Fuel Cycle Research and Development

Metallic Fuel Casting Development and Parameter Optimization Simulations


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Introduction to metallic fuel casting
  - History
  - Counter-gravity injection casting (CGIC)

Current Development Activities

Experimental Results

Parameter Optimization and Simulations
  - Gas compressibility/venting
  - Surface tension

Conclusions
Metallic fuel has been used for several decades in fast reactors

- Variety of sized and technologies led to a variety of fabrication methods
- Fabrication method influence by fuel design and fabrication environment
  - Large vs. small diameter
  - Hands-on/glovebox fabrication vs. remote/hotcell fabrication
- Several fabrication methods also used
  - Deformation processes (extrusion, swaging, etc.)
  - Casting
  - Combination

EBR-II provided the most recent U.S. experience on larger than laboratory scale

- Fuel for the EBR-II was fabricated using the counter gravity injection casting (CGIC) process
  - Fuel fabrication was done both remotely and hands-on
  - Over 130,000 pins were cast and irradiated using this method
CGIC worked well but had some efficiency disadvantages.

- Large recycle stream - heels and end crops (~40% of melt)
- One time use molds create a large amount of waste
- Reduced pressure may affect transmutation fuel i.e. Am
- Bottom or gravity pour casting was seen as the lowest risk casting development path
  - Wide spread industrial use
  - Scale-able from lab to engineering and production use
  - Does not require a reduced pressure (better for Am bearing fuels)
  - Increases melt utilization (large heel is not required and smaller end croppings)
  - Can be used for permanent mold development

- First system was designed and used for uranium alloys (BCS)

- Second system has been designed and is currently being installed for use with Pu and minor actinide bearing casting (GACS)
Initially using $Y_2O_3$ coated graphite molds and crucibles

Current fuel slug size: 4.3 mm diameter x 250 mm long
- Based on EBR-II fuel diameter and was considered to be conservative

Mold and crucible are independently induction heated

Designed to allow pressure differential assisted casting i.e. mold can be at a reduced pressure
A number of parameters were examined with using uranium alloys - amount and time of pressure assist, mold coating vs. no mold coating, mold pre-heating, and super heat amount

- Pressure assist caused multiple pin segments
- No mold coating performed well but resulted in pre-mature freezing (short pins)
- Level of pre-heating did not have significant effect (800-1000°)
- Too much super heat lead to pins made of many small segment
- Mold vent size greatly affects the flow of the material

Results high light the need to couple experiments with computations and for better defined molten material properties
Two codes were used for simulations of the casting process
- Initially used TRUCHAS when experimental results showed the need for gas compressibility then a switch was made to FLOW-3D

Models based on actual BCS/GACS dimensions were developed while casting pressures and temperatures were based on actual casting runs

Basic simulations accounted gravity, heat transfer, and solidification
- Surface tension and gas compressibility effects were examined in separate simulations

Separate effects testing was done to determine relative importance of thermal and physical properties on casting results

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>17.4 g/cm³</td>
</tr>
<tr>
<td>Specific Heat</td>
<td>201.3 J/kg·K</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>26 W/m·K</td>
</tr>
<tr>
<td>Liquidus Temperature</td>
<td>1340°C</td>
</tr>
<tr>
<td>Solidus Temperature</td>
<td>1240°C</td>
</tr>
<tr>
<td>Latent Heat of Fusion</td>
<td>38,720 J/kg</td>
</tr>
</tbody>
</table>
Initial simulation was run assuming the mold was filled with argon at atmospheric pressure with no vents in the mold.

Following simulations placed vents at one of four locations:

- No vent: Filling time = 1.7 sec.
- Bottom: Filling time = 1.7 sec.
- Midway: Filling time = 2.1 sec.
- Top: Filling time = 1.5 sec.
- Crucible: Filling time = 1.5 sec.
A value of 1.55 N/m was estimated for U-10Zr

Simulations were first done using an evacuated mold then a mold initially filled with argon and vented.

Assumes evacuated mold - left images (black background) does not take surface tension into account.
Simulation - Surface Tension

Argon filled molds - left images do not take surface tension into account
Several simulations were run to determine the importance of melt/mold wetting angle, surface tension, melt viscosity, and viscosity/surface tension relation.

In addition to physical parameters, the importance of liquid thermal properties and the effects on casting results was also examined.

<table>
<thead>
<tr>
<th>Fluid Flow Parameters</th>
<th>Primary</th>
<th>Secondary</th>
<th>Tertiary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Void Fraction</td>
<td>Wetting angle</td>
<td>Surface tension/viscosity</td>
<td>Surface tension</td>
</tr>
<tr>
<td>Solidification</td>
<td>Wetting angle</td>
<td>Surface tension</td>
<td>Surface tension/viscosity</td>
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<table>
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<tr>
<th>Liquid thermal Properties</th>
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<th>Secondary</th>
<th>Tertiary</th>
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</thead>
<tbody>
<tr>
<td>Initial solidification</td>
<td>Heat x-fer coefficient</td>
<td>Latent heat</td>
<td>Specific heat of liquid</td>
</tr>
<tr>
<td>Final Solidification</td>
<td>Heat x-fer coefficient</td>
<td>Heat x-fer coefficient</td>
<td>Latent heat</td>
</tr>
</tbody>
</table>

Parameter effect on casting results ranked based on importance.
Conclusions

Gravity casting is a feasible process for casting of metallic fuels
- May not be as robust as CGIC, more parameter dependent to find right “sweet spot” for high quality castings
- Fluid flow is very important and is affected by mold design, vent size, super heat, etc.
- Pressure differential assist was found to be detrimental

Simulation found that vent location was important to allow adequate filling of mold

Surface tension plays an important role in determining casting quality

Casting and simulations high light the need for better characterized fluid physical and thermal properties

Results from simulations will be incorporated in GACS design such as vent location and physical property characterization