STATUS OF THE SAS4A CODE METALLIC FUEL MODELS FOR THE SIMULATION OF SEVERE ACCIDENTS IN LIQUID METAL COOLED FAST REACTORS

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Introduction

- SAS4A/SASSYS-1 is a reactor dynamics and safety analysis code developed at Argonne National Laboratory (ANL) for the safety analysis of Sodium-cooled Fast Reactors (SFR). Development of SAS4A code began in the mid-1970s and was focused initially SFRs fueled by oxide fuel clad with stainless steel.

- A SAS4A metal-fuel model development effort began around 1985 and initial metal-fuel whole core analyses illustrated the favorable response of metal fuel cores during postulated severe accidents.

- An effort to significantly expand the SAS4A models for the analysis of metal fuel cores was initiated at Argonne in 2014 as part of an ANL-KAERI collaboration focused on the Safety Analysis of the Prototype Gen-IV Sodium Fast Reactor (PGSFR).

- Recent work presented in this paper has extended the SAS4A code metal fuel relocation module LEVITATE-M to allow the simulation of inter-assembly interactions, including the post-assembly-failure inter-assembly material contact and physical interactions and inter-assembly heat transfer.

Introduction (continued)

- The SAS4A code has been developed initially for the analysis of the Initiating Phase of postulated severe accidents in Liquid Metal Fast Reactors (LMR). The Initiating Phase is traditionally defined as the sequence of events that occur before the failure of an assembly wall, when the so-called Transition Phase of the accident begins.

- The implementation of the post-assembly-failure LEVITATE-M models significantly extends the ability of the SAS4A code to analyze extended severe accident sequences. Instead of terminating the SAS-4A calculations at the time of the assembly wall failure, we can now continue the simulation of subsequent events in the framework of SAS4A.

- The new models describing the inter-assembly interactions are introduced and results of simulations of a postulated Unprotected Loss of Flow (LOF) accident and a severe Assembly Blockage accident in a generic metal fuel core are presented.

METAL FUEL PHENOMENA MODELED IN SAS4A

- The SAS4A metal-fuel models describe several important phenomena that occur in metal fuel pins but are not present in the oxide fuel pins:
  - the migration of the U-Zr and U-Pu-Zr fuel components during irradiation, which leads to the formation of radial fuel regions with different composition,
  - the formation of the fuel-cladding eutectic at the interface between the fuel and cladding, which leads to changes in the local composition of both fuel and cladding,
  - the formation of the fuel-cladding eutectic at the outer cladding surface after the cladding failure and fuel ejection in the coolant channel, which affects fuel freezing and cladding ablation,
  - the presence of the in-pin sodium in the molten fuel cavity which can affect the cavity pressure and molten fuel ejection after cladding failure, and
  - the in-pin molten fuel relocation to the pin plenum prior to cladding failure and re-entry from plenum into the pin cavity after the cladding failure.

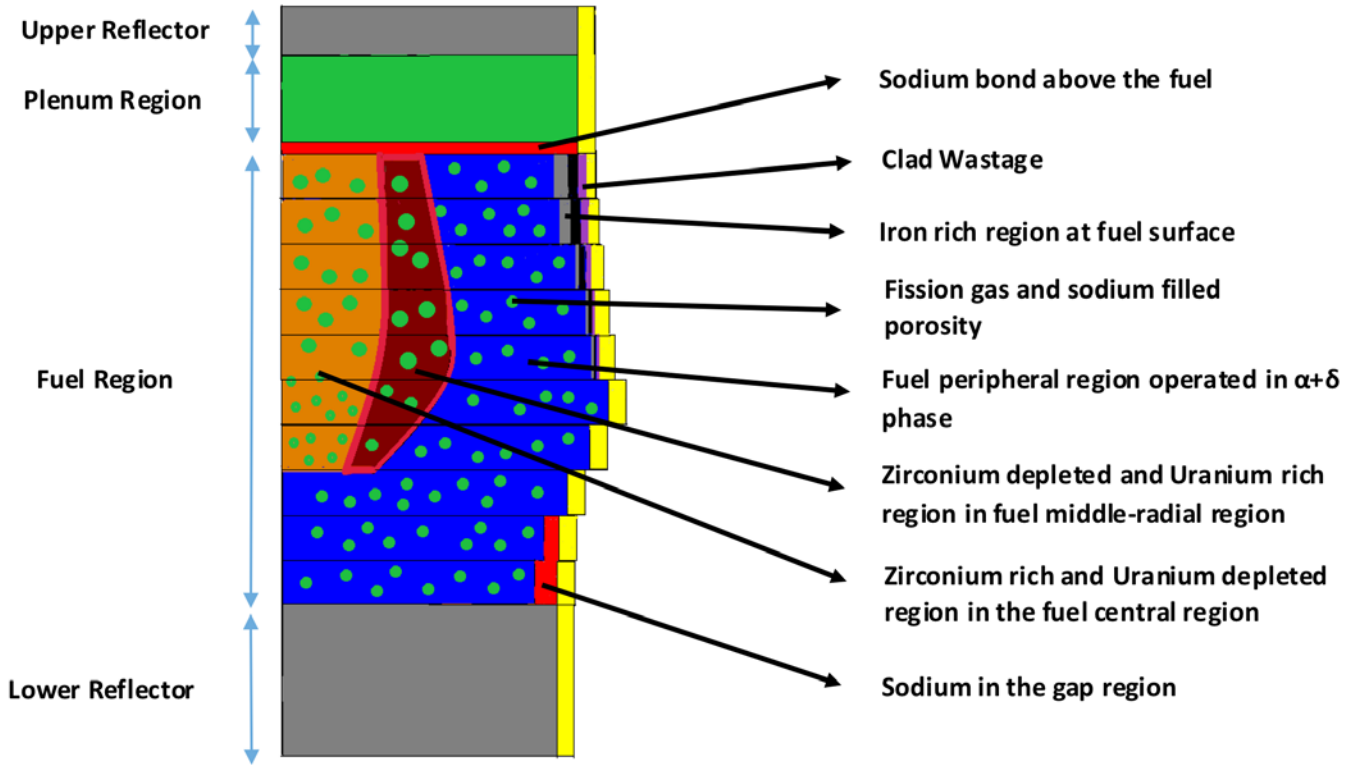
SAS4A METAL FUEL MODELS

- In order to model the metal fuel phenomena described above a significant model development and validation has been undertaken leading to the development of the following new SAS4A metal fuel modules:
  - MFUEL: pre-transient metal fuel characterization
  - MFUEL: transient metal fuel pin mechanics
  - PINACLE-M: pre-failure in-pin metal fuel relocation
  - LEVITATE-M: post-failure metal fuel relocation

- To allow an accurate description of the local fuel composition, the new metal fuel modules track multiple fuel components, including U, Pu, Actinides, Fission Products, Lanthanides, Zirconium, and Iron.

- The changes in the local composition of the fuel and cladding can significantly affect their thermo-physical properties, including the melting and freezing temperatures. These changes in turn can affect the timing and magnitude of cladding failure and fuel relocation events, and ultimately the reactivity feedbacks that determine the core response.

Metallic fuel phenomena modeled in MFUEL



LEVITATE-M: The Post-Pin-Failure Metal Fuel Relocation Module

- The LEVITATE-M module describes the phenomena that occur in a metal fuel assembly after the cladding failure and fuel ejection into the coolant channel.

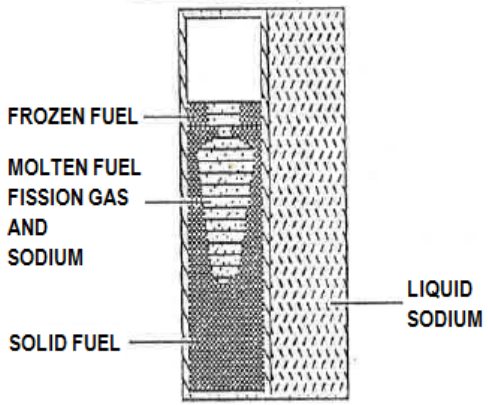
- It describes the post-failure relocation of the multiple fuel components tracked by SAS4A both in the coolant channel and in the pin cavities and uses the composition-dependent thermo-physical properties at each axial location to determine the fuel phase transitions (melting and freezing) .

- LEVITATE-M has been extended to model the metal fuel ejection into unvoided coolant channels replacing the PLUTO-2 model still used in the oxide fuel version of SAS4A to simulate TOP accident conditions.

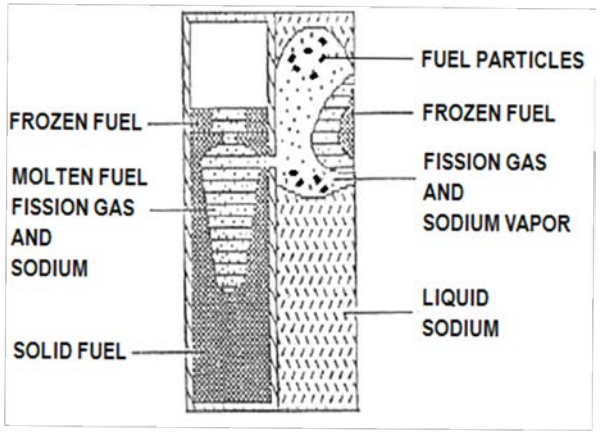
- The local composition of the moving and stationary fuel fields (molten fuel, fuel chunks/particles, frozen crust on cladding and structure) is carefully tracked, allowing an accurate calculation of the time-dependent reactivity changes.

LEVITATE-M: The Post-Pin-Failure Metal Fuel Relocation Module

- LEVITATE-M continues the PINACLE-M calculations after the cladding failure but extends them to model the phenomena that occur in the coolant channel.
- LEVITATE-M describes a large spectrum of physical phenomena which depend on the metal fuel composition and properties, including fuel pin melting and disruption, cladding ablation due to melting or eutectic formation, multiple fuel and steel flow regimes, fuel fragmentation and freezing, and channel blockage formation due to freezing fuel or/and cladding.



PINACLE-M



LEVITATE-M

POST-ASSEMBLY-FAILURE LEVITATE-M MODELS

- The SAS4A code has been developed for the analysis of the Initiating Phase of postulated severe accidents in Liquid Metal Fast Reactors (LMR). The Initiating Phase is traditionally defined as the sequence of events that occur before the failure of an assembly wall, when the so-called Transition Phase of the accident begins.
- Thus, the LEVITATE code was designed to monitor the assembly wall conditions and stop the SAS4A simulations when the failure of the assembly wall was predicted. The Transition Phase is analyzed with codes such as SIMMER which use a different core representation and less detailed models to represent the fuel assembly phenomena.
- It was recognized for some time that terminating the SAS4A calculations at the time of the first assembly wall failure may be too pessimistic, as the effect of the assembly failure on the neighboring assemblies may be limited and the use of the Transition Phase codes may not be necessary.
- The work described in this paper extends the capabilities of the SAS4A code to the simulation of events that occur after the assembly-wall breach, during a period that we will refer to as Pre-Transition Phase.

Post-Assembly-Failure Model Implementation

- To model the post-assembly-failure events we implemented a simplified approach which provided a faster path to the simulation of post-assembly-failure events. More detailed models will be considered for future work.

- The failure of the assembly wall leads to local expansion of the assembly and direct contact of the molten fuel and other components in the coolant channel of the failed assembly with the outer surface of the neighboring assembly wall.

- The sodium in the inter-assembly gap is displaced by the walls of the failed assembly and does not contact the coolant channel materials.

- The expanding assembly walls and/or local freezing of the molten fuel/steel mixture due to contact with the colder neighboring assembly prevent the axial relocation of the molten fuel and other components in the inter-assembly space.

Post-Assembly-Failure Model Implementation

- The post-assembly-failure (PAF) models require that the LEVITATE-M lead channel contains only one fuel assembly, surrounded by the six identical assemblies that belong to the neighboring channel.
- These restrictive conditions are necessary because the modeling of the PAF phenomena require the simulation of physically neighboring assemblies, as opposed to the conceptual channels previously used in SAS4A, which can contain assemblies that are not physical neighbors.
- The models are designed to allow a future extension of these models to the simulation of multiple neighbors of the failed assembly and non-failed assemblies that can see multiple failed assemblies.

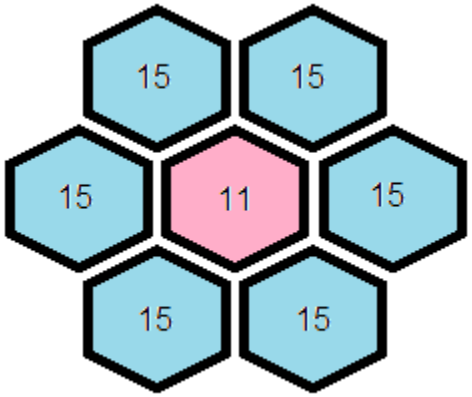


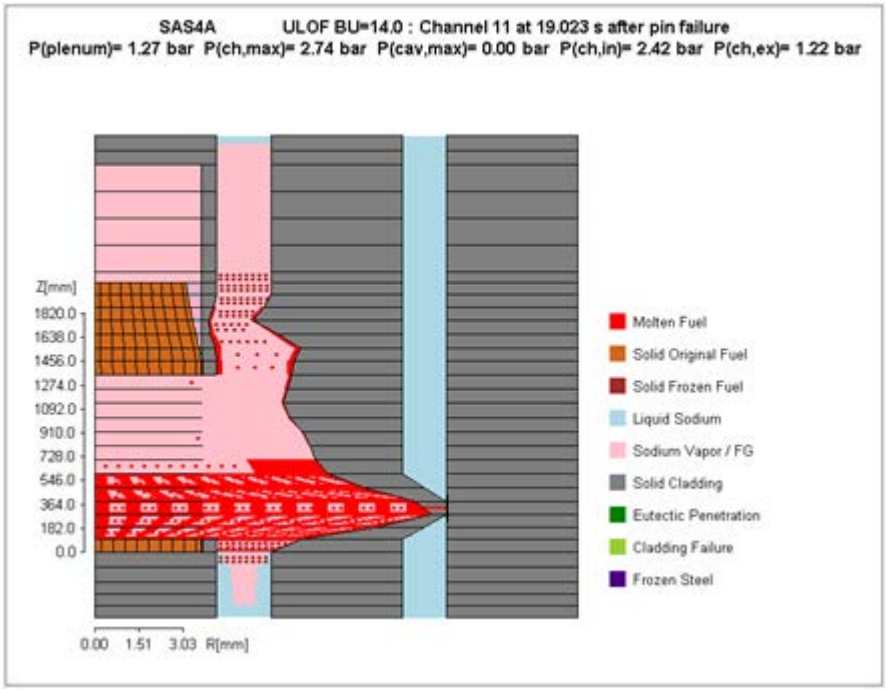
Figure 2 - The lead channel 11 and neighboring assemblies of channel 15

Simulation of postulated ULOF accident

- To evaluate the post-failure simulation capabilities implemented in SAS4A we performed an extended simulation of postulated Unprotected Loss of Flow (ULOF) accident with a flow rate halving-time of ~5s, in a generic 600 MWe SFR metallic fuel core. The fuel pins consist of U-10Zr metallic fuel with HT9 cladding.
- The core was initially modeled by dividing the fuel assemblies into 14 SAS4A fuel channels, with 7 channels containing a single fuel assembly while the remaining 7 channels contained multiple fuel assemblies assumed to behave identically. The fuel pin failure was found to occur first in the Channel 11 which consists of a single fuel assembly and was the “hot” or “peak” channel in these calculations.
- To evaluate the effect of inter-assembly interactions channel 15 was defined to consist of 6 identical fuel assemblies surrounding the peak assembly in channel 11. as illustrated above in Figure 2.
- To help understand the simulation results the LEVITATE-M Visualization program has been extended to allow the visualization of post-assembly failure events. In addition to the traditional LEVITATE geometry pictures of the fuel assembly, the picture now includes the assembly wall failures and the penetration of the neighboring assembly wall at the failure locations.

Post-Assembly-Failure Simulation Results

- The fuel pin failure in the lead channel 11 and the initiation of the LEVITATE-M fuel relocation module occur at ~32s after the initiation of the ULOF accident. At this time the power is P = 0.47 P0 and the net reactivity is ρ_{net}=-0.31$.
- The assembly wall failure is predicted at ~19 s after pin failure in channel 11, and the channel conditions at ~1 s after failure are illustrated in the Figure. At this time the power has decreased to P = 0.23 P0 and ρ_{net}=-0.62$. The reactivity due to the fuel relocation is ρ_{fuel}=-0.32$.
- A foamy molten fuel pool is observed in the axial region where the failure is located. The small early penetration of the neighboring assembly wall is observed.



LEVITATE-M results at 1s after assembly wall failure in channel 11 (19s after pin failure in channel 11)

Post-Assembly-Failure Simulation Results

- The channel 11 conditions at 14 s after the assembly wall failure (32 s after pin failure) or are illustrated in Figure 3. Significant steel freezing is observed to occur at the location of the channel 11 assembly wall failure.
- In this simulation it was assumed that the frozen steel leaves a path or paths for the molten fuel to reach the neighboring assembly wall.
- Some of the fuel is now frozen in the form of particles/chunks that are seen moving upward.
- Three axial cells of the assembly wall have failed at this time. The penetration of the neighboring assembly wall has advanced but remains less than 25% of the wall thickness.

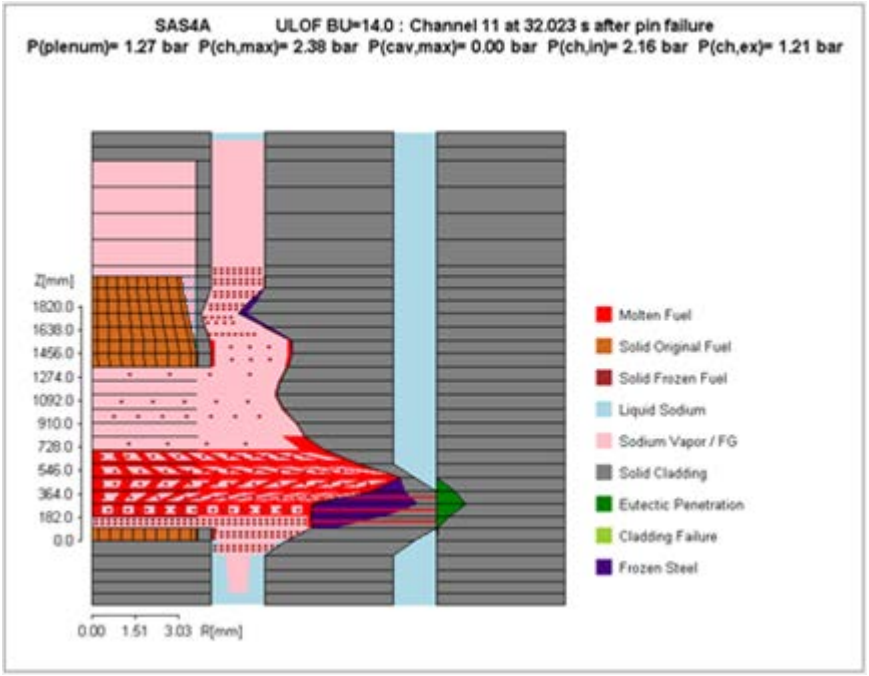


Figure 3. – LEVITATE-M results at 14s after assembly wall failure in channel 11 (32s after pin failure in channel 11)

Post-Assembly-Failure Simulation Results

- Figure 4 shows the results of the extended simulation at 26.5s after assembly wall failure (44.5s after pin failure) in channel 11.
- The penetration of the neighboring assembly wall has reached over 50% of the wall thickness, but the penetration rate is near zero at this time due to decreased fuel temperatures in channel 11.
- All the fuel in channel 11 is now frozen, either as solid chunks/particles or frozen crust on the walls.
- Sodium coolant re-entry continues at the channel inlet. Penetration of the fuel debris bed by the liquid sodium is slow but appears to continue monotonically.
- The power has decreased to P = 0.12 P0 and ρ_{net}=-0.75\$. The reactivity due to the fuel relocation is ρ_{fuel}=-0.58\$.

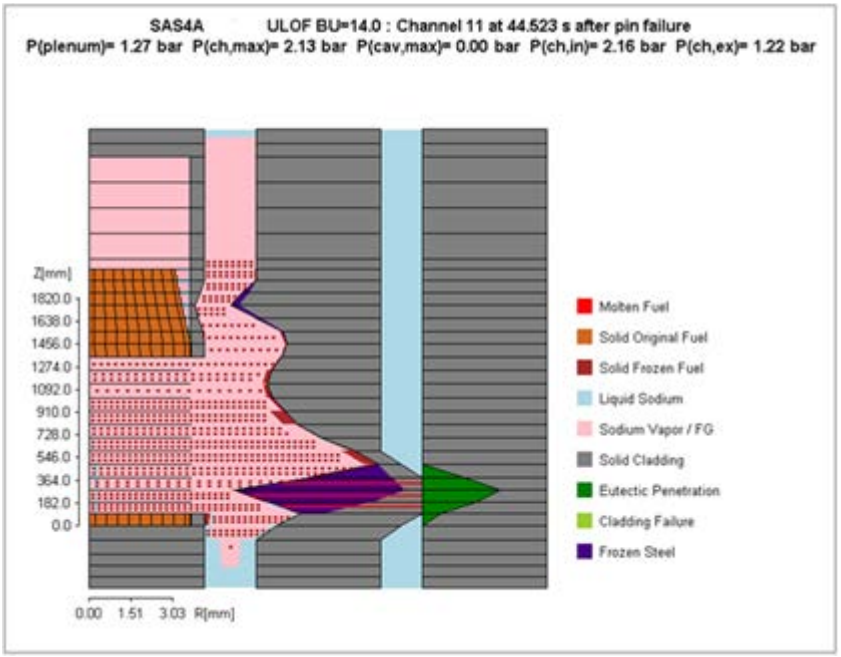


Figure 4. – LEVITATE-M results at 26.5s after assembly wall failure in channel 11 (44.5s after pin failure in channel 11)

Post-Assembly-Failure Simulation Results

- The simulation was extended for another 10s to observe the assembly wall penetration, and sodium coolant re-entry. At 37s after assembly wall failure (55s after pin failure) the penetration of the neighboring assembly wall remained stationary, as the penetration rate is now nearly zero.

- Sodium re-entry in the channel from the bottom plenum has continued and increasing amounts of liquid sodium can be observed in the frozen fuel debris region.

- The results show that even if a failure of the lead assembly wall occurs, the damage to the neighboring assemblies can be limited and the assembly failure will not propagate to other parts of the core.

- As the power continues to decrease, the postulated ULOF accident is expected to terminate with only limited core damage.

INTER-ASSEMBLY HEAT TRANSFER MODELS

- The ULOF accident simulations described above did not consider the inter-assembly heat transfer through the inter-assembly gap. Only the direct contact heat transfer which occurs after the assembly wall failure was considered,
- The SAS4A channels were assumed to be thermally isolated from their neighbors prior to the assembly wall failure and an adiabatic boundary condition was applied at the outer surface of the assembly walls.
- It was recognized that the inter-assembly heat transfer can play a significant role during certain accidents, transferring heat from the hotter assemblies to the colder neighboring assemblies and mitigating the accident consequences.
- An example is the assembly blockage accident, where the temperatures of the blocked assembly increase rapidly after the blockage formation, leading to large temperature differences between the blocked assembly and its neighbors.
- In other accidents such as the ULOF accident described above, the temperature differences between the lead assemblies and their neighbors become significant after the fuel pin failure in the lead assembly.
- The implementation of the inter-assembly interaction models described in this paper allows the definition of the physical neighbor assemblies of the lead assembly studied. The sides of the neighbor assemblies that face the lead assembly are also identified, and their temperature is tracked independently of the other sidewalls.

INTER-ASSEMBLY HEAT TRANSFER MODEL IMPLEMENTATION

- The implementation of the inter-assembly heat transfer (IAHT) models in the SAS4A code allows the definition of the physical neighboring assemblies of the lead assembly studied.
- The sidewalls of the neighboring assemblies that face the lead assembly are also identified, and their temperature is tracked independently of the other sidewalls which are not facing the lead assembly.
- Previously the SAS4A models assumed that all sidewalls of an assembly have the same temperature.
- However, the temperature of the neighboring assembly wall that faces the blocked assembly can be significantly higher than the temperature of the other assembly wall faces.
- The inter-assembly heat transfer models transfer heat between the blocked assembly wall and the neighboring assembly faces with higher temperatures than the other assembly wall faces.
- The heat transfer between the coolant in the neighboring assemblies and the assembly wall faces and is based on the actual temperature of each assembly face.

Assembly Blockage Accident Simulation

- To evaluate the assembly blockage capabilities of the SAS4A models and the effect of the inter-assembly heat transfer models we simulated an assembly blockage (ASBL) accident in a generic 100 MWe pool-type sodium-cooled fast reactor with a metal fuel core at the Beginning of Life (BOL).
- The SAS4A core model consisted initially of 11 channels. Two additional SAS4A channels were defined: channel 12, which contains the blocked assembly, and channel 13, which contains 6 identical assemblies that surround the blocked assembly, in an arrangement similar to that shown in Fig. 2.
- The assemblies used for channels 12 and 13 were removed from some of the original 11 channels.
- The inlet blockage in channel 12 is imposed by increasing the inlet coolant flow pressure drop at the beginning of the accident simulation. For the case presented the original pressure drop coefficient was multiplied by a blockage factor KBL=260.
- The initial simulation was performed without considering the effect of the inter-assembly heat transfer.

Assembly Blockage Accident Simulation without Inter-Assembly Heat Transfer

- The coolant boiling begins at ~18s after blockage initiation.
- As boiling continues the flow rate becomes zero W=0.0 at 31s.
- The first cladding failure occurs at 37.6s after blockage initiation, prior to fuel melting and triggering the plenum fission gas ejection into the coolant channel.
- The post-pin-failure fuel relocation module LEVITATE-M is initiated at 47.47s. The assembly blockage simulation was extended to ~30 s after pin failure.
- The status of the blocked assembly at 28.5s after pin failure is illustrated in Fig. 5.

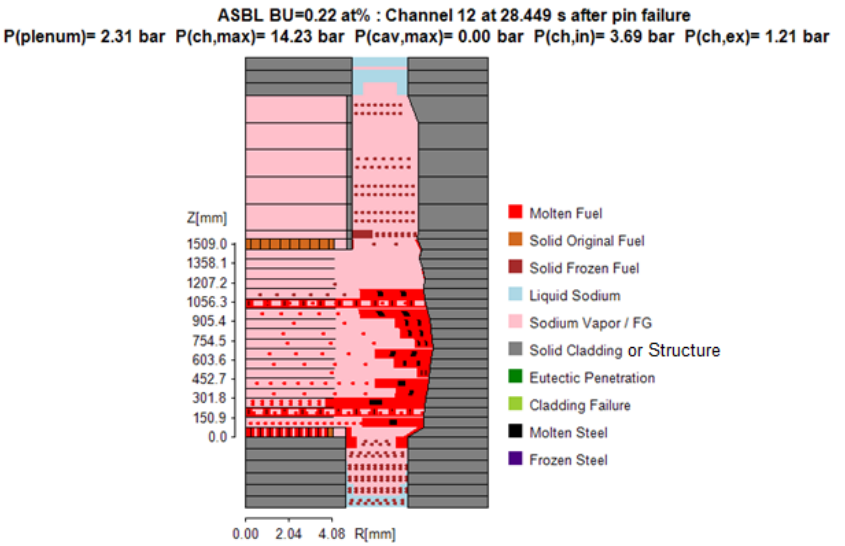


Figure 5. Status of the blocked assembly at 28.5s after pin failure

Assembly Blockage Accident Simulation without Inter-Assembly Heat Transfer

- The fuel pins are largely disrupted, and molten fuel is present in the core region. A fraction of the fuel is in the form of frozen particles.
- Ablation of the assembly wall can be observed. The maximum ablation at this time is ~24% of the assembly wall.
- Based on the current penetration rate, assembly wall failure would occur after another ~44s.
- The core net reactivity at the same time is -0.13 $ and the relative power has decreased to Prel=0.64 P0.
- The maximum temperature difference between the wall of the blocked assembly and its neighboring assemblies is 1061 K, suggesting that the effect of IAHT is likely to be significant.

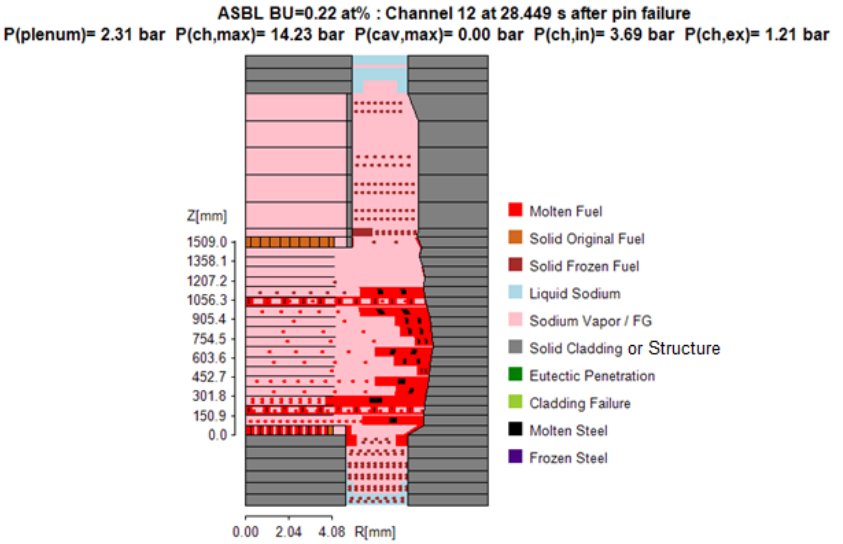


Figure 5. Status of the blocked assembly at 28.5s after pin failure

Assembly Blockage Accident Simulation including Inter-Assembly Heat Transfer

- The assembly blockage accident simulation presented above was repeated including the Inter-Assembly Heat Transfer (IAHT) models for the post-pin-failure phase.
- The simulation was extended to ~45 s after pin failure. The status of the blocked assembly at 41.5s after pin failure is illustrated in Figure 6.
- Little molten fuel is present in the core region. Most of the relocated fuel is in the form of frozen particles or crusts.
- Ablation of the assembly wall is limited and significantly smaller than calculated in the case without IAHT.
- The core net reactivity is -0.02 $ and the relative power has decreased to Prel=0.78 P0.

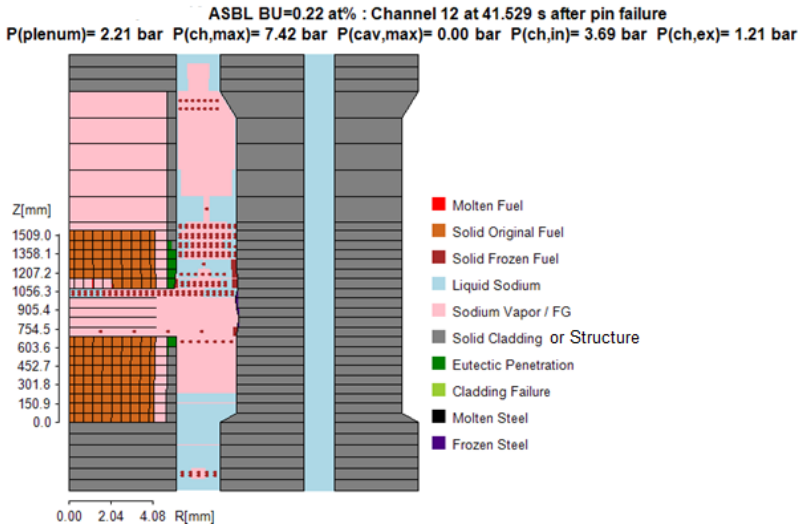


Figure 6. Status of the blocked assembly at 41.5s after pin failure. (IAHT included after pin failure)

Assembly Blockage Accident Simulation including Inter-Assembly Heat Transfer

- Recent simulations have examined the effect a more sever blockage with inlet pressure loss multiplying constant KBL=520 and included the effect of the IAHT during the Boiling and Pre-Boiling phases of the accident.

- These simulations were extended to 73 s after the blockage occurrence. At this time all the mobile fuel is frozen, only little ablation of the assembly wall is predicted, and liquid sodium is re-flooding the damaged blocked assembly.

- These initial results of the assembly blockage (ASBL) simulation show that the IAHT can significantly affect the accident outcome providing an effective path for removing heat from the blocked assembly in the absence of the sodium coolant flow in the blocked assembly.

CONCLUSIONS

- The implementation of the post-assembly failure models described in Section 3 allows the SAS4A code to explore the accident events that could occur after a potential assembly wall failure.

- The results of a postulated severe ULOF accident show that even if a failure of the lead assembly wall occurs, the damage to the neighboring assemblies can be limited and the assembly failure will not necessarily propagate to other parts of the core.

- As the reactor power is already low and continues to decrease, the liquid sodium continues to re-enter the damaged lead assembly and the postulated ULOF accident is expected to terminate with only limited core damage.

- The use of a Transition Phase code which uses a coarser core description to model large scale core disruption is not necessary in this case and the accident termination can be simulated using the more detailed metal fuel models available in SAS4A.

CONCLUSIONS (continued)

- The inter-assembly heat transfer models described in section 4 are essential for the correct simulation of postulated assembly blockage accidents where significant temperature differences between the blocked assembly and its neighbors.

- Initial results of assembly blockage simulation including the IAHT models show that the IAHT can provide an effective path for removing heat from the blocked assembly in the absence of the sodium coolant flow, allowing the blocked assembly to reach a stable coolable configuration.

- The fuel melting and relocation remains limited to the blocked assembly and the damage does not extending to the neighboring assemblies.

- The IAHT can also play an important mitigating role in other severe accidents such as the ULOF accident described above. The IAHT models will be used in future work to analyze the outcome of these accidents.