EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Molybdenum-Alloy Fuel Cladding Development and Testing

Update from April 2014 NEA ATF Meeting

Andrew Sowder (presenting for Bo Cheng)

2nd OECD/NEA EGATFL Meeting

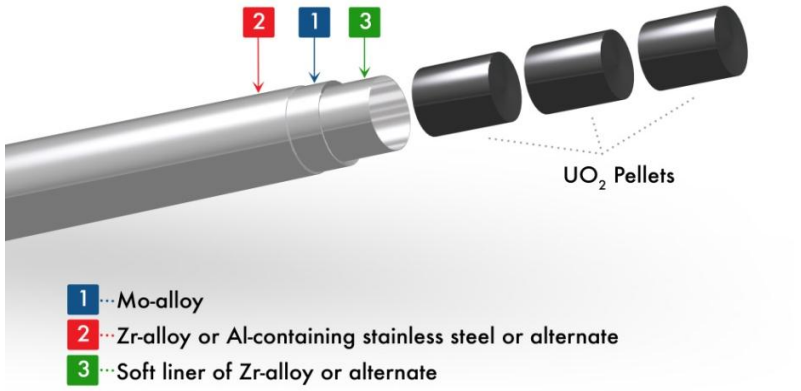
Task Force 2 – Cladding & Core Materials

NEA Headquarters; Paris, France

September 24, 2014

Coated Mo-alloy Cladding Concept

- All metal cladding
  - Mo-alloy as core material
  - Coating on outer surface
    - Zr-alloy or
    - Al, Cr-containing stainless steel
  - Optional inner coating: Zr or Nb



- Anticipated/desired coating properties
  - Under normal operations
    - Zr-alloy or (Cr, Al)-containing stainless steel are compatible with coolants
  - In accidents at >1000ºC
    - Zr completely forms protective ZrO_2 in <10 min at >1000ºC
    - FeCrAl forms thin protective Al_2O_3
    - Rod integrity maintained

© 2014 Electric Power Research Institute, Inc. All rights reserved.

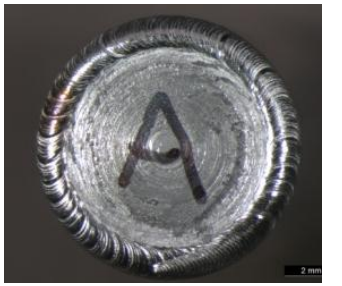
Scope of Feasibility Study

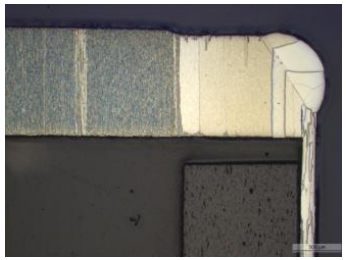
- Fabricability of thin-wall tubes: 0.2-0.25 mm (8-10 mil)
  - Process and property optimization
- Reliable coating of Zr-alloy or FeCrAl
- Characterizations of key properties
  - Corrosion resistance in LWR coolants
  - Oxidation resistance at 1000-1500^{o}C
  - Welding
  - Coating chemical/mechanical stability (inter-diffusion)
  - Mechanical and burst/creep properties
- Irradiation effects
  - Coolant compatibility and embrittlement
- Analysis:
  - Neutronic property (MCNC/Lattice Codes)
  - Thermal-mechanical behavior (FALCON)
  - Accident tolerance (MAAP/MELCOR)

© 2014 Electric Power Research Institute, Inc. All rights reserved.

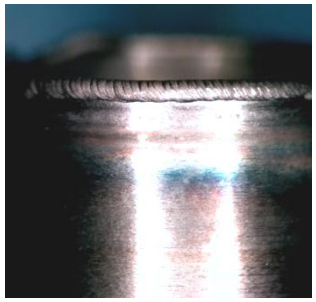
Demonstration of Tube to Plug Welding

Plasma Welding

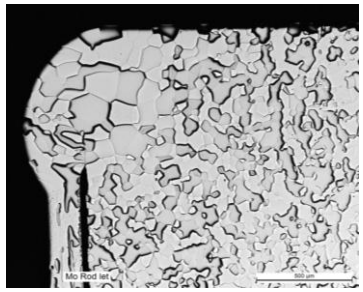




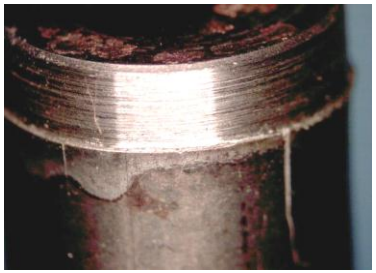
TIG (GTAW) (EWI)

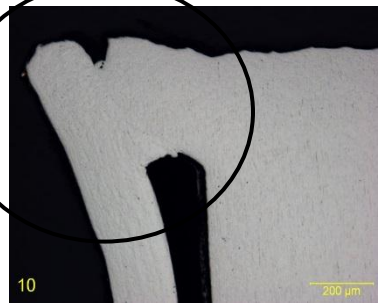


Electron Beam Welding (ORNL) ATR Rodlets



Resistance Projection Welding (Solid State)





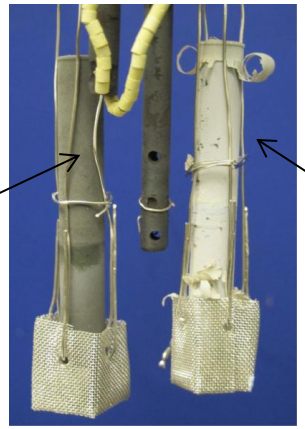
Will develop with Areva on resistance projection Welding

© 2014 Electric Power Research Institute, Inc. All rights reserved.

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Oxidation of Sealed Tubes at 1000ºC for 3 Days

Steam, Steam + 10% Oxygen, Steam +10% Hydrogen

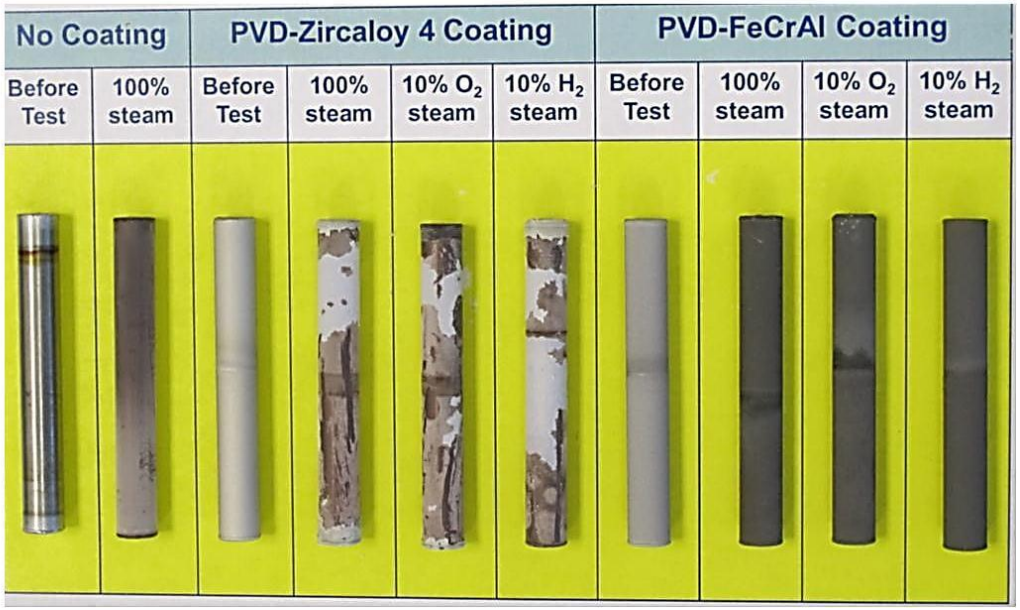


~8 cm long sealed tubes

FeCrAl Coated

Zr-4 coated

Testing conducted at GE/GRC



- Results are consistent with previous tests on open tube samples
- Flaking of ZrO_2 coating needs improvement

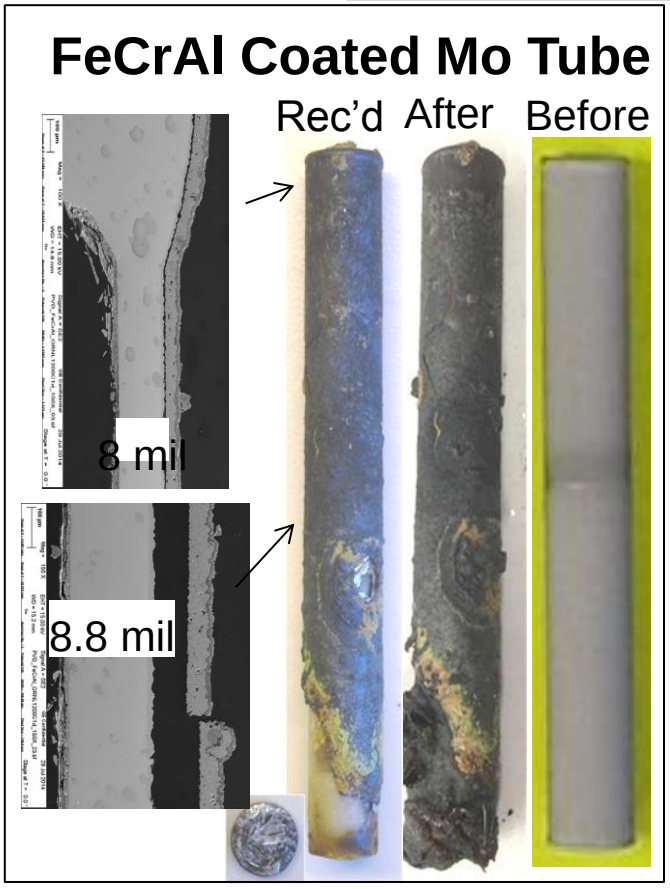
© 2014 Electric Power Research Institute, Inc. All rights reserved.

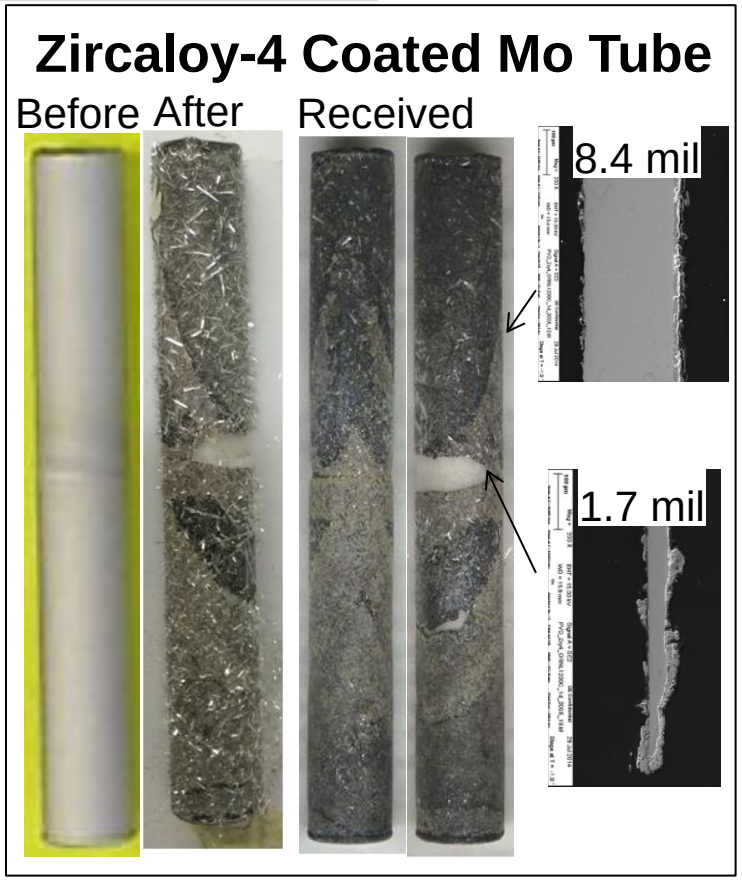
EPRI ELECTRIC POWER RESEARCH INSTITUTE

Oxidation of Sealed Tubes at 1200°C for 24 hrs

Steam + O_2

Testing conducted at ONRL courtesy of Kurt Terrani and DOE-FCRD funding





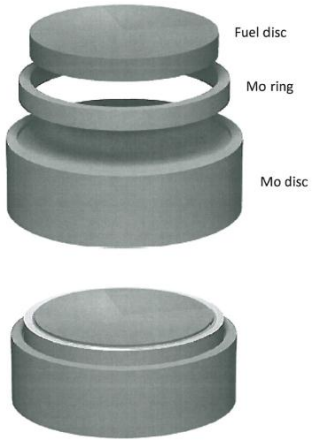
Cause of localized oxidation under evaluation

© 2014 Electric Power Research Institute, Inc. All rights reserved.

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Irradiation of Mo-alloy Cladding

- Participation in DOE funded ATR-1 irradiation
  - 4 rodlets (~8 cm long with 4% enriched UO_2) in inert He gas
  - Irradiation starts in February 2015
- Participation in possible future irradiations
  - Halden Program based funded irradiation starting in 2016
  - INL ATR-2 in PWR water loop in 2016
  - Others
- Compatibility of Mo with UO_2 Pellets
  - PIE of coupled Mo-UO_2 discs irradiated at 500-400^{o}C in Halden Reactor to 112 GWd/MTU



Data Needed for Consideration of Potential Segmented Rod Irradiation in LWRs

© 2014 Electric Power Research Institute, Inc. All rights reserved.

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Challenges Ahead

- Process optimization for Mo and Mo-ODS (Generation-3 tubes)
  - Fine equiaxed grain structure with uniform properties
- Mechanical co-reduction of outer layers
  - New Zr-alloy to optimize corrosion resistance and avoid flaking of ZrO_2 in elevated steam
- Steam oxidation tests at ≥1200°C (to ~1500°C)
- Solid state welding via resistance projection process
- Irradiation tests for irradiation embrittlement
- Pursue new Mo alloys:
  - Corrosion and oxidation improvements of Mo through alloying: Mo-Nb and Mo-Cr systems

© 2014 Electric Power Research Institute, Inc. All rights reserved.

Research Team

Major contributors (outside of EPRI)

- Young Kim + +, GE-GRC: coating, testing, evaluation
- Todd Leonhardt, Rhenium Alloy Co.: tube fabrication
- Ross Luther, PMT (now Thermocore Materials Technology), new Mo alloys
- Sam Armijo, consultant/Advisor

Analysis:

- RT Chiang: Neutronics
- Frank Rahn, MAAP accident analysis (+Fauske)
- Joe Rashid: Fuel rod thermal-mechanical behavior analysis

Collaborators

- Kurt Terrani/Richard Howard, Oak Ridge National Laboratory: 1200^{o}C steam test, ATR rodlet welding
- Stuard Maloy, Los Alamos National Laboratory: nano-grain size Mo alloy support
- Kristine Barratt, INL – ATR test manager
- Peter Hosemann, U.C. Berkeley
- Areva (and GNF): fuel pellets for ATR irradiation rodlets
- Peter Ring: Mo alloy heat treatment
- Brian Cockeram, Bettis Laboratory
- Plasma Process Co: plasma coating
- Wah Chang: Zr-alloy supply
- Heany Corp: HVAF coating
- EWI: Welding

EPRI Utility Advisory Committee

© 2014 Electric Power Research Institute, Inc. All rights reserved.

Together…Shaping the Future of Electricity

© 2014 Electric Power Research Institute, Inc. All rights reserved.