Accident Tolerant Fuel: FeCrAl Cladding Development

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Core Degradation Phenomena

Behavior of Fuel/Core Materials Affects Accident Progression

- Onset of core degradation processes and fission product release
- Degradation in fuel and core components that lead to further enthalpy production and hydrogen generation

Focus on Radionuclide Retention

- significant core relocation and melting leading to release of fission products

Dominated by System Response

- Decay heat drives decline in core water level

Lead Up

800ºC

Mid-Phase

1500ºC

Late-Phase

300ºC

300ºC

800ºC

1500ºC

Power

Balloon

Burst

Quench

No ECCS

Cladding Temperature

Time
• Materials with slower oxidation kinetics in steam (~ 2 orders of magnitude or less) delay rapid cladding degradation
Oxidation Behavior in Steam

- Advanced Fe-based alloys and SiC materials offer significant improvements over Zr alloys and conventional stainless steels.

### Oxidation Behavior

<table>
<thead>
<tr>
<th>Material</th>
<th>Specimen Mass Change (mg/cm²)</th>
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<tbody>
<tr>
<td>Zirc-2</td>
<td>87.50</td>
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<tr>
<td>304L</td>
<td>91.41</td>
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<tr>
<td>310</td>
<td>1.00</td>
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<tr>
<td>FeCrAl</td>
<td>0.50</td>
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<tr>
<td>CVD SiC</td>
<td>0.32</td>
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</table>

- **Conventional Alloys:** Full or Near Full Consumption
- **Advanced Fe-Alloys:** Minimal Reaction

1200°C – 8 hours – 3.4 bar Steam

Fully oxidized 304L

300µm

300µm

APMT (FeCrAl)
Baseline: steam oxidation
8h exposures, 3.4bar (50 psig) steam

- Initial test matrix
  - 800°, 1000°, 1200° C
  - 100%H₂O, H₂-50%H₂O
  - 50-300 psi (3.4-20.4bar)
- Zircaloy-2, 304L tubing
- High mass gain = thick oxide
Conventional choices: poor at 1200°C
Only 2h in 10.3 bar (150 psig) steam

Typical fuel cladding \(~600\mu m\) wall thickness
These alloys would provide no benefit in a severe accident
Screening Fe-Cr alloys: T effect
8h exposures, 3.4bar (50 psig) steam

- Expanded matrix to 1350° C
- More Cr = more protection
- Spallation lowers 310 mass
Screening: best candidates
8h exposures, 3.4bar (50 psig) steam

- FeCrAl and CVD SiC
- Low 1350° C mass gains
- Kanthal APMT: forms protective Al$_2$O$_3$ scale
Al₂O₃ and SiO₂ are protective
3.4 bar steam exposures

Obvious benefits for FeCrAl
SiC widely considered for fuel and support roles
SiO₂ water vapor problem: less relevant at 8h
Screening: Composition effects
8h exposures, 1200° C, 3.4bar steam

- Fe-Cr binary alloys
- Oxidation 101: more Cr makes it easier to form protective Cr$_2$O$_3$ layer
Screening: Composition effects
8h exposures, 1200° C, 3.4bar steam

- Fe-Cr-Ni alloys
- Commercial and model
- Cr+Ni beneficial
- Ni not desirable for cladding
Screening: obvious Al benefit
8h exposures, 1200°C, 3.4bar steam

- APMT chosen initially
- Commercial tube alloy
- Surprisingly, leaner FeCrAl alloys did poorly
ODS alloys benefit from Al too
8h exposures in 10.3 bar of H₂-50%H₂O

ODS alloys very resistant to irradiation
Most work focuses on Fe-(9-13)Cr ODS alloys
Fundamentals of Steam Oxidation Kinetics

Parabolic Oxidation Rate Constant

Temperature [°C]

1500 1400 1300 1200 1100 1000

Zirconium Alloys
- Baker-Just
- Leistikow-Schanz
- Urbanic-Heidrick
- Pawel-Cathcart
- Moalem-Olander
- Zry-4
- Duplex
- Zirlo
- M5
- E110

Iron Alloys
- 304SS - Ishida et al.
- 304SS - Brassfield et al.
- 310SS - Pint et al.
- APMT - Pint et al.

2-3 orders of magnitude reduction in oxidation kinetics
MELCOR: Long-Term Station Blackout

Delayed Lower Head Dryout

- UO₂ – Zircaloy: 16 h
- UO₂ – FeCrAl: 23 h

*Degradation in the UO₂ FeCrAl core dominated by Zr channelbox oxidation

Delayed and Reduced H₂ Generation

- UO₂-Zr
- UO₂-Zr No Clad Ox.
- UO₂-FeCrAl
- FCM-FeCrAl
- TAF
- BAF

Hydrogen Generated in Core [kg]

Time [hrs.]
Commercial FeCrAl alloys
TGA exposures at 1200°C in Ar-50%H₂O

Hard to explain results
Need for more model alloys to clarify boundary
Hot-rolled FeCrAlY model alloy plate

- No technical difficulty to hot-roll the alloys (0.032” thickness).

- Cold-roll can also be done at RT after GS control
  - No intermediate annealing required
  - Up to 2mil thickness
Chemistry of the Alloys Studied

Table: Chemistry of the alloys

<table>
<thead>
<tr>
<th>ID</th>
<th>Composition, wt%</th>
<th>Cr content, wt%</th>
<th>Al content, wt%</th>
<th>Y content, wt%</th>
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<td>B154N</td>
<td>80.84</td>
<td>15.16</td>
<td>3.98</td>
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</tbody>
</table>

- Compared with commercially available FeCrAl alloys
  - APMT (Fe-22Cr-5Al + Y₂O₃ base, ODS)
  - Alkrothal 14 (Fe-15Cr-4Al + Zr base)
Model FeCrAl alloys
TGA exposures at 1200°C in Ar-50%H₂O

Established kinetic boundary for protective alumina
Exception may be few additions in K14 (no Y)
Effect of steam on APMT oxidation
4h test in 100% steam in High T module

Similar results in both test modules
circles (high T module); stars (Rubotherm TGA)
Surface roughness due to weak substrate?
Quality of Trial FeCrAlY Tube (B155Y)

OM micrographs (cross-sectional view)

- Uniform grain structure with spherical Fe$_{17}$Y$_2$ particles.
- Average grain size: ~69μm
- Forging resulted in slightly deformed grain morphology, not recrystallization.

Machined tube (OD 9.5mm x WT0.6mm x L51mm)

- Successfully machined tube form with 2” length.
- It was drilled at the center, EDMed inside and outside, and then ground/polished for making final size/surface.
Preliminary Tensile Test Results of ORNL ATF FeCrAl Alloys (1st Gen.)

- First attempt was made with non-controlled grain size specimens (~250-500 μm).
  - YS exceeded min. requirement of Zircaloy 2 or 4, at both RT and 300°C.
  - Higher Cr is good for ductility, but lowers YS at 300°C.
- Optimization of the grain size (~30-50 μm) is currently in progress.
- Further property improvement via solution/precipitate strengthening is planned, as the 2nd generation ORNL ATF FeCrAl alloys.
Welding trials

- Understand the mechanical properties of weldments made in model FeCrAlY alloys
  - 3 alloys selected with varying Cr and Al content
  - 2 welding types tested
    - E-beam: initial screening
    - Laser: in-depth investigation
  - Demonstrate weld of top and bottom caps for cladding

<table>
<thead>
<tr>
<th></th>
<th>Nominal, wt%</th>
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<tr>
<td></td>
<td>Cr</td>
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<td>B183Y-2</td>
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</table>
Summary of FeCrAlY Welding Trials

1. E-beam welding of FeCrAlY alloys resulted in defect free welds

2. Laser welding lead to decreased strength levels and increased ductility levels
   - Neck and fracture occurred in fusion zone
   - No evidence of welding-caused embrittlement
   - B125Y alloy has the best strength level after welding compared to other alloys

3. FeCrAlY alloys are suitable for complex geometry weldments

Good weldability of unirradiated FeCrAlY model alloys
HFIR Irradiation Design and PIE

- 4 ORNL ATF candidate + 2 commercial alloys to be inserted to HFIR
  - Varying Cr content across selected alloys
- Planned PIE:
  - Tensile tests at RT, 320 °C, & accident temperature to determine mechanical performance
  - SANS to determine α’ volume fraction
  - Analytical electron microscopy from non-gauge section of tensile specimens

FY2013

Low Dose: FY2014
High Dose: FY2015
Neutronics and Economics of Steel Clad

Two strategies to make up for neutron absorption in the cladding and maintain identical cycle lengths to Zr clad:

- **Reduce clad thickness** (steel is stronger and more oxidation resistant)
- **Increase $^{235}\text{U}$ enrichment**

Results in 15-25% Increase in Fuel Cost
Summary/Future Work

• Current ORNL focus on optimizing FeCrAl for cladding
  – Welding and tensile properties acceptable
  – Initial Cr/Al selected based on accident conditions
  – Need ~300°C water corrosion data
  – Irradiation data coming
  – Kanthal AF tubing made by LANL: burst test
  – Fe-15Cr-15Al+Y ready for ATR irradiation

• Other teams developing ATF candidates
  – Range of properties need to be compared/ranked
backups
Severe accident test station

National facility for testing new cladding concepts
- multiple “modules”
- steam to 1700°C, typically 1-10 cm/s
- pressure to 30 bar

“Keiser rig”
high P/T ~1500°C

Rubotherm
TGA

standard
LOCA

high T
~1700°C
in- & ex-cell units
Strength and Creep Behavior of Some Candidate Cladding Materials

Comparison of 100 h creep rupture strengths of candidate fuel cladding materials
Consideration from Phase Diagrams

- No sigma formation between 10-20Cr, but $\alpha$-Cr.

- Little Y solubility in Fe, $\text{Fe}_{17}Y_2$ may form (but very little).

- Ferrite single-phase at around 1000°C (hot-rolling temperature).