Development of Advanced Ferritic Steels for Fast Reactor Cladding

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Approach to Enabling a Multi-fold Increase in Fuel Burnup over the Currently Known Technologies

**Ultimate goal:** Develop advanced materials immune to fuel, neutrons and coolant interactions under specific reactor environments

- **Coating**
- **Liners**
- **Advanced Alloys**

**Enhancements with Fabrication Complexity**

Different Reactor options to change requirements LFR, GFR

- **F/M Steels**
  - HT-9

- **Advanced F/M Steels**
  - e.g. NF616

- **ODS Steels**

- **Advanced Alloys**

**Different Reactor options to change requirements LFR, GFR**

- **FCCI**

**Ultra-high Burnup Fuels**

- Radiation
- Temperature

- Reduced embrittlement, swelling, creep

- Enhancements with Fabrication Complexity

**Corrosion**

**Increasing content**

- Cr
- Si
- Al

**Radiation Temperature**

- 200 dpa
- 300 dpa
- 400 dpa

- 500 C
- 600 C
- 700 C

**Advantages**

- Reduced embrittlement, swelling, creep

**Enhancements with Fabrication Complexity**
Outline

Qualify HT-9 to Radiation Doses >250 dpa
- Calculations for CEFR Irradiation
- Development of new heat of HT-9

Develop Advanced Radiation Tolerant Materials
- ODS processing of new heat of 14YWT (FCRD-NFA1)
- Testing of Advanced ODS alloys after Irradiation
- Progress on Tube Processing

Develop Coatings and liners to prevent FCCI
- Testing coated tubes in fueled irradiations (CRADA’s with KAERI and Terrapower)
Significant data has been obtained on previously irradiated materials. How do we obtain data to dose levels out to 400 dpa?

How do we get here??

International Collaborations
New irradiations in CEFR
FFTF/MOTA extended irradiations in other irradiation facilities (BOR60).

Model Development
High Dose Ion irradiations
Continuing to work toward collaboration agreement with CIAE

- Thermal hydraulic calculations continue while working on CRADA
- Initial version of CRADA was sent to CIAE on 8/20/15
  - Export review is done
  - Safety and security forms are approved.
Improved Radiation Response of New NQA1 Heat of HT-9

- 300 lb heat of HT-9 produced by Metalwerks following NQA-1 quality control
- Tensile specimens irradiated in ATR to 6 dpa at 290° C
  - Hardening observed but excellent ductility retained after low temperature irradiation
- Ion irradiations performed to 600 dpa at 425° C
  - Minimal swelling observed in tempered martensitic grains after ion irradiation to >500 dpa.
- Two new heats of HT-9 were produced by Metalwerks with controlled interstitial content.

**INL-HT-9 Heat, best ductility**

**Graph:**
- Engineering Stress vs. Engineering Strain
- Different materials and conditions are plotted, including HT-9 Control TB#1, HT9 IRR TB01, Control T91 TA#1, Irr T91 TA04, Control Eurofer ER07, Eurofer IRR ER04, NF616 Control NF08, NF616 Irr NF04, and F82H-IEA Irr HA05.

**Key Points:**
- INL heat ferrite (<5% volume fraction)
- 33% CW heat – tempered martensite
- INL heat tempered martensite

**Temperature Ranges:**
- 290° C (6 dpa)
- 425-450° C (600 dpa)
Reduction of Area Measurements

- HT-9 heat retains UE and reduction of area after irradiation to 6 dpa at 290 C.
- In addition, less cracking observed near fracture surface compared to T91 and NF616.

<table>
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<tr>
<th>Material</th>
<th>ID</th>
<th>Type</th>
<th>Yield MPa</th>
<th>UTS MPa</th>
<th>Uniform Elongation %</th>
<th>Total Elongation %</th>
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Previous Results showing Reduction of Ductility in irradiated F/M steels

## Exact Elemental Analysis on Control Materials

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<th>Alloy</th>
<th>C</th>
<th>Cr</th>
<th>Mn</th>
<th>Ni</th>
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<th>Mo</th>
<th>Nb</th>
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Effects of Interstitial content on Luder’s band formation in Ferritic steels

Fig. 3. The stress–strain curve for the specimen along the rolling direction of the experimental steel after different annealing treatments at the strain rate of 0.001 s⁻¹.

Proposed Hypothesis and Future Research

**Proposed Hypothesis:**

- Nitrogen attracts point defects under irradiation.
- This creates stronger pinning centers in ferritic alloys.
- Under stress, when the pinning centers are overcome, defect free channels are formed leading to localized deformation and reduced uniform elongation.

**Next steps**

- Procure new heats of HT-9 with controlled nitrogen (two heats produced by Metalwerks).
- Perform ion irradiations followed by mechanical testing. Investigate deformation microstructure with TEM.
- Microstructural analysis of irradiated tensile specimens after deformation.
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Nanostructured Ferritic Alloys

- Strength & damage resistance derives from a high density Ti-Y-O nano-features (NFs)
- NFs complex oxides (Ti$_2$Y$_2$O$_7$, Y$_2$TiO$_5$) and/or their transition phase precursors with high M/O & Ti/Y ratios (APT)
- MA dissolves Y and O which then precipitate along with Ti during hot consolidation (HIP or extrusion)
- Oxide dispersion strengthened alloys also have fine grains and high dislocation densities
• Any desired combination of powders: metals, alloys, and dispersoid, such as oxides, carbides, borides, etc.

The conventional approach is to ball mill alloy and $Y_2O_3$ powders together.

Typical Processing Route for ODS Alloys

1. Ball mill alloy and $Y_2O_3$ powders together.
2. Hot rolling.
3. Extrusion press.
4. Ram.
5. Steel can.
6. Water-cooled chamber.
7. Ball mill.
8. Rotating impeller.
9. HIP (near net shape final product).
10. Machining.
11. Final product.
4 of 4 ball milling runs completed by Zoz

- V540-01: 15 kg of coarse (>150 µm) powder
- V540-02: 15 kg of medium (45-150 µm) and fine (<45 µm) powder
- V540-03: 15 kg medium, fine and small amount of V540-01 coarse powder
- V540-04: 15kg medium, fine powder mixed with yttria for the oxide dispersion.

EPMA showed 40 h ball milling distributed Y uniformly in fine and medium powders

40 h ball milling did not distribute Y uniformly in coarse powders

Mechanical testing underway. **LANL, ORNL**
Extrusion and plate fabrication

- 4 new extrusions of FCRD-NFA1 heats were performed
  - 2 extrusions are for EPRI Program
  - 2 extrusion is for FCRD Program

- Each bar section was cross-rolled to 50% reduction in thickness at 1000°C
  - 12 plates were fabricated (6 for EPRI and 6 for FCRD Programs)
  - 10 plates were decanned
### Characterization of FCRD-NFA1 Material – APT

<table>
<thead>
<tr>
<th>Y/Ti/O</th>
<th>Y/Ti/Cr/O</th>
<th>Number Density (10^23/m^3)</th>
<th>Diameter (nm)</th>
<th>Solute Fraction (%)</th>
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</thead>
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<tr>
<td>13.7/41.8/44.5</td>
<td>10.5/32.0/23.6/34.0</td>
<td>6.86</td>
<td>2.02 ± 0.78</td>
<td>0.74</td>
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**Diagrams:**
- Ti
- TiO
- O
- YO
- Y
- Y-YO-O-TiO-Ti

**UCSB**
Mechanical Properties
Round tensile specimens will be used for high temperature strain-rate jump tests.
NFA-1 Strength, Ductility and Toughness

- Unusual combination of high tensile strength and ductility
- Very low brittle-ductile transition temperature (-150 to -175 °C) → high isotropic strength and ductility in the presence of deep-sharp cracks (toughness)

Atypical isotropic toughness

Deeply pre-cracked bend bars
The high temperature creep strength of NFA-1 is comparable to that of the stronger variants of MA957.

MA957 rupture time @ 100 MPa & 800°C > 38,000 h!
“Best Practice” processing of NFA1: Stable crack growth toughness

- High tensile strength controlled stable crack growth ductile tearing toughness and very high “ductility” down to -175°C
- Behavior due to a delamination toughening mechanism
“Best Practice” Processing of 14YWT: Significant increase in high-temperature fracture toughness (FT)

- FT of the three 14YWT heats is higher than that of SM10 from 25º to 700ºC and up to 4x higher than SM10 at 500ºC.
- FT of SM170 and SM185 are above 100 MPa√m^{1/2} at 700ºC.

The improvement in high-temperature fracture toughness is unprecedented for ODS ferritic alloys.
Radiation Resistance
Ductility Retention in MA957 after irradiation to 6 dpa at 290°C

T91 vs MA957

Engineering Stress (MPa)

Engineering Strain %

Control T91
Irradiated T91
Control MA957
Irradiated MA957

LANL, UCSB, NSUF
Fabrication of Cladding Tubes from ODS alloys

- 3 cans were extruded with mandrel at 850°C and decanned
  - 6-7 mm wall thickness; 31-32 mm diameter; 10.5-11.3 cm long

- Working with PNNL (Curt Lavender) and CEA on Pilger processing of starting thick walled tubing and J. Lewandowski (CWRU) on hydrostatic extrusion

1. Hydrostatic EXTRUSION TEMP: 1500F (815°C)
2. RAM SPEED: 0.5 in/min, however 1st 0.5” of extrusion, speed was 0.7 in/min
3. SOAK TIME: 10 min
4. OVERALL EXTRUSION: 25 min
5. ER: 4:1, 45 DEG TAPER DIE (actual 0.495 diam)
6. CLAD/MANDREL DESIGN DIFF FROM PREVIOUS
High Dose Ion Irradiations

Core Materials Research and Development – 5 Year Plan

Qualify HT-9 for high dose clad/duct applications (determine design limitations)

FFT (ACO-3 and MOTA) Specimen PIE

Advanced Material Development (improved radiation resistance to >400 dpa)

STIP-IV (PSI) Specimen PIE

ODS Ferritic Steel Material Development

Produce ODS Tubing

Develop ODS Tubing and Weld specifications

Advanced Materials Irradiation in BOR-60 and CEFR

Advanced Material Development (improved FCCI resistance to >40 % burnup)

Development of Coated and Lined Tubes

PIE on Lined Irradiated Tube

Use data for physics-based model development of cladding

FY’12

FY’13

FY’14

FY’15

FY’16

FY’17

Rev. 6 of AFCI (FCRD) Materials Handbook

Re-irradiation of FFTF specimens in BOR-60

MATRIX-SMI and 2 (Phenix) Specimen PIE

Data to 250-300 dpa on F/M and 10 dpa on ODS

Data on Advanced Materials to 80-100 dpa