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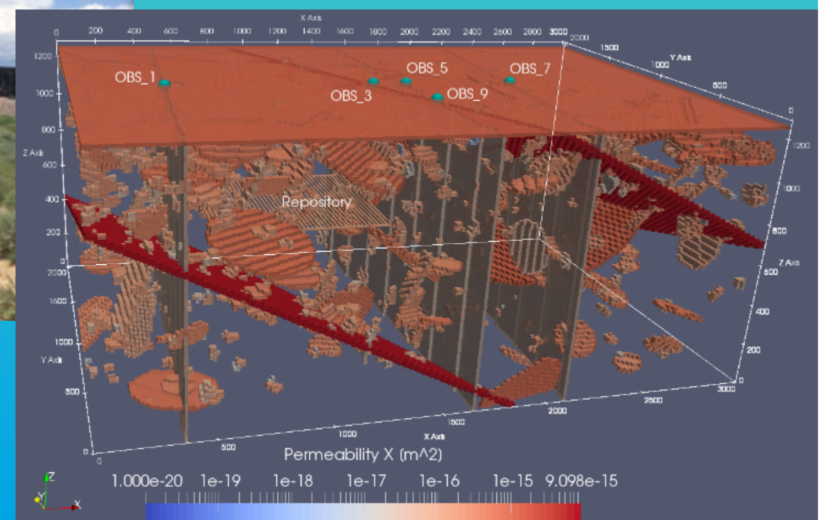
Spent Fuel and Waste Science and Technology (SFWST)



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Filler Approach and Testing

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This is a technical presentation that does not take into account the contractual limitations or obligations under the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (Standard Contract) (10 CFR Part 961). For example, under the provisions of the Standard Contract, spent nuclear fuel in multi-assembly canisters is not an acceptable waste form, absent a mutually agreed to contract amendment.

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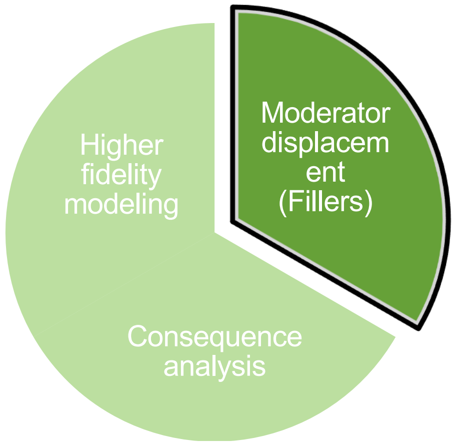
Filler materials are being investigated as an option to prevent post-closure criticality

- Dual-purpose canisters (DPCs) can be preconditioned by adding filler materials to displace moderator from being between the fuel assemblies/rods
- Key assumption includes
  - Access to DPC internal void volume is limited to original vent/drain ports, or
  - Purpose-built ports (e.g., through canister shell)
- Cutting open the canister lid is currently out of consideration



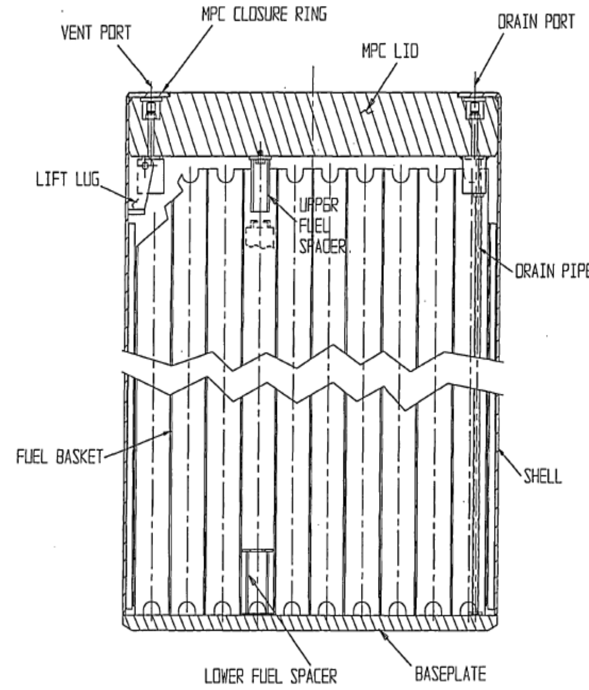
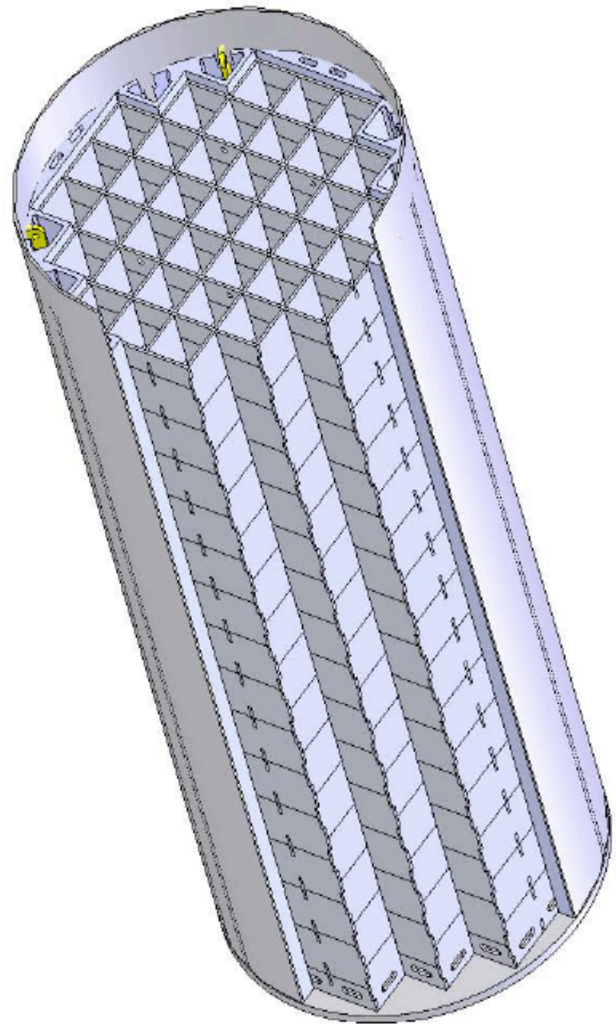


FIGURE 1.1.2; CROSS SECTION ELEVATION VIEW OF MPC

Key attributes of DPC fillers

- Material compatibility with disposal system
- Well-understood long-term durability
- Moderator displacement
- Minimal neutron moderation
- Filler material should be able to incorporate neutron absorbers
- Ease of injectability and favorable rheological properties
- Minimum gas generation
- Radionuclide sequestration
- Reasonable cost

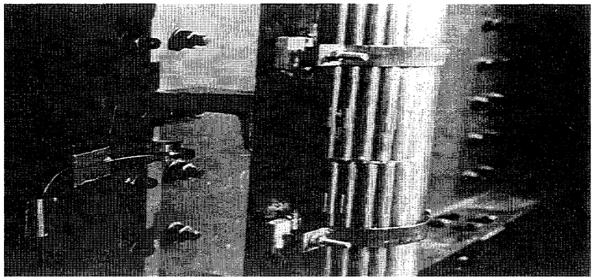


MPC-37 canister (from Greene et al. 2013)

Filler materials have been studied in past for spent nuclear fuel (SNF) disposal

- Various fillers have been considered, but only solid fillers (particulates) were experimentally evaluated (open canister)
- Previous work successfully demonstrated filling of SNF basket[1]
  - Steel shot was used
  - Selection criteria included ease of handling, low cost, availability, chemical buffering, and moderator displacement
  - Eight tests (2 dummy assemblies, 2 shot sizes, with/without vibration) were performed
- Atomic Energy of Canada Ltd demonstrated filling with glass beads[2]

Waste Package multi-assembly particulate fill test[2]



Two fuel assembly particulate fill test on a shake table[2]

1. Cogar, J. 1996. Waste Package Filler Material Testing Report. BBA000000-01717-2500-00008 Rev 01. OCRWM.
2. Forsberg, C.W. 1997. Description of the Canadian Particulate-Fill Waste Package (WP) System for Spent Nuclear Fuel (SNF) and its Applicability to Light-Water Reactor SNF WPs with Depleted Uranium Dioxide Fill. ORNL/TM-13502.

Current R&D focus includes molten filler materials that solidify upon cooling or chemical reaction

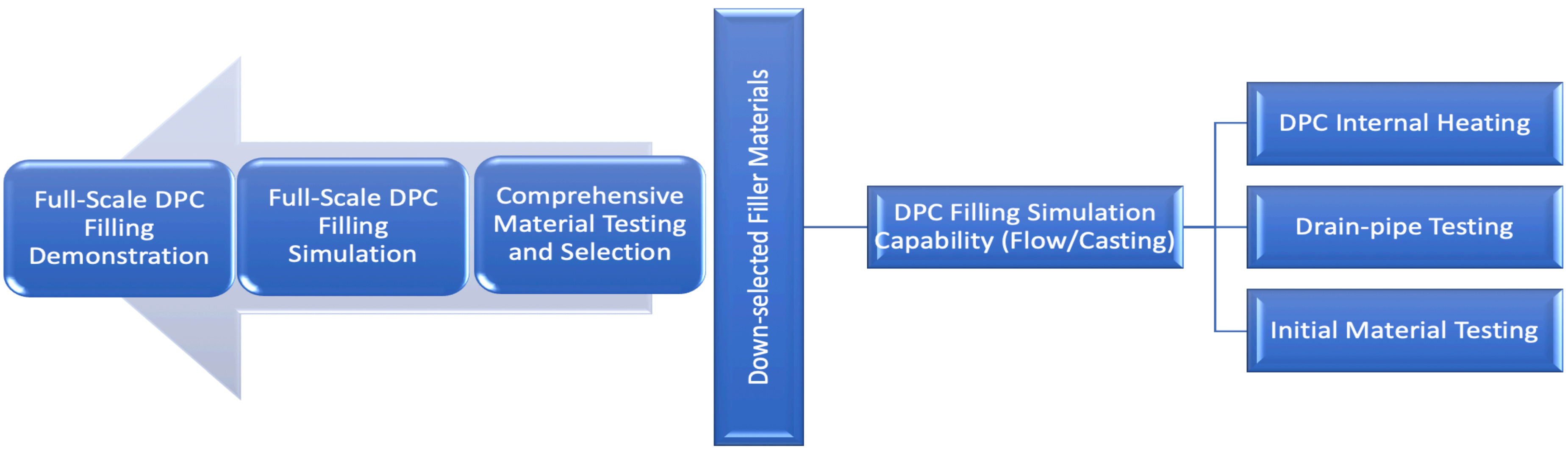
- Filling DPC with solid (particulates) fillers using existing vent/drain ports will be investigated in future
  - Uniformly filling DPCs without cutting open the lid and using existing ports could be challenging (particulate must flow)
  - The interstitial volume of particulate fillers would allow significant water in a flooded DPC
  - Neutron absorber may be need for particulate filler to be effective
  - Vibration will be needed to increase packing fraction
- Current focus is on solid fillers that can be placed in a DPC as liquids using existing drain/vent ports
  - Include cement slurry, low temperature metals, alloys, and glass
  - Previously considered, but not tested
  - No experimental data of filling DPCs using molten solid fillers
  - No handling experiences
  - No purpose-built validated simulation capability

Step by step development towards full scale DPC filling demonstration using a selected filler

- Fully validated filler simulation capability development for down selecting filler materials and assess DPC filling process (Under development)
  - Initial flow simulation to determine injectability, void filling, filling time, filling method (pump vs. gravity)
    - Validation using surrogate liquid filler and DPC mock-up
  - Initial casting/Solidification to determine casting defects, stress/strain on various components
    - Validation using molten metal/cementitious fillers and scaled DPC sections
  - Investigation of DPC internal heating for high temperature molten filler
    - Validation may be performed using full-scale DPC

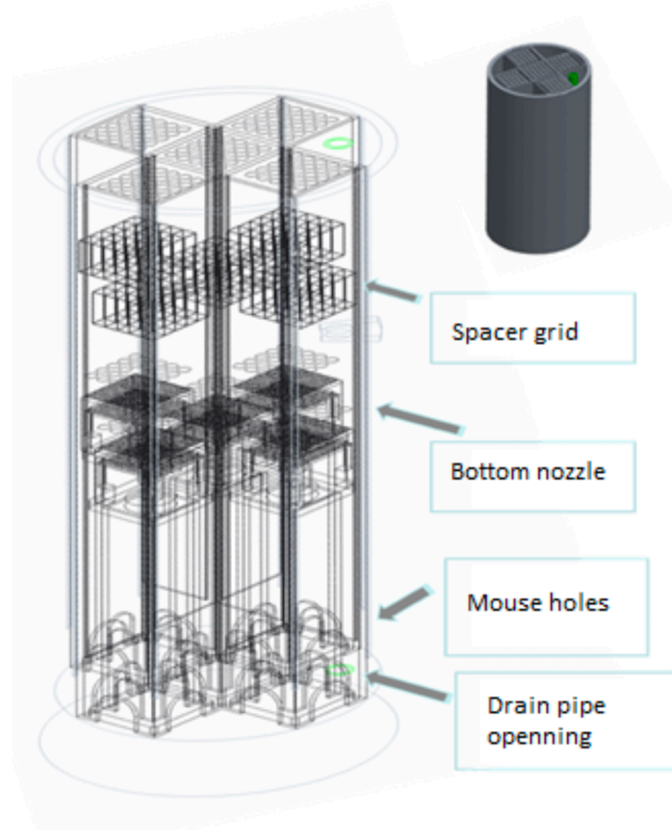
Step by step development towards full scale DPC filling demonstration using a selected filler (Contd.)

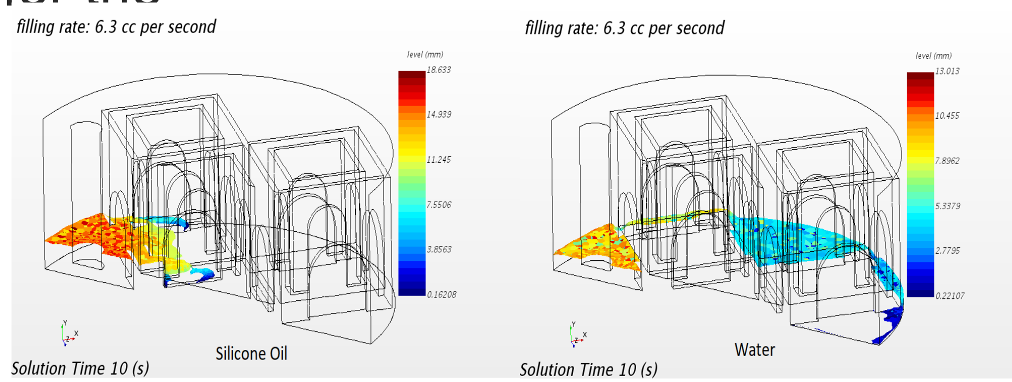
- Separate drain-pipe study to determine whether the drain-pipe can support DPC filling (Planned)
- Initial cement-based filler material testing (Underway)
- Filler materials down selection using the validated simulation capability (Future)
  - Comprehensive filler material testing (e.g., corrosion, radiation hardening, radiolysis) after down selection
  - full-scale DPC filling demonstration



Filler flow simulation has been performed using 3D Computational Fluid Dynamics (CFD) methods

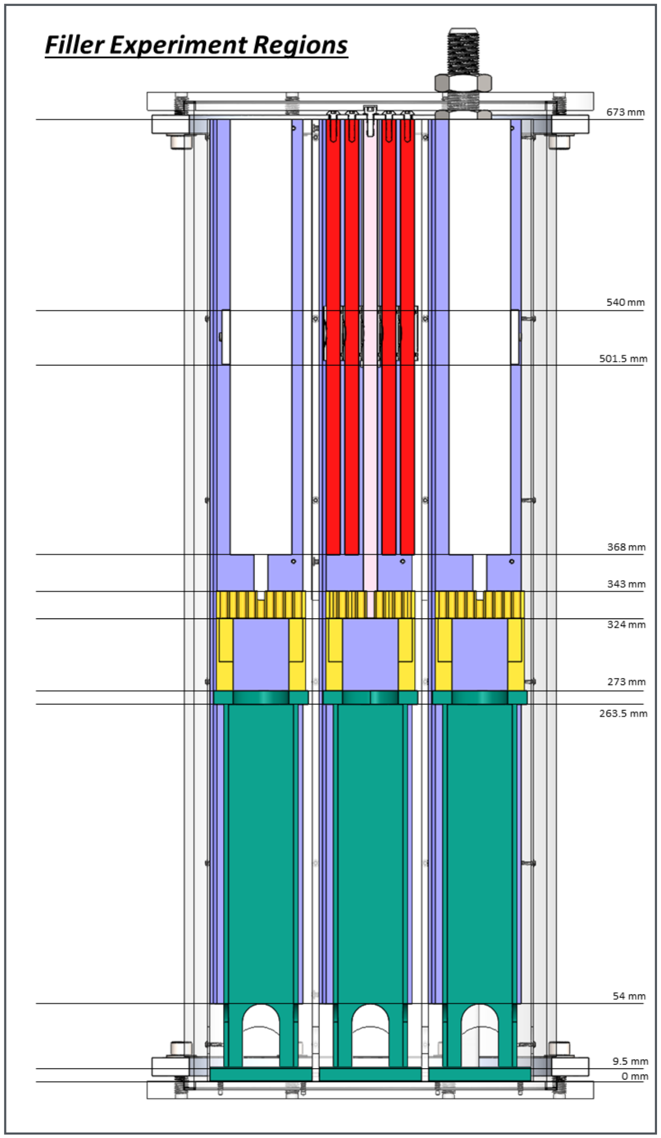
- STARCCM+ is being used as the computational code with
  - surrogate filler materials (e.g., water, Glycerin, Silicon oil, lead)
  - mock-up DPC with 5X5 dummy assemblies
- Viscosity effect expresses itself in two phenomena: level rise around the inlet area, and liquid propagation before the entire domain is filled
  - Water being less viscous propagates further in the region than the silicone oil for the same period of time





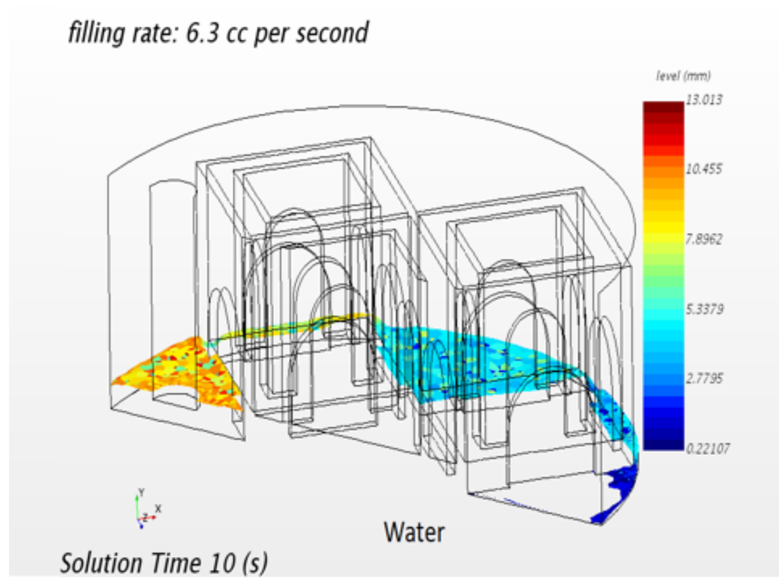
Viscosity effect demonstration on two liquids: water and silicone oil

Initial flow demonstration/simulation validation focused on the DPC mouse hole region



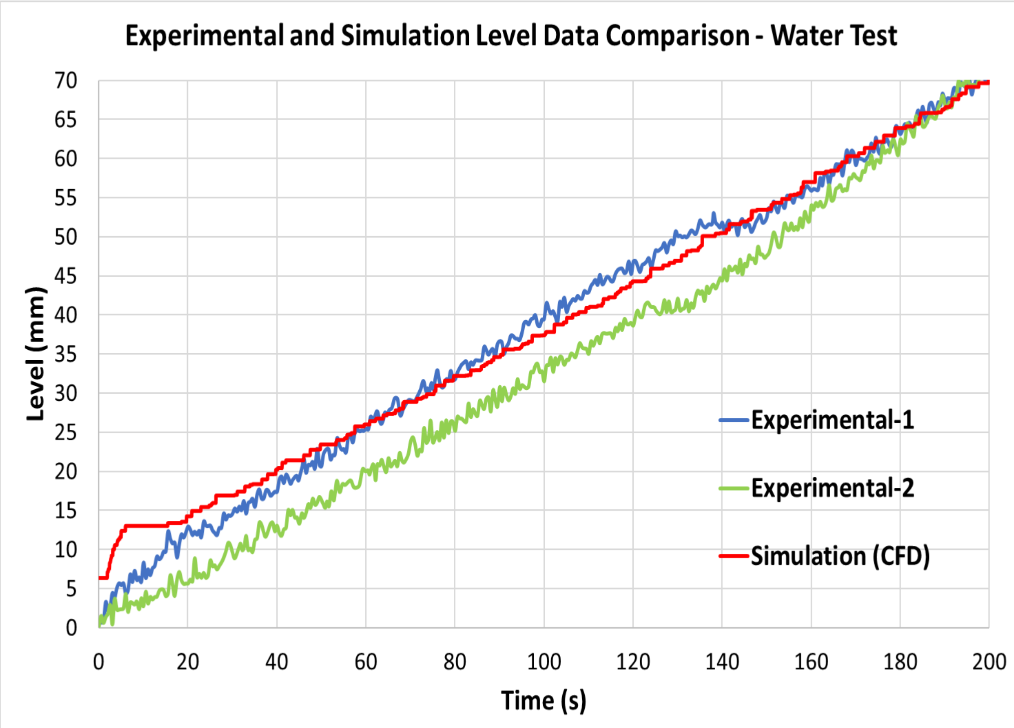
Experiment test system schematics

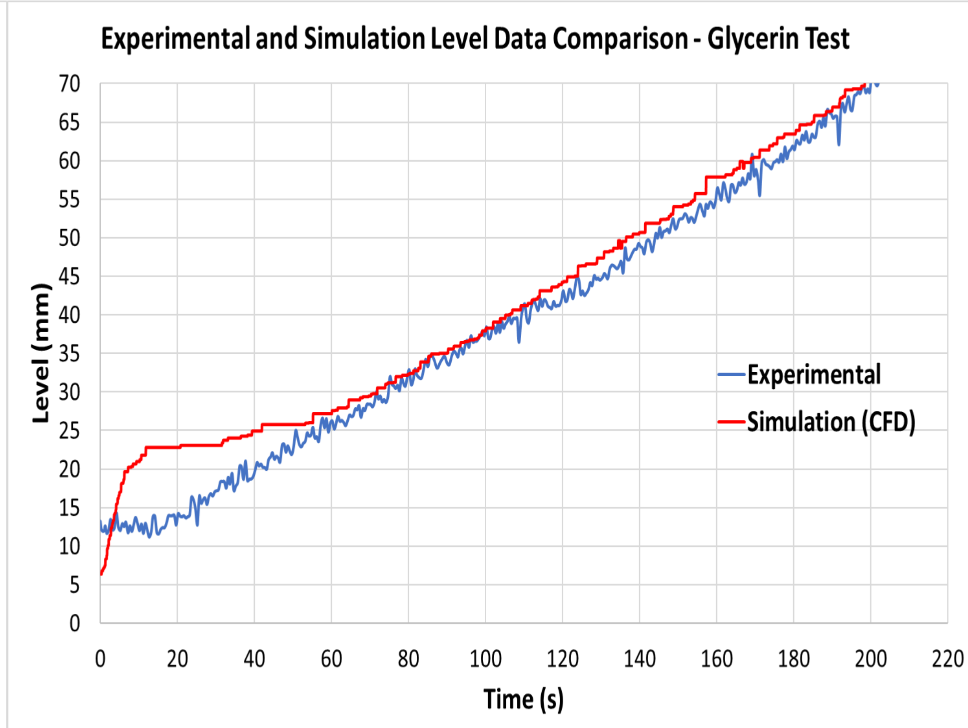
- The CFD simulations were carried out applying
  - A 180º symmetry
  - A constant flow rate of 6.3 cc/sec
- A constant flow rate of 12.6 cc/sec (6.3*2)
  - A peristaltic pump was used for glycerin



Simulation animation capture at 10 sec

Experimental data using surrogate fillers agreed with the flow simulation results



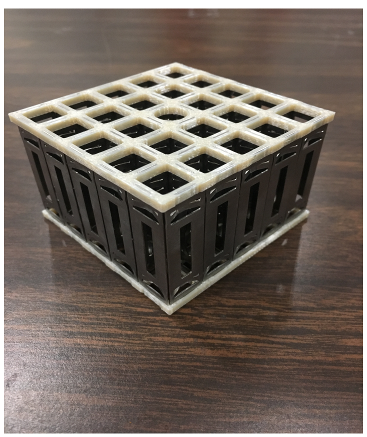


- The water level progression was tracked by two level sensors
- Measured level progression by time showed agreement with the computational results from the CFD simulation

- Glycerin is considered due to its higher viscosity
- The CFD runs showed no trapped voids
- Same fill rate is applied 12.6 cc/sec
- The results showed good agreement on the level progression

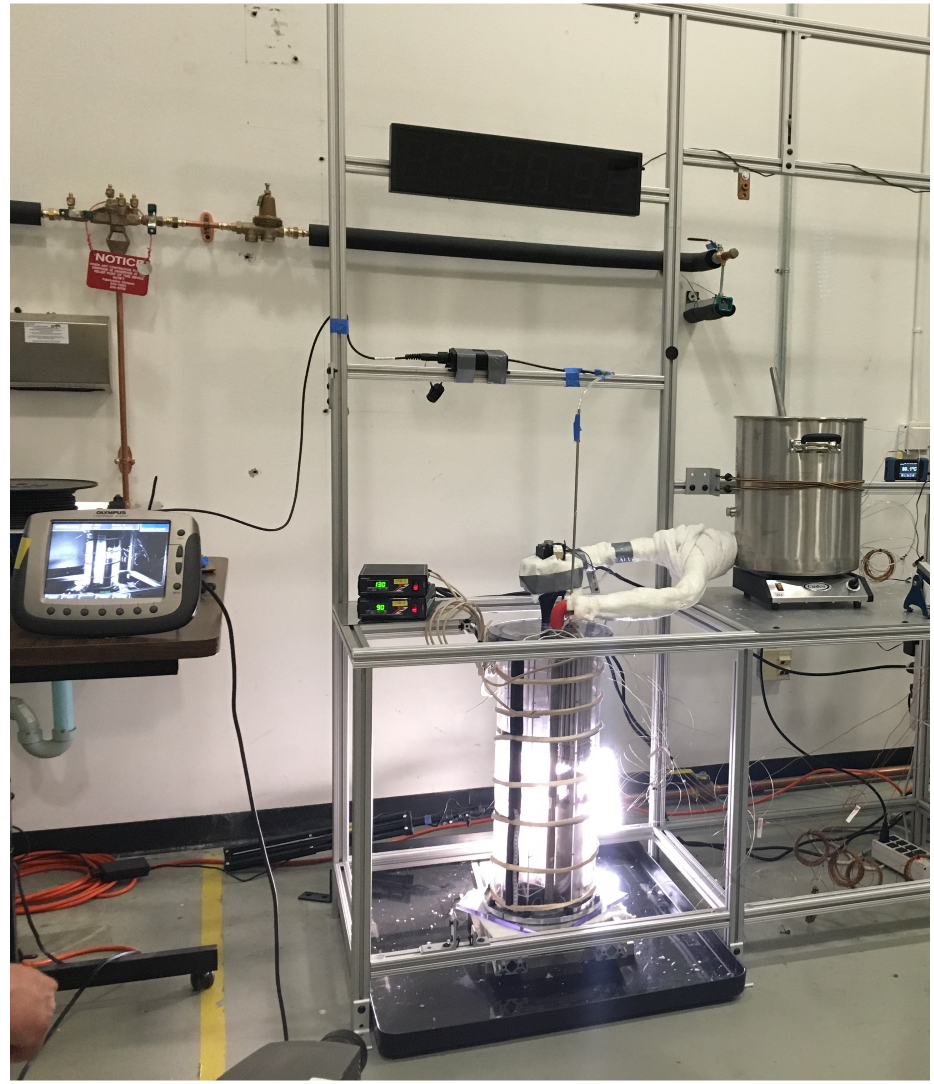
Initial solidification experiment using wax as surrogate filler has been performed

- Objective is to gain insight into phase change effects and the formation of voids
  - Wax was considered due to its low density and high viscosity compared to liquid metals, making it an unfavorable agent for filling
  - Low melting point, easy to handle, and provide excellent data source for solidification simulation validation
- Test set up incorporates a source of heat to keep the wax in liquid state during filling
- The filling process was also recorded with a high-speed camera, focusing specifically to investigate the propagation of the initial spurt once the filler comes out of the pipe



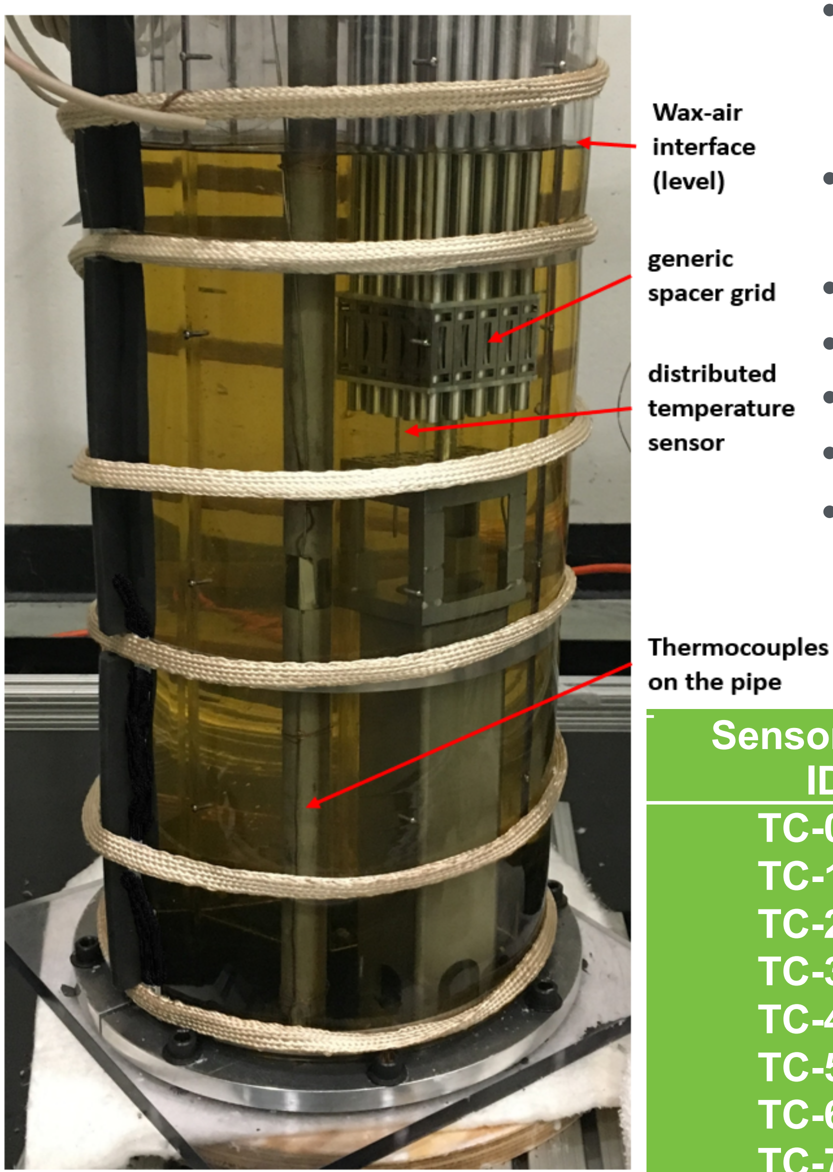
Generic spacer grid

Paraffin wax melting point is 64°C



Paraffin wax testing set up

Temperature distribution is well-monitored during the wax experiment



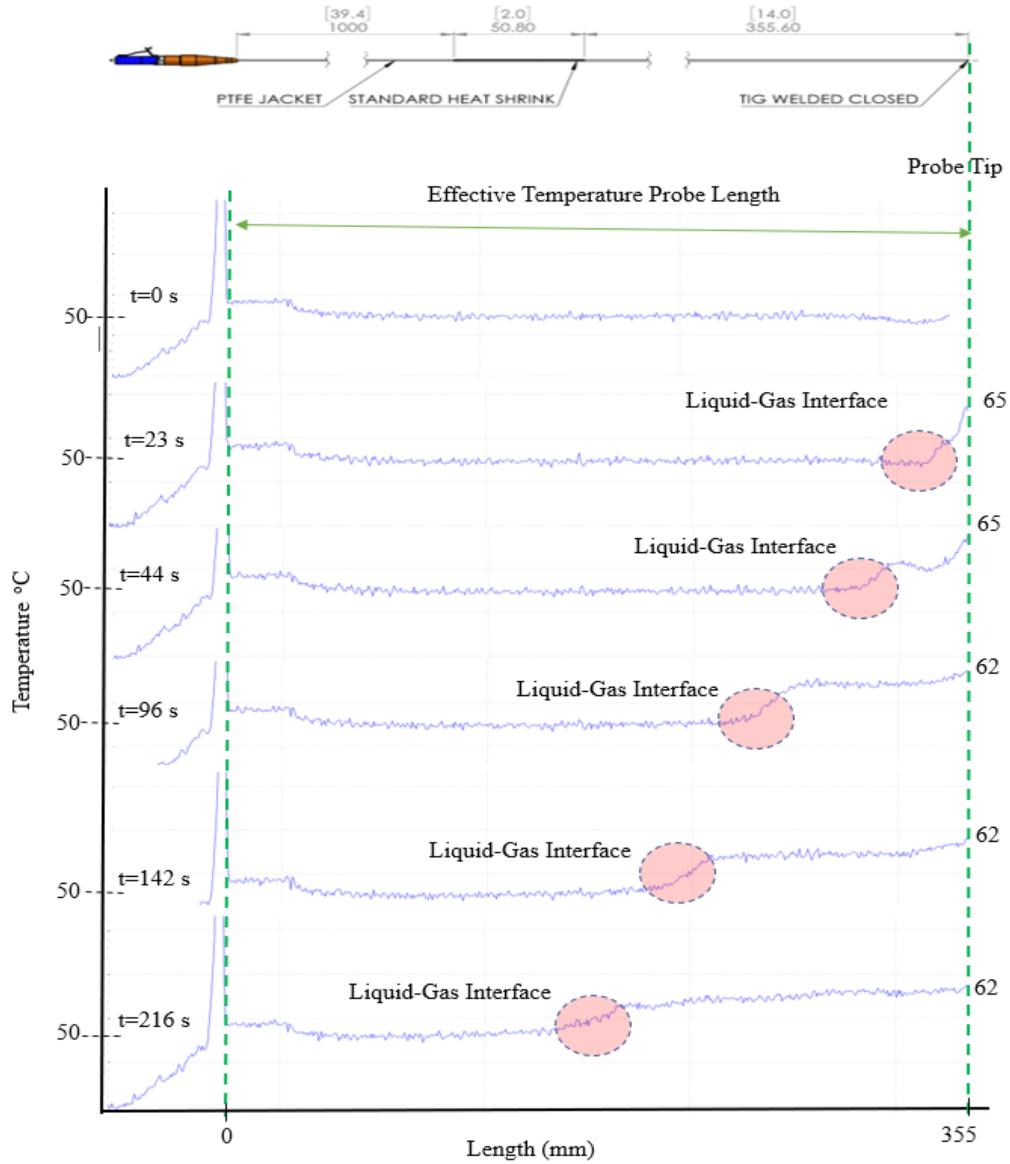
- Multiple thermocouples were installed at various spots inside the canister to monitor the temperatures during filling and cooling
- Before filing, the canister was heated with heat tapes for 2 hours
- Insulator is used to minimize heat losses
- Average overall temperature measured ~55°C
- Min internal temperature was ~43 °C
- Molten wax temperature was ~75 °C
- 3 thermocouples were installed on the bottom, middle, and top of the fill pipe

Sensor ID	Position
TC-0	Canister center middle
TC-1	Canister side top
TC-2	Canister side bottom
TC-3	Spacer grid
TC-4	Pipe bottom
TC-5	Pipe middle
TC-6	Pipe top
TC-7	
TC-8	Ambient

- Evaluating the temperature gradient along the pipe is important for understanding the solidification effects
  - One risks under consideration for the real application is clogging of the pipe outlet during pouring process

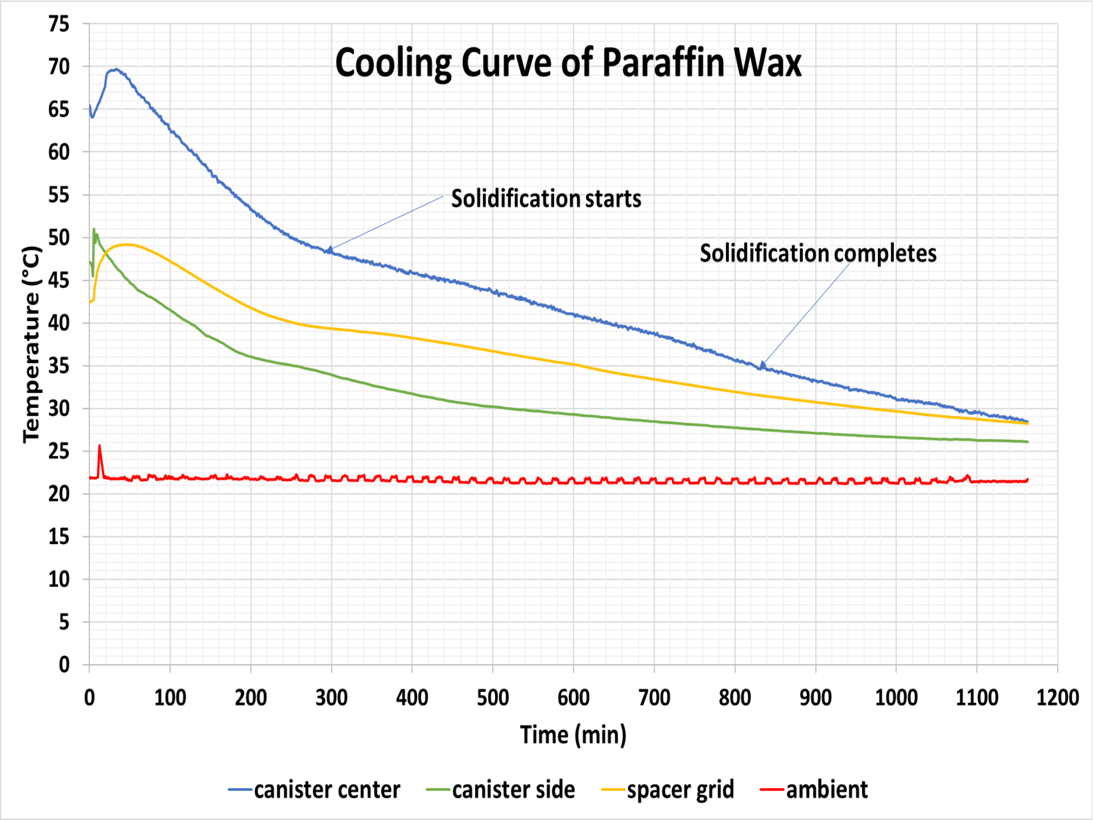
A high spatial resolution temperature probe was also used to monitor internal temperatures

- The probe was inserted in lieu of a fuel rod in the fuel bundle and was extended from the nozzle to the top of the bundle
- The probe was fabricated by a commercial company using a fiberoptic embedded into a 316 stainless steel capillary tube and has a capability to allocate ~ 511 temperature sensors with a spatial resolution of 0.65 mm along 355 mm of optical fiber length
- Data acquired during the filling and solidification process with a time resolution that ranged from 0.016 s to 60 s
- The temperature profiles of the 511 sensors were plotted as a function of distance from the probe's tip at discrete time intervals
- The abrupt temperature changes, including a significant temperature gradient at the liquid-gas interface, were captured correctly by the probe



Cooling of wax was recorded during the post-filling solidification process

- Transient filling and cooling data are plotted
- The phase change can be seen from the plots at each location where temperatures are measured



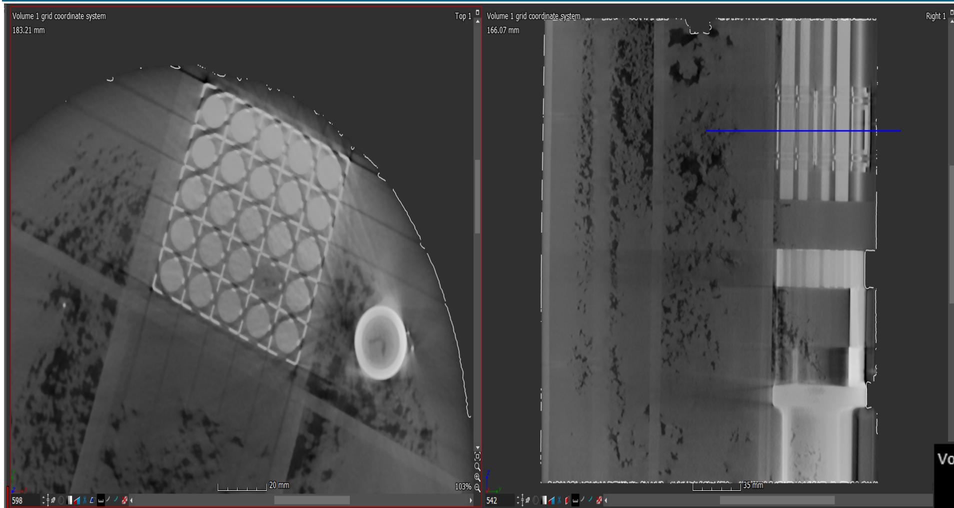
- The temperature at the center of the canister increased to ~70°C during the filling process
- The side of the canister and the spacer grid close to the side were at slightly lower temperatures

➢ The only aspect of wax that is better than liquid metal is its thermal capacity due to its high specific heat compared to that of metal:2.5 J/g °C (wax) to 0.1-0.25 J/g °C (liquid metals)

CT scan was performed to examine the solidified wax to gain insight into void formations

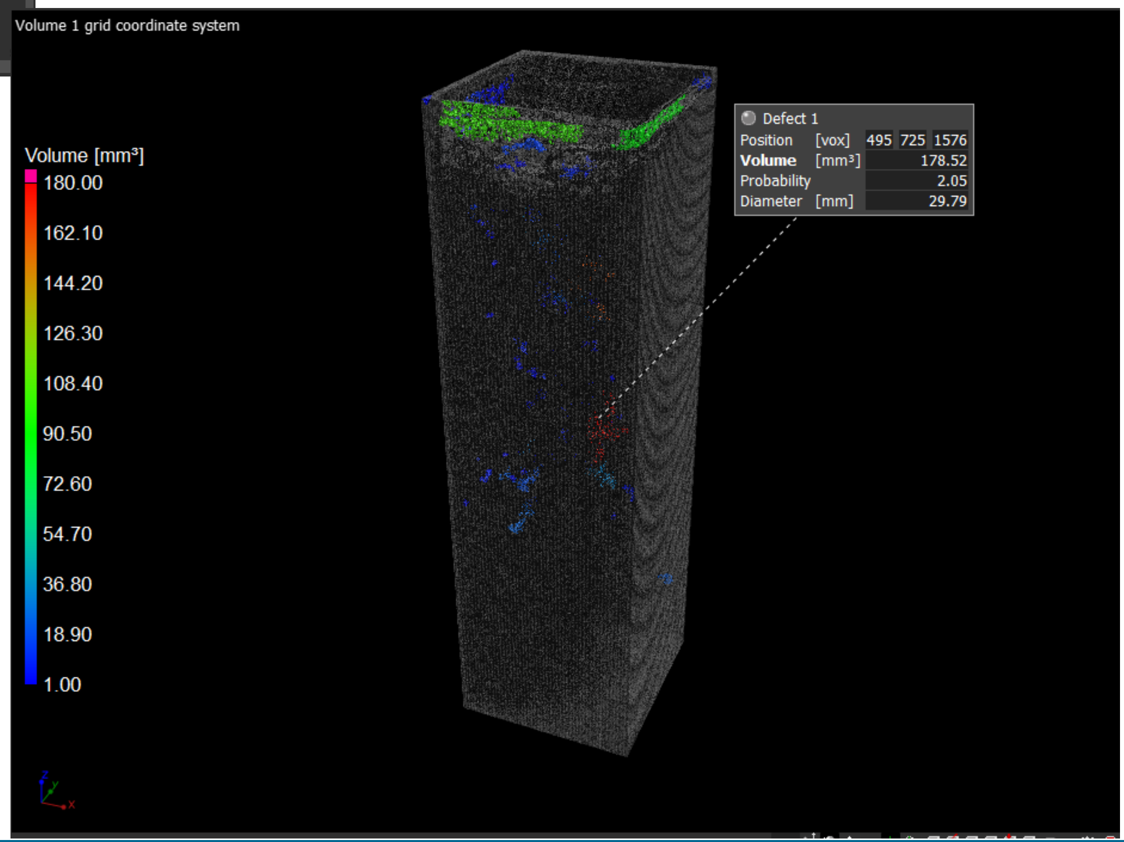
- Total defects (voids) are currently being evaluated from the CT scan data
- A simple experiment was also performed to estimate the external connected void fraction
  - Wax canister was filled with water up to the level of the wax surface. Weight difference w and w/o water was recorded.
  - **0.0013m3 (1300 cc)** of external connected void fraction was calculated

Detailed analysis is being performed using the wax experiment CT scan data



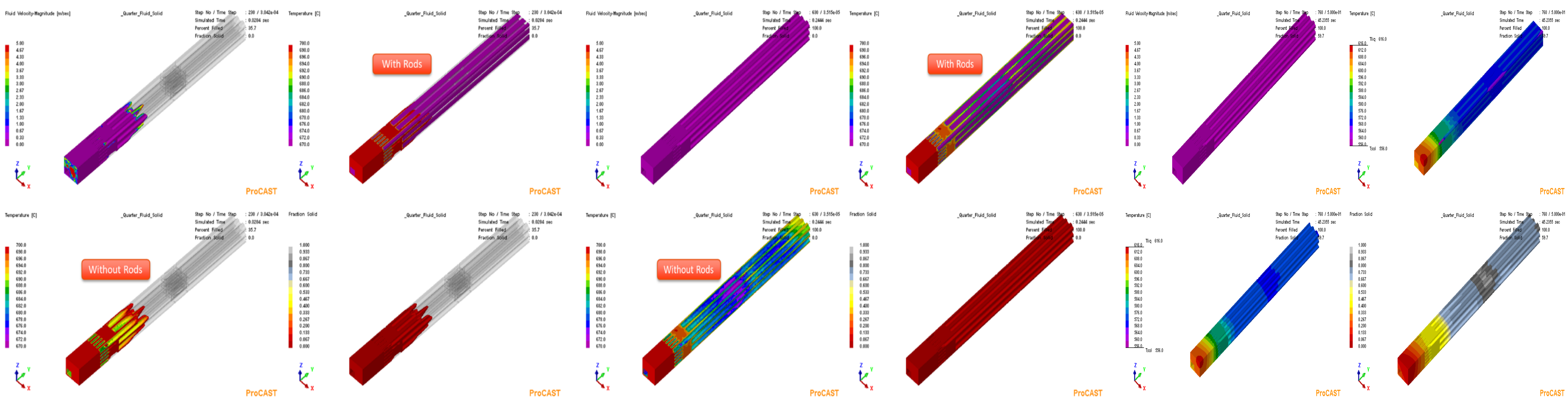
- VGSTUDIO MAX (CT analysis software) is used for analyzing scan data
- Information on void size, location can be obtained with a min void diameter
- Largest void in each section can be visualize with its properties as seen in the figure below

- High resolution reconstruction and 3-D rendering allowed nondestructive evaluation of porosity/defects with sensitivity of 0.5 mm diameter
- CT scan showing more porous solidification on empty pockets of the basket, but less void formation around the assembly area



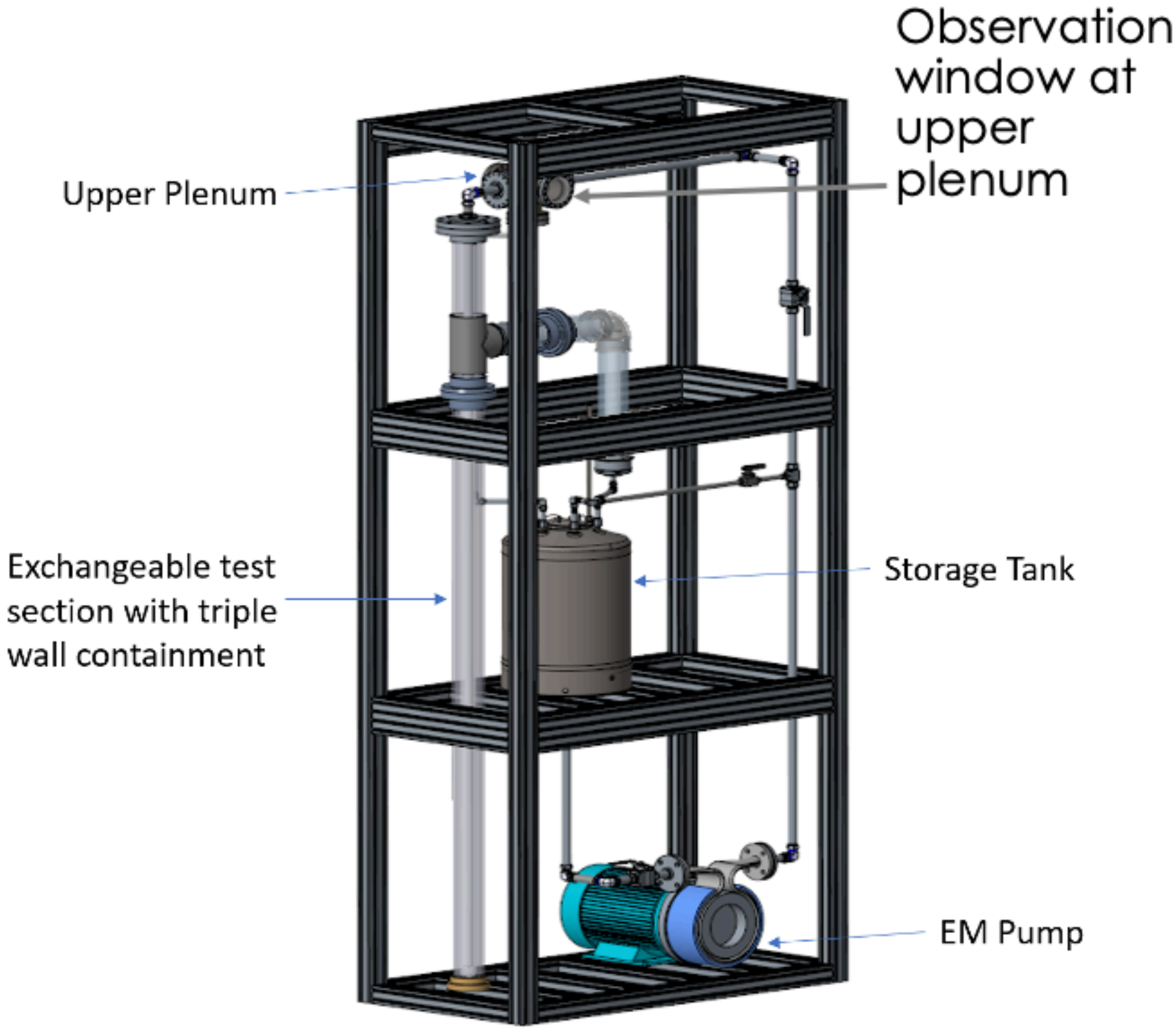
Casting/solidification simulation capability with step-by-step validation is currently under development

- ProCast casting simulation software has been selected for casting simulation
  - Can handle both metal and composite
- ProCast uses the Finite Element Method to model flow, thermal, and stress behavior in casting process
- The wax experiment will be modeled, and data collected will be used for validation along with other unit-cell tests leading to full-scale DPC simulation



35.7% filling 100% filling solidification

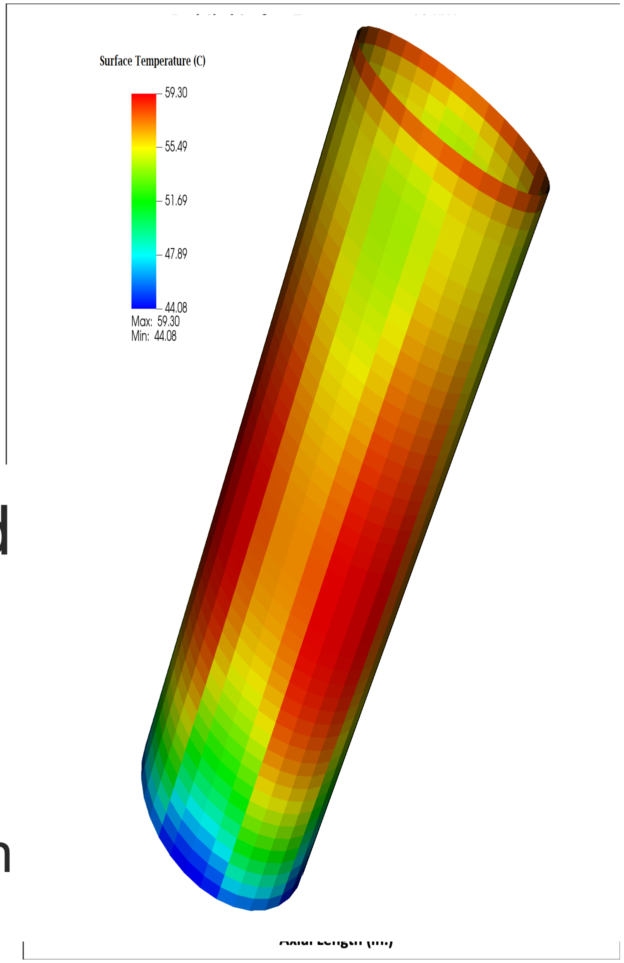
Drain-pipe experiment will provide maximum sustainable flow rate (Initial condition)



- Mercury will be used as a surrogate (liquid in room temperature)
- The experiment will be used to determine
  - Maximum filling flow rates and required power
  - Characterization of jet impingement forces
  - Hydraulic lock characterization
  - Strain distribution along pipe
  - Pipe vibration
  - Liquid film studies

DPC internal heating evaluation will determine initial/boundary conditions for DPC filling simulation

- DPC must be preheated for metal/glass based liquid fillers or to cure concrete slurries
- DPC internal heating evaluation has been started using thermal cask analysis code COBRA-SFS
- Heating options currently being investigated
  - External insulation only
  - Circulation of hot gas in the system through drain/vent ports
  - External heaters (blanket/furnace) in combination with the above options
- DPC heating simulation model may be validated using a full-scale DPC with dummy assemblies



Preliminary results showing surface temperature of a 37-assembly DPC with 10 kW heat load

Modeling and simulation with gradual validation are being used as a key approach to enable DPC filling

- A CFD model was developed to simulate the filling of a prototypic DPC
  - Demonstrated successful removal of void spaces and smooth liquid level progression
- Several experiments were performed to validate the numerical models and the results showed good agreement
- Solidification experiment was conducted using wax to investigate thermal effects and void formation
- A computational casting model is under development and will be validated using wax and other unit-cell experiments
  - The goal is to develop a validated full-scale DPC filling simulation capability
- Separate drain-pipe study is planned and DPC internal heating simulation is under development
  - DPC heating simulation validation may use full-scale DPC