Design and Analysis for Melt Casting Metallic Fuel Pins

Advanced Accelerator Applications University Participation Program

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Overview

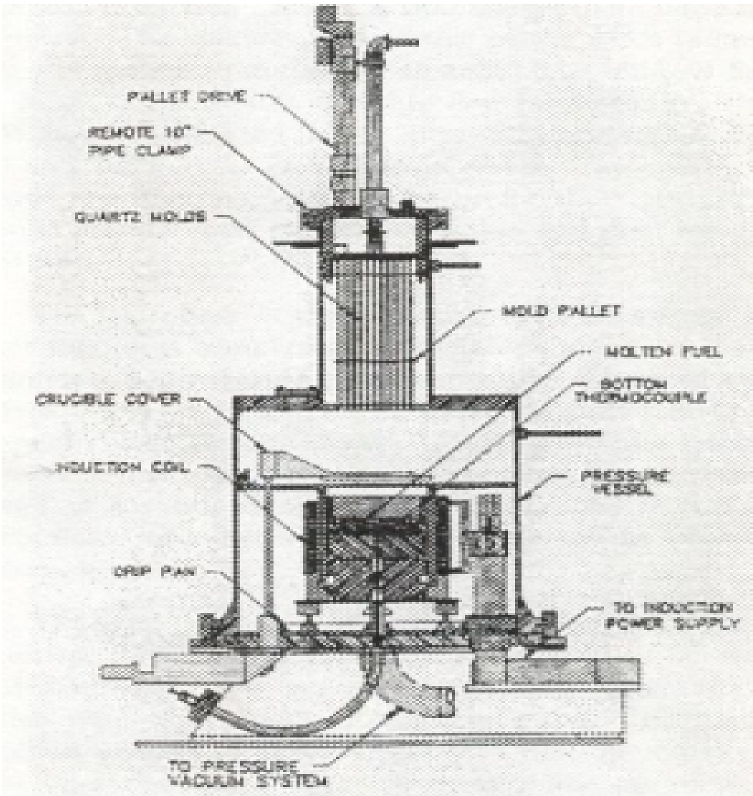
- *Project Overview*
  - AAA Project
- *Background - Casting Volatile Actinides*
  - Need to Contain Americium
- *Process to Select Casting Furnace Concept*
  - Casting Process Variables
- *Overview of Furnace Options*
- *Proposed Casting Furnace Concept*
  - Important phenomenon
- *Fuel Rod Model*
- *Preliminary Modeling Results*
- *Summary*

Project Overview - Background

- *UNLV AAA Program Objectives*
  - establish a world-class program for accelerator-driven transmutation technology.
  - building core competencies and facilities to promote the University's strategic growth goals.
  - involve UNLV students in research on the refinement of spent nuclear fuel.
  - Long-term goals:
    - increase the University's research capabilities,
    - attract students and faculty of the highest caliber,
    - while furthering the national program to address one of the nation's most pressing technological and environmental problems.

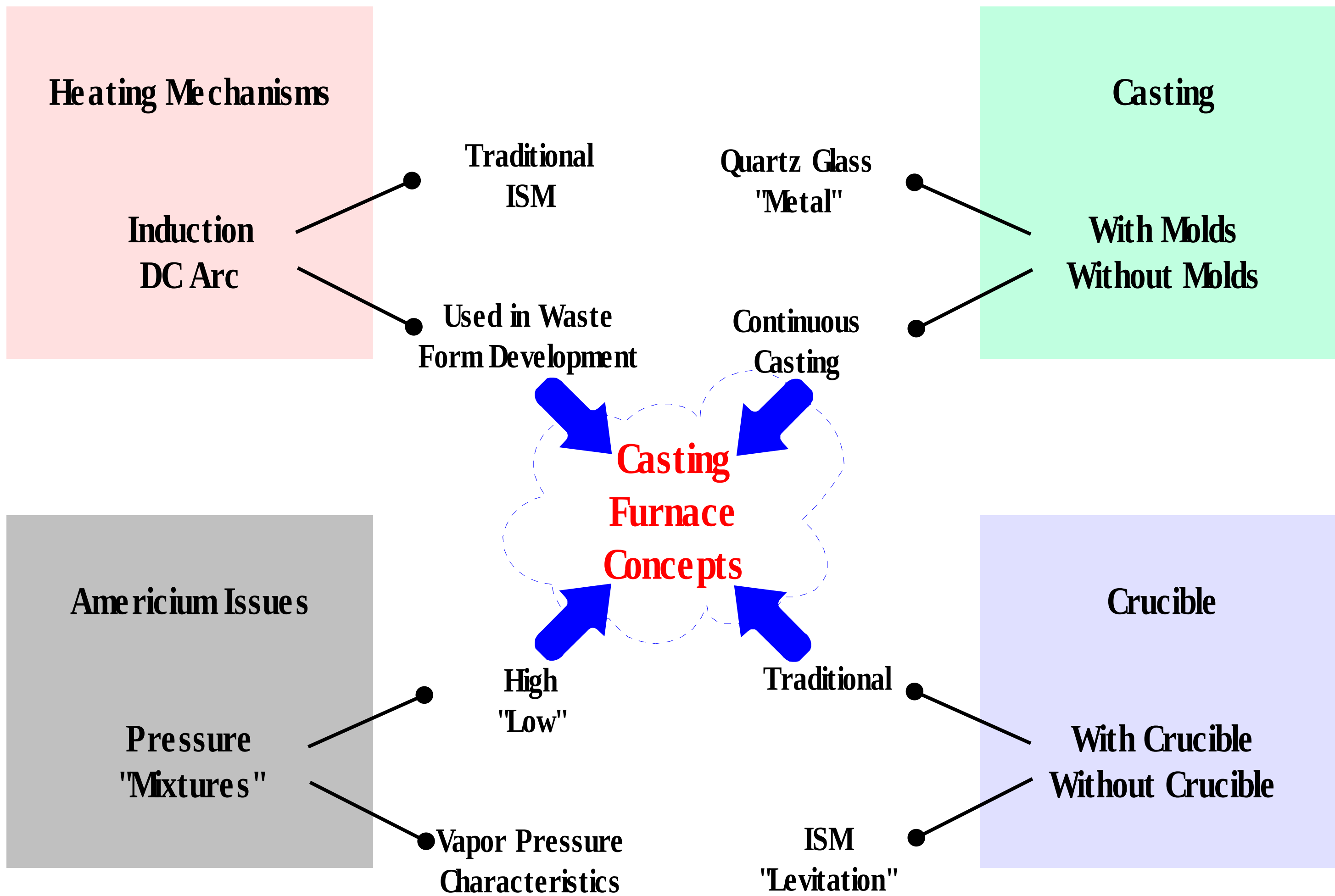
Background – Casting Volatile Actinides

- *Advantages of Present Technique*
  - Alloy uniformity due to intense stirring of the induction
  - Fast(no preheating), consistent, and selective heating
  - Pinpoint accuracy (directional)
  - The induction field and constant stirring of metal maintain a high level of superheat throughout the melt
  - Easily controllable heating
- *Casting Process*
- *Previous ANL Experience*
  - Americium Loss During Casting
- *Must Develop a Technique to "Contain" Americium*



Argonne Furnace

Casting Process Variables

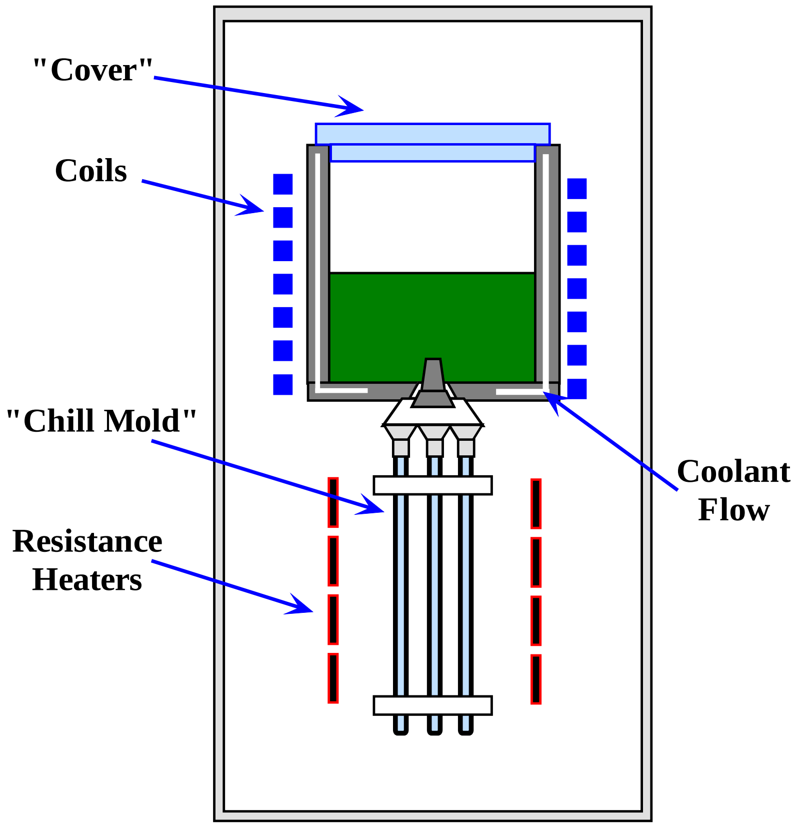


Overview of Furnace Options

- *Brainstorming resulted in several options*
  - Inductively heated, pressurized chamber, vacuum Molds
  - Inductively heated, pressurized – closed chamber
  - Inductively heated, continuous casting
  - DC arc melting
  - Semi-levitation melting
  - Induction skull melting, gravity or pressurized casting
- *Evaluation of system characteristics*
  - ISM with pressurized or gravity casting

Proposed Concept - Induction Skull Melting (ISM)

- *Advantages:*
  - Alloy uniformity due to intense stirring of the induction; a high level of superheat throughout the melt
  - Copper "skull" vs. graphite crucible
  - Flexible in charge materials
  - Segmented crucible
  - Suitable for reactive metals
  - No waste stream from crucible
- *Disadvantages:*
  - Electrical efficiency unknown
  - Limited practical experience
  - Cooling system required and its interaction with melt (NaK)
  - Uncertainty in coupling to fuel casting



Proposed Concept – cont.

- *Complex physical system*
  - Induction heating
  - Americium transport ← critical issue
  - Casting of fuel pins
- *Multi-year plan to assist in furnace development*
  - Development of numerical models
  - Selection of surrogate materials and testing in furnace concept
  - Ultimately – testing in hot cell conditions.

Project Overview - Research Approach

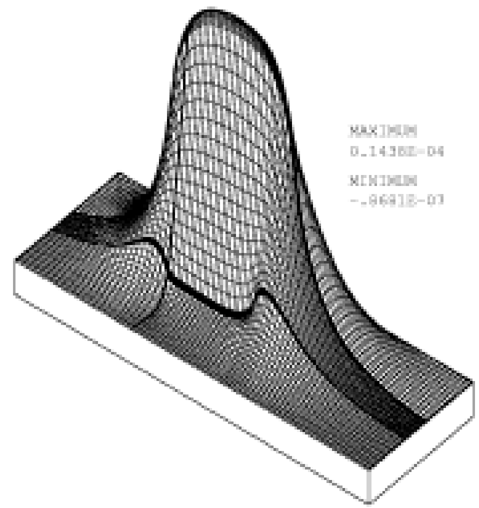
- *Three general models will be developed*
  - *Induction Heating Model*
    - Induction heating in system
    - Coupling of mixing and mass transfer
  - *Parametric Modeling of Volatile Actinide Transport*
    - Examine a range of operating conditions
    - What conditions are feasible?
  - *Flow of melt into molds*
    - Parametric study of important phenomenon

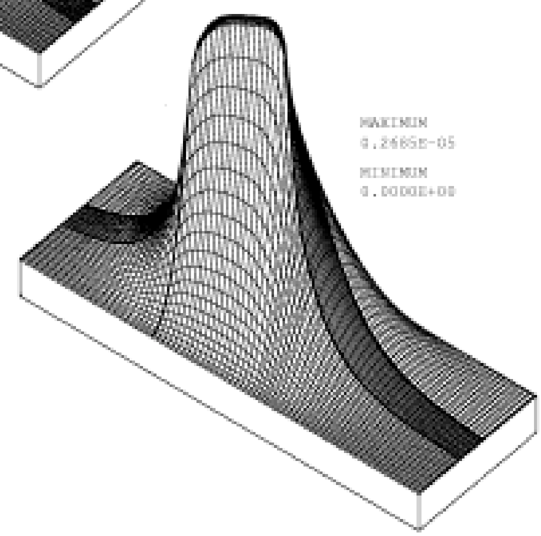
Induction Heating Model

$$\nabla \cdot (\tfrac{1}{r} \nabla C) = -\mu J_o$$
$$\nabla \cdot (\tfrac{1}{r} \nabla S) = 0$$
Coil

$$\nabla \cdot (\tfrac{1}{r} \nabla C) = 0$$
$$\nabla \cdot (\tfrac{1}{r} \nabla S) = 0$$
Elsewhere

$$\nabla \cdot (\tfrac{1}{r} \nabla C) = \frac{\mu\sigma\omega}{r} S$$
$$\nabla \cdot (\tfrac{1}{r} \nabla S) = -\frac{\mu\sigma\omega}{r} C$$
Conductor

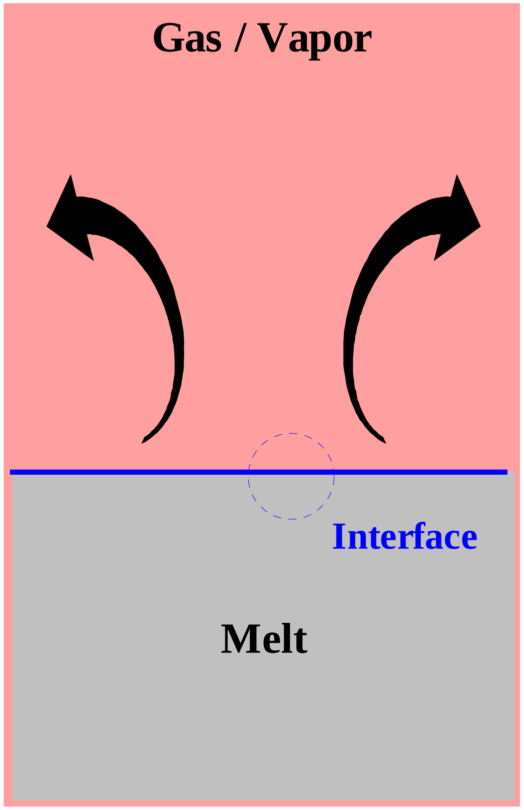




C, S	=	real and complex components of function substituted into governing equations to simplify solution process
r	=	radial coordinate
J_o	=	current density
μ	=	permeability
ω	=	frequency
σ	=	electrical conductivity

Mass Transfer Model

- *Develop a simplified modeling approach*
  - Implement model for a known fluid mixture (liquid with volatile species)
  - Verify approach gives correct trends
  - implement and study americium transport
- *Theoretical estimates of properties based on activities*
  - estimates of properties or model constants
  - Potential for property tests

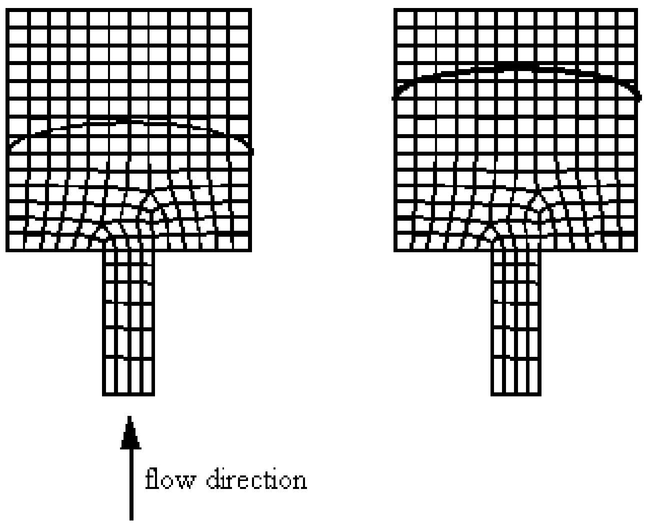


Fuel Rod Model

- *Baseline fuel rod casting model*
  - long length-to-diameter ratio
  - heat transfer
  - phase change (solidification – future work)
  - ability analyze a wide range of potential operating conditions
- *FIDAP™ used for a preliminary model*
  - Finite element technique
  - Volume of Fluid (VOF) method used to model filling (free surface)
  - Free surface approach => significant re-meshing
  - Preliminary results demonstrate capabilities

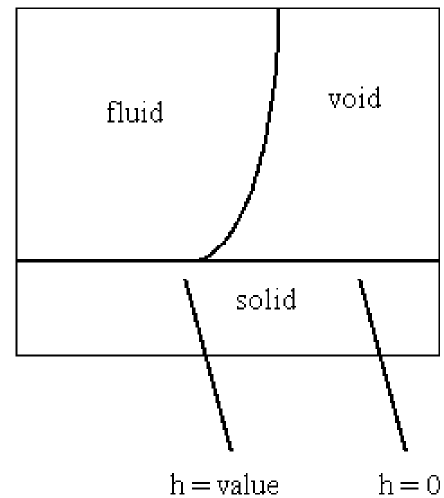
Fuel Rod Model (Cont.)

Volume of Fluid (VOF)



$$\frac{\partial F}{\partial t} + \bar{V} \cdot \vec{\nabla} F = 0$$

$$F(\vec{x}, t) = \begin{cases} 1 \; Fluid \\ 0 \; Void \end{cases}$$



Pictures used from FIDAP Documentation

Fuel Rod Model (Cont.)

$$\rho \frac{\partial \vec{u}}{\partial t} + \rho(\vec{u} \bullet \nabla)\vec{u} = -\nabla p + \mu \nabla^2 \vec{u}$$ Momentum

$$\nabla \bullet \vec{u} = 0$$ Continuity

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \vec{u} \bullet \nabla T = k \nabla^2 T$$ Energy

Interface

$$\begin{cases} T_l = T_s \\ k_l \frac{\partial T_l}{\partial n*} - k_s \frac{\partial T_s}{\partial n*} = \rho_s L u* \end{cases}$$

Governing Equations

$$H(T) = \int_{T_{ref}}^{T} (C_p(T) + L\eta(T - T_m))dT$$

Modeling enthalpy change

$$\eta(T - T_m) = \begin{cases} 1 & if\,(T - T_m) \geq 0 \\ 0 & if\,(T - T_m) < 0 \end{cases}$$

Fuel Rod Model (Cont.)

$$C_{eqiv} = \frac{dH}{dT} = C_p(T) + L\delta(T - T_m)$$

$$C_{eqiv} = C_p(T) + L\delta^*(T - T_m, \Delta T)$$

Viscosity = *f(T)* for flow solution

$$\rho C_p \frac{\partial T}{\partial t} = k\nabla^2 T$$

Interface Between Liquid and Mold

(Convective)

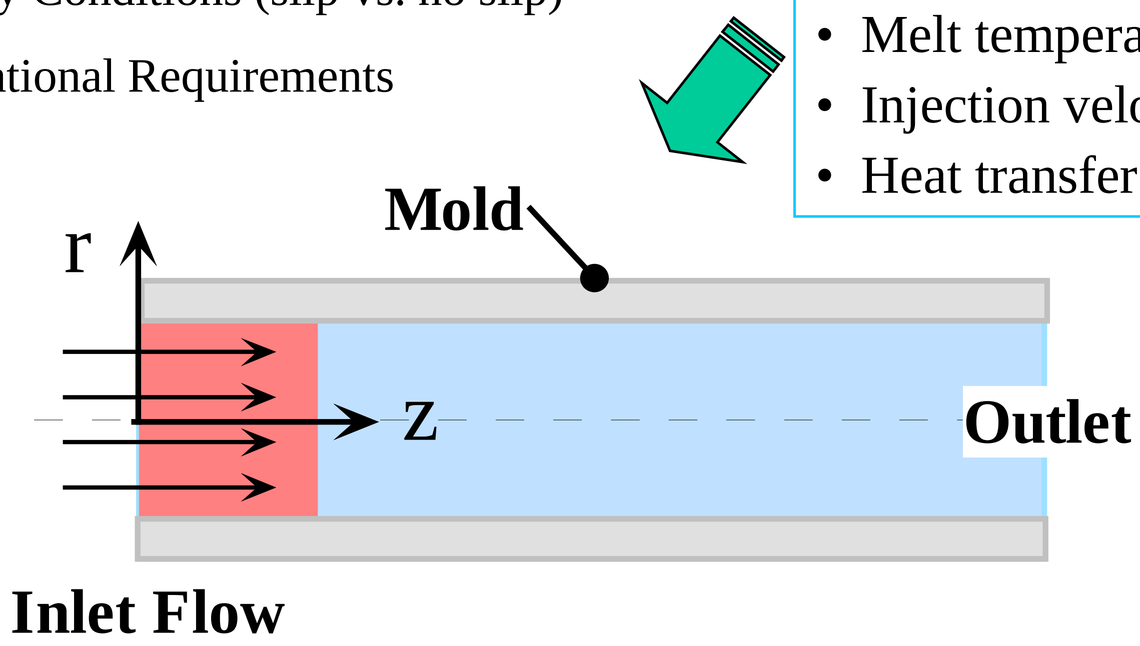
$$k_{mt}\frac{\partial T_{mt}}{\partial n} = k_l \frac{\partial T_l}{\partial n} = h(\Delta T)$$

Fuel Rod Model (Cont.)

- Model - Symmetry Section
- Boundary Conditions (slip vs. no slip)
- Computational Requirements

Parameters:

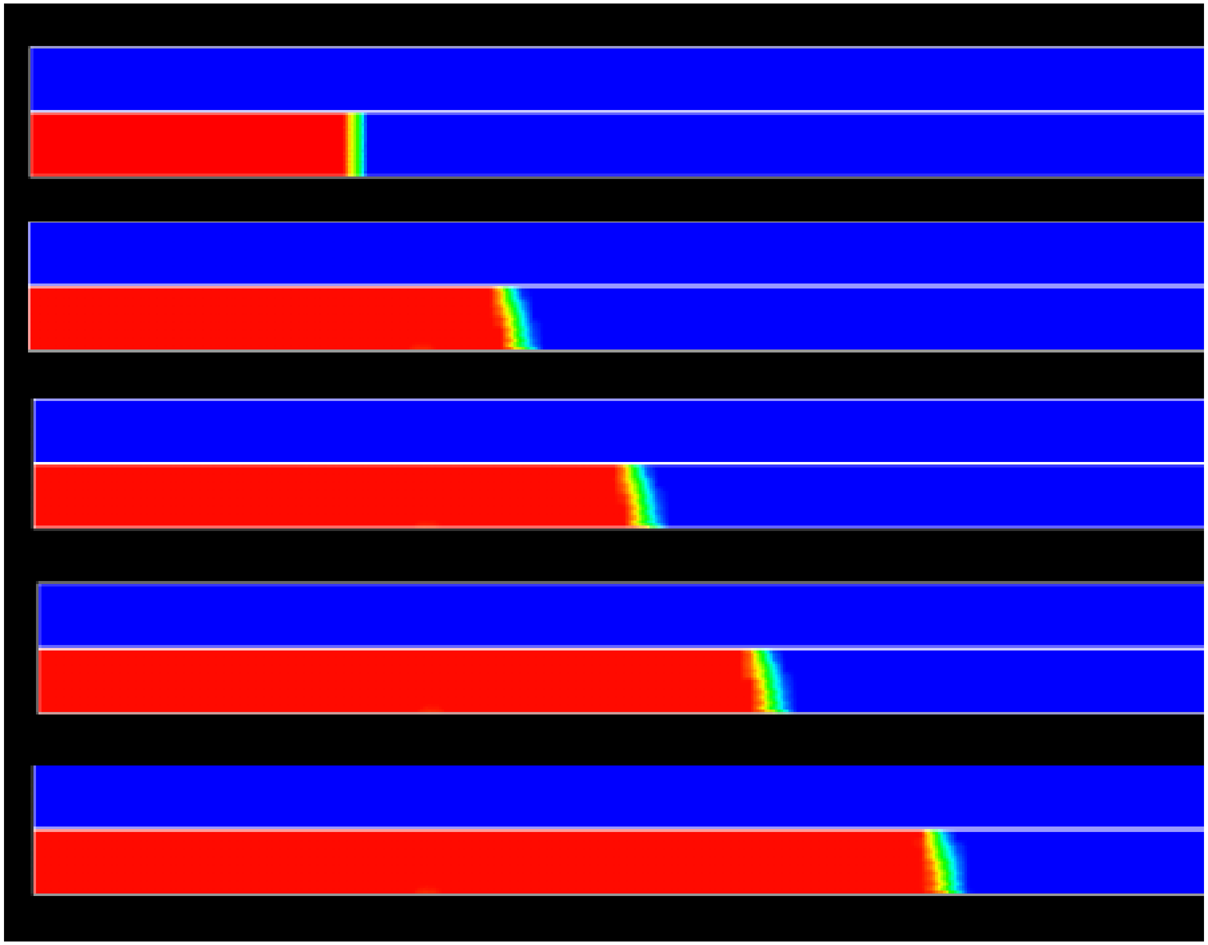
- Mold preheating
- Mold design
- Melt temperature
- Injection velocity
- Heat transfer



Fuel Rod Model – cont.

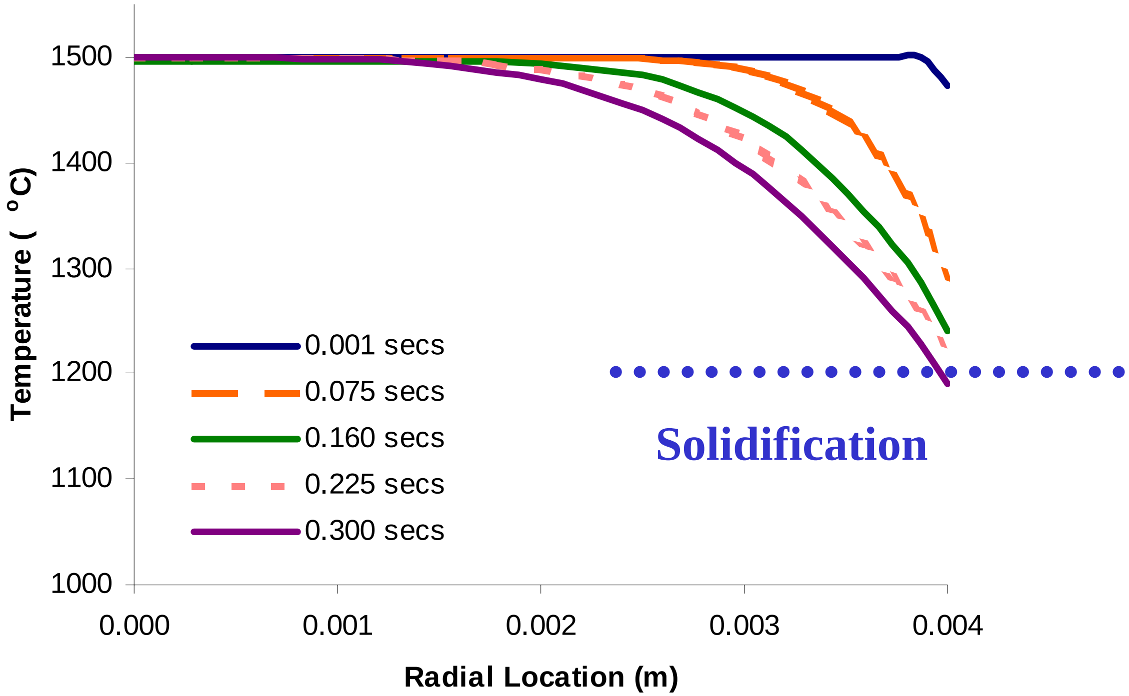
- *Melt temperature of 1500^{o}C.*
- *Average fill velocity of 1.6 m/sec.*
- *Mold thermal properties assumed to be "similar" to copper.*
- *Pin diameter of 0.008 m.*
- *Mold outside diameter of 0.016 m.*
- *Mold length of 0.50 m.*
- *Properties of melt assumed to be dependent on plutonium, americium, and zirconium.*
- *Heat transfer coefficient between the melt and the mold assumed to be 10,000 W/m^{2}K, unless otherwise noted.*
  - Range from 2,000 to 10,000 W/m^{2} K.
- *Initial mold temperatures were varied (1000^{o}C, 800 ^{o}C, or 600 ^{o}C).*

Preliminary Modeling Results – cont.



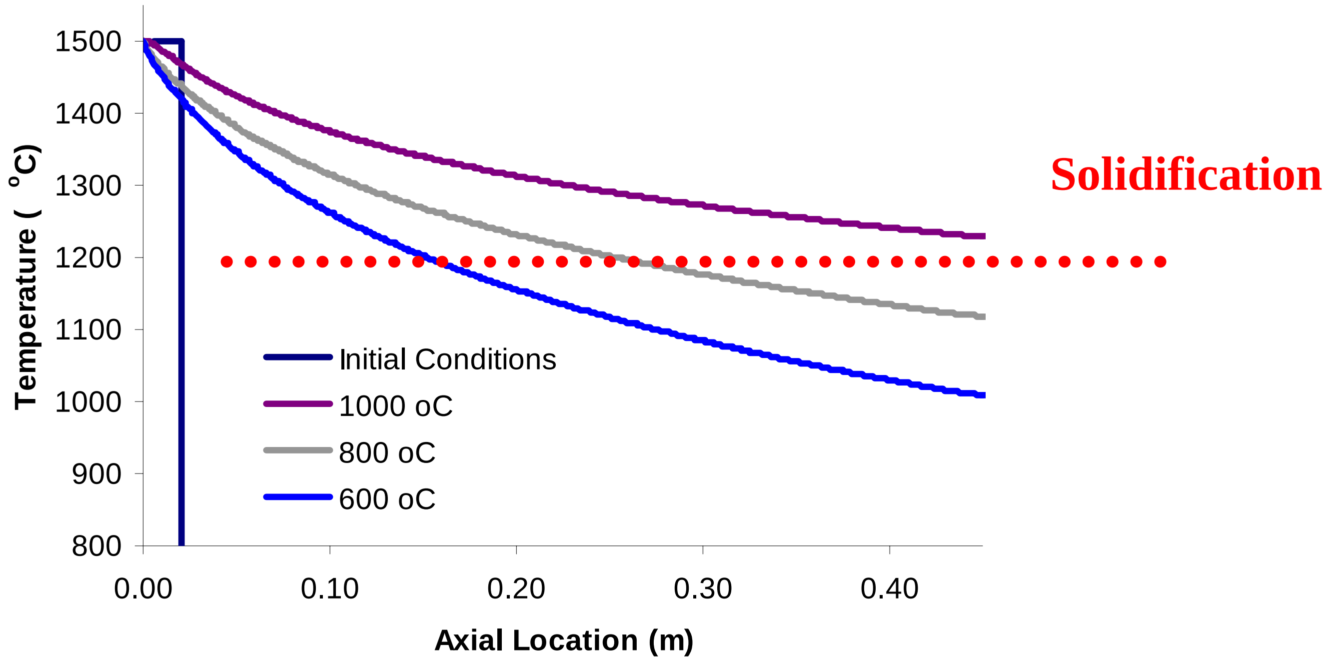
Contours of Fill Fraction as Flow Enters the Mold

Preliminary Modeling Results – cont.



Temperature profiles from the centerline projected radially outward for an initial mold temperature of 1000 °C. The axial location of each profile is slightly behind the front of the melt. Last profile is near the end of the mold.

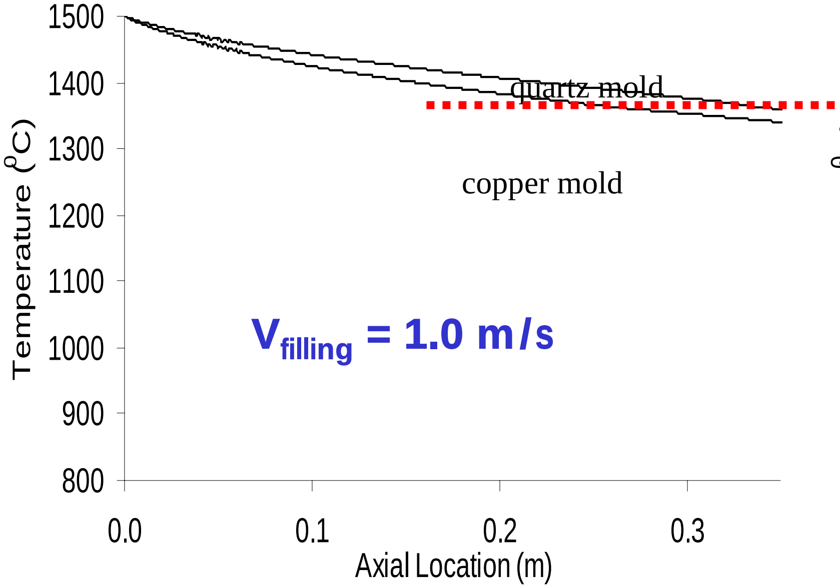
Preliminary Modeling Results – cont.

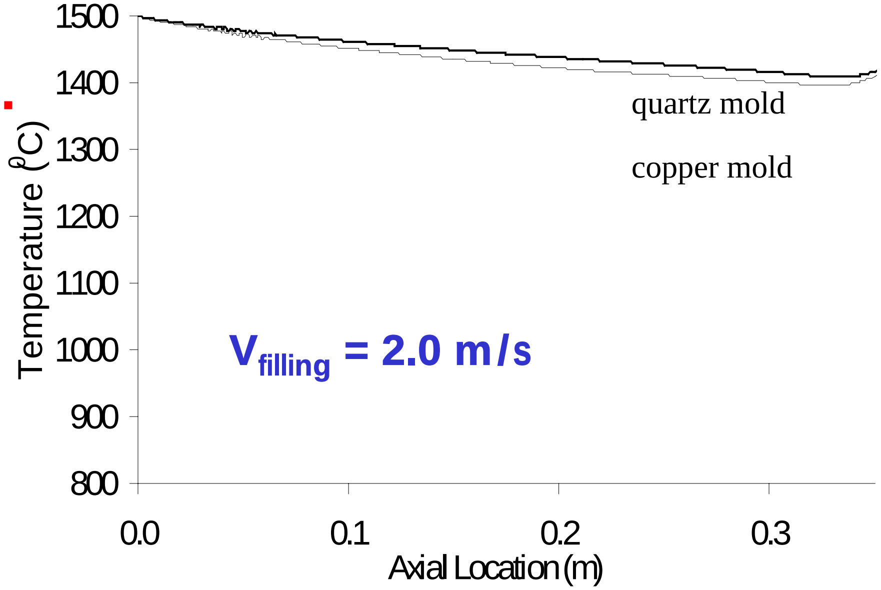


Temperature profiles of melt material near the mold interface at 0.30 seconds. Lower to upper curves represent mold temperatures of 600°C, 800°C, and 1000°C. Velocity = 1.6 m/sec.

Preliminary Modeling Results – cont.

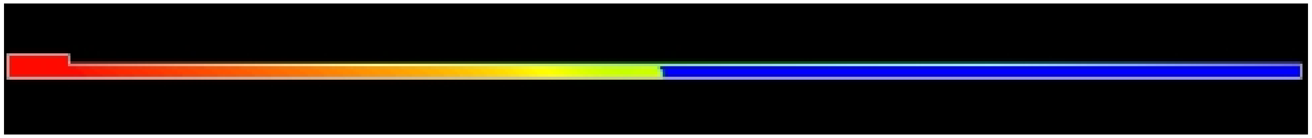
Impact of the mold materials on the cooling of the melt:





h = 2,000 W/m^{2}K, T_{mold} = 800 ^{o}C

Preliminary Modeling Results – cont.



- *Long length-to-diameter ratio*
- *Demonstrates the ability to model complex phenomenon*
  - not without limitations (heat transfer: mold/melt)
  - Impact of different process parameters
  - General trends on casting
- *Remaining issues*
  - phase change needs to be included
  - specify known “melt” properties
- *Include species transport (americium)*

Summary

- *Proposed casting furnace concept*
- *Developed a plan to evaluate the ability to cast high vapor pressure materials (americium)*
- *Specified three general modeling approaches*
- *Presented preliminary modeling results for fuel casting*
  - Parametric study
  - Ability to determine impact of process parameters
- *Future work to enhance capabilities of the models*
  - Phase change other process parameters

Acknowledgements

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