Fuel behaviour in the case of severe accidents and potential ATF designs

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This presentation reviews the conditions of fuel rods under severe loss of coolant conditions, approaches that may increase coping time for plant operators to recover, requirements of advanced fuel cladding to increase tolerance in accident conditions, potential candidate alloys for accident-tolerant fuel cladding and a novel design of molybdenum (Mo) -based fuel cladding. The current Zr-alloy fuel cladding will lose all its mechanical strength at 750-800°C, and will react rapidly with high-pressure steam, producing significant hydrogen and exothermic heat at 700-1 000°C. The metallurgical properties of Zr make it unlikely that modifications of the Zr-alloy will improve the behaviour of Zr-alloys at temperatures relevant to severe accidents. The Mo-based fuel cladding is designed to (1) maintain fuel rod integrity, and reduce the release rate of hydrogen and exothermic heat in accident conditions at 1 200-1 500°C. The EPRI research has thus far completed the design concepts, demonstration of feasibility of producing very thin wall (0.2 mm) Mo tubes. The feasibility of depositing a protective coating using various techniques has also been demonstrated. Demonstration of forming composite Mo-based cladding via mechanical reduction has been planned.

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Fuel Behavior in Severe Accidents and Potential Accident Tolerance Fuel Designs

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OECD – NEA Meeting
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EPRI Breakthrough Fuel Technology Program

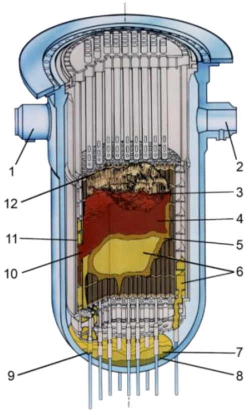
- **EPRI started evaluation of BFT for enhancing fuel reliability, efficiency, and safety in late 2010**
- **Utility executive committee approved two tasks (post- Fukushima)**
  - Accident tolerant fuel cladding
  - SiC channel (led by Ken Yueh)
- **Objectives:**
  - Develop technical needs and basis 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

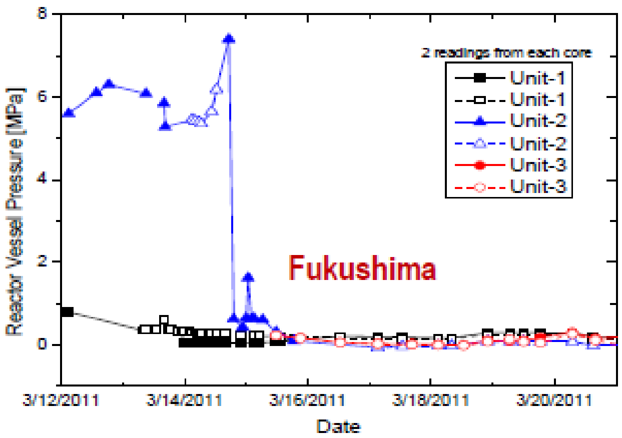
Fuel in Severe Accidents

- **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



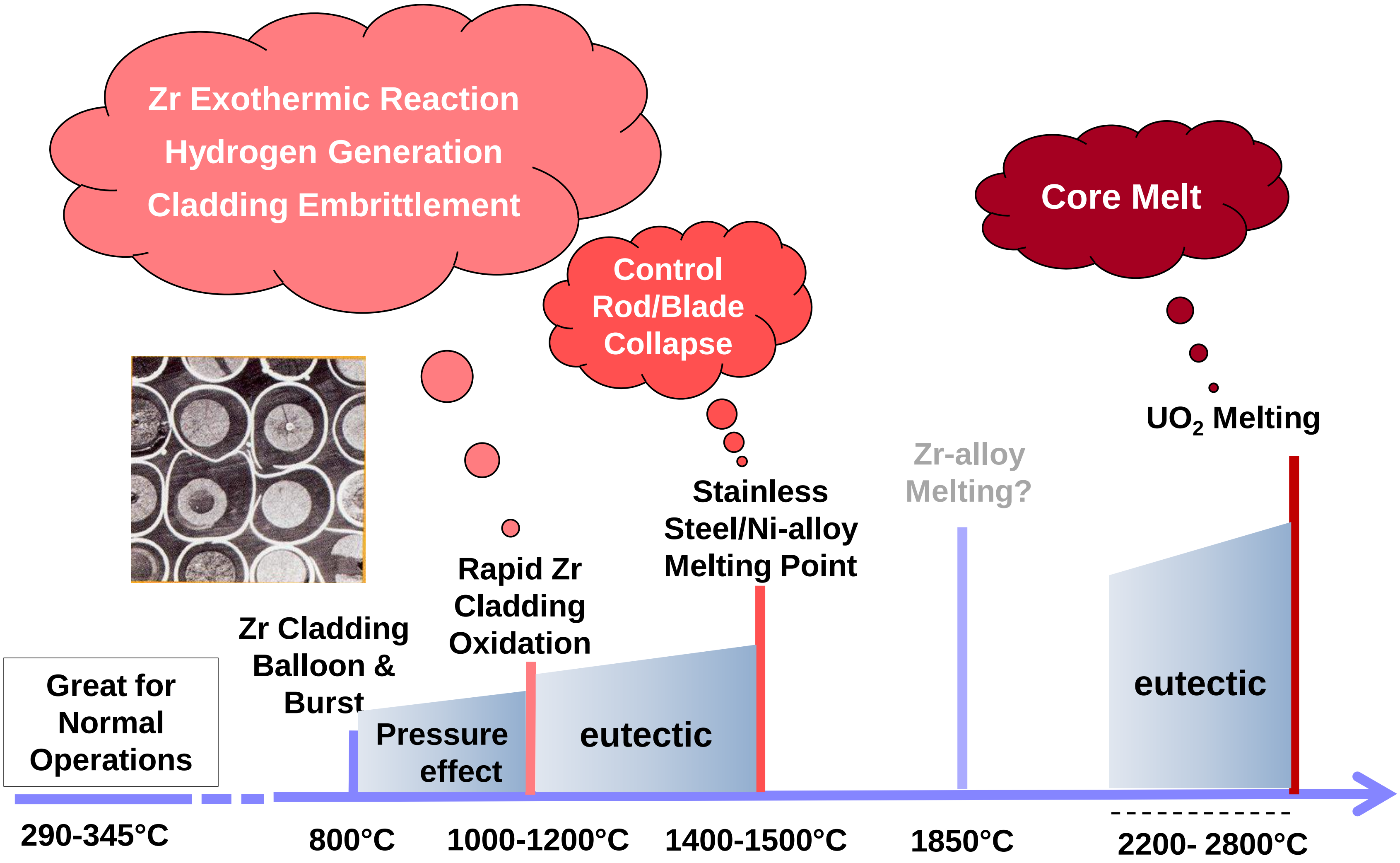
TMI-2 Core End-State Configuration (NRC)

- **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



Zr Exothermic Reaction

Hydrogen Generation

Cladding Embrittlement

Control Rod/Blade Collapse

Core Melt

Great for Normal Operations

Zr Cladding Balloon & Burst

Pressure effect

Rapid Zr Cladding Oxidation

eutectic

Stainless Steel/Ni-alloy Melting Point

Zr-alloy Melting?

UO_2 Melting

eutectic

290-345°C

800°C

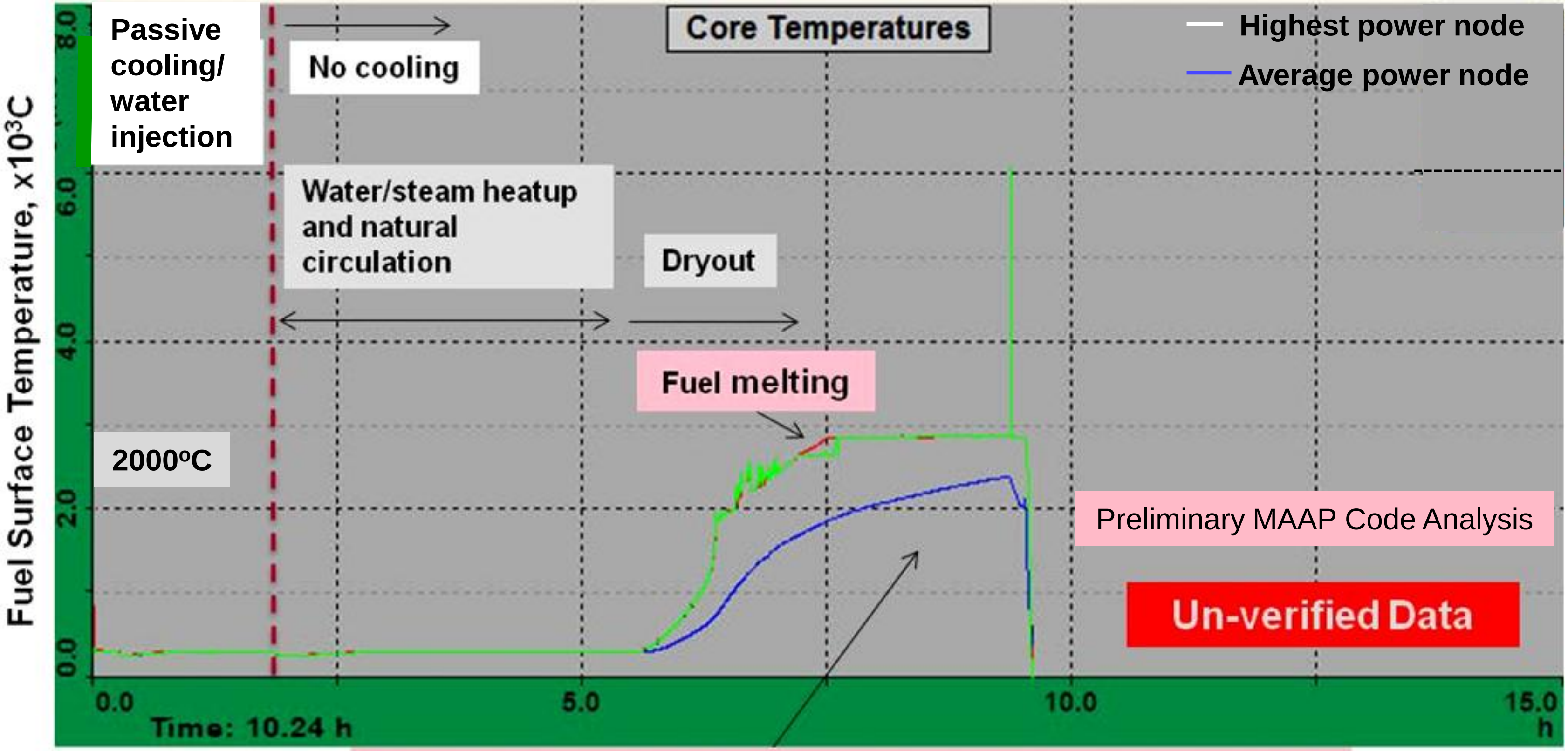
1000-1200°C

1400-1500°C

1850°C

2200- 2800°C

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



Passive cooling/ water injection

No cooling

Water/steam heatup and natural circulation

Dryout

Fuel melting

2000ºC

Preliminary MAAP Code Analysis

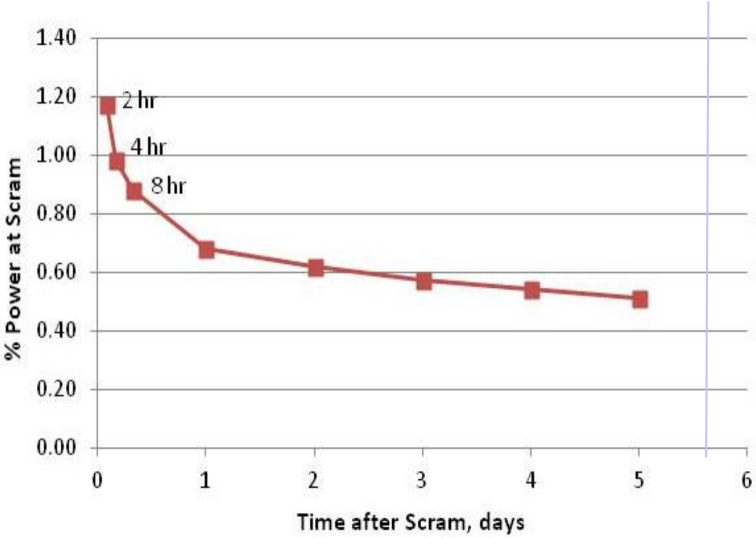
Un-verified Data

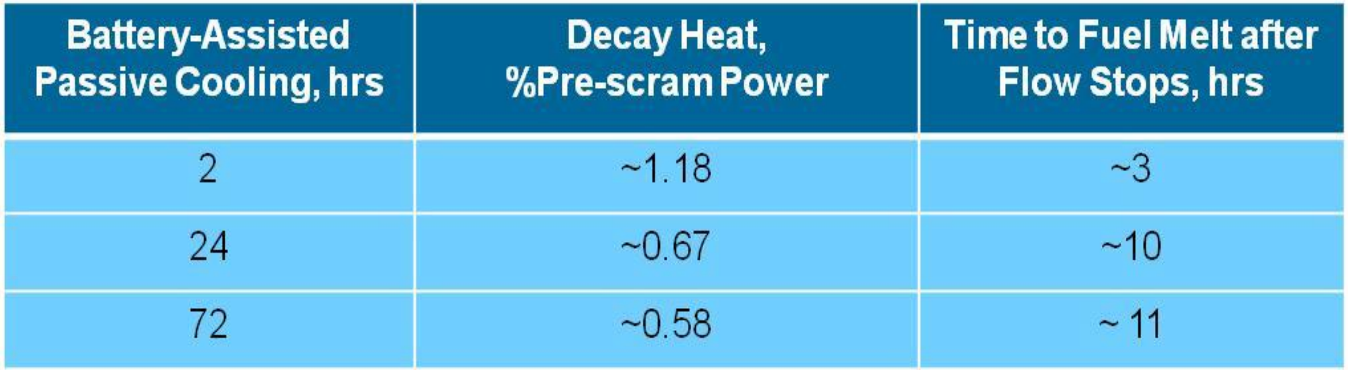
Some low power rods peak temperature may be <~2000ºC

Fuel rod surface “dryout” leads to rapid cladding temperature rises

Passive Cooling Capability is Most Important Parameter

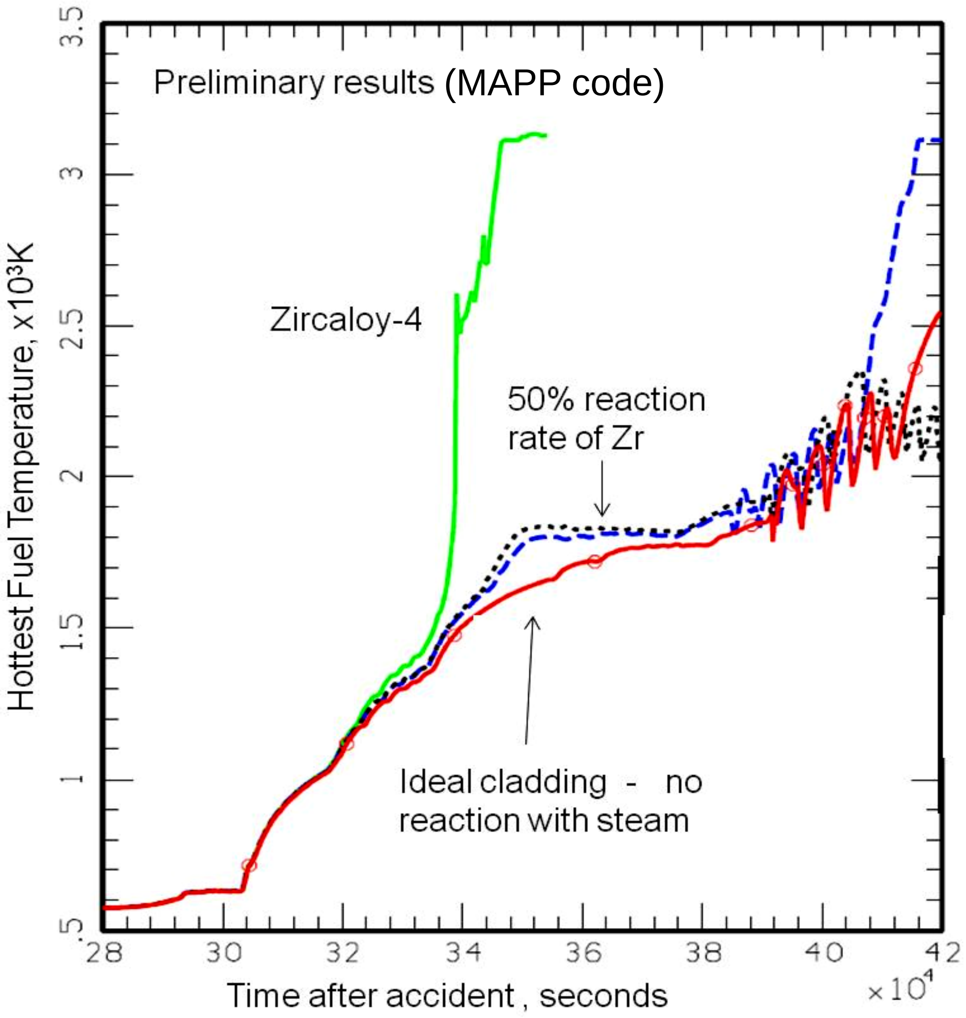
- Increasing passive cooling capability from 2 to 24 hrs can
  - decrease decay heat by ~43%
  - Increase time to initiation of fuel melting from ~3 to ~10 hrs (Zircaloy cladding)





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 ~1500^{o}C for ~10 hrs longer than Zr cladding

- “Improved cladding” requires material other than Zr-based alloys

Requirements for Accident Tolerant Fuel Cladding

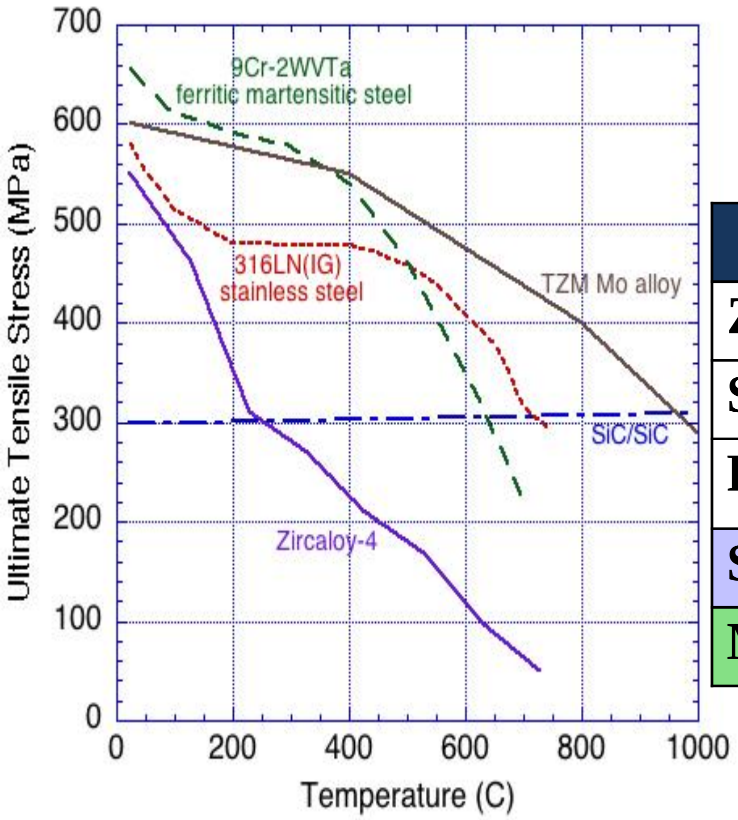
- **Good high temperature properties:**
  - high melting temperature
  - resistance to steam (+hydrogen) corrosion at 1200-1500°C
  - adequate cladding tensile & creep strength at 1200-1500°C
- **Viable economics**
  - acceptable neutronic absorption cross sections
  - material availability at reasonable 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	300^{o}C	1000^{o}C
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 ~800^{o}C

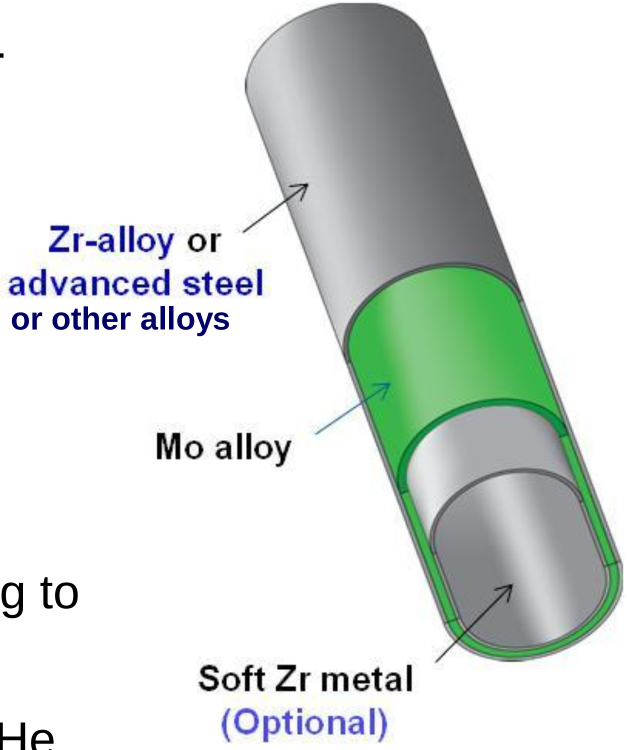
** Phase transition of Fe at ~900^{o}C

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^oC
  - 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

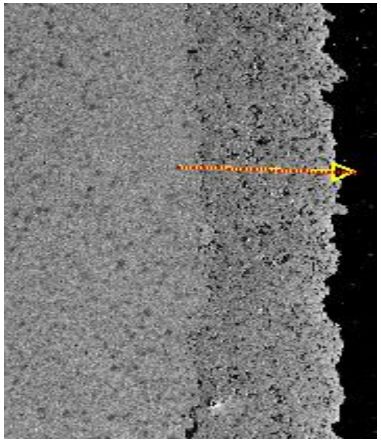


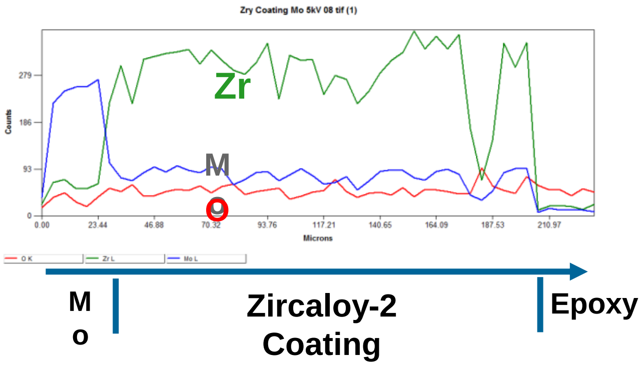
Fabrication of Mo Alloy, Duplex and Triplex Cladding – EPRI Feasibility Studies

- **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…..

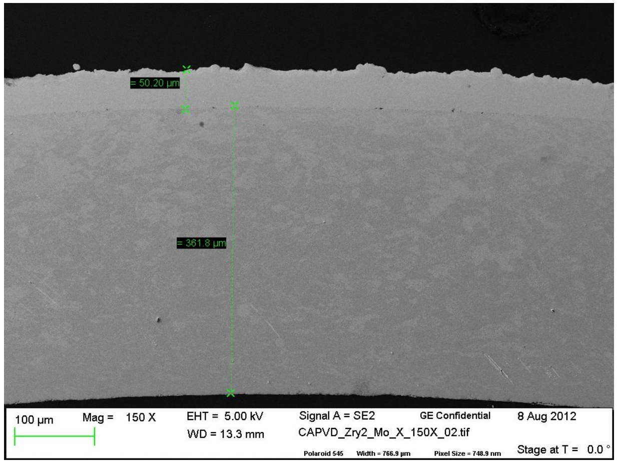
Some Duplex Cladding by Coating Technologies

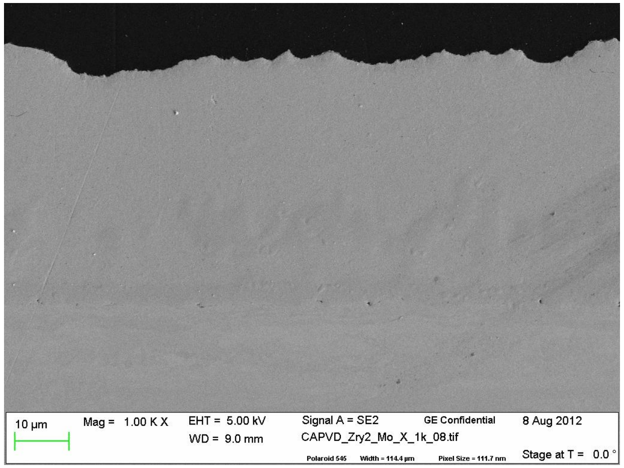
Plasma Spray Coating in Air: Zry-2 on Mo



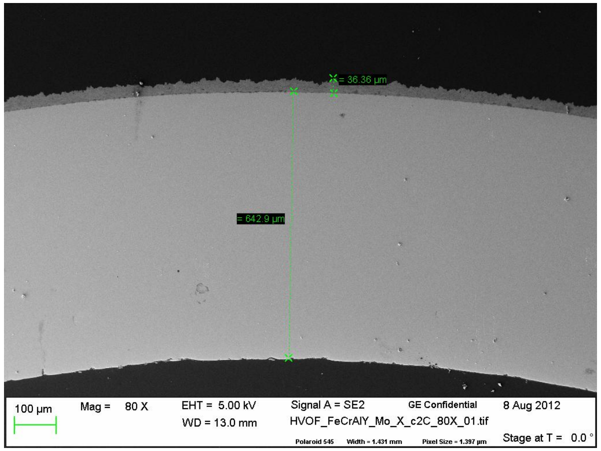


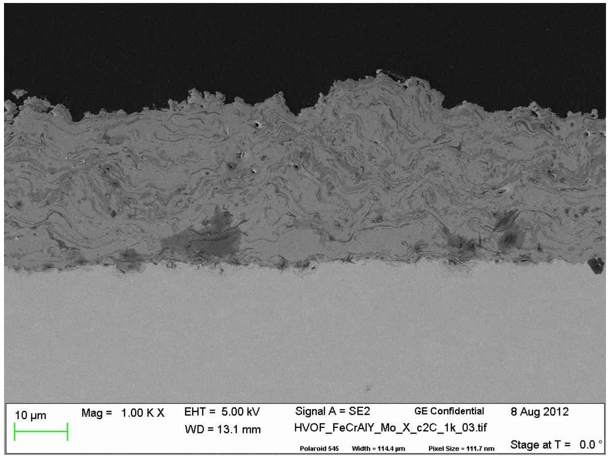
Zry2 Coating by CA-PVD on Mo (GEGRC)





FeCrAlY Coating by HVOF on Mo (GEGRC)





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 1000^{o}C
  - 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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