Fuel Behavior in Severe Accidents and Potential Accident Tolerance Fuel Designs

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EPRI Breakthrough Fuel Technology Program

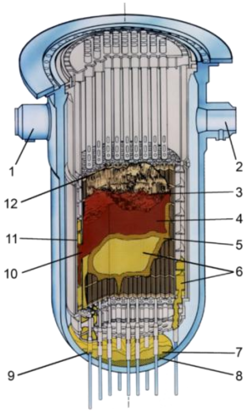
- **EPRI started evaluation of BFT for enhancing fuel reliability, efficiency, and safety in late 2010**
- **Utility executive committee approved two tasks (post- Fukushima)**
  - Accident tolerant fuel cladding
  - SiC channel (led by Ken Yueh)
- **Objectives:**
  - Develop technical needs and basis from utility/fuel user perspectives
  - Supplement efforts undertaken by DOE and fuel vendors, as needed
- **Science Advisory Panel (SAP) established to guide BFT efforts**
  - TVA, Dominion Generation, Exelon Generation, Constellation Energy, Duke Energy, PPL
  - EDF, KKL

Outline

- Behavior of fuel rods during a severe accident
- Key parameters controlling fuel degradation and possible improvements
- Candidate materials for accident tolerant fuel (ATF) cladding
- Novel cladding designs based on molybdenum alloys
  - feasibility studies
- SiC channel
- Summary

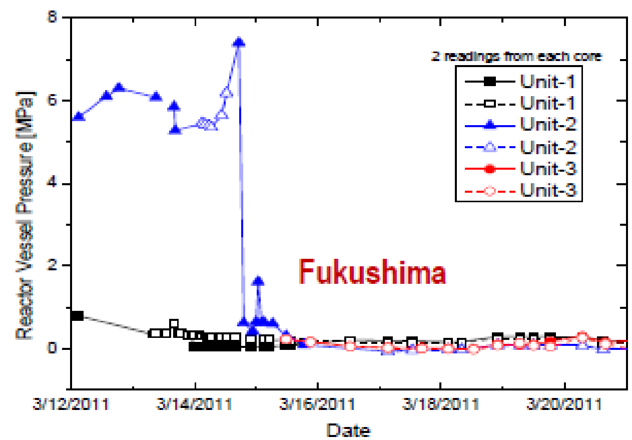
Fuel in Severe Accidents

- **TMI-2 accident in 1979**
  - Fuel failure detected ~2.7 hr after loss of coolant flow
  - 50% core melted in 7 hours
  - Small hydrogen explosion in ~10 hrs, no RPV breach



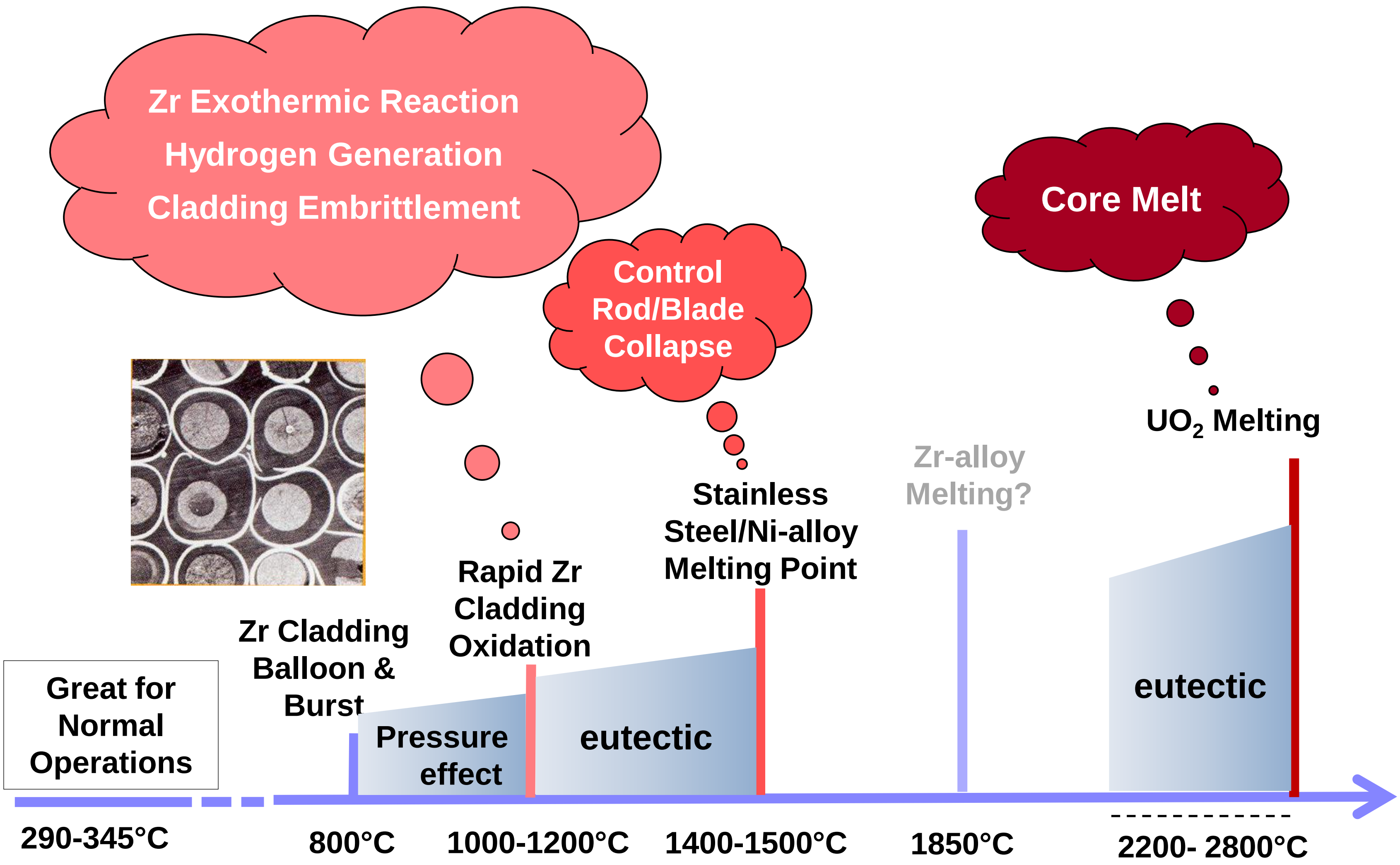
TMI-2 Core End-State Configuration (NRC)

- **Fukushima Daichi Units 1-3 Station Blackout (SBO)**
  - Some passive cooling after tsunami
  - Hydrogen explosion and RPV breach
    - Unit 1 in <1 day
    - Unit 3 in ~2 days
    - Unit 2 in ~3 days



Fuel exposed to high temperature, high pressure steam, leading to rapid oxidation of Zr-alloys and generation of heat and hydrogen

Behavior of Fuel/Core Materials in Severe Accidents
- Zr-alloys, Fe-based, Ni-based Alloys and UO_2



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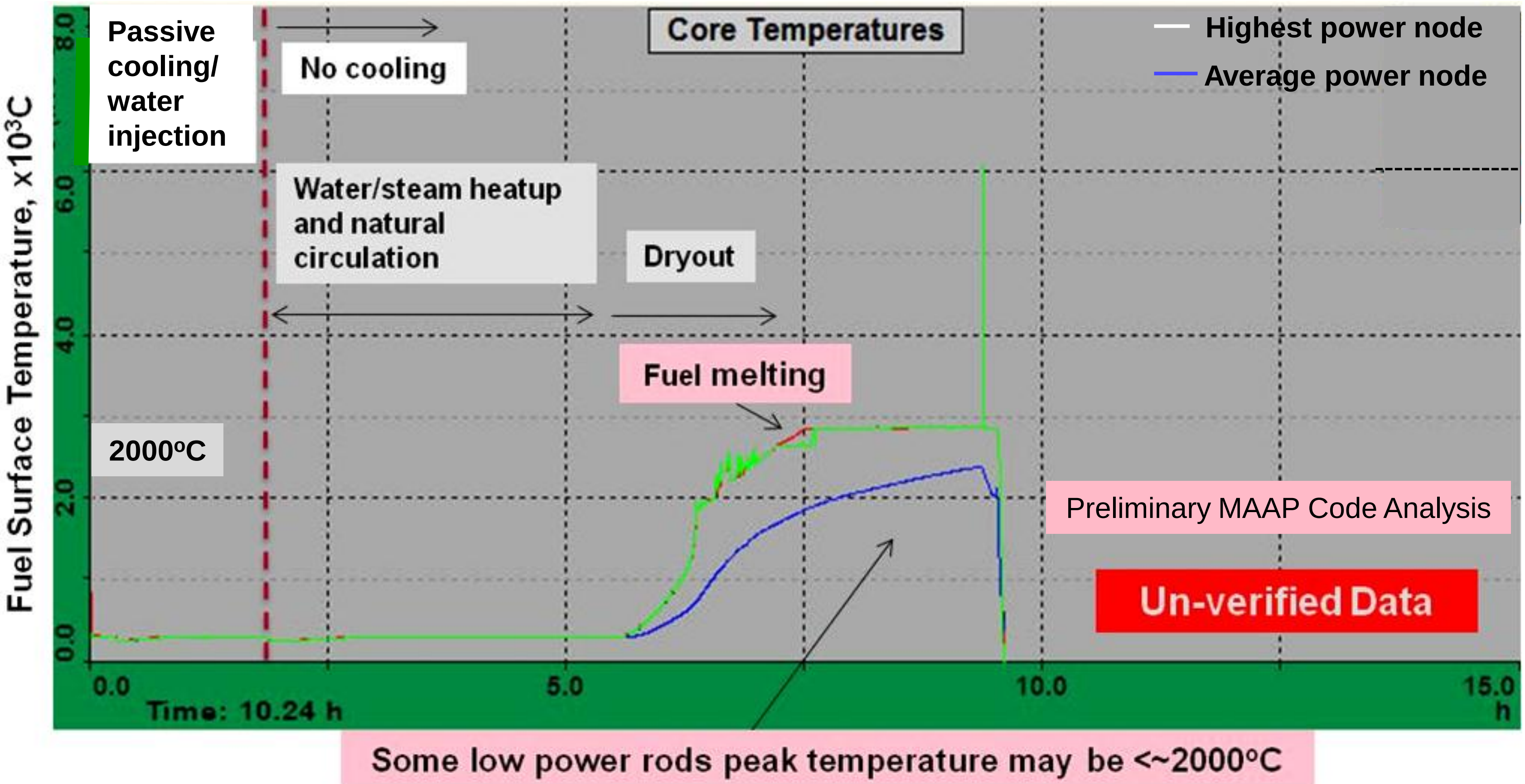
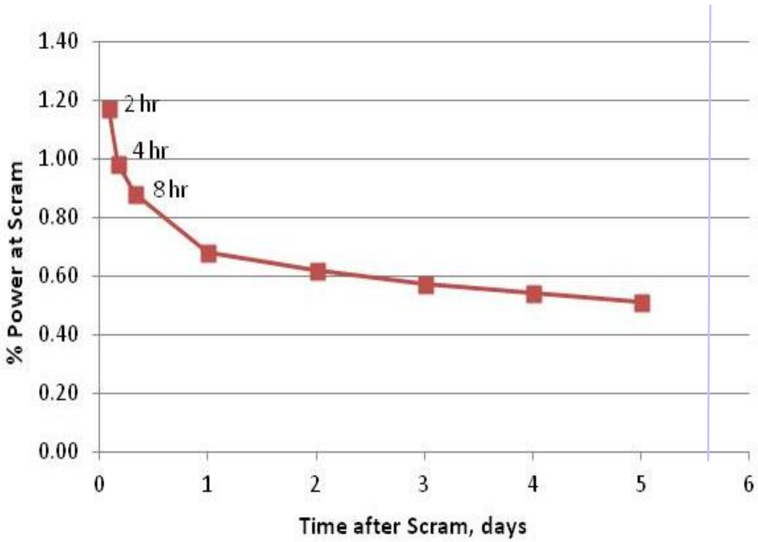
Fuel Cladding Temperature in a Simulated Station Blackout (SBO) Accident – EPRI MAAP Code Analysis



Fuel rod surface "dryout" leads to rapid cladding temperature rises

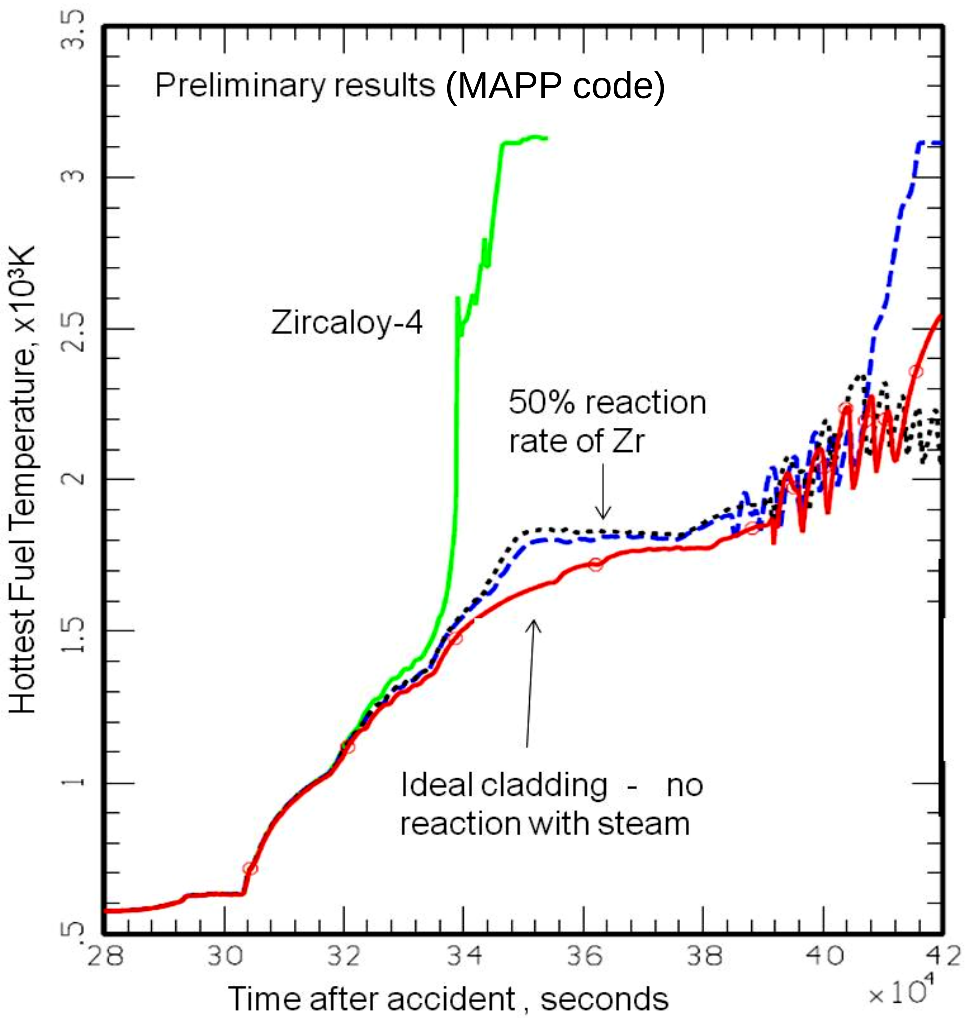
Passive Cooling Capability is Most Important Parameter

- Increasing passive cooling capability from 2 to 24 hrs can
  - decrease decay heat by ~43%
  - Increase time to initiation of fuel melting from ~3 to ~10 hrs (Zircaloy cladding)



Battery-Assisted Passive Cooling, hrs	Decay Heat, %Pre-scram Power	Time to Fuel Melt after Flow Stops, hrs
2	~1.18	~3
24	~0.67	~10
72	~0.58	~ 11

Reducing Cladding Steam Reaction Rate can Delay Fuel/Core Melting



(Assume 72 hr passive cooling)

- All 3 “hypothetical” improved-cladding cases stabilize at ~1500ºC for ~10 hrs longer than Zr cladding
- “Improved cladding” requires material other than Zr-based alloys

Requirements for Accident Tolerant Fuel Cladding

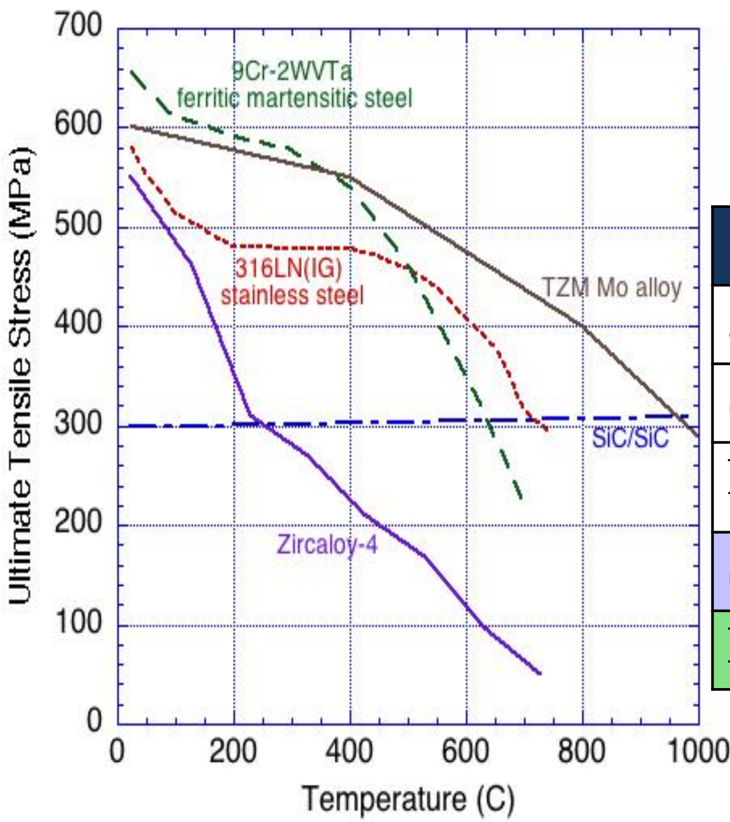
- **Good high temperature properties:**
  - high melting temperature
  - resistance to steam (+hydrogen) corrosion at 1200-1500^{o}C
  - adequate cladding tensile & creep strength at 1200-1500^{o}C
- **Viable economics**
  - acceptable neutronic absorption cross sections
  - material availability at reasonable costs
- **Fabricable into full length cladding tubes**
  - can be hermetically sealed
- **Compatible with current LWR designs and coolants**
- **Good fuel reliability under normal operation**
- **No fuel storage and disposal issues**

Candidate Advanced Cladding Materials:
- Ceramics, Refractory Metals, Fe-based Alloys

Material	Melting Temp (°C)	Thermal Neutron Absorption, barns	Thermal Conductivity, W/m-K	Comments
Zr alloys	~1800	~0.19	22	Weakens at ~750-800°C
Stainless Steels	~1400-1500	~2.6-2.8	16	Fe-B eutectic melting at 1161°C; with Al addition resists steam to 1350°C due to formation of Al_2O_3
Inconel/Ni alloy	~1400	~4.0-4.2		Produce Co-58 isotope
SiC	(2600)*	0.09	20 (composite)	*sublimation; ceramic, brittle
Mo	2623	2.6	138	Vaporize as MoO_3 in oxidizing condition; stable in reducing condition to 2000°C
Nb	2477	1.15	53	Limited supply; hydriding
ZrO_2	2715		2	Stable in steam to 1900°C

Candidate materials limited; SiC, Mo, stainless steel; and naturally forming surface protective coating: Al_2O_3 ZrO_2, SiO_2 and Cr_2O_3

High Temperature Mechanical Properties of ATF Cladding Material Candidates



Tensile properties of ATF cladding candidate materials (after S. Zinkel)

Ultimate Tensile Strength, MPa

Material	300ºC	1000ºC
Zircaloy-4*	270	nil
Stainless Steel 304**	475	<10
Ferritic Martensitic Steel	480	<10
SiC/SiC Composite	300	300
Molybdenum alloys	400-570	200-300

*Phase transition of Zr at ~800ºC

** Phase transition of Fe at ~900ºC

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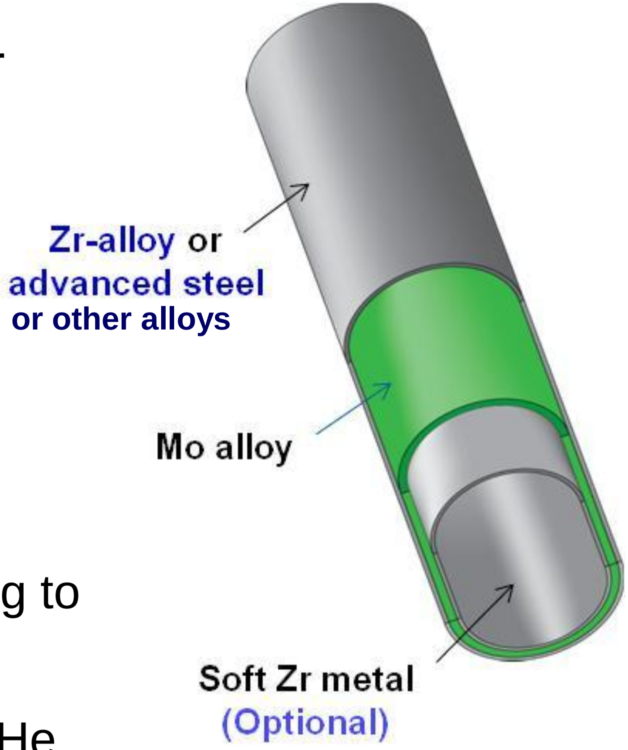
Molybdenum Alloy Cladding Design Concepts

- Utilizing Mo alloys' unique properties:
  - Tensile and creep strength at 1000-1800^{o}C
  - High stability in reducing and inert environments to ~2000^{o}C
  - Fabricability into long, thin wall tubes
  - Can be welded to end caps
- Challenges for LWR fuel applications:
  - Reacts with oxygen/steam; needs improvement/protection
  - Higher neutron absorption cross sections than Zr; cladding wall thickness needs to be reduced (<0.25 mm or 10 mils)
  - Irradiation embrittlement is known and needs further evaluation
  - Industry infrastructure for Mo cladding not well established

Mo-Alloy Based Cladding for LWR Accident Tolerant Fuel Designs

- Thin-wall Mo alloy tube protected by Zr alloy (ZrO_2), or advanced steel (Al_2O_3) on the OD surface (duplex)
- Mo inner surface protected by a soft Zr alloy or others as an option (triplex)
- May achieve
  - Accident tolerance to 1200-1500°C
  - Eliminate design base LOCA issues
- Monolithic Mo alloy cladding?
  - Need focused R&D on alloy development to bring to LWR applications
  - Mo is compatible with GEN-IV reactor coolants: He, liquid metal, or molten salts



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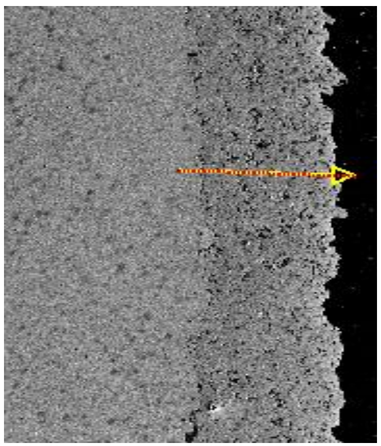
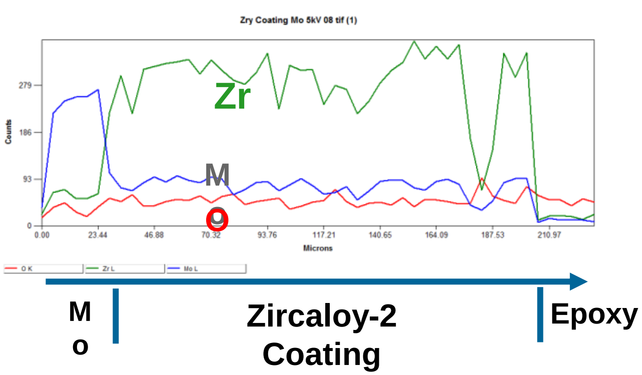
Fabrication of Mo Alloy, Duplex and Triplex Cladding – EPRI Feasibility Studies

- **Making thin wall Mo cladding**
  - 0.37 mm (14.7 mil) wall Mo (M) and Mo+La_2O_3 (ML)
  - 0.20 mm (8 mil) M and ML tubes (2 meter -6 ft tubes)
- **Fabricating duplex and triplex tubes**
  - Coating technologies
    - Plasma spray (air or vacuum), HVOF (high velocity oxi-field), physical vapor deposition (PVD), and CVD
    - Feasibility demonstrated
  - Mechanical forming
    - Co-extrusion/rolling/drawing
    - Plans developed
- **Developing and testing new Mo alloys**
  - Better corrosion resistance, ductility/formability
  - Mo material vendors, UC Berkeley, ORNL…..

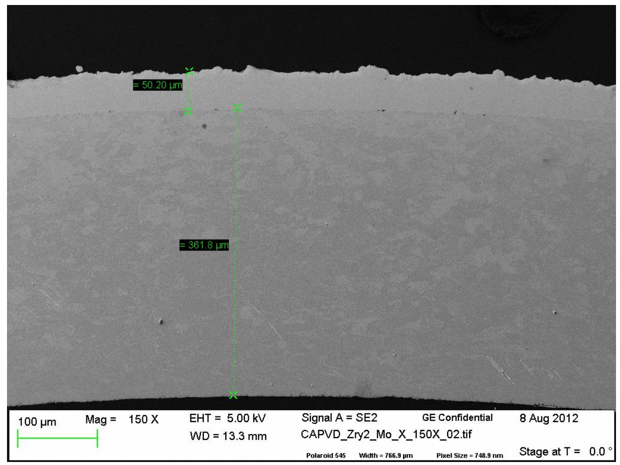
Some Duplex Cladding by Coating Technologies

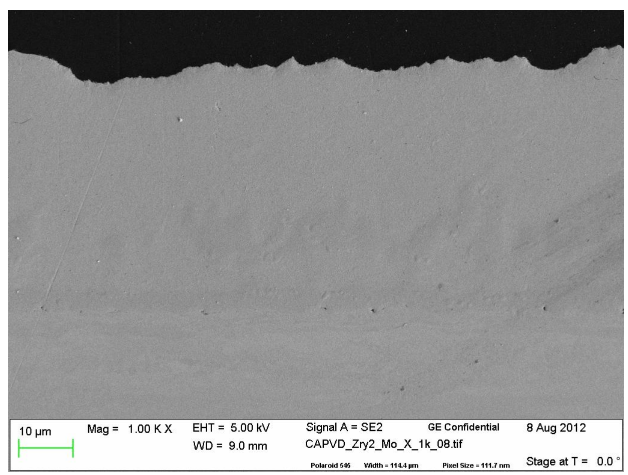
Plasma Spray Coating in Air: Zry-2 on Mo



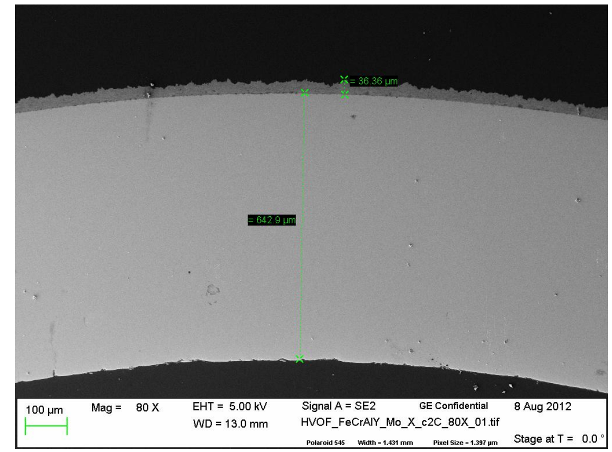


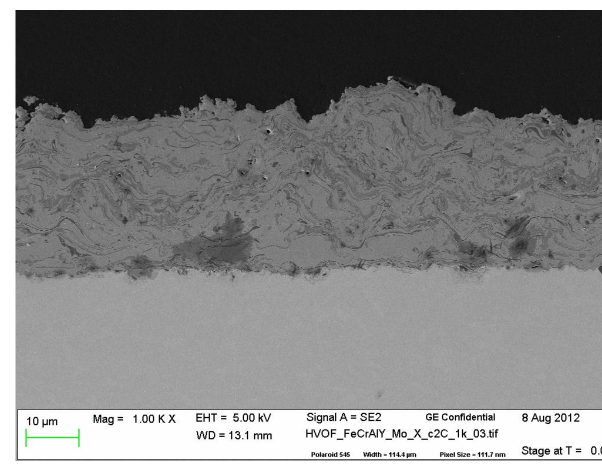
Zry2 Coating by CA-PVD on Mo (GEGRC)





FeCrAlY Coating by HVOF on Mo (GEGRC)





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Testing of ATF Cladding

- **Material properties:**
  - Corrosion resistance at operation temperatures (3 autoclaves)
  - Layer bonding strength, durability and chemical stability
  - Resistance to steam and steam + hydrogen reaction at 1000ºC
  - Microstructures
- **Optimizing fabrication process**
  - Vacuum plasma spray
  - HVOF, PVD, and CVD coating
  - Co-rolling/extrusion
  - Making tubes with new Mo alloys
- **Irradiation**

SiC BWR Channel Application Background

- **Silicon carbide used in multiple applications**
- **Recent years considered for LWR fuel applications**
- **Rationale for BWR channel development**
  - Existing zirconium channels are susceptible to channel bow
  - High temperature steam environment stability desired for accident scenarios (~40% of total Zr loading in BWRs)
  - Much simplified requirements compared to cladding
  - Could provide information for cladding development

EPRI SiC BWR Channel Program

- **Initial feasibility evaluation performed**
  – In-core functional requirements
    - Initial volumetric swelling may be an issue, but limited to few positions
  – Lower neutron capture cross-section, ~$3.1M in fuel savings/reload
  – Impacts tests showed prototype is resistance to fragmentation
- **Irradiation program planned at ORNL and MIT research reactors**
  – Irradiation swelling, creep and corrosion
  – Small scale demonstration
  – Project co-funded by DOE NEET program
- **Characterization of mechanical and thermal properties**
- **Full scale commercial demonstration may be possible around 2019 time frame**

Summary

- Maintaining passive cooling is utmost important for avoiding fuel/core damage in severe accidents
- Safety margins of Zr alloys over ~800^{o}C may be small
- Cladding materials with lower steam reaction rate in combination with higher tensile/creep strength to maintain fuel integrity and coolability may increase tolerance to accidents
  - Candidate cladding materials for LWR is limited
  - Mo-alloy and SiC/SiC composite are being considered; both have attractive features and technical challenges
- A novel ATF design based on Mo-alloys (metallic) is proposed and is under feasibility evaluation
- EPRI effort is intended for industry/laboratory collaboration and eventual implementation

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