Experimental Determination and Modeling of Used Fuel Drying by Vacuum and Gas Circulation for Dry Cask Storage

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Outline

• Motivation
• Experimental setup and test plan
• Vacuum drying test results
• Forced circulation helium test results
• Conclusions and future directions
Used Fuel Drying Research

• DOE IRP Awarded 2014
• Collaboration: USC, UF, SCSU, Areva
• Motivation and Goals
  – Quantify water remaining in dry cask after typical industry drying operation
  – Science based understanding of the cask drying process
  – Evaluate range of conditions, features likely to encounter for storage of used fuel
  – Develop modeling tools for utilities, vendors, regulators
Team*,**, University teams include graduate students and undergraduate researchers and post doctoral staff

* Travis W. Knight, ME, USC (PI)
* Tanvir Farouk, ME, USC
* Jamil Khan, ME, USC
* James Ritter, ChE, USC
* Armin Ebner, ChE, USC
* Elwyn Roberts, ME, USC
* Joshua Tarbutton, ME, UNCC
* James S. Tulenko, UF
* Musa Danjaji, SCSU
* Bill Bracey, Areva
* Kevin Elliot, Areva
* Tom Galioto, Areva
* Paul Murray, Areva
* Arthur Niemoller, Areva
Key assembly features to evaluate

- Some key features to be evaluated or require consideration in modeling and design of the experiment:
  - BWR water rods
  - PWR dashpot in guide tube
  - Failed fuel rods
  - Neutron absorber sheet; i.e. Boral
  - Cask spacer disks
  - Trapped spaces between hardware
  - Surface area: rods, hardware, structures
Key conditions to simulate

• Vacuum and forced circulation
• Sequence, number, timing of stages in drying process
• Low/high power (simulate decay heat with heater rods)
  – 0.25 to 1 kW; may need higher to match temperature in key locations.
• Ice formation
  – Is ice formed under standard practice for difficult drying conditions/scenarios?
  – What conditions would allow for ice formation (margin assessment)?
Key parameters to measure or evaluate indirectly

- Temperature: rods, heater rods, gas (forced circulation: inlet, outlet)
  - Thermocouples, IR cameras
- Chamber pressure
- Gas composition: RGA, OES
- Gas flow rate
  - Vacuum drying
  - Forced circulation
- Water removed as a function of time
- Indication of ice formation
Mock Fuel Assembly Design

- **Areva 10x10 Atrium 10A BWR assembly**
  - DU rods
  - Heater rods to simulate decay heat
  - Instrumentation, thermocouples
- **Interchangeable rod position** on the corner of assembly on diagonal of water channel for symmetry:
  - **Simulated failed fuel rod** (perforation at 175 cm in height, not occluded by spacer grid; Swagelok fitting at top for filling with water, CeO₂ pellets to simulate UO₂)
  - **PWR guide tube with dashpot** (simulated by Zr-4 tube plugged at bottom, weep holes at 40 & 43 cm height not to be occluded by spacer grid)
  - **BWR water rod** (Zr-4 tube, weep holes at 175 & 178 cm height not to be occluded by spacer grid, plugged at bottom)
- No part length fuel rods
- No empty rod positions
Mock Fuel Assembly

- Areva Atrium 10A design, modified
- Heater rods, DU rods, interchangeable rod (PWR guide tube, BWR water rod, failed fuel rod)
- Ceria pellets for simulated failed fuel rod

mock fuel assembly packaged for shipment
heater rod, lower tie plate
Ceria pellets
Heater Rod Configuration

• Heater rods to simulate decay heat and for temperature measurement (thermocouples)

The blue denotes heating rods. The inner ones used as temperature sensors.

Note: all locations are occupied with DU rods except for locations where heater rods (12) or test rod (1) are present.

8 heated rods, heat load of 0.5 kW. Temperature distribution @ Z = 2.4 m (mid plane)
Ceria Surrogate Fuel Pellets
- Fabricated by University of Florida
- Ceria a surrogate for UO$_2$
- Powder 99.99% cerium oxide
- Pellets were pressed double action at 340 MPa
  - Dished but not chamfer
- Sintered at 1400°C for 10 hours with a heating rate of 200°C/hr.
- Optimized based on:
  - Varying sintering conditions
  - Die and punch dimensions and surface quality
  - Variance of green density and
  - Quality of starting powder
- Investigating limited cracking to simulate fractured UO$_2$.  

<table>
<thead>
<tr>
<th></th>
<th>UO2</th>
<th>CeO2</th>
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</thead>
<tbody>
<tr>
<td>Crystal Structure</td>
<td>Fluorite</td>
<td>Fluorite</td>
</tr>
<tr>
<td>Lattice Parameter (Å)</td>
<td>5.47</td>
<td>5.41</td>
</tr>
<tr>
<td>Density (g/cm$^3$)</td>
<td>10.97</td>
<td>7.215</td>
</tr>
<tr>
<td>Melting Temperature (°C)</td>
<td>2865</td>
<td>2600</td>
</tr>
<tr>
<td>Thermal diffusivity (m$^2$s$^{-1}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>@ 600°K</td>
<td>1.82x10$^{-6}$</td>
<td>1.96x10$^{-6}$</td>
</tr>
<tr>
<td>@ 1000°K</td>
<td>1.15x10$^{-6}$</td>
<td>1.15x10$^{-6}$</td>
</tr>
</tbody>
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Vacuum Chamber

- **black** = spacer grid
- **green** = interchangeable rod
- **red** = DU rod
- **light blue** = heater rod
- **orange** = BWR channel
- **blue** = basket/box 1/8” stainless steel
- **brown** = Boral sheet 0.075” thick
- **yellow** = basket/rails 3/16” stainless steel

View ports, instrumentation ports
Chamber – View Ports

- View ports 5 and 6 (left) and view ports 3 and 4 (middle), view ports 1 and 2 (right).
- View/monitor key locations
  - VP1=Lower tie plate
  - VP2=Dashpot
  - VP3=Failed rod defect
  - VP5=Top spacer grid
  - VP6=Center spacer grid
Loading Mock Fuel Assembly and Heater Rod Installation
**Experimental Design**

- Some necessary departures from typical industry equipment

### Sequence of Hold Pressure/Time

<table>
<thead>
<tr>
<th>Vacuum Step, Hold Pressure</th>
<th>Hold Time</th>
<th>Criteria to Proceed to Next Step</th>
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</thead>
<tbody>
<tr>
<td>&lt;50 torr</td>
<td>5 min.</td>
<td>&lt;100 torr</td>
</tr>
<tr>
<td>&lt;25 torr</td>
<td>5 min.</td>
<td>&lt;50 torr</td>
</tr>
<tr>
<td>&lt;15 torr</td>
<td>5 min.</td>
<td>&lt;25 torr</td>
</tr>
<tr>
<td>&lt;10 torr</td>
<td>5 min.</td>
<td>&lt;15 torr</td>
</tr>
<tr>
<td>&lt;5 torr</td>
<td>5 min.</td>
<td>&lt;10 torr</td>
</tr>
<tr>
<td>&lt;3 torr</td>
<td>5 min.</td>
<td>&lt;5 torr</td>
</tr>
<tr>
<td>&lt;2 torr</td>
<td>30 min.</td>
<td>&lt;2.6 torr</td>
</tr>
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Chamber and Vacuum Drying System