Fuel Cycle Research and Development

Severe Accident Test Station (SATS) and alloy developments

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Oak Ridge National Laboratory
Severe Accident Test Station at ORNL

- National facility for evaluating new cladding concepts
  - Four modules with different capabilities
  - Steam to 1700°C and 1-30 bar
Several candidates meet >100X lower steam oxidation kinetics

Several different experiments available in SATS modules

- **Rubotherm TGA (thermogravimetric analysis)**
  - Isothermal (4h) experiments → *parabolic rate constant*
  - Ramp (5°C/min) test in steam to 1500°C → maximum use Temp.

- **High Temperature Furnace Module**
  - Isothermal (~4h) experiments → *mass change/microstructure*
  - 1700°C maximum

- **Integral LOCA Furnace Module**
  - Burst test of pressurized tubes in steam → *burst T vs. pressure*
  - 305mm (12”) long, 9.5mm diameter tubing (not coupons, high TRL)

- **High Pressure/Temperature “Keiser” Rig**
  - 2012: minimal pressure effect on steam oxidation
Upgrade of LOCA furnace: View port for burst test

- Furnace with observation window
- Blue light used as background.
- High-resolution camera with long-focal lens
- Specimen image
Trial run with optical imaging using port in IR furnace

- 304SS tube specimen heated to 1100°C.
  - No steam
  - ~450 psi at burst
  - Internal tube pressure
- Images taken during test
  - In-situ measurements possible
- Development in progress
  - air convection issue
  - Incorporate quartz tube

Images obtained during the trial burst test from RT to 1100°C (gif-animation)
- **Data from trial run**
  - Tube pressurized
  - Heated in air
  - Heating to 1100°C
  - Plastic strain -> burst
  - Burst T, P identified
  - Image: diameter vs. time

- **Accuracy**
  - Current ±0.7%
    - Air convection issue
  - Possible ±0.2%

- **Future upgrade**
  - Incorporate quartz tube
  - Burst in steam

- **Unique Data for Modeling**
  - 2D strain data for BISON
In-cell SATS ready to deploy in hot cell

- High temperature and Integral LOCA modules
- FY15: Worked with hot cell staff to correct minor issues
- Hot cell space has been prepared to receive SATS and plugs ready to install
- Operating procedure complete and reviewed
- Awaiting insertion and demonstration funding
  - Demo on commercial fuel rod
Community Testing

- General Electric – work now covered under FOA
- Westinghouse – SiC/SiC steam testing 1300°-1500°C
- Halden Project – CrN coatings on Zircaloy
Initial results on steam oxidation of FeCr alloys

- Plan “B” (FeCrAl is plan A)

Surprising that few were protective at 1200°C

Further work will examine the effect of minor elements on oxidation resistance

- Mn, Si, Ti, Y, etc.
- Model Fe-Cr-X alloys
ICP analysis of Fe-Cr alloys

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Cr</th>
<th>Mn</th>
<th>Si</th>
<th>Al</th>
<th>N</th>
<th>S</th>
<th>Other</th>
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<tbody>
<tr>
<td>Gr.91</td>
<td>9.1</td>
<td>0.39</td>
<td>0.24</td>
<td>&lt;</td>
<td>0.052</td>
<td>0.0122</td>
<td>0.86 Mo</td>
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<tr>
<td>405</td>
<td>12.9</td>
<td>0.48</td>
<td>0.37</td>
<td>0.26</td>
<td>0.023</td>
<td>&lt;3</td>
<td>0.003 Ti</td>
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<tr>
<td>430</td>
<td>16.7</td>
<td>0.49</td>
<td>0.26</td>
<td>0.004</td>
<td>0.031</td>
<td>0.0009</td>
<td>0.002 Ti</td>
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<tr>
<td>446</td>
<td>24.9</td>
<td>0.76</td>
<td>0.19</td>
<td>&lt;</td>
<td>0.108</td>
<td>0.0098</td>
<td>0.003 Ti</td>
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<tr>
<td>4C54</td>
<td>25.4</td>
<td>0.71</td>
<td>0.49</td>
<td>&lt;</td>
<td>0.167</td>
<td>0.0036</td>
<td>0.004 Ti</td>
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<tr>
<td>E-Brite</td>
<td>25.8</td>
<td>&lt;</td>
<td>0.22</td>
<td></td>
<td>0.008</td>
<td>0.0100</td>
<td>1.0 Mo</td>
</tr>
<tr>
<td>Model</td>
<td>25.0</td>
<td>0.67</td>
<td>0.25</td>
<td>0.01</td>
<td>0.001</td>
<td>0.0030</td>
<td>0.002 Y</td>
</tr>
</tbody>
</table>

Inductively coupled plasma analysis – optical emission and mass spectroscopy
Westinghouse: SiC/SiC composite specimens at 1300°-1500°C

- Very long exposures
  - Normally 4h tests
  - Several furnace failures
- Several SiC/SiC compositions
- Much higher mass gains than for CVD SiC
Coated tubes received from Halden Project

- Proprietary, wear-resistant CrN coating
  - Not an ATF concept
  - Resistant to fretting wear
  - Completed in-pile testing with fuel

Similar burst temperatures as uncoated Zircaloy-4 tubes
Metallography of burst tubes

Zircaloy-4

CrN coated Zr-4
Similar oxide scale formed with and without the CrN coating
FeCrAl oxidation: Ramp testing followed 1200°C screening

2012-2013 testing

~2014 testing

Stop ramp when mass jumps up

Steam on

Furnace cool

5°C/min
Ramp testing of new FeCrAl compositions

1st Gen. FeCrAl alloys

2nd Gen. FeCrAl alloys

Cr content (wt. %)

Al content (wt. %)
Inconsistent behavior between ramp and 1400°C isothermal tests

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Ramp $T_{\text{max}}$</th>
<th>1400°C isothermal</th>
</tr>
</thead>
<tbody>
<tr>
<td>B 20Cr 5Al</td>
<td>1500</td>
<td>✓</td>
</tr>
<tr>
<td>B 10Cr 6Al</td>
<td>1500</td>
<td>✗</td>
</tr>
<tr>
<td>B 10Cr 7Al</td>
<td>1136</td>
<td>–</td>
</tr>
<tr>
<td>B 10Cr 8Al</td>
<td>1377</td>
<td>✓</td>
</tr>
<tr>
<td>B 13Cr 6Al</td>
<td>1500</td>
<td>✗</td>
</tr>
<tr>
<td>B 13Cr 7Al</td>
<td>1500</td>
<td>✗</td>
</tr>
<tr>
<td>B 16Cr 6Al</td>
<td>1500</td>
<td>✗</td>
</tr>
<tr>
<td>C 10Cr 6Al</td>
<td>1500</td>
<td>✗</td>
</tr>
<tr>
<td>C 13Cr 6Al</td>
<td>1425</td>
<td>✗</td>
</tr>
</tbody>
</table>

Hypothesis: 1400°C steam too severe for bare, low-Cr FeCrAl
“Step” test at 1200°-1475°C developed to test hypothesis.

Rubotherm TGA: stop testing if rapid oxidation
Step test results more consistent with ramp test results

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Ramp $T_{\text{max}}$</th>
<th>$1400^\circ\text{C}$ steam</th>
<th>Step to $1475^\circ\text{C}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B 20Cr 5Al</td>
<td>1500</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>B 10Cr 6Al</td>
<td>1500</td>
<td>✗</td>
<td>✔</td>
</tr>
<tr>
<td>B 10Cr 7Al</td>
<td>1136</td>
<td>☐</td>
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<td>✔</td>
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- Final “step”: 1h steam oxidation at $1475^\circ\text{C}$

- Solidus temperature: $\sim1520^\circ\text{C}$

- Pre-oxidation important to $\geq1400^\circ\text{C}$ steam resistance

- Initiated study of flow rate effect on oxidation
Top view Fe-10Cr-8Al-Y after 4h at 1400ºC

Dense Yttria-rich alumina area + Areas with alumina grain clusters
New alumina degradation mechanisms at 1400°C in steam?

Degradation mechanisms not observed at 1350°C in Air
Could affect early formation of alumina scale

12Cr-5Al-Y, 1200°C

10Cr-8Al-Y, 1400°C

10µm

4h steam testing
3D macroscopic height maps show grain deformation.

Fe-10Cr-6Al
4h at 1200°C

Fe-10Cr-6Al
4h at 1400°C
Burst testing of 1\textsuperscript{st} generation FeCrAl alloys

- Additional tubing made by LANL
  - 1\textsuperscript{st} generation alloys
  - Fe-13Cr-5Al+Y
  - Fe-15Cr-4Al+Y

- Awaiting commercial tubing to test 2\textsuperscript{nd} generation FeCrAl alloys
Severe Accident Test Station is deployed and actively operating
- Four modules with different capabilities for high temperature steam testing
- ~240 specimens so far in FY15
- New imaging capability to assist model development

In-cell version is awaiting deployment in hot cell
- Re-establishing US capability for LOCA testing of commercial fuel rods

SATS used to support FCRD community
- GE work supported under FOA
- SiC/SiC exposures for Westinghouse
- Halden Project: Burst test CrN coatings

ORNL focus on FeCrAl oxidation
- Expanded composition matrix to 8%Al and 0-13%Cr
- “ramp” and “step” tests confirm alumina formation to 1475°C
- Current interest in 6%Al and 10-13%Cr alloys