Computational Modeling of Flow Blockage in Fuel Subassemblies and Molten Material Relocation in Sodium Cooled Fast Reactors

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Abstract

By 3-D Computational Fluid Dynamics simulations, thermal hydraulics within SFR fuel subassemblies (SA) with partial flow blockers has been investigated. It is seen that when the blockage is in active region, local sodium boiling and the associated damages are imminent before blockage detection by core monitoring thermocouples. Decoupled multi-phase thermal models developed to analyse, total instantaneous blockage (TIB) at the SA inlet indicate that the extent damage due to TIB is restricted to 7 SA. Under this event, the blocked SA is seen to completely melt within ~16 s and due to inter SA heat transfer, neighbouring SA coolant temperature increases over 10°C and reactor trip is possible in about 38 s. In the event of an energetic core disruptive accident (CDA), due to Unprotected Loss Of Flow (ULOF) core debris reaches core catcher within 1000 s, after melting the grid plate. It is seen that a single tray core catcher can easily handle about 70% of whole core thermal load. A multi-layer core catcher of single tray design exhibits a strong potential to tackle whole core debris with a 4 cm thick Thoria layer as a delay bed. Integrity of inner vessel is not threatened even when about 50% of whole core debris settles in the annular gap between radial shielding and lower shell of inner vessel in the hot pool.

1.0 Introduction

Fuel pins in Sodium cooled Fast Reactors (SFR) are arranged in a tightly packed triangular pitch within a hexagonal sheath forming a fuel SA. Each fuel pin has a helically wound spacer wire. Tiny subchannels (hydraulic diameter, ~3.5 mm) combined with helical wire wrap enhance the possibility of flow blockages in fuel SA. Such blockages at the upstream of active fuel zone with adequate length for flow development can be detected by core monitoring thermocouples which are located at the top of the SA. But, large size blockages may not be detected by the thermocouples due to low velocity of sodium issuing from the blocked subassembly, eventually leading to core damage. The extent of damage propagation before reactor shuts down depends on the size of the blockage and its rate of growth. The thermal hydraulics phenomena involved during damage progression are very complex, involving phase change heat transfer with moving solid-liquid interfaces. After a severe core damage, the core debris relocate to core catcher, after melting the grid plate. The time for this relocation decides the thermal load on core catcher. Thermal transients on core catcher also depend strongly on the amount of degraded core material that relocates to core catcher. Such transients can be mitigated by adopting multiple layer core catcher design with delay bed on top of core catcher. During an energetic CDA, there is large risk of significant quantity of core debris settling in the hot pool, especially, in the annular region between core periphery and inner vessel. Under this condition, the debris may eventually reach main vessel after damaging inner vessel which depends on the quantity of debris that settles in hot pool.

To understand these complex thermal hydraulics phenomena, decoupled mathematical models have been developed and are linked with commercial CFD tools. This includes development of a special purpose 3-D structured mesh generator and CFD code for fuel SA thermal hydraulics and enthalpy based melting / freezing models for fuel, clad and hexcan, and grid plate. Suitably using these models, (i) thermal hydraulics of fuel SA with partial blockage in active region and the associated risk of sodium boiling, (ii) consequences of TIB in a single fuel SA, extent of core damage and detection of TIB by core temperature monitoring, (iii) molten material relocation to core catcher during an energetic whole core CDA, (iv) potential of current designs of core catcher with single tray for post accident heat removal, (vi) capacity of single tray core catcher with an integrated delay bed to accommodate full core debris, and (vii) potential of inner vessel to survive the attack by core debris that can settle in hot pool, have been investigated. Major findings of these studies are presented in this paper.

2.0 Investigation of Partial Flow Blockage in Active Region of Fuel Subassembly

Blockages in pin bundle could be initiated by different mechanisms including weld spatter present in the primary circuit and irradiation induced swelling of fuel pins. There is a need to understand the consequences of possible blockages and the permissible blockage should not lead to clad failure or sodium boiling. Though reactivity changes in case of local sodium boiling is less severe, it may result in local fuel melting and the consequent reactivity addition. Though many experimental and numerical studies have been reported on bundles with small number of pins, blockage study on large size bundles is rather limited. Traditional, subchannel models cannot capture 3-D temperature and velocity distributions within blocked bundle, specifically behind the blocked zone. Hence, a CFD investigation into blocked SA thermal hydraulics is out. The major focus of the study is determination of permissible axial length of porous blockage that excludes the risk of sodium boiling as a function of blockage parameters. Generation of structured mesh for fuel bundle with helically wound spacer wire has been accomplished using a customized mesh generator [1]. The whole computational domain for 7 helical pitch lengths is divided into 84 blocks and processed in parallel by 84 processors on a cluster with 48 GB RAM and 131 GFLOPS speed for each node.

The CFD models adopted in the analysis are validated with a physically similar SCARLET II experiment on a 19 pin wire wrapped bundle with porous blockage [2]. The cross-sectional layout of SCARLET II bundle and the CFD model are illustrated in *FIG. 1*. Also shown in the same figure is comparison between the predicted temperatures in various planes with measurements. The comparison exhibits an over-prediction in the peak temperature ~11 %, which is judged to be satisfactory. In the wake region the comparison is even better.

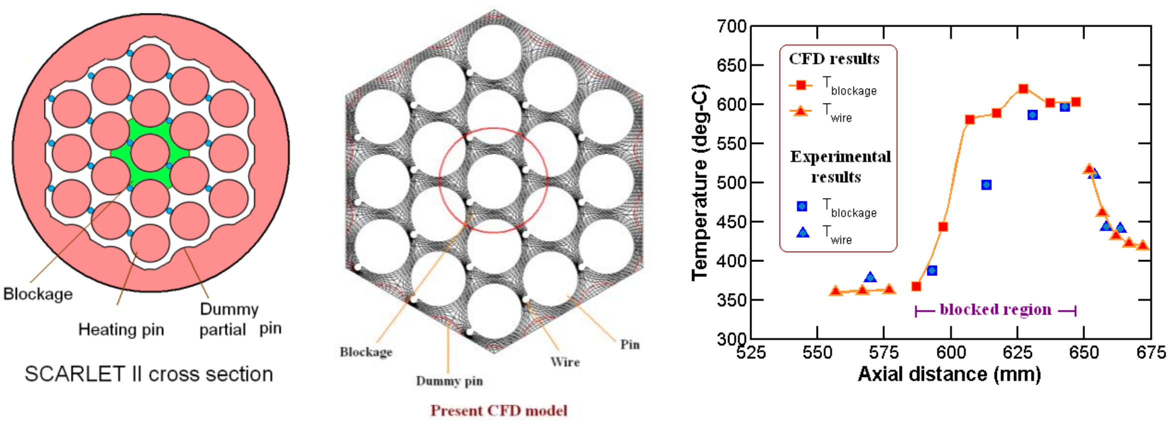
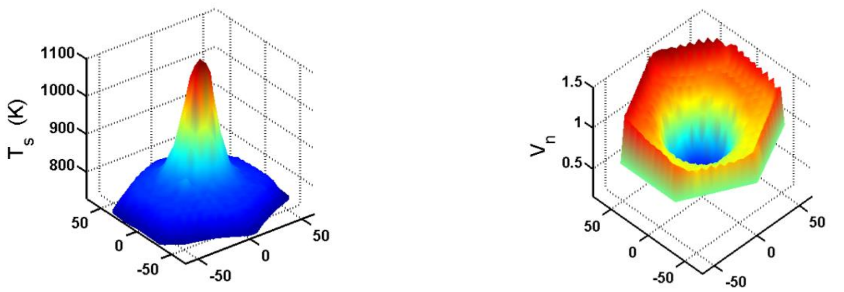
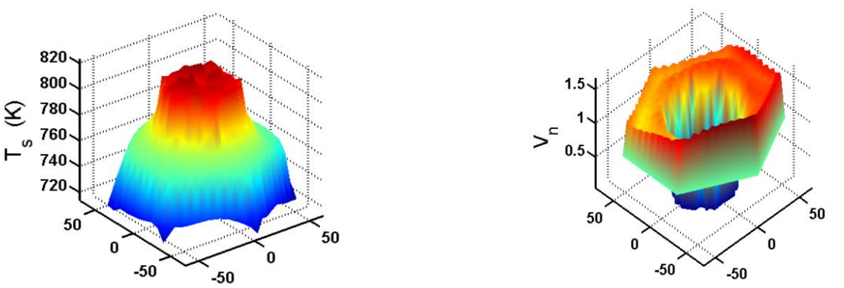


FIG. 1: SCARLET II bundle with blockage and comparison of measured & predicted results

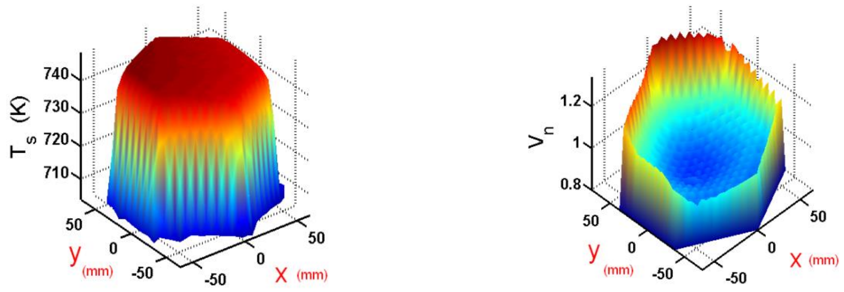
Subsequently, thermal hydraulic features of blocked fuel SA with various blockage configurations have been investigated for the prototype SA with 217 pins [1]. The fuel pellet diameter is 5.5 mm, clad ID/OD are 5.6 / 6.6 mm, pin pitch is 8.28 mm, spacer wire diameter is 1.65 mm, helical pitch is 200 mm, hexcan wall thickness is 3.4 mm and inter-wrapper gap is 3.3 mm. The fuel SA power considered is 8 MW with Cosine power profile. The case considered is BOEC. A wide range of blockage radius (8.28-33.12 mm), porosity (5-60%), mean particle diameter (0.25-0.75 mm) and location of blockage (corner/central) has been considered. The critical length of blockage that would result in local sodium boiling and the parametric zone posing risk of sodium boiling are determined. Special attention is paid to coolant mixing and flow and temperature fields downstream of the blockage zone. A large non-recirculating wake zone is seen to prevail in the downstream side of the porous blockage, with the extent of the wake zone increasing with blockage radius. It is seen that the total coolant flow reduction as a result of blockage is < 2.5% for all the blockages that can lead to local sodium boiling. This suggests, that global bulk sodium temperature monitoring at SA outlet is unlikely to detect internal porous blockages. It is found that the wake induced temperature non-uniformity sustains upto 3 helical pitch lengths (*FIG. 2)*.



(a) Z = 800 mm (100 mm after the blockage)



Z = 700 mm (within the blockage zone)



Z = 600 mm (100 mm before the blockage zone)

FIG. 2: Temperature and velocity fields at various elevations for 4-row blockage: particle size = 0.5 mm, porosity = 40%, blockage length (60 mm)

The peak clad temperature is found to be a strong function of porosity and particle size. Fuel-clad that are partly exposed to blockage are subjected to large circumferential temperature variation and the resulting thermal stress. Further, for a six subchannel blockage with 40% porosity and 0.5 mm mean particle diameter the critical length is 80 mm, whereas for the same blockage the critical length reduces to 7 mm when its porosity reduces to 5%. Similarly, six subchannel blockage with 60% porosity and 0.5 mm mean particle diameter, does not induce boiling even up to a blockage length of 400 mm. It may be indicated that when there is sodium boiling persisting for long duration, clad is expected to fail due to thermal fatigue. Once clad fails, there is likelihood of delayed neutron precursors to be released into the flowing coolant. The released delayed neutron precursors will provide signals in the Delay Neutron Detectors (DND) located in the hot pool around the IHX primary inlet window. The detection by DND involves transport of precursors and response time of the DND. Reactor trip by DND is estimated to take 10 – 70 s, depending on the SA that has failed [3].

3.0 Investigation of Total Instantaneous Blockage (TIB) at Fuel SA Inlet

Coolant temperature monitoring thermocouples at SA top are capable of detecting inlet flow blocks at their infancy [4]. But, large size blockages may not be detected by them due to low sodium velocity. TIB is considered as an envelope of all sizes of blocks [5-6]. During initial stage of TIB event, there is continuous rise in temperatures of fuel, clad and sodium within the blocked SA. Hence, coolant boiling takes place, followed by clad and fuel melting. Under this condition, it is possible that fission products would be discharged into pool by sodium vapor that could evolve from the affected SA, which could be detected by DND. But the detection time is a strong function of fission product that reaches the hot pool around the DND. Focus of this study is to investigate if core temperature monitoring is capable of detecting the TIB. During these transients, there is heat transfer from the blocked SA to neighboring SA. Monitoring the sodium outlet temperature of the neighboring SA and initiating safety action is one of the means to detect the blockage in the SA. During the TIB, the sequence of damages in the blocked SA, results in progressive change in the geometric configuration of the blocked SA. Further a fuel pool is formed attacking the neighboring six SA. These are complex thermal hydraulic phenomena involving moving solid-liquid interfaces and natural convection in fuel pool. Towards understanding various phenomena, a transient 2-D model has been developed accounting turbulent natural convection in fuel pool. Details of the SA are same as given in Section-2. From literature survey, it is found that most of TIB studies are either experimental based or adopt complex numerical models. Multi-phase, multi-component and multi-physics transient models such as the ones used SIMMER-IV code [7] are complex and highly demanding on computer time. The sequence of principal events during TIB in a fuel SA predicted in the present study is presented in Table-1 along with results reported for prototype fuel SA of CEFR [8] and Phenix reactor [9]. The present results compare satisfactorily with reported data from SIMMER code. The results of SCARABEE Test [10] carried out on small subassemblies are also presented in Table-1. The present study does not account for any reentry of sodium to the accident zone from other part of the SA. It also does not consider Fuel Coolant Interaction (FCI) considering the fact that that the molten oxide fuel-liquid sodium interface contact temperature is well below the sodium homogeneous nucleation temperature eliminating the potential for large-scale vapor explosions [11].

TABLE 1. Instants of occurrence of various events during a TIB (Time in seconds)

Process	Numerical study			Experiment study		
				SCARABEE-Test		
	PFBR (Present)	Phenix reactor	CEFR	BE+1	BE+2	BE+3
Start of TIB	0	0	0	0	0	0
Start of sodium boiling	0.5	0.5	1	3	2	-
End of sodium boiling	4.0	5	2.5	-	3	-
Start of clad melting	4.3	6	2.5	6	5.5	-
End of clad melting	8.5	9.2	6	-	-	-
End of fuel melting	16	-	15	-	-	-
End of blocked hexcan melting	18	18.5	16.6	-	-	21

It was seen that sodium boiling initiates around the central pin at 0.5 s and leads to complete voiding of the SA at 4 s [12-13]. While fuel melting initiates at 9 s, it completes at 16 s (*FIG. 3*). The molten fuel forms a pool at the bottom of the active fuel zone (see, *FIG. 3f*). Due to poor inter-wrapper flow, blocked SA hexcan melts within another ~1 s. A temperature rise of 10°C in the neighboring SA thermocouple is registered at ~37 s after the initiation of TIB with a thermocouple time constant of 8 s. The residual thickness of hexcan at this instant is 51%. This demonstrates that the damage initiated by TIB does not propagate beyond 7 SA.

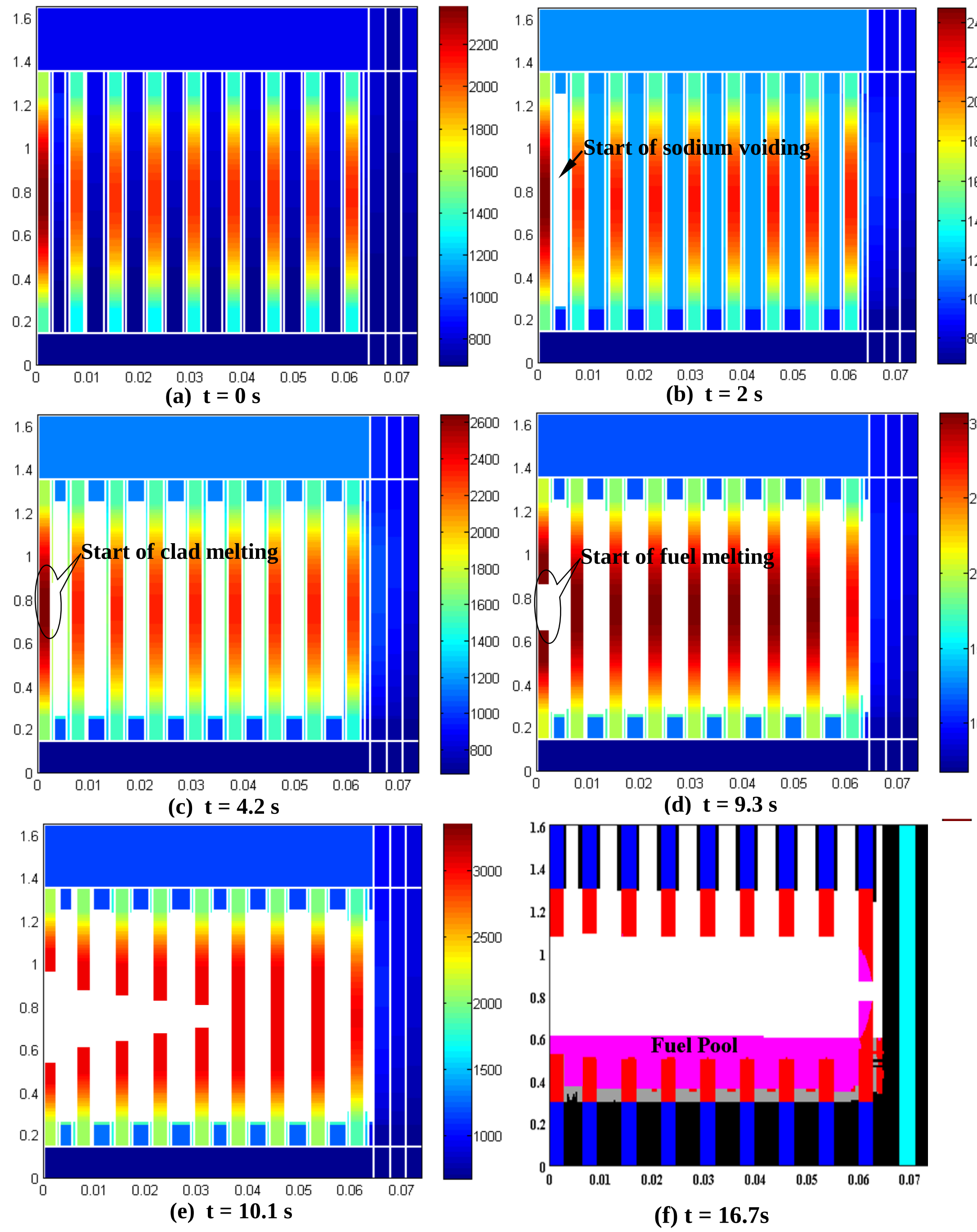


FIG. 3: Temperature distribution in blocked SA: (a) Normal condition, (b) Onset of sodium voiding, (c) Onset of clad melting, (d) Onset of fuel melting, (e) Incoherent melting of fuel pins and (f) Formation of fuel pool

It is essential to know as how the reactor power influences the sequence of various phenomena that take place during a TIB. Hence, additional study was carried out for various values of SA power viz., 4, 2 and 1 MW. The SA sodium flow rate is assumed to be proportional to SA power. The sequence of various processes when SA power is 4 MW is depicted in *FIG. 4* along with the predicted reading of the neighboring SA thermocouple. Significant variations are noticed in time duration for completion of each event, which leads to an overall increase in detection time. It is observed that stage-I (viz., fuel melting) completes by ~40 s which is almost double the time taken in 8 MW case (~18 s). However, stage-II (viz., blocked SA hexcan melting) takes nearly the same time as that of 8 MW case. But stage-III has significant variation both in time as well as in temperature rise. An increase in reading of 10 K is recorded by the neighboring SA thermocouple at ~90 s after TIB is initiated. The residual thickness of hexcan at the time of SCRAM is found to be 93% which is higher than the 8 MW case. No melting of hexcan of the neighboring SA is noticed for 1 MW power. In fact, SCRAM takes place even before sodium boiling in the blocked SA. Thus, detection of TIB is more likely at low power condition. The adjacent SA thermocouple reading as a function of pin power is depicted in *FIG. 5*. It clear, that when the power density is low (with proportionately low coolant flow rate), the temperature increment is high.

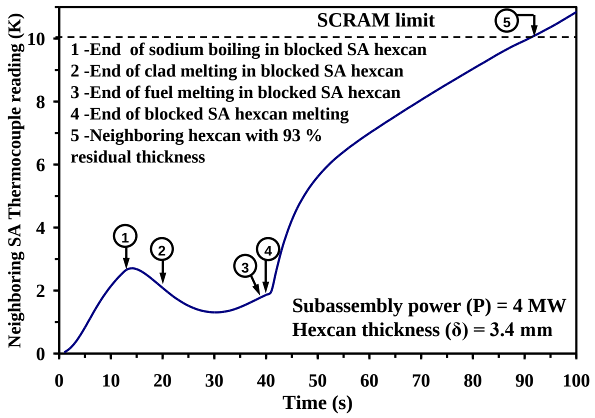


FIG. 4: Neighbouring SA thermocouple reading at 4 MW power

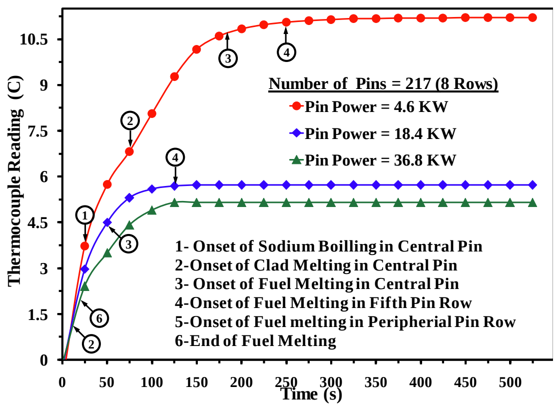


FIG. 5: Neighbouring SA thermocouple reading as a function of pin power in 217pin SA

4.0 Investigation of Core Melt Relocation following a Whole Core Accident

During an energetic CDA due to ULOFA, most of the molten fuel inside the expanding high pressure corium bubble quickly reaches the bottom plate of the grid plate through the partially intact hexcans. The core melt rests on the grid plate surface with its decay heat. Two different modeling assumptions (*FIG. 6*), viz., (i) melting steel mass is allowed to stay below the fuel mass and (ii) core melt sinks into molten steel, are considered. The radial extent of core-melt spreading on the grid plate is varied from 1-3 m, the former being the radius of the active core and the latter being the radius of grid plate. Deterministic calculations do not exist for 'melt arrival time' and this time estimate is taken from open literature. It is varied from 1 – 100 s [14]. Consolidated results in Table 2 indicate that melt-through of grid plate takes about 1000 s after arrival of the corium.

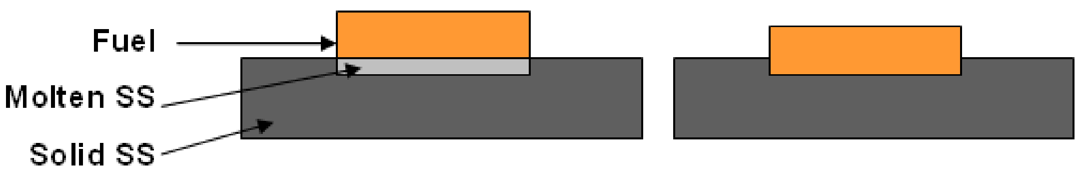


FIG. 6: Grid plate melting models: molten steel not removed (left) and molten steel removed (right)

TABLE 2. Grid plate melt-through time following a whole core ULOFA

Radius of fuel mass (m)	Melt arrival time (s)	Time to melt grid plate (s)	
		Normal (melting steel mass not removed)	Melting steel mass removed
1	1	986	791
	10	1011	815
	100	1097	897
3	1	1037	850
	10	1063	874
	100	1157	968

5.0 Assessment of Inner Vessel Damage due to Debris Settlement in Hot Pool

During an energetic CDA, the entire core debris is unlikely to reach the core catcher. A significant part of the debris is likely to settle in core periphery between radial shielding subassemblies and the inner vessel. This radial gap is 100 mm in width and 2.75 m in depth. Failure of inner vessel due to the decay heat can lead to core debris reaching the main vessel (*FIG. 7*). On the other hand, retention of a part of debris in core periphery can reduce the load on main core catcher. It is essential to quantify the amount of heat generating core debris that can be retained safely by the single tray core catcher and the potential of inner vessel to accommodate a part of the debris.

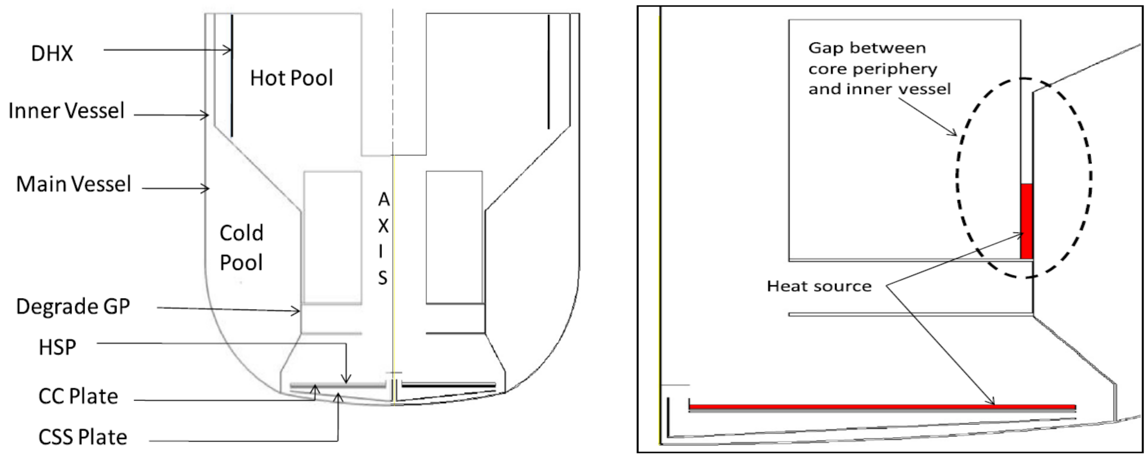
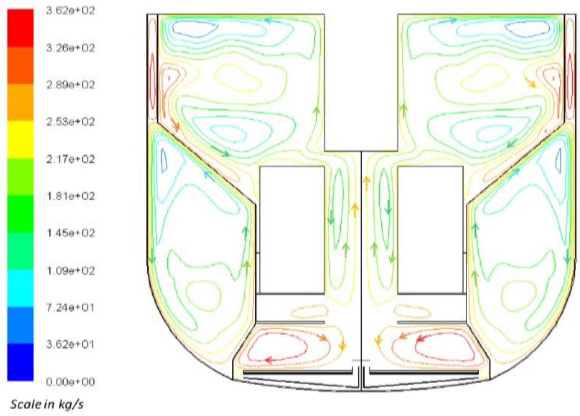


Fig. 7. Physical model for integrated pool hydraulics (left) and enlarged view of debris locations in hot and cold pools (right)

Towards this, a pool thermal hydraulics study coupling heat transfer interaction among (i) debris settling on core catcher and hot pool, (ii) core support structure plenum, cold pool and hot pool through inner vessel, and (iii) hot pool and decay heat removal system, has been carried out using a commercial CFD code. The CFD model is validated against in-house experimental data. Transient evolutions of natural convection in the pools and structural temperatures in critical components have been predicted [15]. It is found that 50% of the core debris can be safely accommodated in the gap between radial shielding subassemblies and inner vessel without exceeding structural temperature limit. The stream lines in the pool 1 h after the accident are depicted in *FIG. 8a*, when 50% of the debris settles in hot pool. Evolution of inner vessel temperature under this condition, with various numbers of DHX in service, is depicted in *FIG. 8b*. It is clear that the maximum temperature of inner vessel is around 950 K when 2 or more DHX are available.



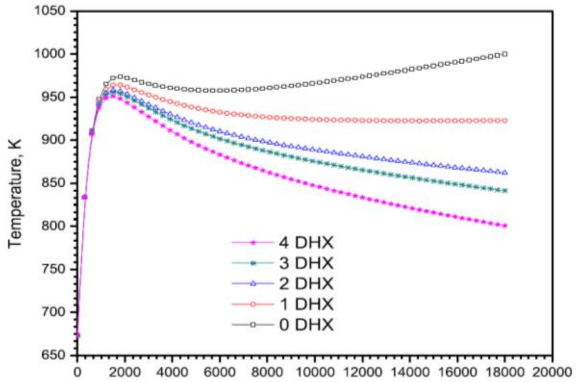


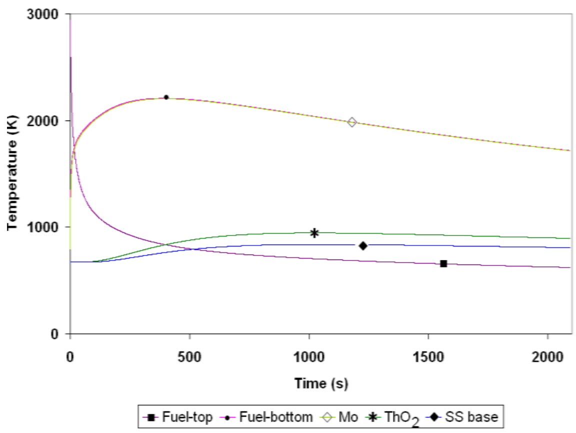
FIG. 8a. Streamlines 1 h after CDA, for 50% core debris in hot pool

Fig. 8b. Temperature evolution in inner vessel for 50% core debris in hot pool

It is also established that a single tray core catcher can safely accommodate decay heat arising due to ~70% of the core debris by establishing natural circulation in the lower sodium pool. The influence of heat removal rate by natural circulation on availability of the number of decay heat exchangers dipped in the upper pool is also analyzed. It is seen that the temperatures in the inner vessel, source plate and the maximum debris temperature do not increase significantly even when the DHXs are deployed 5 h after the accident, demonstrating the benefit of large thermal inertia of the pool.

6.0 Investigation of a Multi-Layer Core Catcher

The concept of multi layer core catcher is studied to qualify the same for a whole core debris handling. The relative merits and demerits of a few candidate materials for the different layers of core catcher have been evaluated and preliminary design for multi-layer core catcher has been arrived at. The multi layer core catcher consists of a top sacrificial layer, a middle refractory ceramic layer (which can itself be single / multiple layers) and a base layer. For the thermal analysis, molybdenum is taken as the top layer material and magnesia / thoria are considered as the middle layer acting as the delay bed. The base layer is SS 316LN which supports the entire core catcher assembly. Thermal analysis predicts that a delay bed of thoria (4 cm in thickness) or of magnesia (5 cm in thickness), can cater to the need of restricting the core catcher base temperature below the design safety limit of 923 K, when the whole core debris spreads evenly on the entire core catcher (*FIG. 9*).



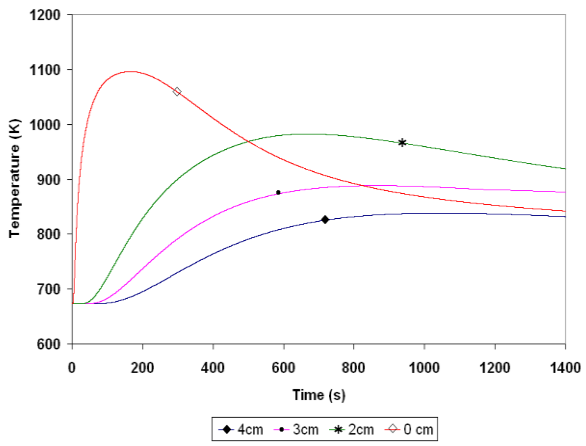


FIG. 9: Temperature history for 4 cm thick thoria in multi layer core catcher

FIG. 10: Comparison of single and multi layer core catcher base plate temperatures

Even for a case of the debris occupying 2/3rd radius of core catcher, with 4 cm thickness of thoria bed, the base SS layer temperature does not exceed sodium boiling point which rules out downward sodium boiling [16]. The superiority of multi-layer core catcher against traditional single layer core catcher is shown in *FIG. 10*. The multi layer core catcher has to undergo further feasibility study, considering metallurgical / manufacturing aspects and validated with experiments.

7.0 Conclusions

Decoupled computational models have been developed to understand the effects porous flow blockages within the active region of fuel pin bundles of SFR. It is seen that there is possibility of local sodium boiling / clad failure due to these blockages it is difficult to detect them by core temperature monitoring. Transient enthalpy based 2-D thermal models have been developed to study the effects of TIB. It is seen that the blocked SA completely melts within about 16 s. Further, due to inter SA heat transfer, SA blockage can be detected by monitoring the coolant outlet temperature from the adjacent SA. By this parameter, reactor can trip within about 38 s after the TIB event in the SA. Thus, the number of SA that can get damaged due to TIB in a single SA is only seven. Similar multi-phase models were used to predict core debris relocation after a whole core accident. The grid plate melt through time for ULOFA is ~1000 s. The traditional single tray core catcher can handle 70% of whole core thermal load. Multi layer core catcher is seen to have strong potential to handle whole core thermal load.

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