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Mo-alloys for LWR Fuel Cladding to Enhance Accident Tolerant

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Basic Requirements for Accident Tolerant Fuel Cladding

- **Good fuel reliability under normal operation**
  - Can meet fuel design, operation, and licensing constraints
- **Good high temperature properties at 1200-1500°C:**
  - adequate tensile & creep strength: maintain core coolability
  - resistant to steam oxidation: reduce heat and hydrogen generation
- **Viable economics**
  - acceptable neutronic absorption cross sections
  - material availability at reasonable costs
- **Fabricable into full length cladding tubes**
  - Can be hermetically sealed
- **No fuel storage and disposal issues**

Coated Mo-alloy Cladding Design

- Why Mo alloy?
  - Zr-based alloys lose strength at >800°C
  - Fe based alloys lose strength at >~1000°C (Can extend to ~1200°C with ODS)
  - Mo-alloys may maintain sufficient strength at >1500°C

Melting Temp (°C)	
ZrO_2	2715
Al_2O_3	2072
Steel	~1400-1500
Zr	~1800
Mo	2623

- Why coating?
  - Mo-alloys are susceptible to oxidation by oxygen
  - Need protective coating or advanced Mo alloys
- EPRI design: all metallic cladding
  - Compatible with LWR coolants/UO_2
  - At accident temperatures, Zr-coating completely converts to ZrO_2 and Al-containing steel forms a protective Al_2O_3
  - Target to protect Mo to ~1200-1500°C

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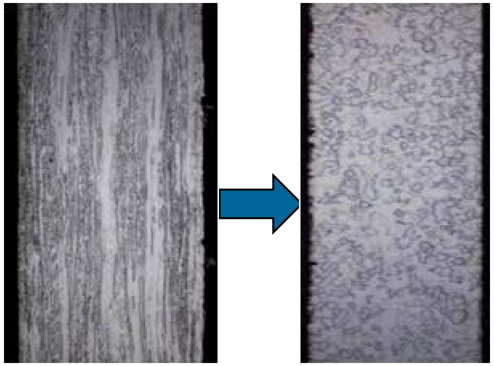
Key Properties	Zr alloy	Mo	FeCrAl
Melting Temperature, °C	~1800°C	2623°C	1400°C
Oxidation resistance - Steam	to 500-1200°C	to 500°C	to 1300°C
Oxidation resistance - Reducing gas	hydriding	to 2000°C	?
Tensile and Creep Strength	Nil at >800°C	to >1500°C	
Material cost	Average	Average	
Neutronic absorption	Low	Higher (Mo-95 depleted Mo ~same as Zr)	~Mo
Fabricability into long tube	Good	OK	OK
Hemetically sealed/welded	Good	Possibel for some alloys	
Compatible with coolant (corrosion	Good	Need protection with Zr-alloy or FeCrAl	
Thermal-mechanical compatibility (Power ramp, RIA, Swelling)	Good	Appears OK	
Wear resistance	Adequate	Very High	Very High
Irradiation embrittlement	Adequate	Relatively lower than Zr	?
Radioactive waste issue	No	No	

Mo-alloy for LWR Fuel Cladding - Background

- Mo is reported to be:
  - Brittle and hard to form
  - Susceptible to oxidation by oxygen and steam at >~600^{o}C
  - Compatible with most salts and liquid metals
- Mo alloy cladding
  - No prior use of thin-wall Mo tubes - fabrication is challenging
    - Some high strength Mo-alloys exists
      - Mo-50%Rh, TZM Mo, ODS MO (+La_2O_3)
  - Some prior irradiation data from Bettis/ORNL study for a DOE funded Space Reactor Program
- Coating on Mo alloy
  - No prior work
  - Can import technologies developed for jet and rocket engines

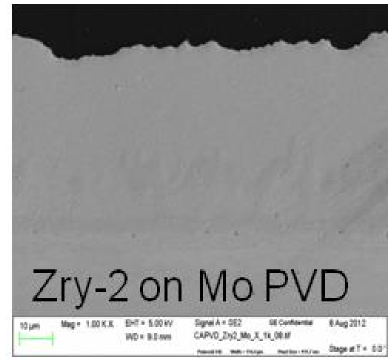
Project Status: Mo Tubes

- Fabricated 8 mil (0.2 mm) tubes of pure Mo and Mo+La_2O_3 (ML) (Generation 1 tubes)
  - For coating, testing, and welding
  - Microstructure with highly deformed grains in longitudinal direction
- Fabricating Generation 2 tubes with fine equi-axial grain structure (Generation 2)
  - Should have adequate properties with ML alloy for irradiation
- Evaluating new Mo alloys for improved corrosion, oxidation resistance and ductility (Generation 3)

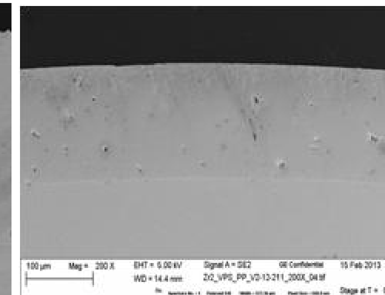


Project Status: Coatings

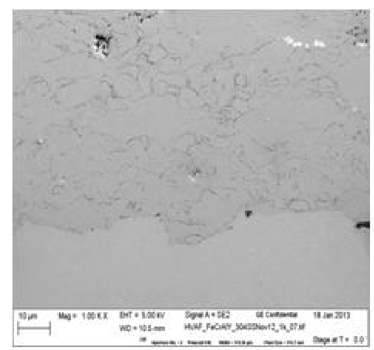
- Coatings successfully formed on Mo tubes and sheets
  - Physical vapor deposition (**PVD)** and Vacuum plasma spray (**VPS**) for Zr-alloy
  - **VPS, PVD** and **HVAF** (high velocity air fuel) for Al-containing stainless steel
- Process parameters optimized
  - Good bonding of coating on Mo
  - Good coating density
  - Good interface structure



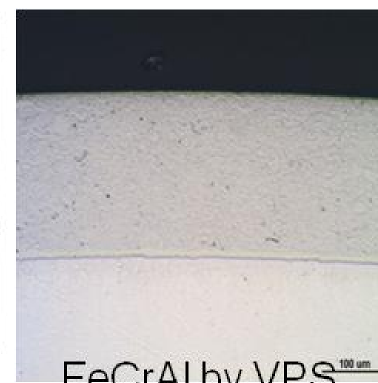
Zry-2 on Mo PVD



Zr-2 on Mo VPS



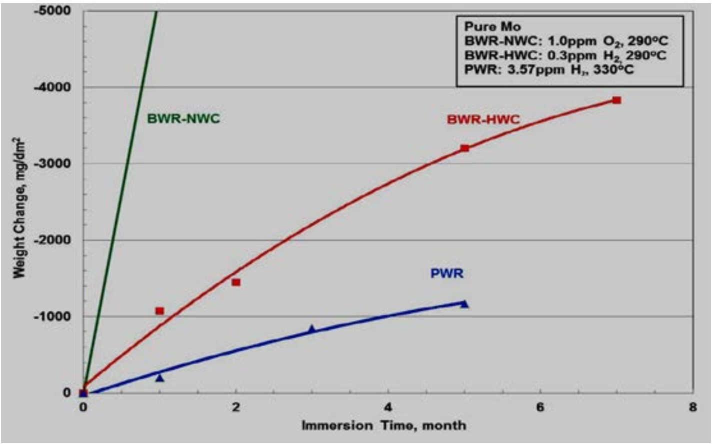
FeCrAl by HVAF

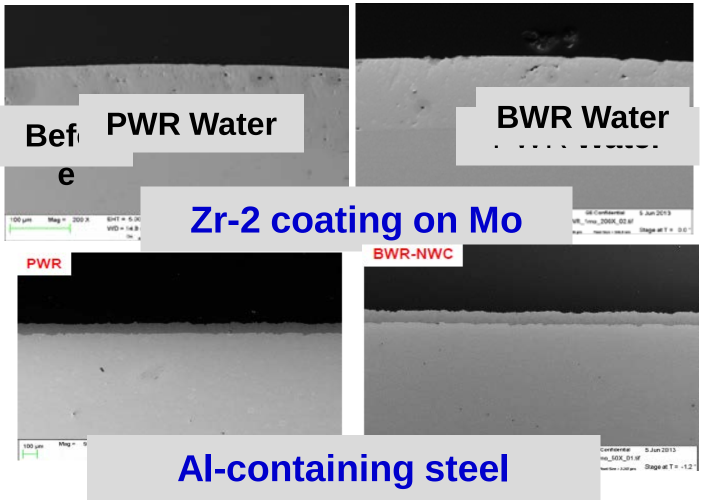


FeCrAl by VPS

Proof of Concepts
- Corrosion under Normal Operation

- Corrosion resistance under normal operation
  - Tests in autoclaves simulating PWR and BWR operation conditions
  - Both coatings have low corrosion and are intact after 30 days
  - Tests continue
- Corrosion of bare Mo
  - PWR water (3 ppm H_2) ~1 µm/mo (rate of dissolution)
  - BWR-HWC water: (0.3 ppm O_2) ~5 µm/mo
  - BWR-NWC (1 ppm O_2): ~50 µm/mo



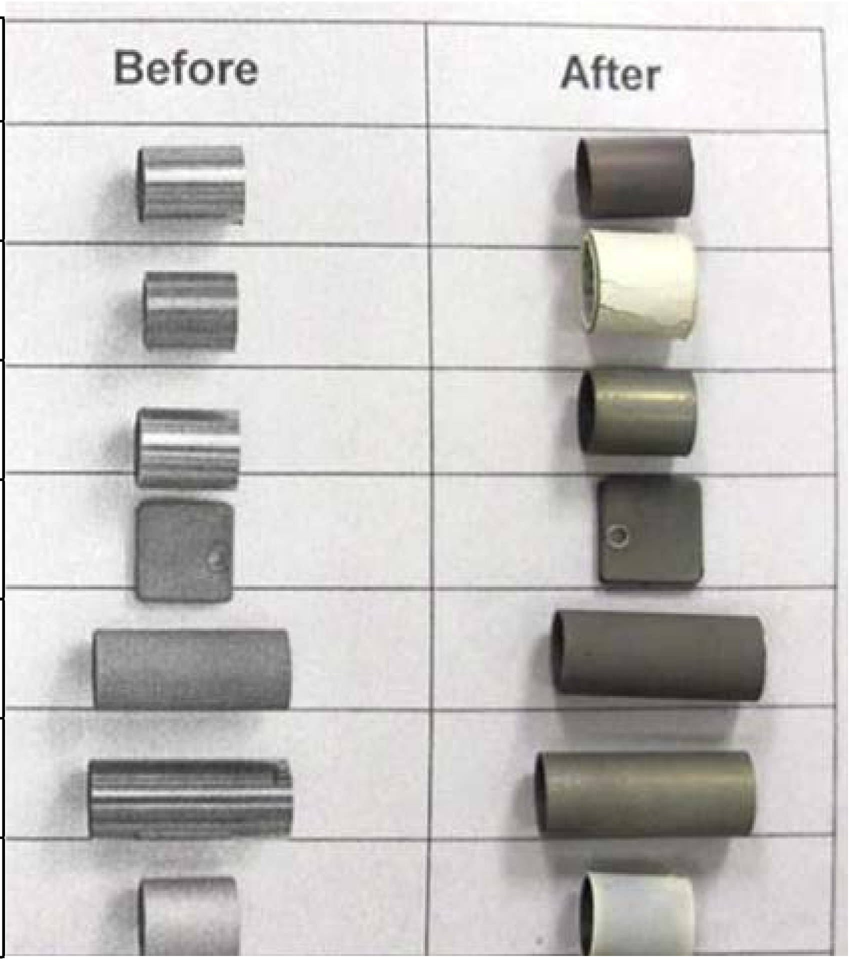


Proof of Concept:
- Resistance to Steam Oxidation at 1000-1500°C

- Test performed at:
  - UC Berkeley
  - GE-GRC
  - ORNL (pending negotiation)?
- Test conditions:
  - Temperature: 1000-1500°C
(Only ORNL can test at >1200°C)
  - Pressure: atmospheric (15 psi) to ~400 psi
  - Duration: up to 7 days

Flowing Steam Test: 1000^{o}C for 24 hours
- 6, 8, 24 hour tests completed; 3 and 7 days planned

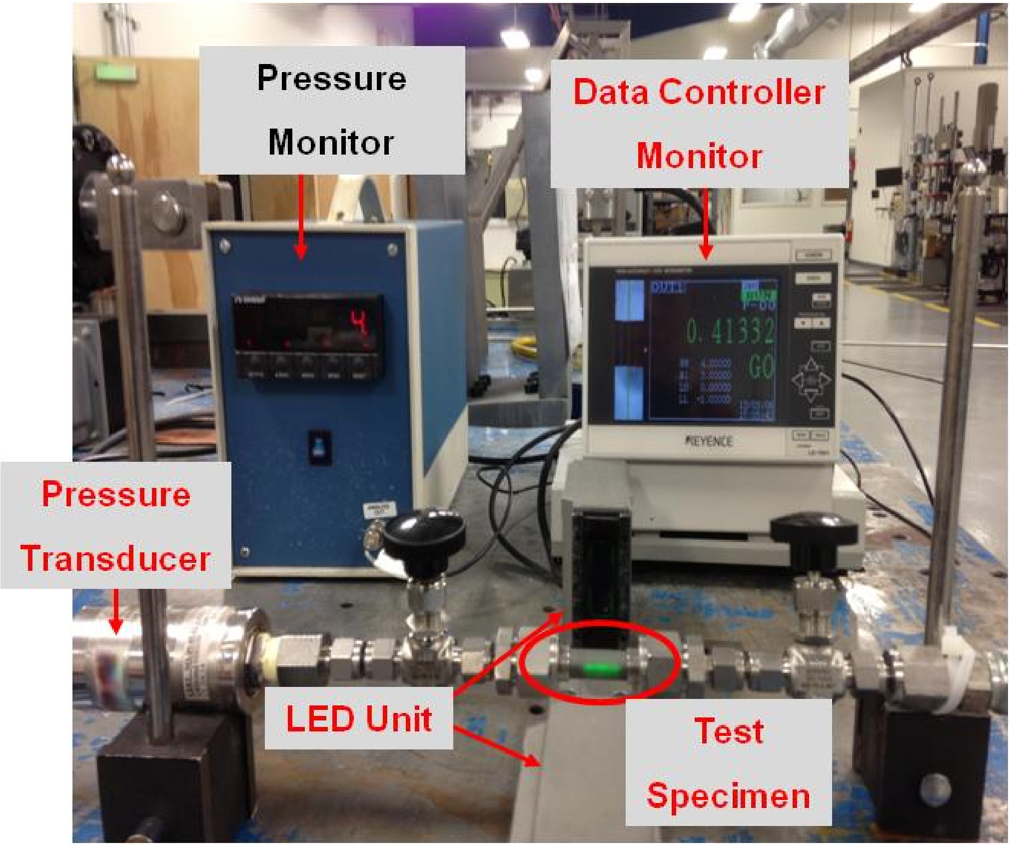
Specimen
Mo tube (8 mil)
Zry-2 tube (26 mil)
Al containing steel (FeCrAl) (16 mil)
FrCrAl coated on Mo sheet (40 mil)
FeCrAl (2 mil) coated on Mo tube
FeCrAl coated on Mo tube - polished
Zry-2 (1.5 mil) coated on Mo tube

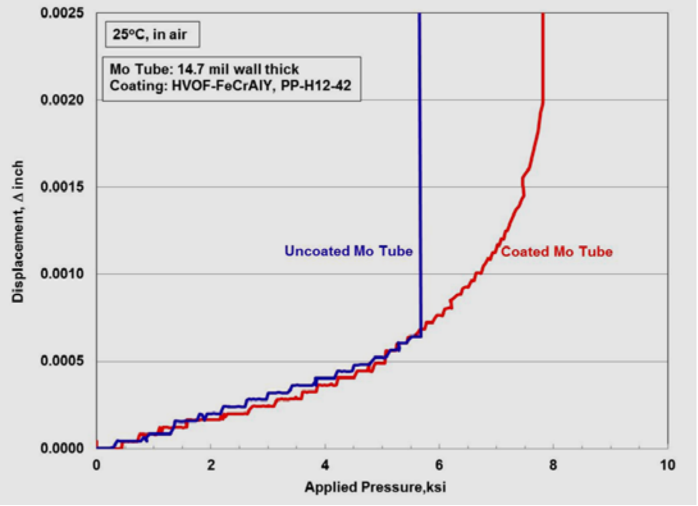


Pleasantly surprising results: Mo is resistance to oxidation in steam

Proof of Concept: Tube Burst Test
- Tube diametral strength/ductility and coating stability

Burst Test-LED System





(Test planned for 4Q13 or 1Q14)

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Additional Tasks

- Welding of Mo tubes (in progress)
- Mo tubes
  - Optimize tube fabrication procedure to improve diametral strength/ductility (Generation 2 tubes) (in progress)
  - Develop advanced Mo alloys for testing (started) (Generation 3 tubes)
- Coating
  - Making long coated tubes (in planning)
  - Mechanical co-reduction of coated tubes (in planning)
    - Economics and quality need for large scale production

Key Milestones

- Complete steam oxidation tests Date: 4Q 2013
- Interim Feasibility Report: Corrosion and Oxidation Resistance and Bonding Strength of Coated Mo Tubes in Simulated Normal Operation and Accident Conditions (1100-1200^{o}C).
  Date 1st Q 2014
- Coated Mo Tubes with Fine Grain Microstructure (Generation 2).
  Date: 1st Q 2014
- Delivery of Coated Generation 2 Mo Tubes with Qualified Welding Procedure for Irradiation Tests. Dates: March 2014+ for ATR and Later for BOR60 and Halden
- Irradiation Property Report Date: 4th Q 2016
- Final Feasibility Report Date: 1st Q 2017
- In-plant demonstration (segmented rods)? Date: 4Q 2020

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