OECD/NEA NUCLEAR SCIENCE COMMITTEE
FOURTH MEETING OF THE EXPERT GROUP ON ACCIDENT TOLERANT FUELS FOR LIGHT WATER REACTORS (EGATFL-04), Paul Scherrer Institute, 17-18 September 2015

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

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Imagination at work.

OAK RIDGE National Laboratory

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

GE Global Research

GNF
Global Nuclear Fuel
A Joint Venture of GE, Toshiba, & Hitachi

SANDVIK

Oak Ridge National Laboratory

Brookhaven National Laboratory

INL
Idaho National Laboratory

Michigan Engineering

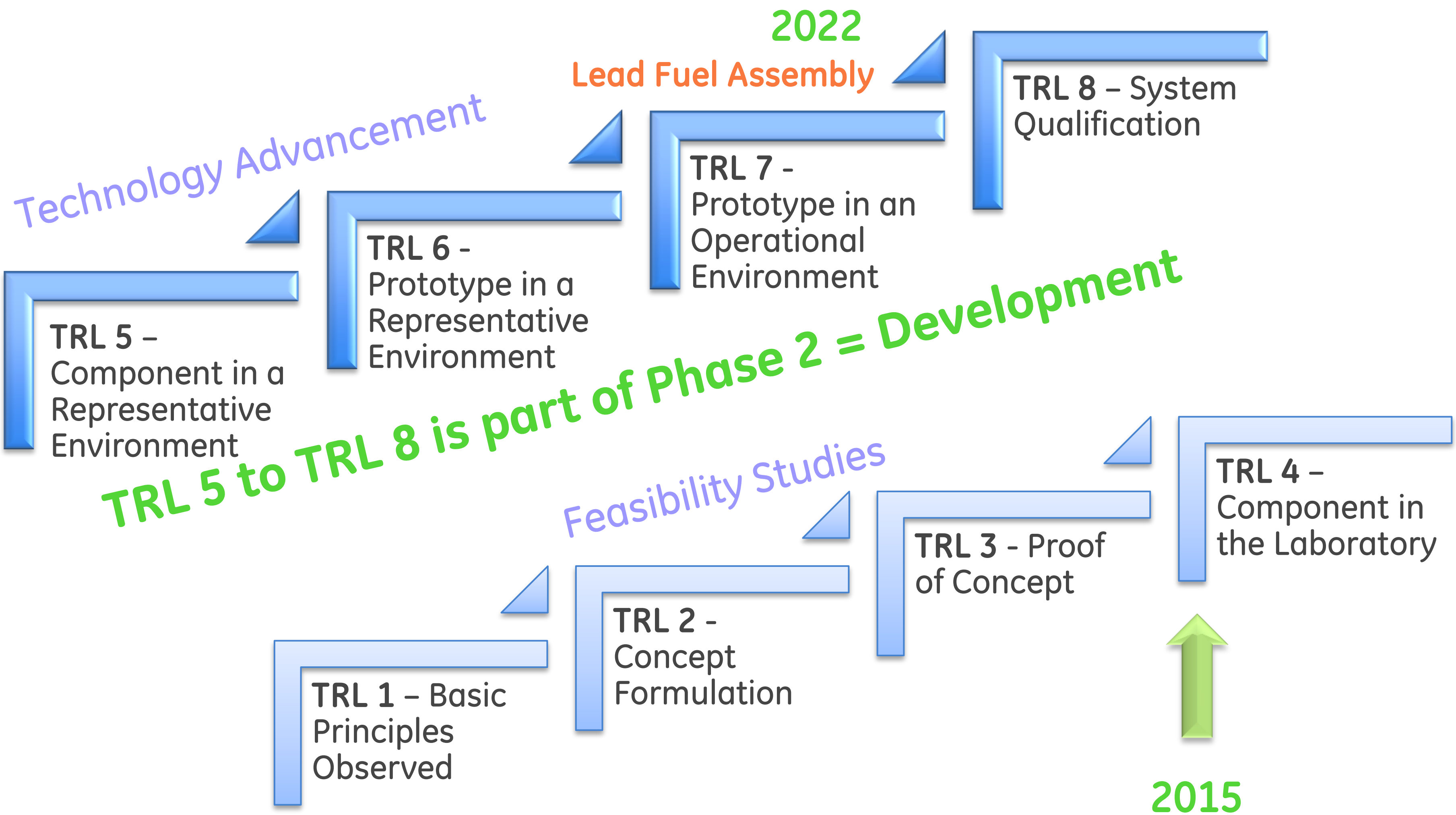
Los Alamos National Laboratory

Why Advanced Ferritic Steels for Cladding?

Commercial Materials Selected to Study plus Model Alloys from ORNL

Alloy	Nominal Composition
Zirc-2 UNS R60802	Zr + 1.2-1.7 Sn + 0.07-0.2 Fe + 0.05-0.15 Cr + 0.03-0.08 Ni
Ferritic steel T91 K90901	Fe + 9 Cr + 1 Mo + 0.2 V
Ferritic steel HT9 S42100	Fe + 12 Cr + 1 Mo + 0.5 Ni + 0.5 W + 0.3 V
Nano ferritic alloys -NFA	e.g. 14YWT; Fe + 14 Cr + 0.4 Ti + 3 W + 0.25 Y_2O_3
MA956 or UNS S67956	Fe + 18.5-21.5 Cr + 3.75-5.75 Al + 0.2-0.6 Ti + 0.3-0.7 Y_2O_3
Sandvik APMT	Fe + 22 Cr + 5 Al + 3 Mo CURRENT CANDIDATE
Super ferritic, e.g. 4C54	Fe + 26.5Cr + 0.8 Mn + 0.5Si + 0.2N + ≤0.20C
VDM Aluchrom	Fe + 14-21Cr + 4-6Al
ORNL Experimental Alloys	Fe + 9-15Cr + 4-6 Al CURRENT CANDIDATE
Alloy 33 – UNS R20033	33 Cr + 32 Fe + 31 Ni + 1.6 Mo + 0.6Cu + 0.4 N

Technology and Manufacturing Readiness Levels for the Development of Advanced Steel Cladding



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

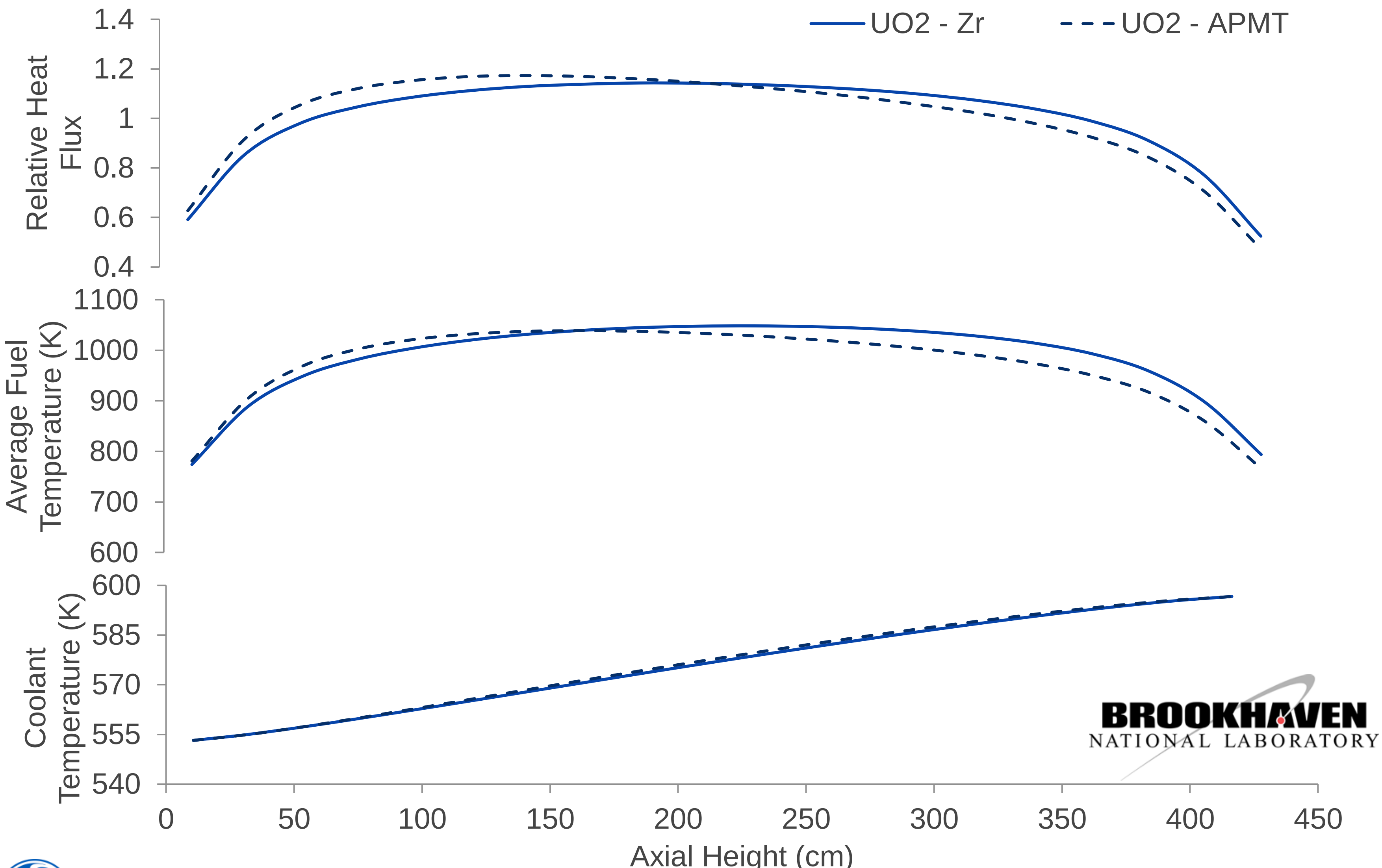
Enhanced LWR ATF Performance Attributes and Metrics , FCRD-FUEL-2013-000264 and OECD NEA

1 – Normal Operation & Anticipated Operational Occurrences

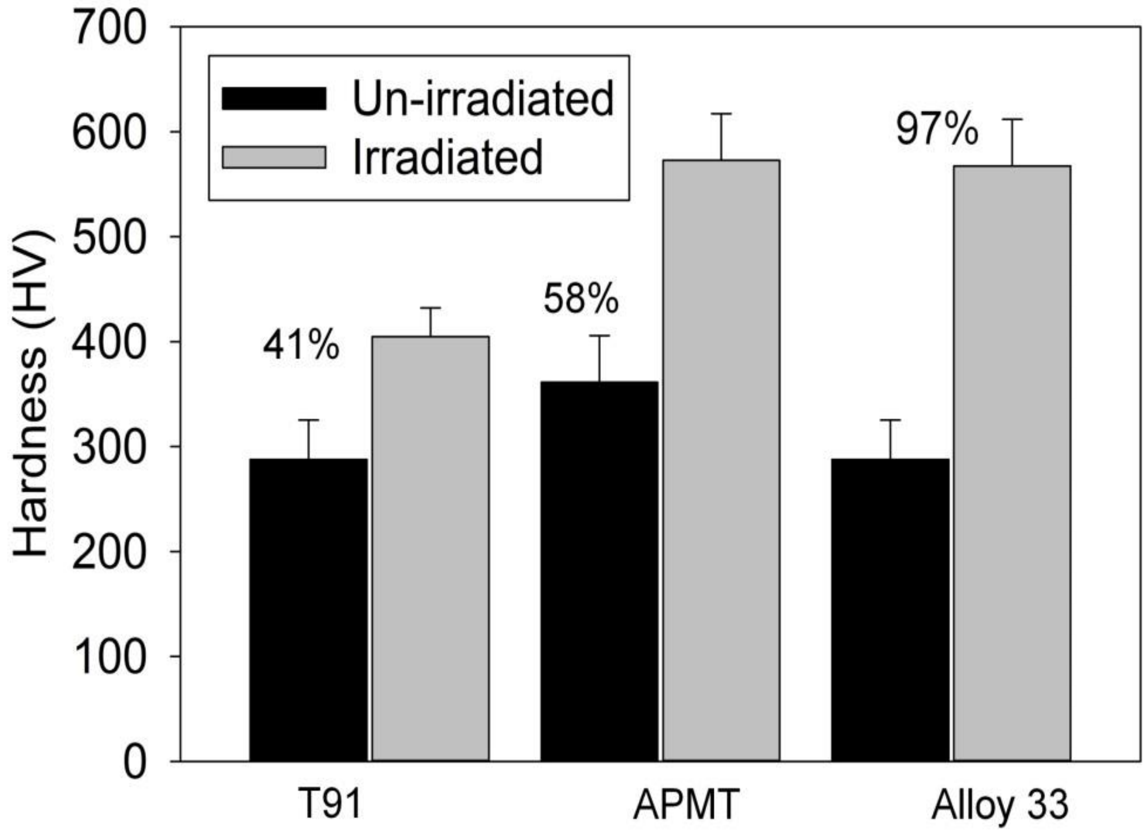
1

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

Brookhaven Calculations on Thermal Hydraulics for an Average PWR Rod shows no major impacts by replacing Zircaloy cladding by FeCrAl

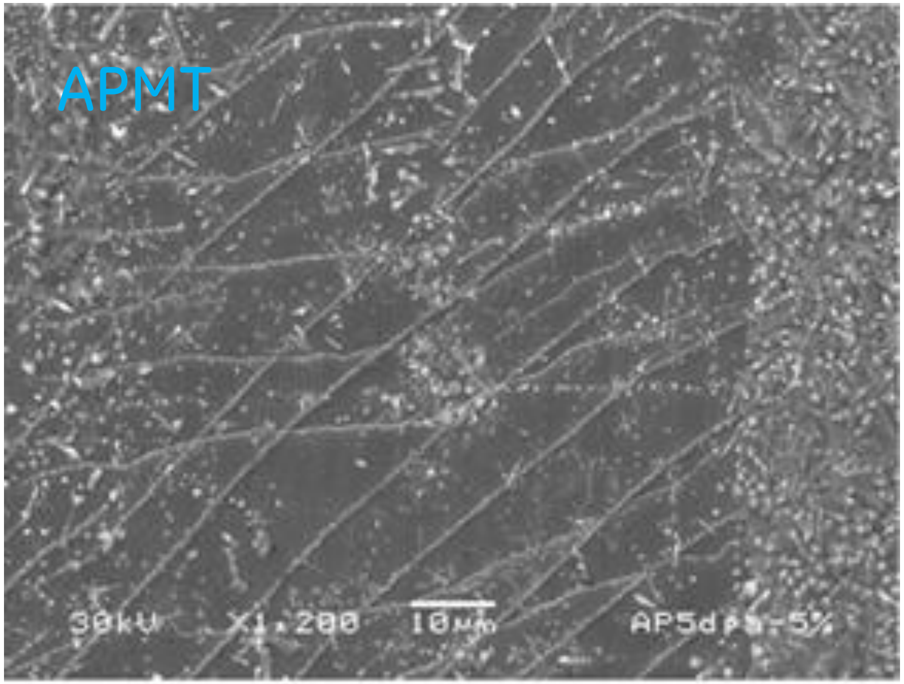


Irradiation-induced hardening studies at Michigan U. shows increase in micro-hardness after proton irradiation

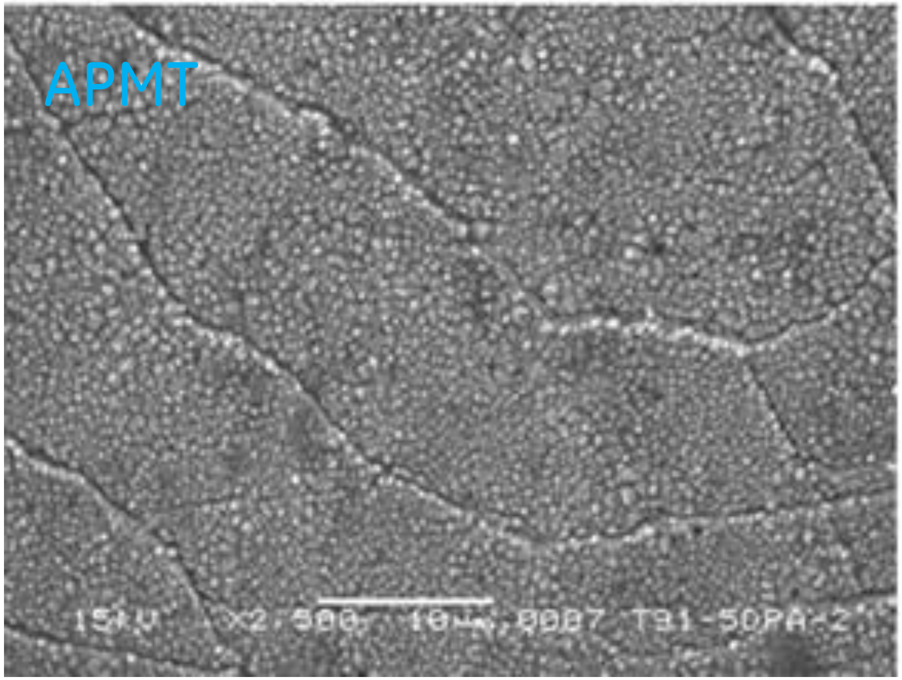


GE-ORNL, Rebak-Terrani, FeCrAl Cladding, NEA-OECD, PSI, 17-September-2015

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



After 5% strain

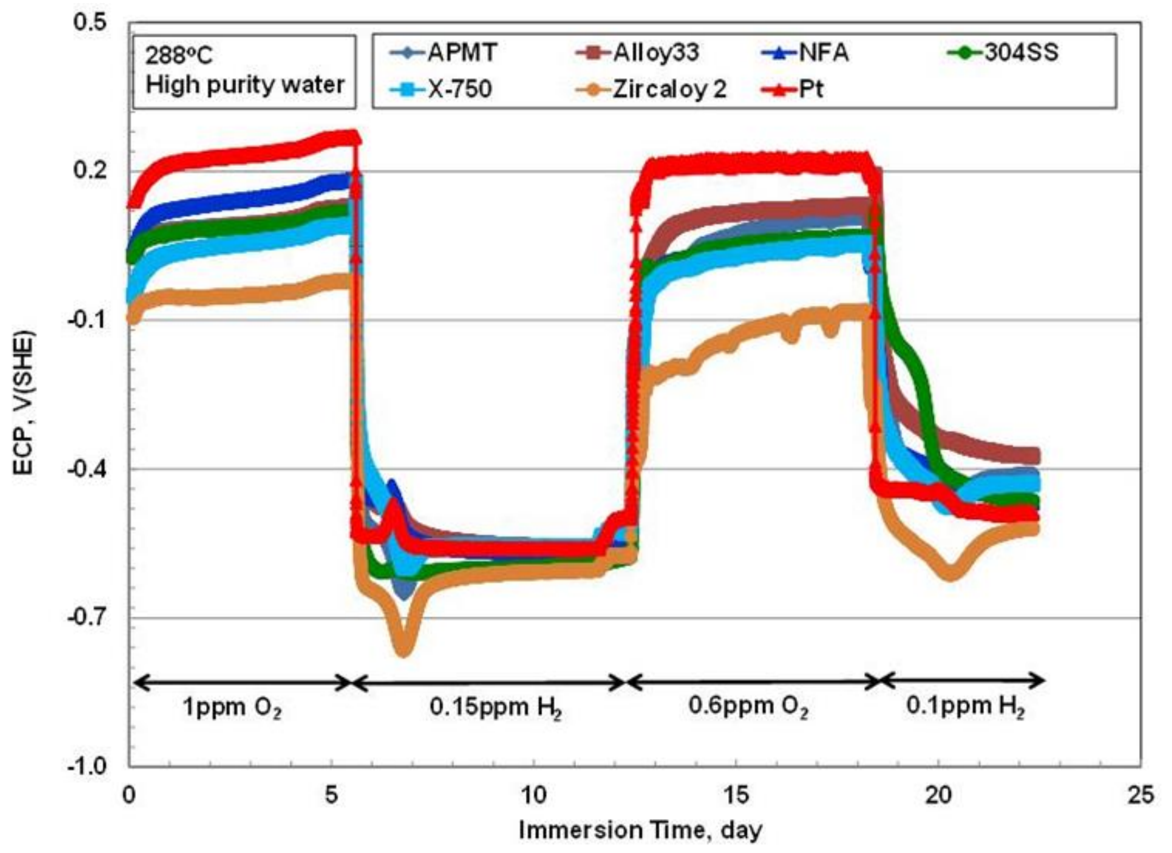


After 10% strain

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

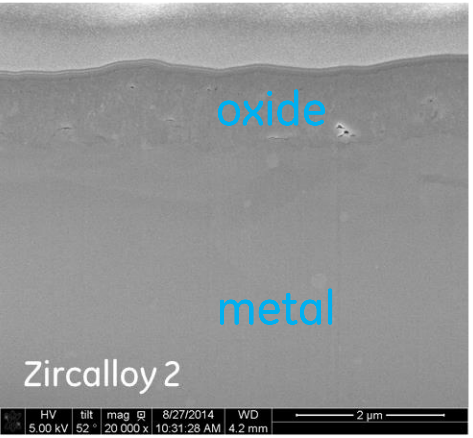
GE-ORNL, Rebak-Terrani, FeCrAl Cladding, NEA-OECD, PSI, 17-September-2015

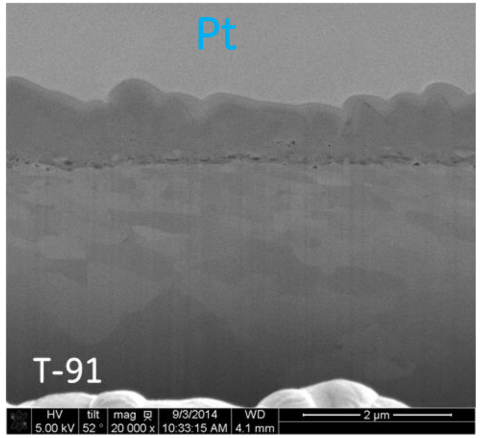
Corrosion Potential of Zirc-2, 304SS, X-750, APMT, Alloy 33, NFA and Pt under different water chemistry conditions

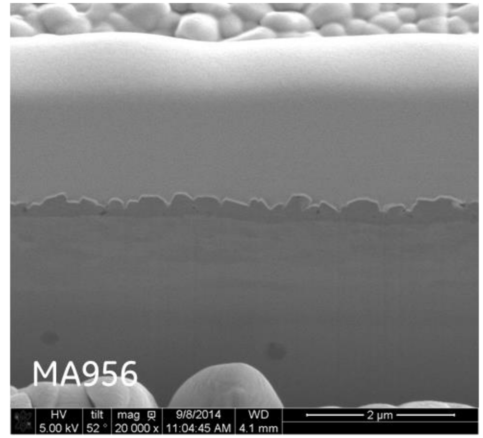


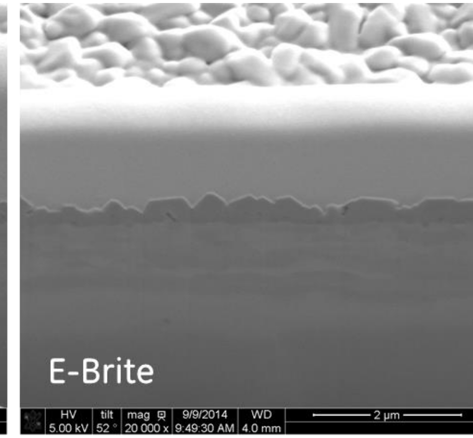
Redox kinetics on APMT, NFA and Alloy 33 alloys shows that APMT and other ferritic alloys behave similarly to well known 304 SS or X-750 in high temperature water

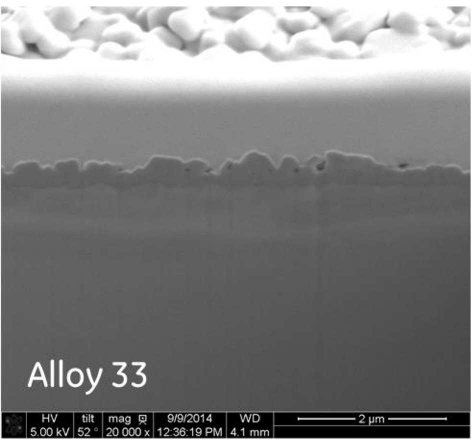
Compatibility between Cladding and Coolant

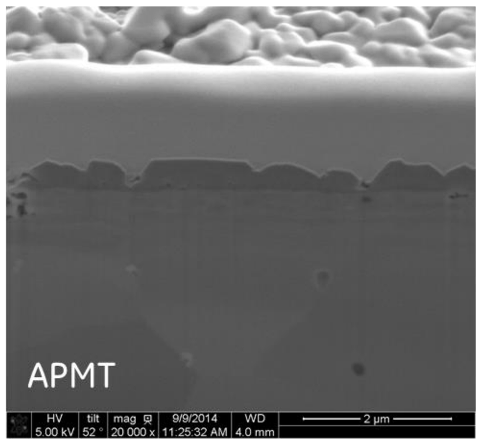


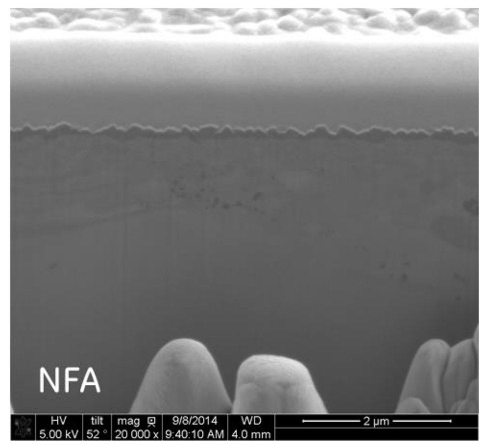


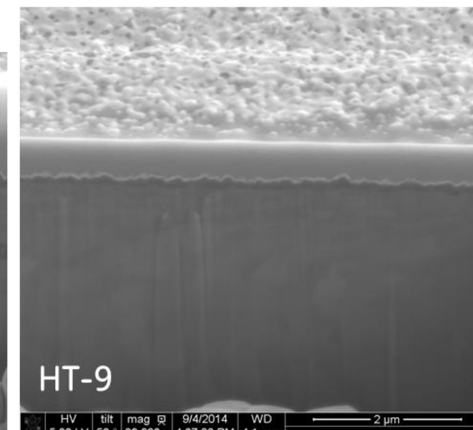








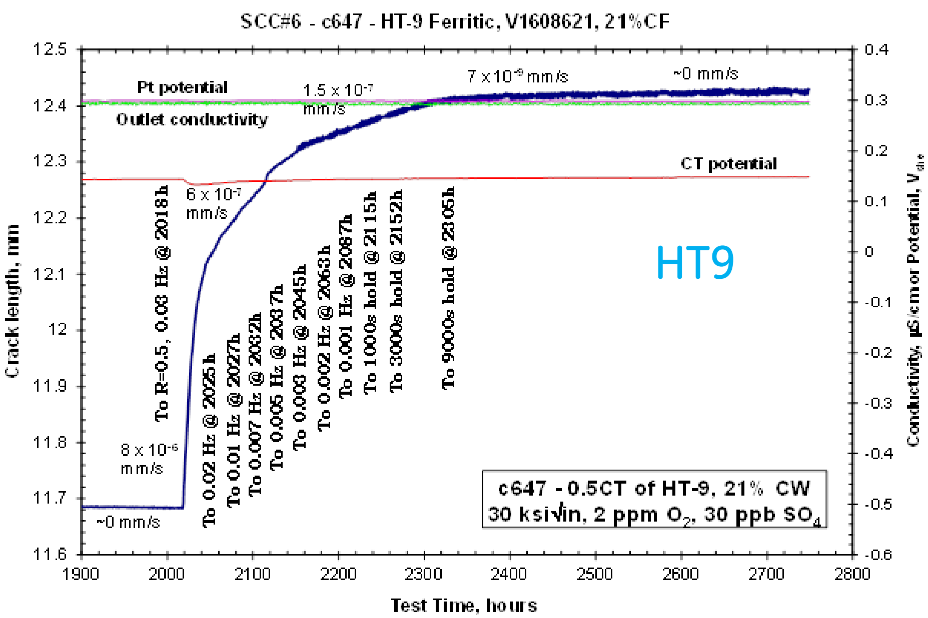


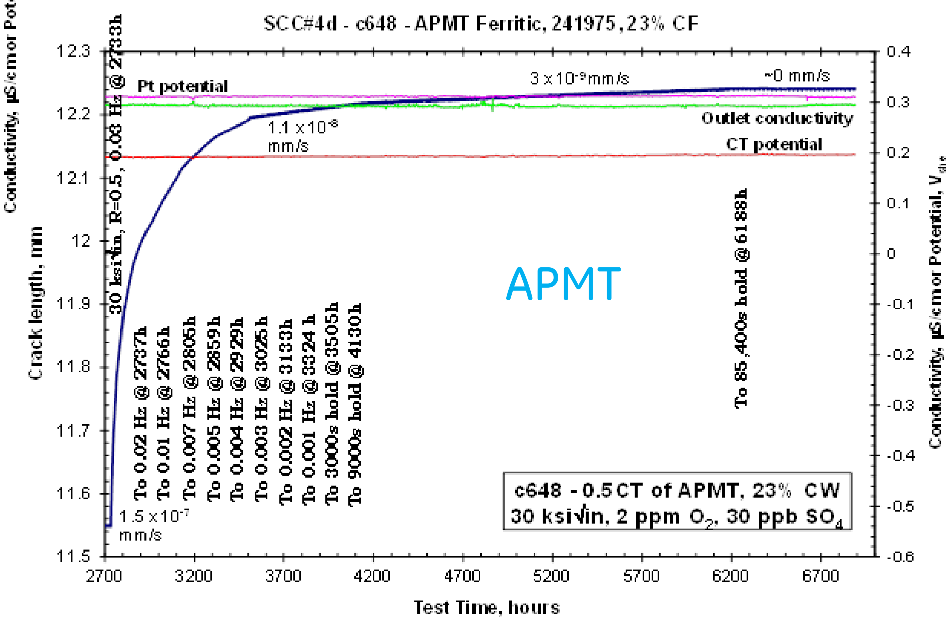


X20,000

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 O_2

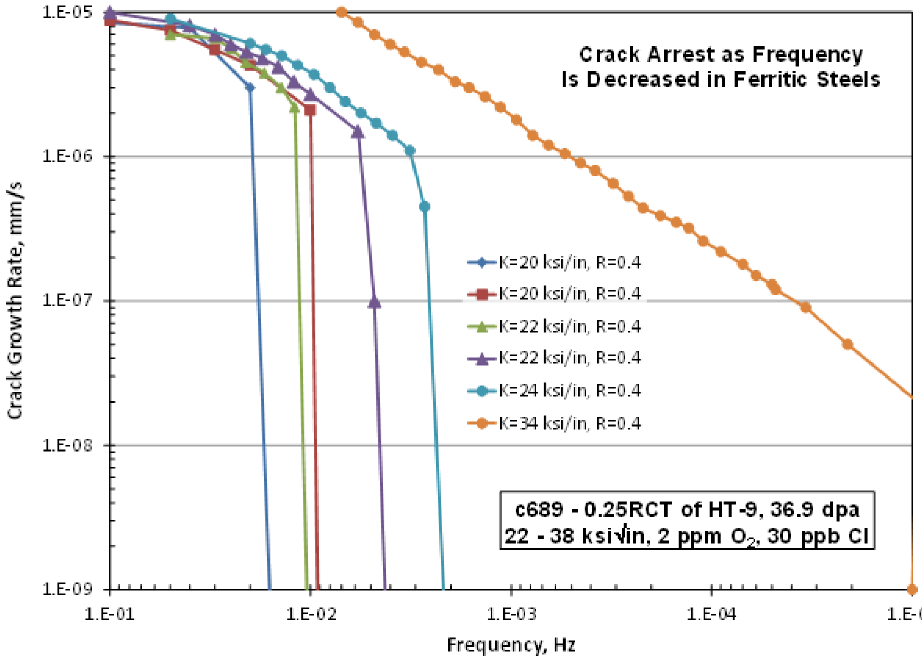
Ferritic Steels Resistant to Environmental Cracking





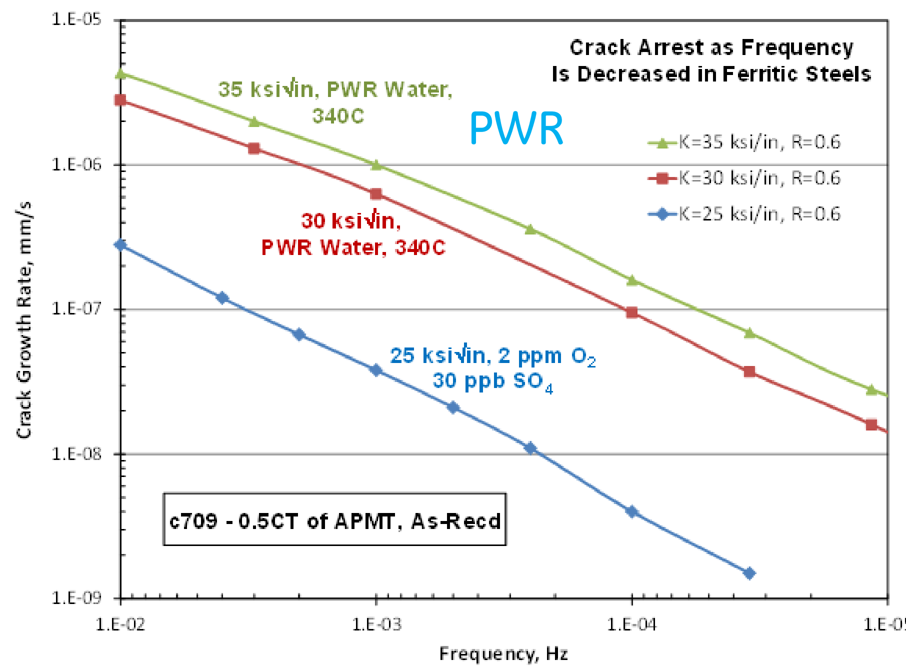
Tests involved multiple attempts at multiple K levels and in different water chemistries to sustain cracking at low frequency or constant K

Typical Examples of Crack Arrest



BWR Testing Conditions
Neutron Irradiated Specimen

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

Oak Ridge National Laboratory

Hu, Terrani, Wirth, Snead: Journal of Nuclear Materials, 2015

- 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

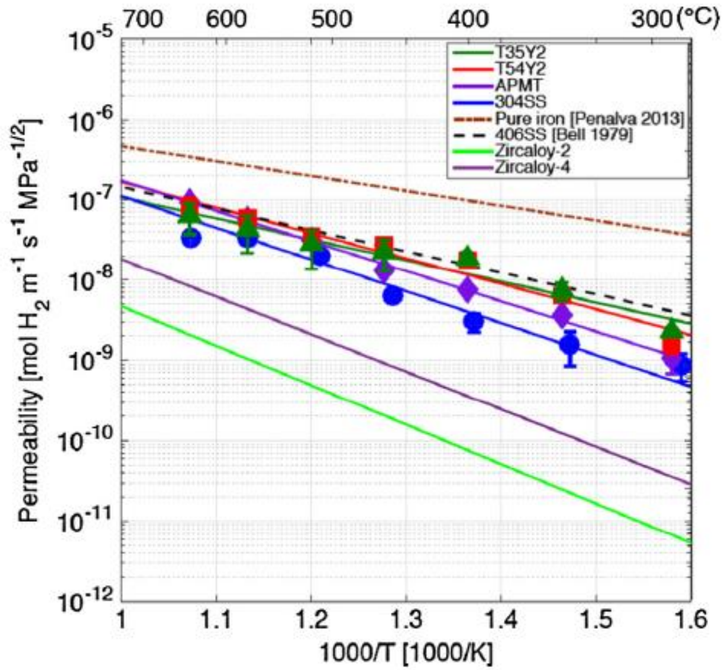


Fig. 6. Arrhenius plot of the fitted hydrogen permeability for T35Y2, T54Y2, APMT, 304SS, 406SS, Zircaloy-2, Zircaloy-4, and pure iron over a 350–650 °C range. The permeability of Zircaloy-2 and Zircaloy-4 was computed using the data in Refs. [33,34].

T35Y2 (13Cr + 4.4 Al) & T54Y2 (15Cr + 3.9 Al)

Irradiation Studies

ATF-1 = in progress, ATR dry

ATF-2 = planned in PWR water loop at ATR & BWR in Halden

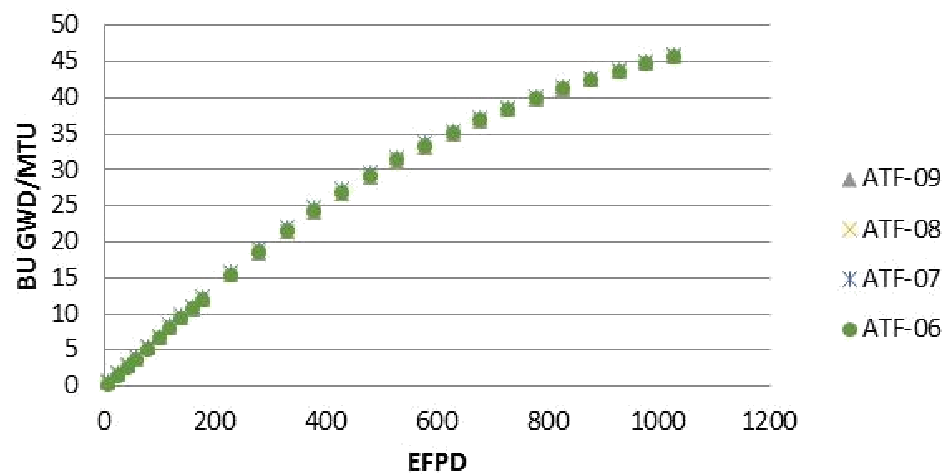
ATF-3 = TREAT

GE Participation in ATF Irradiation Test Series

Test Series	ATF-1	ATF-2	ATF-3	CM-ATF-x
Test Reactor	ATR - INL	ATR + Halden	TREAT - Idaho	Commercial Power Plant
Test Type	Drop-in	Loop	Loop	LFA
Test Strategy	Scoping — Two Alloys	Scoping — Targeted FeCrAl Alloys	Focused Compositions	Focused Composition
	Nominal conditions	Nominal conditions	Accident conditions	Nominal conditions
Fuel	UO_2			
Cladding	Advanced Steels, APMT and Alloy 33	APMT & Two Other FeCrAl	Fuel rods from ATF-2, Three Irradiation Levels. Comparison between FeCrAl and Zircaloy	Concepts to be selected in 2016
Key Features	In dry capsules for Fuel-cladding interactions	In contact with PWR coolant for Fuel-cladding-coolant interactions	Power ramp test to determine burst enthalpy	Commercial Plant steady state irradiation
Timeframe	FY14 – FY18+	FY17 – FY22	FY18 – FY25	FY22 – ?

ATF-1 Tests will Determine Compatibility between Cladding and Fuel

Rodlet	Concept	LHGR (W/cm)	Peak Fuel T (°C)	PICT (°C)	Target BU (GWD/MTU)
Target Conditions:		300-400	<1600	300-450	
G02	UO_2 / Alloy 33	289.9	1351	362	60
G01	UO_2 / Alloy 33	291.2	1360	378	20
G04	UO_2 / APMT	283.1	1310	382	60
G03	UO_2 / APMT	284.6	1333	402	20



~175 EFPD per year

Enhanced LWR ATF Performance Attributes and Metrics FCRD-FUEL-2013-000264 and OECD NEA

2 – **Postulated Accidents (Design Basis)**

2

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

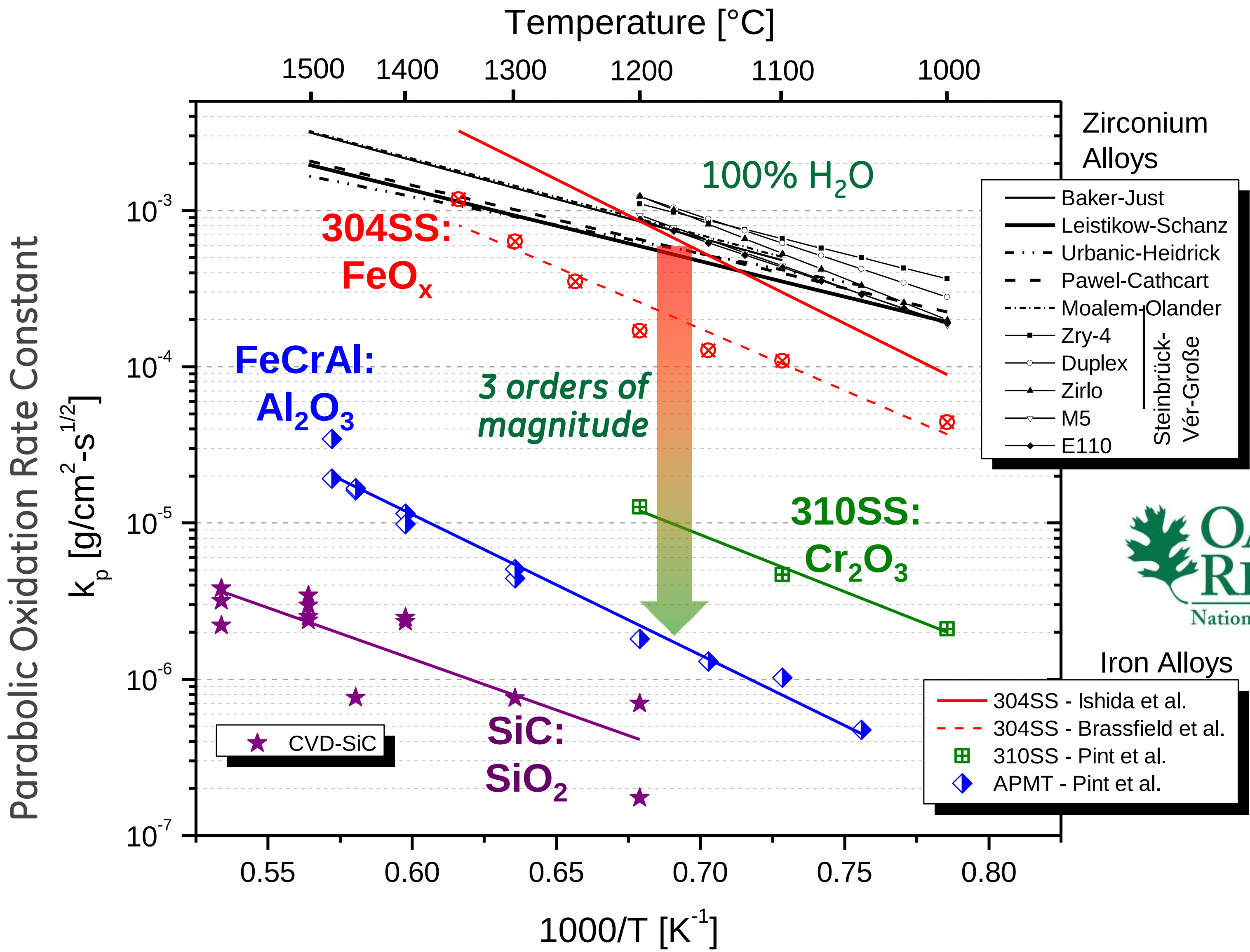
3 – **Severe Accidents (Beyond Design Basis)**

3

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

K.A. Terrani, S.J. Zinkle, L.L. Snead, "Advanced oxidation-resistant iron-based alloys for LWR fuel cladding," *J. Nucl. Mater.*, **448**, (2014) 420.



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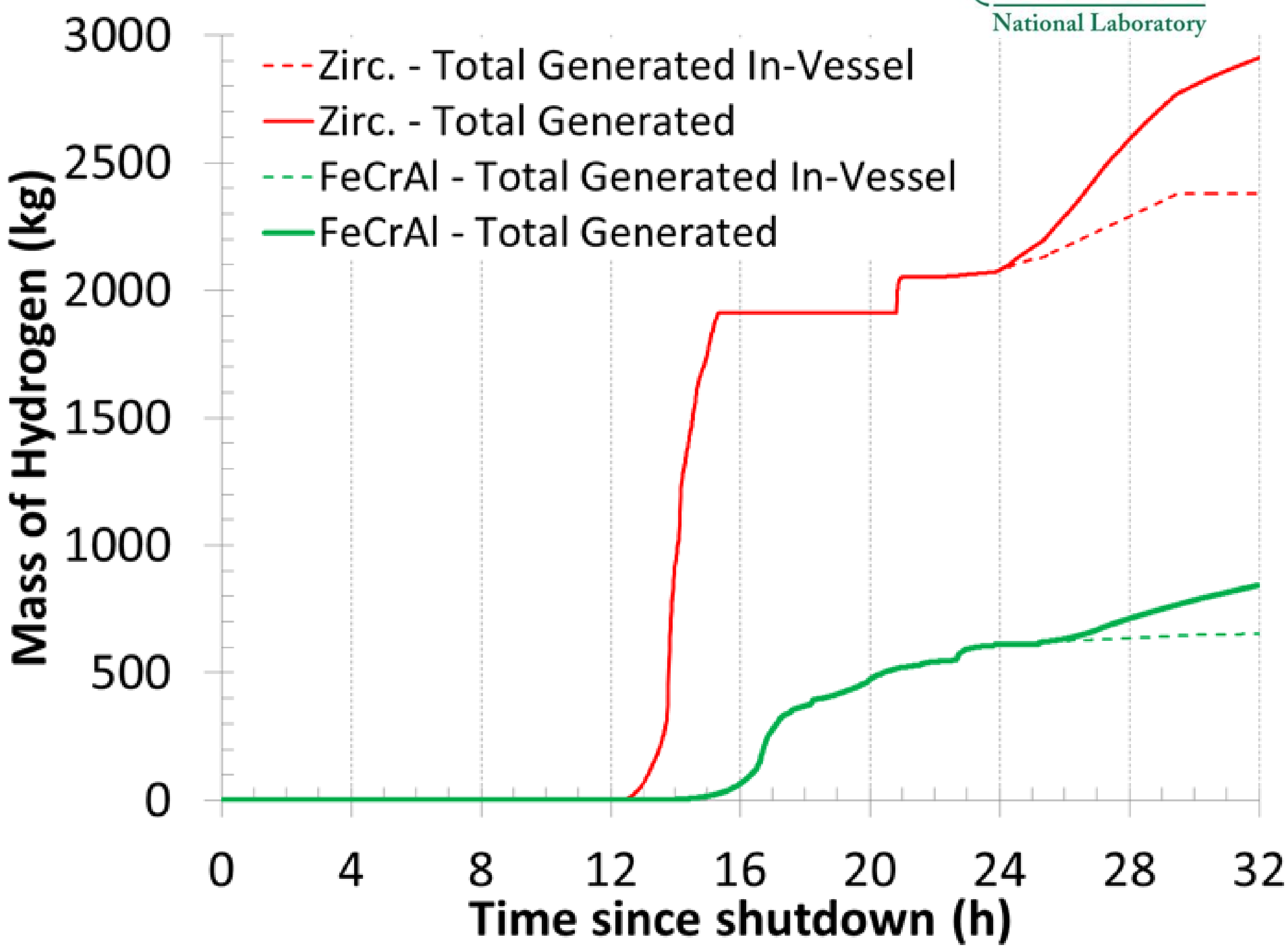
MELCOR Analysis of ATF Concepts Progress at ORNL, Kevin Robb



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:

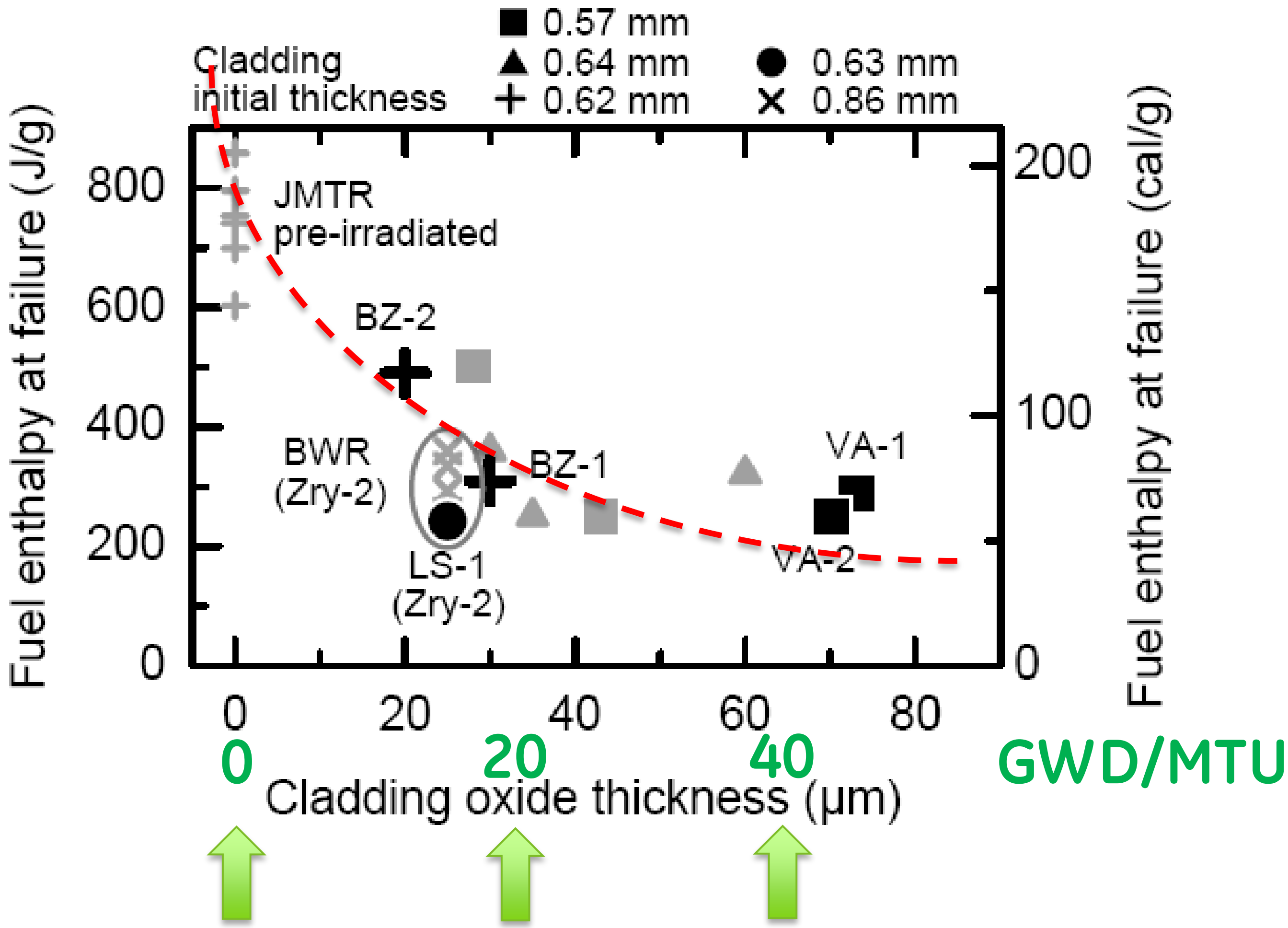
~1000x slower oxidation kinetics,

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

4

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

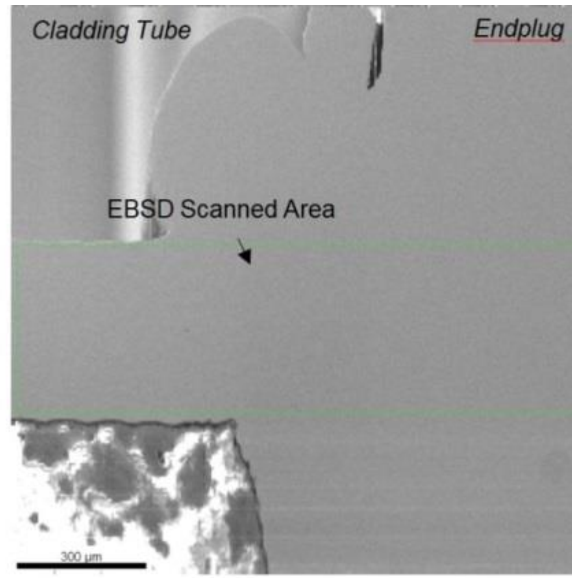
- Tube drawing process of the 2nd gen ATF FeCrAl alloy at Rhenium Alloys Inc., North Ridgeville, OH, was completed. The C35M3 (Fe-13Cr-5.2Al-2Mo-0.2Si-Y, wt.%) was drawn into the aim tube size with 9.5 mm OD and <0.40 mm wall thickness (Y. Yamamoto)

OAK RIDGE National Laboratory

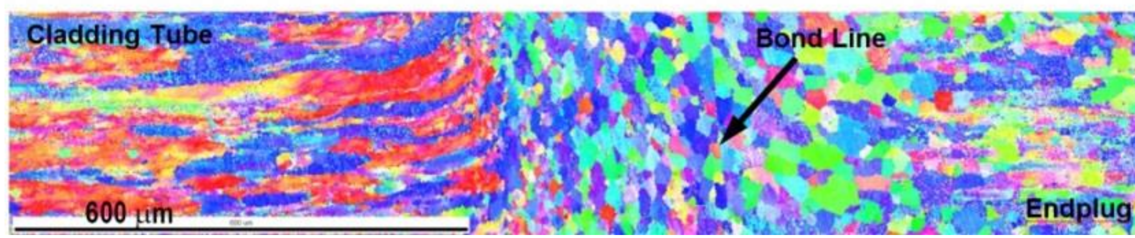
Welding of Kanthal-D alloy (similar to APMT) at INL using Pressure Resistance Welding (PRW)

(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



SEM image showing the area of the second EBSD scan on sample 24-2



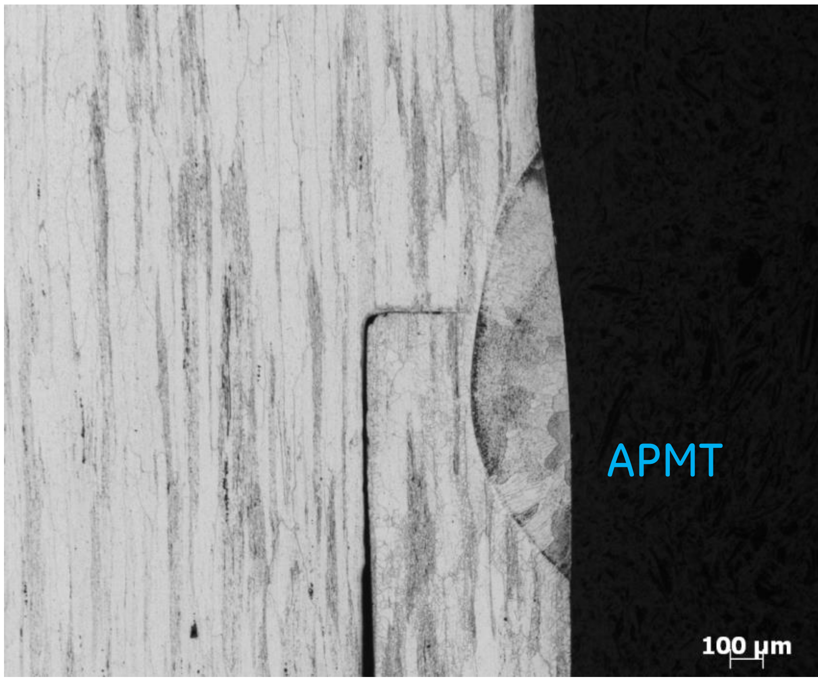
Rodlets of APMT fabricated at INL using standard procedures of TIG welding in glove box after fuel insertion

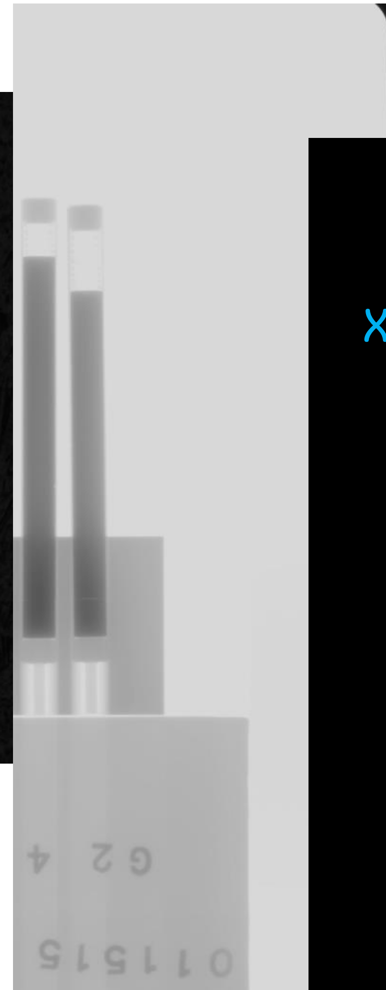
Traditional welding used to hermetically seal the APMT rodlets for ATF-1 Test

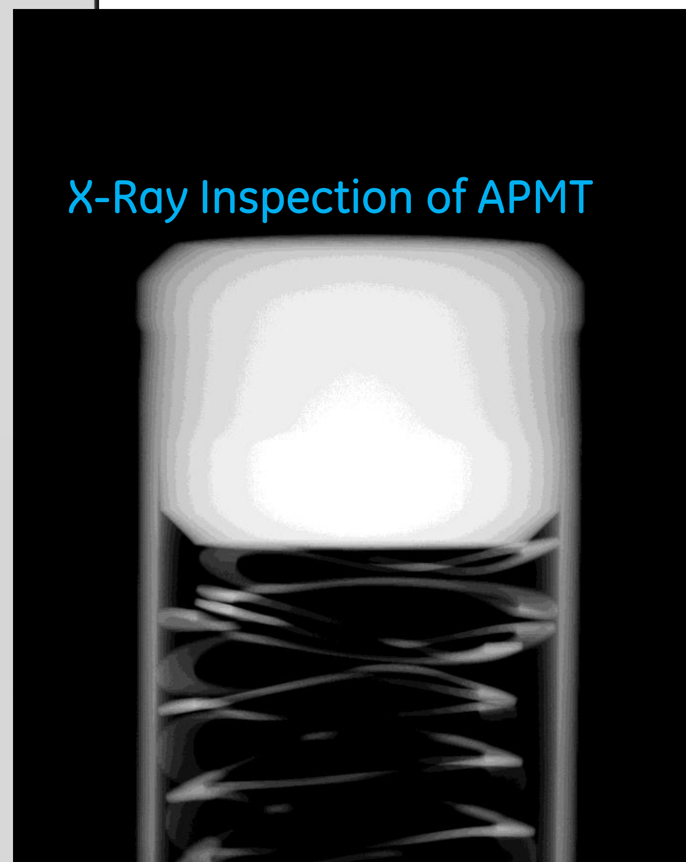
Idaho National Laboratory

Rodlets of APMT fabricated at INL using standard welding procedures

Idaho National Laboratory







Enhanced LWR ATF Performance Attributes and Metrics FCRD-FUEL-2013-000264 and OECD NEA

5 – **Used Fuel Storage/ Transport/Disposition**

5

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-ORNL 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

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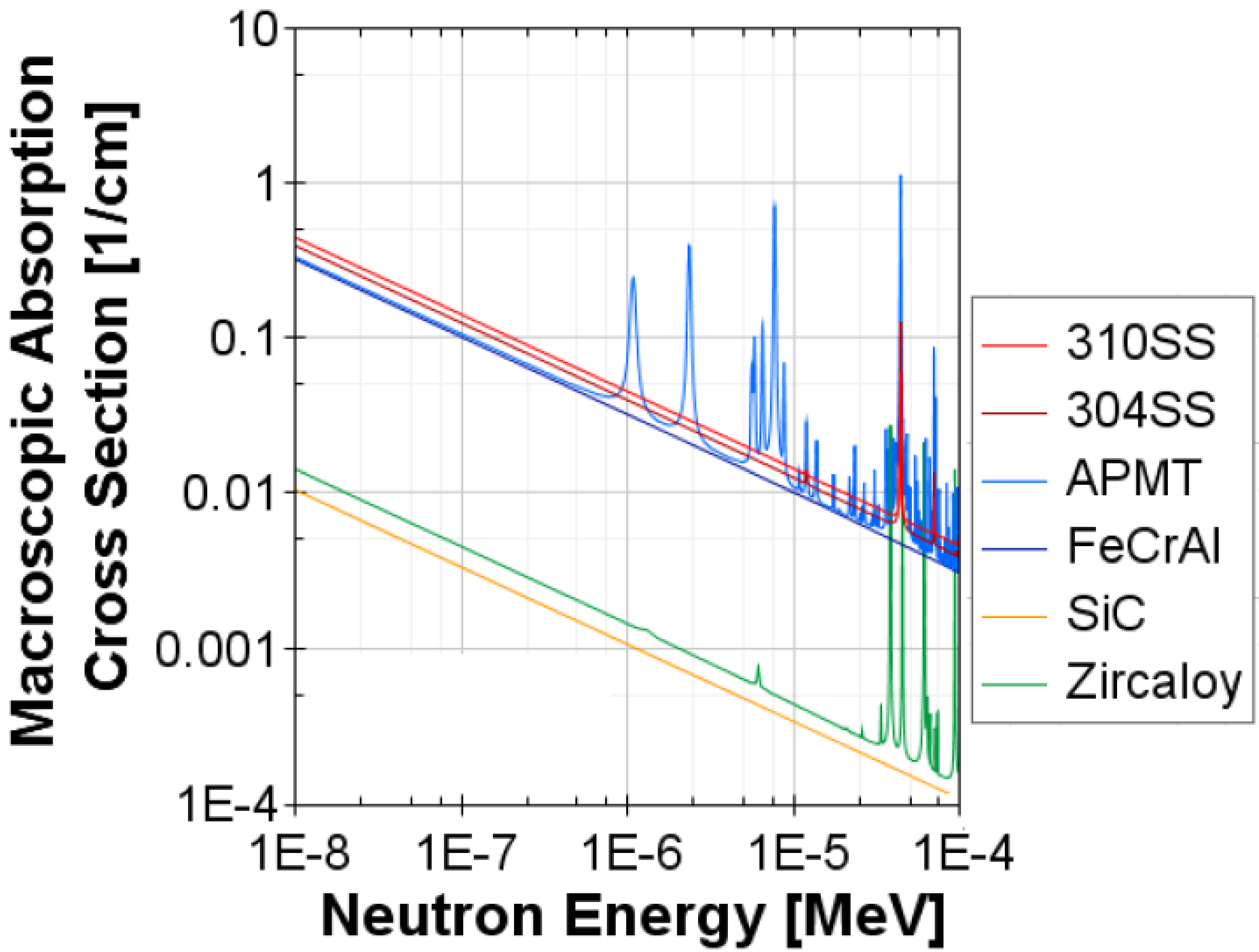
Calculations from Jeff Powers at ORNL



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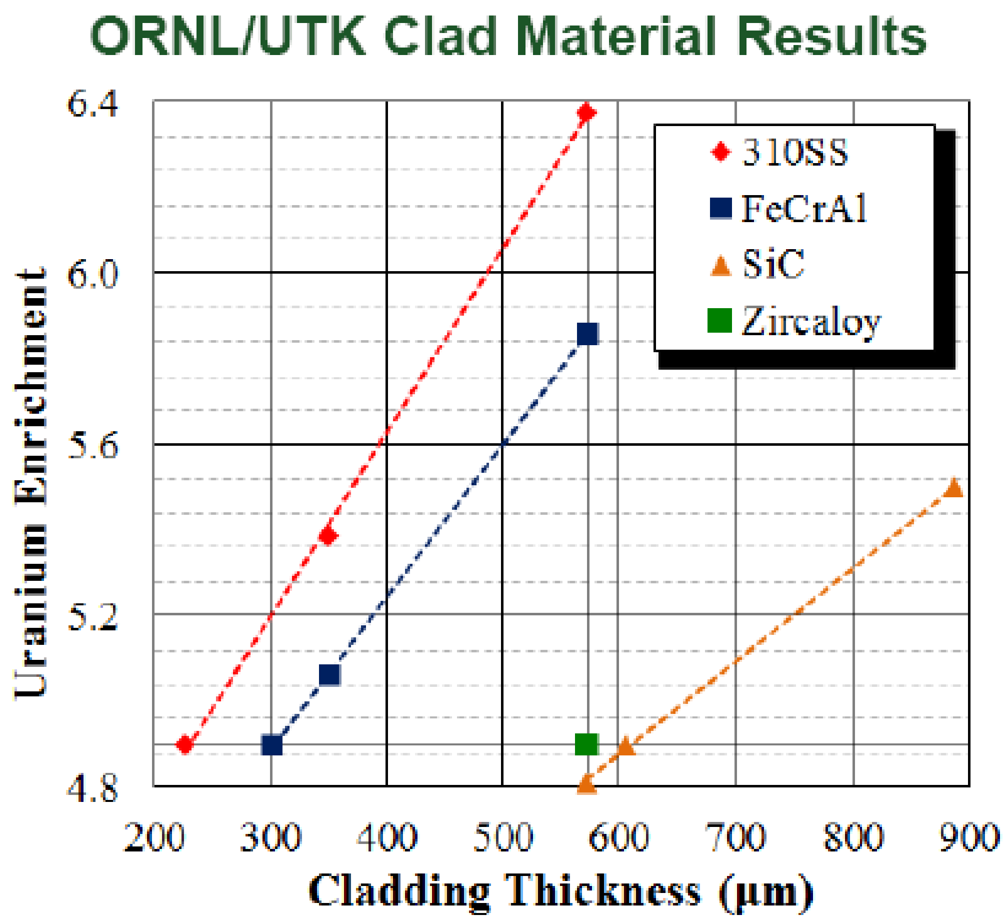

In order to maintain the current U enrichment of 4.9%, the cladding thickness has to be in the order of 300-400 µm

RD&D Strategy For Enhanced Accident Tolerant Fuels – 10 Year Goal