Update on the R&D on advanced steels at GE/ORNL

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Objective of the DOE-GE-ORNL Project

1) The United States Department of Energy partnered with General Electric to develop a FeCrAl fuel cladding for current design light water power reactors

2) The cladding will offer superior environmental degradation characteristics both under normal operation conditions and severe accident conditions (loss-of-coolant)

3) No current development on fuels

4) The project is data driven and systematic
The GE Team on Accident Tolerant Fuel is Focused on Cladding Material for Current UO$_2$ Fuel
Why Advanced Ferritic Steels for Cladding?

Ferritic Steels have Low Coefficient of Thermal Expansion and High Thermal Conductivity

The Combination of Chromium and Aluminum Provide Outstanding Protection Against Attack by Steam

Are Orders of Magnitude More Resistant to Environmental Cracking than Austenitic Steels

Do not Have Nickel, which can get Activated, and also Increase the Cost of the Alloy

They have Good Mechanical Properties even Above Operation Conditions

Due to bcc Structure they are Resistant to Radiation Damage such as Swelling

GE-ORNL, Rebak-Terrani, FeCrAl Cladding, NEA-OECD, PSI, 17-September-2015
# Commercial Materials Selected to Study plus Model Alloys from ORNL

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Nominal Composition</th>
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</thead>
<tbody>
<tr>
<td>Zirc-2 UNS R60802</td>
<td>Zr + 1.2-1.7 Sn + 0.07-0.2 Fe + 0.05-0.15 Cr + 0.03-0.08 Ni</td>
</tr>
<tr>
<td>Ferritic steel T91 K90901</td>
<td>Fe + 9 Cr + 1 Mo + 0.2 V</td>
</tr>
<tr>
<td>Ferritic steel HT9 S42100</td>
<td>Fe + 12 Cr + 1 Mo + 0.5 Ni + 0.5 W + 0.3 V</td>
</tr>
<tr>
<td>Nano ferritic alloys -NFA</td>
<td>e.g. 14YWT; Fe + 14 Cr + 0.4 Ti + 3 W + 0.25 Y$_2$O$_3$</td>
</tr>
<tr>
<td>MA956 or UNS S67956</td>
<td>Fe + 18.5-21.5 Cr + 3.75-5.75 Al + 0.2-0.6 Ti + 0.3-0.7 Y$_2$O$_3$</td>
</tr>
<tr>
<td>Sandvik APMT</td>
<td>Fe + 22 Cr + 5 Al + 3 Mo</td>
</tr>
<tr>
<td>Super ferritic, e.g. 4C54</td>
<td>Fe + 26.5Cr + 0.8 Mn + 0.5Si + 0.2N + ≤0.20C</td>
</tr>
<tr>
<td>VDM Aluchrom</td>
<td>Fe + 14-21Cr + 4-6Al</td>
</tr>
<tr>
<td>ORNL Experimental Alloys</td>
<td>Fe + 9-15Cr + 4-6 Al</td>
</tr>
<tr>
<td>Alloy 33 – UNS R20033</td>
<td>33 Cr + 32 Fe + 31 Ni + 1.6 Mo + 0.6Cu + 0.4 N</td>
</tr>
</tbody>
</table>
Technology and Manufacturing Readiness Levels for the Development of Advanced Steel Cladding

- **TRL 1** – Basic Principles Observed
- **TRL 2** – Concept Formulation
- **TRL 5** – Component in a Representative Environment
- **TRL 6** – Prototype in a Representative Environment
- **TRL 7** – Prototype in an Operational Environment
- **TRL 8** – System Qualification

**Feasibility Studies**

- **2015**
- **2022**

**Technology Advancement**

- **Lead Fuel Assembly**

- **TRL 3** – Proof of Concept
- **TRL 4** – Component in the Laboratory
- **TRL 5 to TRL 8** is part of Phase 2 = Development

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Five Steps Systematic Metrics Provided by DOE to Evaluate the ATF Performance

1. Normal Operation & AOO
2. Postulated Accidents (Design Basis)
3. Severe Accidents (Beyond Design Basis)
4. Fabrication, Manufacturability, Licensing
5. Used Fuel Storage/Transport/Disposition
Enhanced LWR ATF Performance Attributes and Metrics, FCRD-FUEL-2013-000264 and OECD NEA 1 – Normal Operation & Anticipated Operational Occurrences

1) Thermal hydraulic interaction -
2) Reactivity control systems interaction
3) Mechanical strength, ductility (beginning of life and after irradiation)
4) Thermal behavior (conductivity, specific heat, melting)
5) Chemical compatibility (fuel-cladding) / stability
6) Chemical compatibility with and impact on coolant chemistry
7) Fission product behavior

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Brookhaven Calculations on Thermal Hydraulics for an Average PWR Rod shows no major impacts by replacing Zircaloy cladding by FeCrAl.
Irradiation-induced hardening studies at Michigan U. shows increase in micro-hardness after proton irradiation.

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However, APMT Resistant to Environmental Cracking. Proton Irradiation does not increase Susceptibility

Deformation bands in irradiated zone after CERT test in High Temperature Water. No Cracks on the surface

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Corrosion Potential of Zirc-2, 304SS, X-750, APMT, Alloy 33, NFA and Pt under different water chemistry conditions

Redox kinetics on APMT, NFA and Alloy 33 alloys shows that APMT and other ferritic alloys behave similarly to well known 304 SS or X-750 in high temperature water
Compatibility between Cladding and Coolant

In decreasing order of oxide thickness. Thickest oxide for Zircaloy-2 and thinnest for HT9. Coupons Immersed 1 year in 288°C Water + 2 ppm O₂

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Ferritic Steels Resistant to Environmental Cracking

Tests involved multiple attempts at multiple K levels and in different water chemistries to sustain cracking at low frequency or constant K.
Typical Examples of Crack Arrest

Crack arrest and/or limited environmental effect with decreasing frequency of loading

Tests involved multiple attempts at multiple K levels and in different water chemistries to sustain cracking at low frequency or constant K
Hydrogen Permeation to Address Tritium Release

The hydrogen permeability of model FeCrAl alloys was determined at various temperatures between 350°C & 650°C.

Hydrogen permeability of FeCrAl alloys is five times greater than that of 304 SS at 350°C and three times higher at 650°C (bcc vs. fcc).

APMT with higher Cr and Al contents had smaller hydrogen permeability in comparison with T35Y2 and T54Y2.

Hydrogen permeation in the FeCrAl alloys is nearly 2 orders of magnitude higher than for Zr- Alloys.

An alumina layer in the ID may reduce hydrogen permeation from fuel.

Fig. 6. Arrhenius plot of the fitted hydrogen permeability for T35Y2, T54Y2, APMT, 304SS, 406SS, Zircaloy-2, Zircaloy-4, and pure iron over a 350–650 °C range. The permeability of Zircaloy-2 and Zircaloy-4 was computed using the data in Refs. [33,34].
Irradiation Studies

ATF-1 = in progress, ATR dry
ATF-2 = planned in PWR water loop at ATR & BWR in Halden
ATF-3 = TREAT
## GE Participation in ATF Irradiation Test Series

<table>
<thead>
<tr>
<th>Test Series</th>
<th>ATF-1</th>
<th>ATF-2</th>
<th>ATF-3</th>
<th>CM-ATF-x</th>
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</thead>
<tbody>
<tr>
<td>Test Reactor</td>
<td>ATR - INL</td>
<td>ATR + Halden</td>
<td>TREAT - Idaho</td>
<td>Commercial Power Plant</td>
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<tr>
<td>Test Type</td>
<td>Drop-in</td>
<td>Loop</td>
<td>Loop</td>
<td>LFA</td>
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<tr>
<td>Test Strategy</td>
<td>Scoping — Two Alloys</td>
<td>Scoping — Targeted FeCrAl Alloys</td>
<td>Focused Compositions</td>
<td>Focused Composition</td>
</tr>
<tr>
<td></td>
<td>Nominal conditions</td>
<td>Nominal conditions</td>
<td>Accident conditions</td>
<td>Nominal conditions</td>
</tr>
<tr>
<td>Fuel</td>
<td>UO₂</td>
<td>APMT &amp; Two Other FeCrAl</td>
<td>Fuel rods from ATF-2, Three Irradiation Levels. Comparison between FeCrAl and Zircaloy</td>
<td>Concepts to be selected in 2016</td>
</tr>
<tr>
<td>Cladding</td>
<td>Advanced Steels, APMT and Alloy 33</td>
<td>In contact with PWR coolant for Fuel-cladding-coolant interactions</td>
<td>Power ramp test to determine burst enthalpy</td>
<td>Commercial Plant steady state irradiation</td>
</tr>
<tr>
<td>Key Features</td>
<td>In dry capsules for Fuel-cladding interactions</td>
<td>In contact with PWR coolant for Fuel-cladding-coolant interactions</td>
<td>Power ramp test to determine burst enthalpy</td>
<td>Commercial Plant steady state irradiation</td>
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<tr>
<td>Timeframe</td>
<td>FY14 – FY18+</td>
<td>FY17 – FY22</td>
<td>FY18 – FY25</td>
<td>FY22 – ?</td>
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</tbody>
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ATF-1 Tests will Determine Compatibility between Cladding and Fuel

<table>
<thead>
<tr>
<th>Rodlet</th>
<th>Concept</th>
<th>LHGR (W/cm)</th>
<th>Peak Fuel T (°C)</th>
<th>PICT (°C)</th>
<th>Target BU (GWD/MTU)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Target Conditions:</td>
<td>300-400</td>
<td>&lt;1600</td>
<td>300-450</td>
<td></td>
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<tr>
<td>G02</td>
<td>UO₂ / Alloy 33</td>
<td>289.9</td>
<td>1351</td>
<td>362</td>
<td>60</td>
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<tr>
<td>G01</td>
<td>UO₂ / Alloy 33</td>
<td>291.2</td>
<td>1360</td>
<td>378</td>
<td>20</td>
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<tr>
<td>G04</td>
<td>UO₂ / APMT</td>
<td>283.1</td>
<td>1310</td>
<td>382</td>
<td>60</td>
</tr>
<tr>
<td>G03</td>
<td>UO₂ / APMT</td>
<td>284.6</td>
<td>1333</td>
<td>402</td>
<td>20</td>
</tr>
</tbody>
</table>

~175 EFPD per year

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2 - Postulated Accidents (Design Basis)

1) Thermal hydraulic interaction
2) Mechanical strength and ductility
3) Thermal behavior (conductivity, specific heat, melting)
4) Chemical compatibility/stability (e.g. oxidation behavior)
5) Fission product behavior
6) Combustible gas production
Enhanced LWR ATF Performance Attributes and Metrics FCRD-FUEL-2013-000264 and OECD NEA 3 – Severe Accidents (Beyond Design Basis)

1) Mechanical strength, ductility
2) Thermal behavior (conductivity, specific heat, melting)
3) Chemical compatibility/ stability (including high temperature steam interaction)
4) Fission product behavior
5) Combustible gas production
Comparison of Advanced Cladding Steam Oxidation Rate


![Graph showing parabolic oxidation rate constant vs. temperature for different alloys, including 304SS, FeCrAl, SiC, and Zirconium Alloys.](image-url)
FeCrAl cladding is modeled as ~1/2 thickness (~400 μm) of the Zircaloy assemblies.

Same gap thickness, 43% less cladding, 18.5% more fuel.

FeCrAl vs. Zircaloy for severe accidents:
~1000x slower oxidation kinetics,
4.5x lower heat of reaction.

Metallic and oxidized cladding has lower melting point.
GE/ORNL Planed TREAT Tests – Zr Based vs. FeCrAl

It is planned to test in TREAT side by side the burst performance of FeCrAl vs. Zircaloy at three irradiation levels (0, 20 & 40 GWD/MTU)

Add values for FeCrAl Claddings
Enhanced LWR ATF Performance Attributes and Metrics FCRD-FUEL-2013-000264 and OECD NEA 4 – Fabrication and Manufacturability

1) Manageable fissile material content
2) Compatible with large-scale production needs (material availability, fabrication techniques, waste, etc.)
3) Compatible with quality and uniformity standards
4) Licensing
Fabrication of the Fe-Cr-Al Cladding

• We may not need powder metallurgy to fabricate FeCrAl. Traditional melting methods may be suitable
• Working currently to determine the minimum amount of Cr in FeCrAl alloys needed to sustain resistance to superheated steam
• Demonstrate that FeCrAl alloys can be fabricated into 5 m long, 9.5 mm OD and 0.4 mm wall thickness
• FeCrAl alloys are weldable by different methods
Tube Fabrication of the Fe-Cr-Al Cladding

• Tube drawing process of the 2nd gen ATF FeCrAl alloy at Rhenium Alloys Inc., North Ridgeville, OH, was completed. The C35M3 (Fe-13Cr-5.2Al-2Mo-0.2Si-Y, wt.%) was drawn into the aim tube size with 9.5 mm OD and <0.40 mm wall thickness (Y. Yamamoto)
Welding of Kanthal-D alloy (similar to APMT) at INL using Pressure Resistance Welding (PRW) (Jian Gan)

Through both the SEM image and the EBSD scan, a sound metallurgical bond is seen to have formed between the end plug and 370 µm thick cladding tube weldment.

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Rodlets of APMT fabricated at INL using standard procedures of TIG welding in glove box after fuel insertion

Traditional welding used to hermetically seal the APMT rodlets for ATF-1 Test
Rodlets of APMT fabricated at INL using standard welding procedures
Enhanced LWR ATF Performance Attributes and Metrics FCRD-FUEL-2013-000264 and OECD NEA 5 – Used Fuel Storage/ Transport/Disposition

1) Mechanical strength, ductility
2) Thermal behavior
3) Chemical stability
4) Fission product behavior
Comparative Analysis of Long Term Storage of Used Fuel containing FeCrAl Cladding

• Used nuclear fuel with zirconium alloy cladding has been stored for decades in water pools and now in dry storage casks

• Even though several possible mechanisms of failure have been identified for the zirconium alloy materials, little degradation during storage has been observed and reported

• Stainless steel claddings have been used in the past for commercial light water reactors in the US. Most of these stainless clad fuels are in interim storage without noticeable degradation.

• It may be predicted that the ferritic clad would perform as well or better than the austenitic steels under long term storage

Need to survive 100 years storage in dry caskets
Summary and Conclusions
Summary and Conclusions

1) Advanced FeCrAl steels have lower corrosion rate than zirconium alloys under normal operation conditions

2) Advanced steels greatly outperform zirconium alloys under accident conditions in superheated steam

3) GE-ORN is following a systematic approach on collecting data toward the deployment of a Lead Fuel Assembly in a commercial light water reactor

4) Other areas currently under consideration
   • Irradiation studies at ATR (dry and water loop) (ATF-1 & ATF-2)
   • Modeling and Simulation = Neutronics, thermal hydraulics
   • Tritium release, hydrogen absorption and transport
   • Fabrication of tubing, welding end cap
   • Licensing and Economics
   • Long term storage of spent fuel in dry casks
   • Crud deposition and Fretting
Acknowledgement

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Calculations from Jeff Powers at ORNL
In order to maintain the current U enrichment of 4.9%, the cladding thickness has to be in the order of 300-400 µm.
RD&D Strategy For Enhanced Accident Tolerant Fuels – 10 Year Goal

Phase 1
Feasibility
Workshops

Feasibility studies on advanced fuel and clad concepts
-- bench-scale fabrication
-- small-scale irradiation tests
-- steam reactions
-- mechanical and chemical properties
-- furnace tests
-- fuel performance modeling

Assessment of new concepts
-- impact on economics
-- impact on fuel cycle
-- impact on operations
-- impact on safety envelope
-- environmental impact

Phase 2
Development/Qualification
Concept Prioritization

Steady State Loop and Capsule Tests

Transient Irradiation Tests

Loss of Coolant Accident (LOCA)/Furnace Tests

Fuel Performance Code

Fuel Safety Basis

Phase 3
Commercialization
Lead Fuel Rod Ready

Industry led projects (Phase 1a)

Industry led projects (Phase 1b)

Industry led projects (Phase 2)


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