height 230 mm and slant inclination of 34 mm at 10° angle. The downcomers are fabricated from a pipe of ID 25.6 mm made of carbon steel.

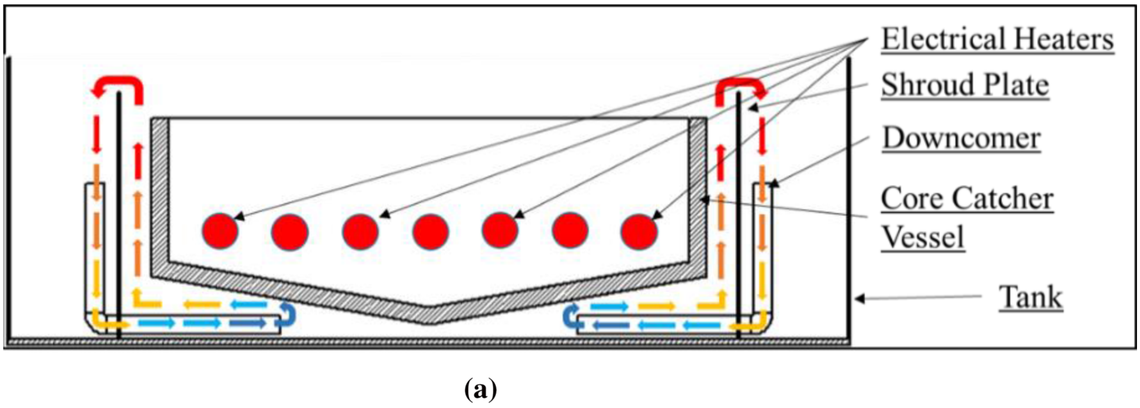
Electrical heaters were used to simulate a decay heat of 1 MW/m^3. These heaters are strategically arranged in such a fashion to homogenize heat source and mimic the volumetric heat release. The total power is divided in 7 heaters which emit the heat flux by the heater surfaces. These heaters are arranged in such that the inner heater distance is less than the diameter of the individual heaters. Therefore, the power delivered over the period time, simulates the volumetric heat release behaviour similar to the heat flux emitted in the real situation.

Sodium borosilicate glass was melted in the cold crucible induction furnace. After the simulant mixture was melted and temperature was raised up to 1200 °C, the molten mixture was delivered to the test section through opening a solenoid valve. About 25 L of molten mixture at 1200 °C was poured in test section. Initially, the tank surrounding core catcher vessel is kept empty. After 15 min from melt pour, the water was filled to the set level. After 45 min from melt pour, the core catcher vessel was completely flooded ensuring the delay of 30 min as envisaged.

Figure 17 shows the melt temperatures inside core catcher. Thermocouples in the melt cavity, show the highest value of 1075 °C in about two seconds. Soon after melt delivery was complete, the heaters were switched on and decay heat of 25 kW from 7 heaters were continuously added into the melt pool, which corresponds to 1 MW/m^3.

Post-test observations revealed the formation of stable solid hard crust at the top as shown in Fig. 18. No gap was observed between vessel inner wall and melt crust, which avoided ingression of water via the gap into the bulk of the molten pool matrix.

This experiment was repeated with immediate flooding of melt top. The results are shown in Fig. 19. It is observed that strong water ingression occurs into the melt pool soon after the water is flooded from the top resulting into melt eruption and formation of a highly porous sand type bed, as shown



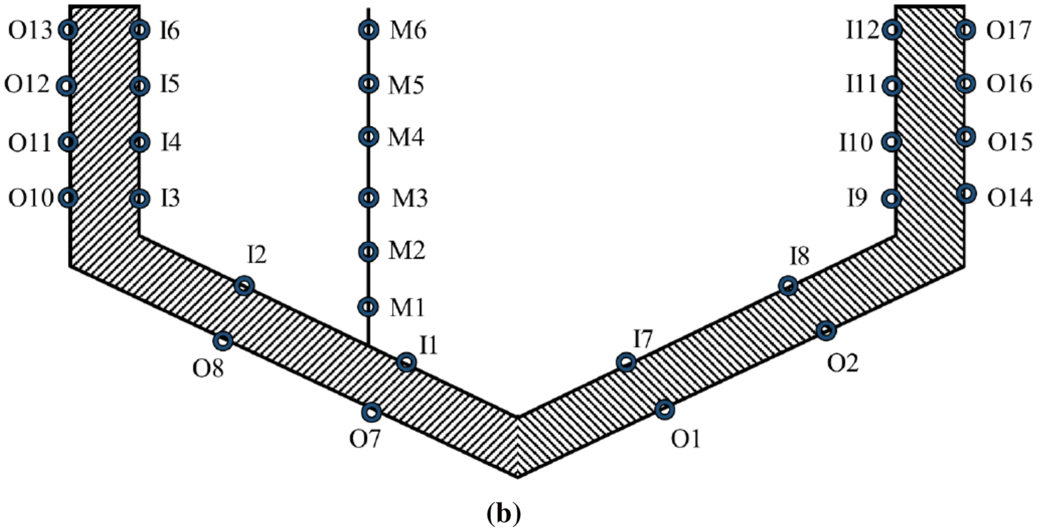


Fig. 16 **a** Details of the core catcher vessel. **b** Schematic of arrangement of thermocouples

in Fig. 19a, and corresponding melt temperatures showing faster cooling is shown in Fig. 19b.

Summary: Prolonged Corium Coolability with Decay Heat Removal The experiment highlighted that:

- Delay in flooding allows formation of stable crust at the top.
- Decay heat of the order of 1 MW/m^3 can be safely removed in core catcher using top flooding with external vessel cooling effectively.

Performance Assessment of Core Catcher with CFD Calculations After validation of design, the final step is performance assessment at actual prototypic condition. A two-dimensional CFD simulation of core catcher is performed to study the thermal ablation behaviour due to interaction of molten corium with sacrificial material. During the corium–sacrificial material interaction, sacrificial material is ablated and the molten pool is stratified in two layers, where oxidic layer is relocated to the top and metallic layer is relocated in to bottom. This complex scenario has been studied using a CFD methodology, in which a multiphase volume of fluid (level set) model coupled with solidification and melting model is used in the pressure-based solver. To minimize the complexity, two immiscible Eulerian phases, namely, melt (simulating the molten corium) and sacrificial material were modelled, where their properties were taken as the weighted average of the respective constituents. The thermal properties like density, specific heat, thermal conductivity and viscosity were temperature variable user defined input. As a part of severe accident management strategy, the core catcher vessel is placed in a water tank pre-filled with water up to the level of melt. The heat transfer coefficient values as obtained in the previous experiments were used

Fig. 17 Temperature variation in the melt

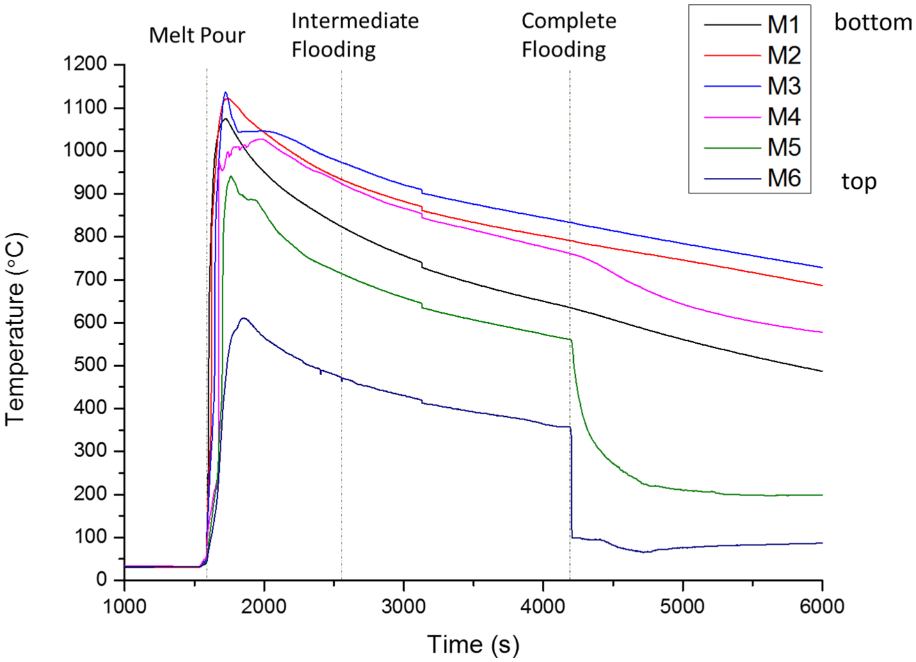


Fig. 18 Solid crust formation at the top

as the boundary conditions for the core catcher vessel walls. The CFD simulation was carried out assuming the melt has already relocated in the core catcher cavity over the sacrificial material arrangement. The simulation was initialized with the melt temperature of 3200 K, while the sacrificial material temperature of 300 K. Rayleigh number and Grashof number calculations suggested the turbulent nature, thus, standard K–ε model with enhanced wall treatment was used to resolve the eddies. The details of the CFD model are given in Table 4.

The primary objective of the CFD simulation was to investigate ablation rate, time and locations of the ablation of sacrificial material in the core catcher vessel and determine the inner vessel temperature so as to check whether it is within design limits. The results are presented in Figs. 20 and 21.

The findings of the simulation are presented below:

- Since the arrangement of the sacrificial bricks is in the steps, to increase the surface area for enhanced interaction between melt and sacrificial material, the edges are ablated preferentially. This can be inferred from the erosion of edges in the ablation contours.
- Ablation rate is higher at location, where it has already initiated due to the increase in surface area at that location. This can be observed prominently from the ablation contours which depict the higher rate of ablation at certain locations.
- After absorbing the latent heat, the molten sacrificial material relocates to the top of the vessel due to its lower density than the molten melt. This confirms, the melt inversion phenomenon, i.e., stratification of the oxidic layer to the top while the metallic layer to the bottom.
- The temperature contour profile indicates the inner vessel temperature within the permissible limits of heat removal using side indirect cooling of the core catcher vessel using the water from the surrounding tank. The inner vessel wall temperature did not exceed 1173 K

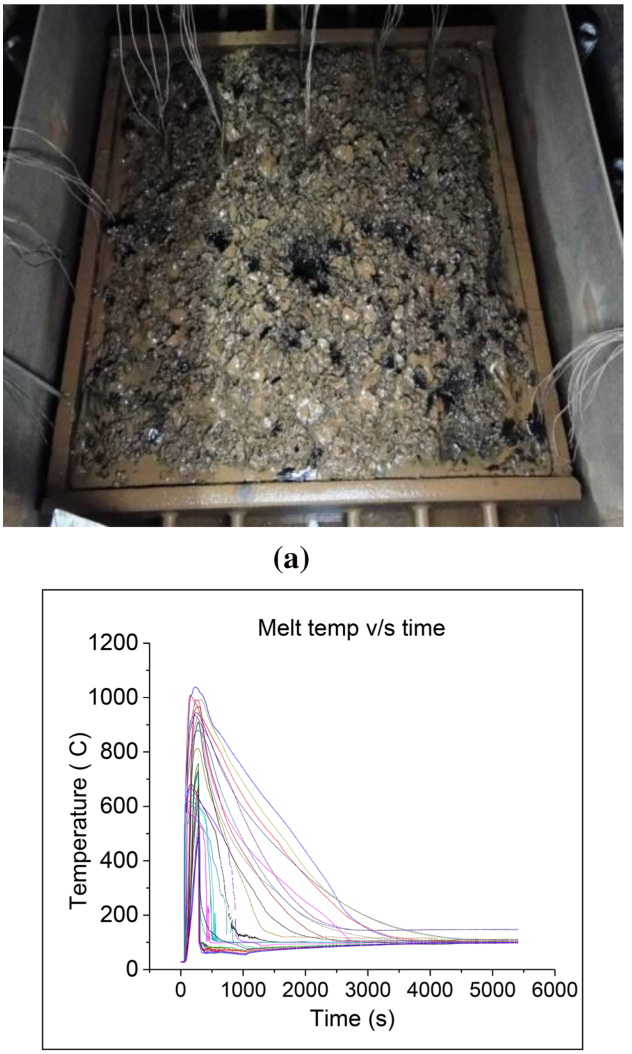

(a)
(b)

Fig. 19 **a** Debris formation due to immediate flooding. **b** Temperature distribution showing rapid quenching due to water ingression

Table 4 Details of the simulation

Models		
Multiphase model	VOF + level set	2 Eulerian phase
	Energy	On
	Viscous	Turbulence
	Solidification melting	On
Boundary conditions		
Outer wall	Momentum	Stationary wall, no slip
	Thermal	Mixed
Top wall	Momentum	Stationary wall, no slip
	Thermal	Mixed
Initial conditions		
Melt zone	Temperature	3200 K
SM layer zone	Temperature	300 K

(900 °C) with the presence of water outside the core catcher vessel.

This demonstrates the performance of the core catcher for prototypic melts.

Closure

For mitigation of severe accidents in Indian Advanced Light Water Cooled Reactors, technology of a new core catcher has been developed. The coolability of molten corium is a complex phenomenon involving precise knowledge of thermo-physical properties of the complex material and their variation with temperature, which is seldom known. Corium coolability with different techniques was studied, the science behind them was understood and the optimum cooling strategy was established. Sacrificial material for core catcher has been developed. The geometry of the core catcher was optimized with several experiments to establish “no-water ingression into the melt pool”, “formation of stable crust” and “melt inversion”. The design of core catcher was validated by conducting integral experiments at very high temperature with decay heat simulation.

- Several key technologies were developed for first time:
    - o Technology for generation and pouring of high temperature (2500 °C) melt of the mass 550 kg using thermite reaction.
    - o Technology for simulation of decay heat inside melt by electric heaters.
- Performance assessment for prototypic condition confirms the efficacy of core catcher for mitigation of core melt accident.

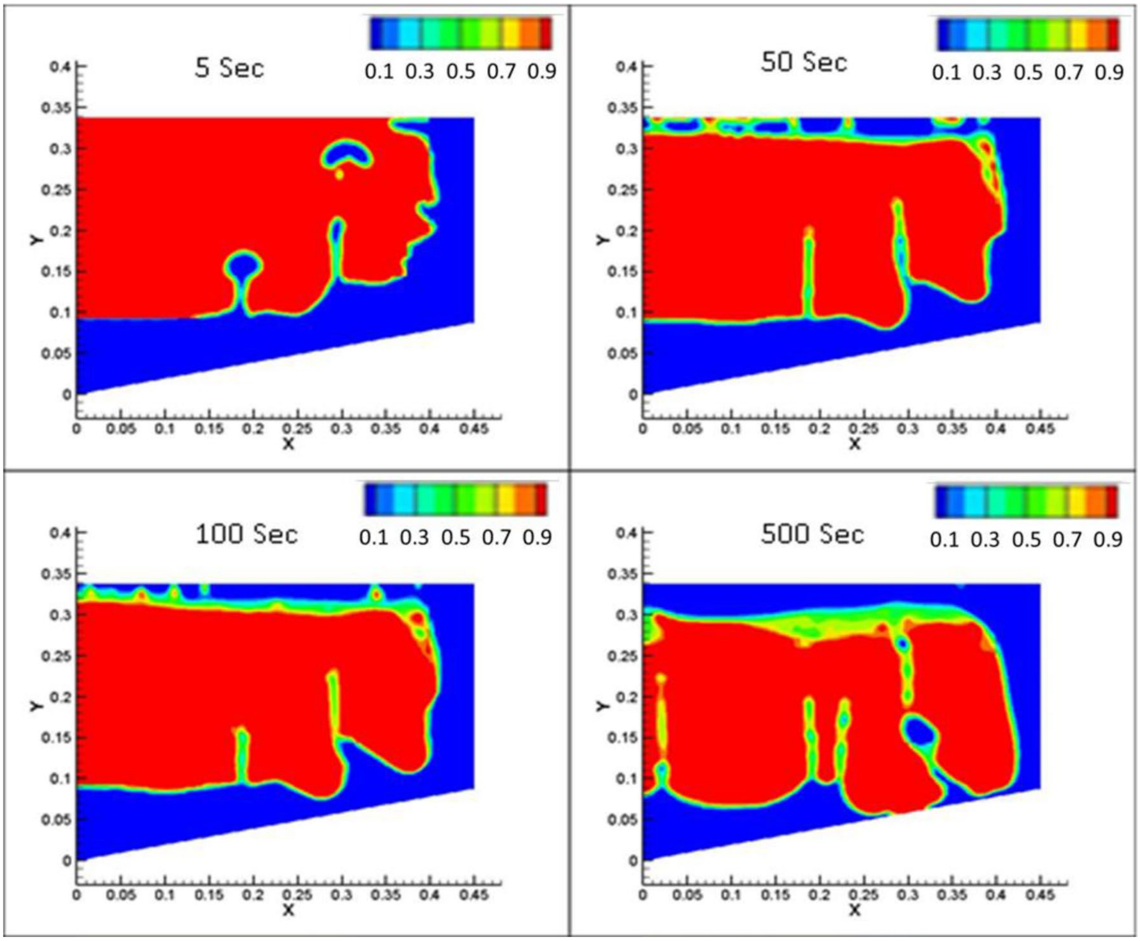


Fig. 20 Phase distribution (liquid phase) contour of the core catcher vessel

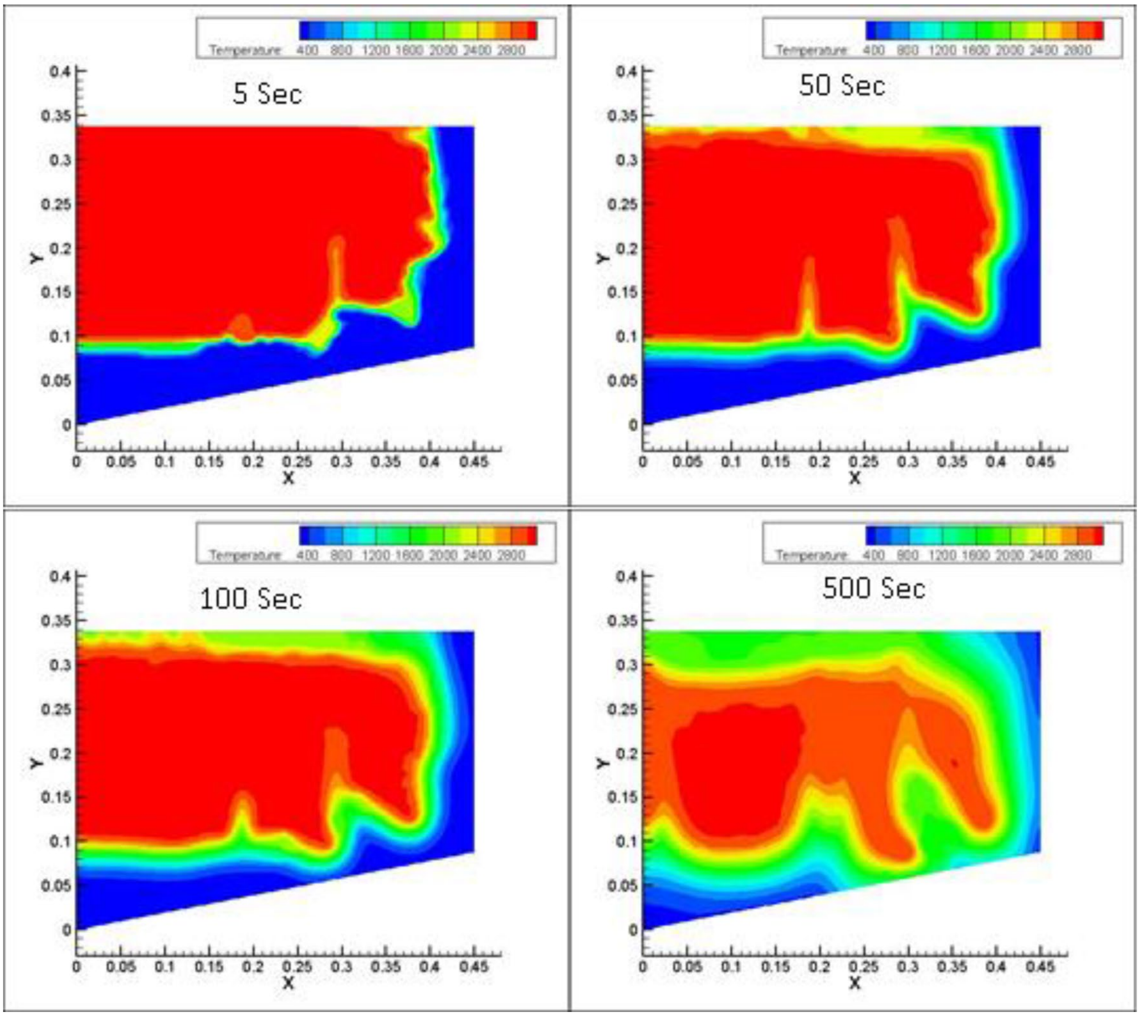


Fig. 21 Temperature (in K) distribution contour of the core catcher vessel

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Availability of Data and Material (Data Transparency) All data generated or analysed during this study are included in this published article.

Code Availability (Software Application or Custom Code) Not applicable.

Declarations

Conflict of interest (include appropriate disclosures) No conflicts of interests.

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