An Analysis of the Melt Casting of Metallic Fuel Pins

Xiaolong Wu
University of Nevada, Las Vegas

Randy Clarksean
University of Nevada, Las Vegas

Yitung Chen
University of Nevada, Las Vegas

Darrell Pepper
University of Nevada Las Vegas, pepperu@nye.nscee.edu

Mitchell K. Meyer
Argonne National Laboratory, West

Follow this and additional works at: http://digitalscholarship.unlv.edu/hrc_trp_fuels

Part of the Nuclear Commons, and the Nuclear Engineering Commons

Repository Citation

This Presentation is brought to you for free and open access by the Transmutation Research Program Projects at Digital Scholarship@UNLV. It has been accepted for inclusion in Fuels Campaign (TRP) by an authorized administrator of Digital Scholarship@UNLV. For more information, please contact digitalscholarship@unlv.edu.
An Analysis of the Melt Casting of Metallic Fuel Pins

DOE's Quarterly Review meeting in Albuquerque, NM
January 22-24, 2003

Mr. Xiaolong Wu, Dr. Randy Clarksean
Dr. Yitung Chen, Dr. Darrell W. Pepper
NCACM
University of Nevada Las Vegas

Dr. Mitchell K. Meyer
Argonne National Laboratory-West
Overview

- Background
  - Casting Volatile Actinides
  - Need to Contain Americium
  - Overview of Project
- Fuel Rod Model
  - Physical System
  - Governing Equations
- Preliminary Modeling Results
  - Mold Materials
  - Injection Casting Velocity
- Summary
**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**
**Background - Casting Volatile Actinides**

**Heat and Mass Transfer**
- Induction heating of material
- Induced fluid flow
- Mass Transfer of americium

**Fuel Rod Casting**
- Heat transfer
- Fluid flow
- Parametric study
Background - Casting Volatile Actinides

- 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
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.)

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

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

Inlet Flow

Mold

"Interface"

Outlet
Volume of Fluid (VOF)

\[ \frac{\partial F}{\partial t} + \mathbf{V} \cdot \nabla F = 0 \]

\[ F (\bar{x}, t) = \begin{cases} 1 & \text{Fluid} \\ 0 & \text{Void} \end{cases} \]

Pictures used from FIDAP Documentation
Fuel Rod Model (Cont.)

\[ \rho \frac{\partial \vec{u}}{\partial t} + \rho (\vec{u} \cdot \nabla)\vec{u} = -\nabla p + \mu \nabla^2 \vec{u} \]
\[ \nabla \cdot \vec{u} = 0 \]
\[ \rho C_p \frac{\partial T}{\partial t} + \rho C_p \vec{u} \cdot \nabla T = k \nabla^2 T \]

**Momentum**

**Continuity**

**Energy**

**Interface**

\[ \begin{align*}
T_i &= T_s \\
-k_i \frac{\partial T_i}{\partial n^*} - k_s \frac{\partial T_s}{\partial n^*} &= \rho_s L u^* 
\end{align*} \]

**Governing Equations**

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

Modeling enthalpy change

\[ \eta(T - T_m) = \begin{cases} 
1 & \text{if } (T - T_m) \geq 0 \\
0 & \text{if } (T - T_m) < 0 
\end{cases} \]
\[ C_{\text{equiv}} = \frac{dH}{dT} = C_p(T) + L\delta(T - T_m) \]

\[ C_{\text{equiv}} = C_p(T) + L\delta^*(T - T_m, \Delta T) \]

Viscosity = \( f(T) \) for flow solution

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

Interface Between Liquid and Mold (Convective)

\[ k_{\text{mt}} \frac{\partial T_{\text{mt}}}{\partial n} = k_l \frac{\partial T_i}{\partial n} = h(\Delta T) \]
Fuel Rod Model - cont.

- Melt temperature of 1500\textdegree{}C.
- Fill velocities: 0.1 m/sec or 1.6 m/sec.
- Mold thermal properties: Quartz glass or “similar” to copper.
- Dimensions:
  - Pin diameter of 0.008 m.
  - Mold outside diameter of 0.016 m.
  - Mold length of 0.50 m.
- Melt Properties: Dependent on plutonium, americium, and zirconium.
- Heat transfer coefficient between the melt and the mold ranged from 2,000 to 10,000 W/m\textsuperscript{2} K.
- Initial mold temperatures: 1000\textdegree{}C, 800\textdegree{}C, or 600\textdegree{}C.
Contours of Fill Fraction as Flow Enters the Mold
Initial mold temperature of 1000°C. Velocity = 1.6 m/sec

Radial temperature profiles of the melt just behind the melt front as it advances into the mold.
Impact of the mold materials on the cooling of the melt:

Preliminary Modeling Results – cont.

\[ h = 2,000 \text{ W/m}^2\text{K}, T_{\text{mold}} = 800 \text{ } ^\circ\text{C} \]
Comparison of mold materials: Quartz (symbols) and Copper (lines). Model conditions are heat transfer coefficient = 5,000 W/m² K, mold temperature = 800°C, velocity = 0.1 m/sec.

Radial temperature profiles of the melt just behind the melt front as it advances into the mold.
Radial temperature profiles of the melt just behind the melt front as it advances into the mold.

Comparison of mold materials: Quartz (symbols) and Copper (lines).
Model conditions are heat transfer coefficient = 2,000 W/m² K, mold temperature = 400°C, velocity = 0.1 m/sec.
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. Fill velocity of 1.6 m/sec and heat transfer coefficient = 10,000 W/m² K.
Examination on the impact of assumed heat transfer coefficient on the cooling of the melt. **Mold temperature = 600 °C.** Fill velocity of 1.6 m/sec.
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
Summary

- Developed a plan to evaluate the ability to cast high vapor pressure materials (americium)
- Demonstrates the ability to model complex phenomenon
  - not without limitations (heat transfer: mold/melt)
  - Impact of different process parameters
  - Parametric study
  - Ability to determine impact of process parameters
- Remaining issues
  - Phase change needs to be included
  - Specify known “melt” properties
- Future work to enhance capabilities of the models
  - Phase change other process parameters
Acknowledgements

Research supported financially by the UNLV Transmutation Research Program (U.S. Department of Energy Grant No. DE-FG 04-2001AL67358)

Thanks to Argonne National Laboratory-West for their participation, support, and feedback.