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EPRI Update Since the 2nd OECD/NEA Meeting on ATF (28-29 October 2013)

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OECD/NEA Start-Up Meeting Of The Expert Group On Accident Tolerant Fuels for Light Water Reactors

28 April 2014

EPRI Supporting Two ATF-Related Activities

- EPRI Breakthrough Fuel Technology Program focusing on two accident tolerant fuel applications (pre-Fukushima initiation):
  - Coated Mo-alloy cladding
  - SiC composite for BWR fuel channels
  - EPRI/INL/DOE Joint Workshops
- Promoting international collaboration to accelerate path from early R&D to commercialization of enhanced accident tolerant fuel technologies (post-Fukushima initiation)

EPRI Breakthrough Fuel Technology Program Update

Coated Mo-alloy Cladding Technology
(Lead: Bo Cheng)

Application of SiC Composites for BWR Fuel Channels
(Lead: Ken Yueh)

EPRI Breakthrough Fuel Technology Program

- EPRI initiated ATF R&D program to supplement DOE FCRD program
- Breakthrough fuel program focused on two technologies:
  - Mo-alloy cladding
  - SiC composite BWR channels
- Funding sources:
  - EPRI Fuel Reliability Program (FRP)
  - EPRI Technology Innovation (TI) Program
  - DOE NEET funding
  - DOE FCRD funded collaboration at national laboratories

Fabricated Thin-Walled Mo Tubes

SiC Composite Channel
10 cm box, 1.5 mm wall
CVD Process

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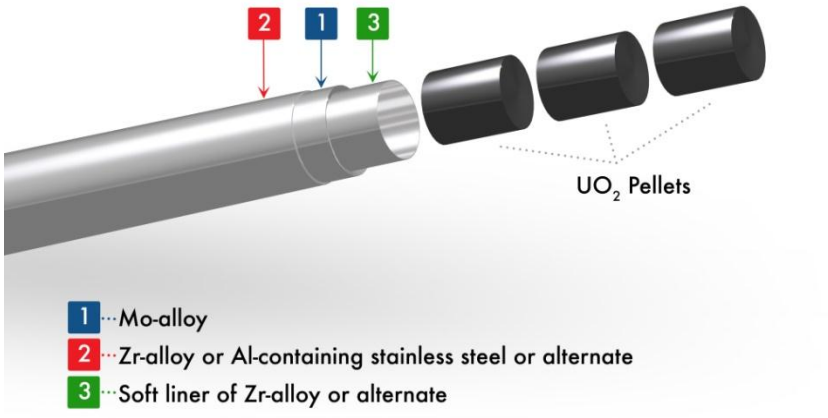
EPRI Coated Mo-alloy Cladding Designs

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



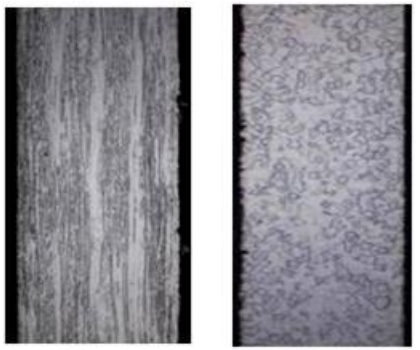
- Advantage
  - High strength of Mo-alloys to 1500°C
  - High steam oxidation resistance
    - In-situ formation of stable ZrO_2 or Al_2O_3 in high temperature steam at >1000°C
  - Under normal operations, expected to have high corrosion resistance of Zr-alloy or (Cr, Al)-containing stainless steel

Feasibility Study of Coated Mo-alloy Cladding

- Fabricability of 8-10 mil (0.2-0.25 mm) thin-wall tubes
- Reliable coating of Zr-alloy or (FeCrAl) on Mo tubes
- Verify basic properties
  - Corrosion resistance in LWR coolant
  - Oxidation resistance
  - Welding
  - Burst/creep properties
  - Coating chemical stability
  - Irradiation properties
- Advanced Mo-alloy: better ductility, corrosion/oxidation resistance
- Manufacturing optimization – mechanically formed tubes

Fabrication of Thin-Wall Mo-alloy Cladding – feasible

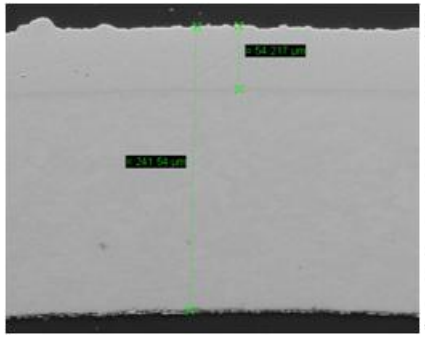
- Pure LCAC Mo and Mo+La_2O_3 (ML) ODS selected
  - Ductile at room temperature (DBTT < room temperature)
  - Have residual ductility after irradiation
- Tubes fabricated: 8 mil (0.2 mm) thick and 6 ft long
  - Generation 1 tubes (no microstructure control)
    - For coating, corrosion/oxidation testing, and welding
  - Generation 2 tubes (stress relief annealed)
    - 3 batches fabricated
    - UTS ~65 mpa (95 ksi), elongation 6-11% at 300°C
    - For ATR irradiation
  - Generation 3 tube (fine equi-axed grain structure)
    - Under development



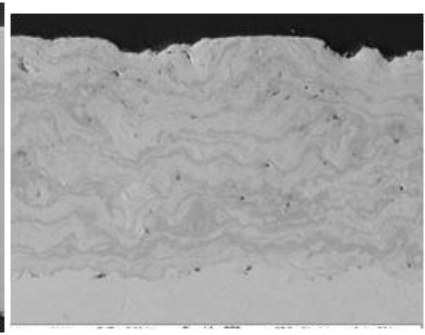
Coating on Mo-alloy Tubes - feasible

- Coatings successfully formed on Mo tubes and sheets
  - Physical vapor deposition (PVD)
  - High velocity air fuel (HVAF) spray
  - Vacuum plasma spray (VPS)
- Process parameters optimized
  - Good bonding
  - Good coating density
  - Good interface structure
- Length of coated samples
  - 8-10” tubes
  - 36” length possible now

Zircaloy-2 on Mo

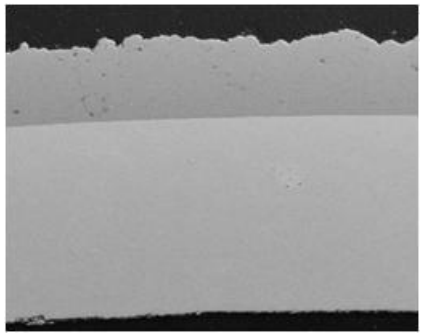


PVD

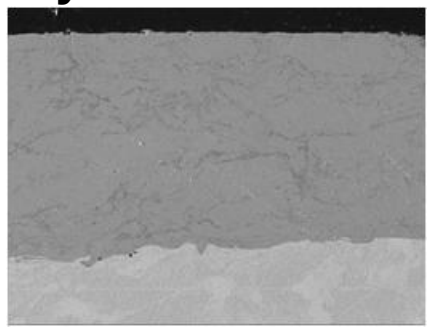


HVAF

FeCrAl alloy on Mo



PVD

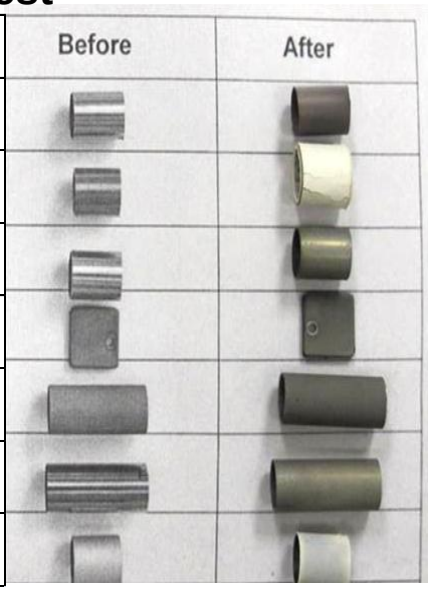


HVAF

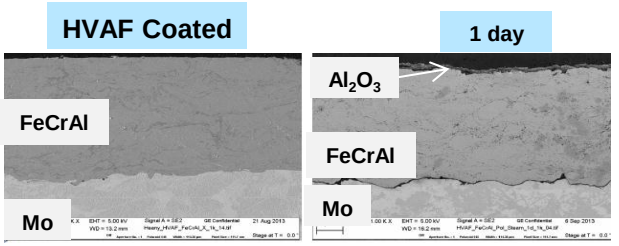
Oxidation in 1000°C Steam (6, 8 hrs. 1, 3 days)
- Steam Flow Rate 2.5 cc/min

1 Day Test

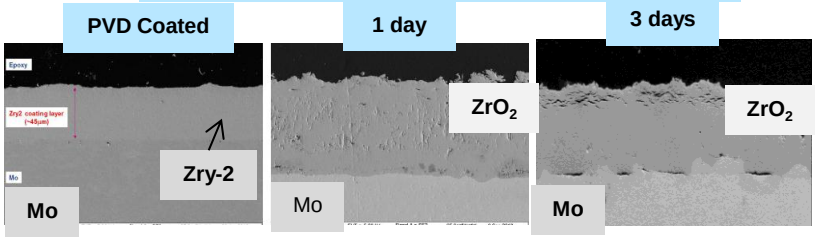
Specimen
Mo tube (8 mil)
Zry-2 tube (26 mil)
Al containing steel (FeCrAl) (16 mil)
FrCrAl coated on Mo sheet (40 mil)
FeCrAl (2 mil) coated on Mo tube
FeCrAl coated on Mo tube - polished
Zry-2 (1.5 mil) coated on Mo tube



FeCrAl (50 µm) on Mo



Zircaloy-2 (45 µm) on Mo

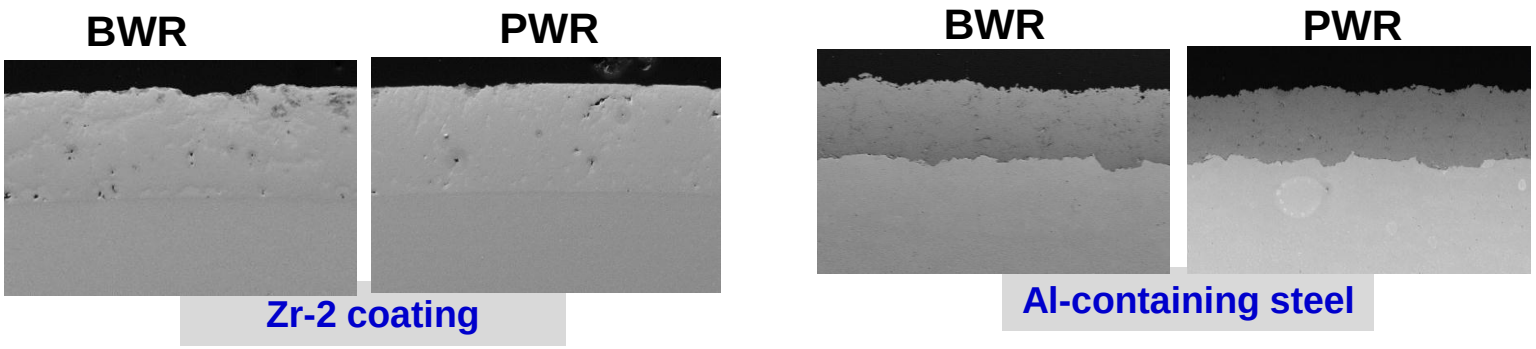


Tube	Reaction Rate	Comments
Zry-2	7.5 mil/hr (180 mil/day)	
Mo (LCAL, ML)	1 mil or 25 µm/day	Uniform surface recess
Zry-2 Coated Mo	Mo Stable	ZrO_2 stable to 3 days
FeCrAl Coated Mo	Mo Stable	Al_2O_3 1-2 µm, delamination

Rates consistent with LANL data; much less than historic data

Corrosion in Simulated Autoclave Tests
- Bare and Coated Mo and Mo-10%Nb

Coated Samples after Autoclave Test (1 mo)

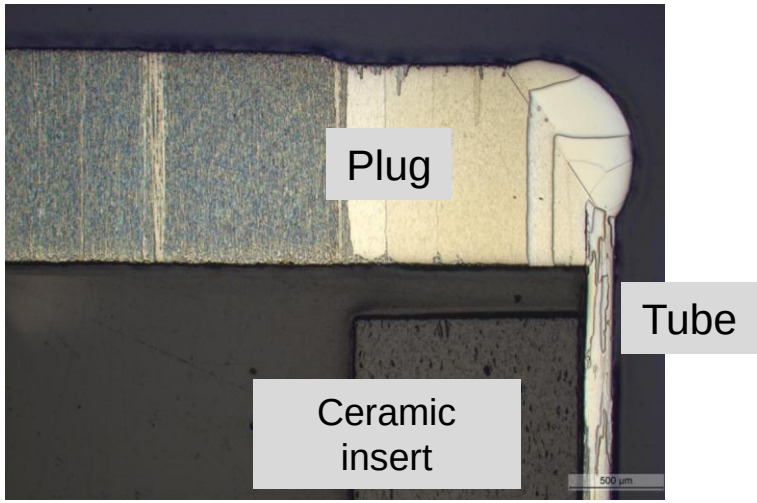


Recess/corrosion rate, µm/mo (Prliminary Data)				
	Mo/ML	Mo-10Nb	Zr-coated	FeCrAlcoated
PWR - 350 °C*	8	5	very low	very low
BWR-HWC - 288°C**	12	0.8	very low	very low
BWR-NWC - 288°C***	40	36	very low	very low
* 3 ppm H_2; ** 0.3 ppm H_2; ***1 ppm O_2				

Coated Mo corrosion rates are low as expected; room for improvement of corrosion resistance of bare Mo

Other Highlights

- Welding technique under development; final configuration:
  - Mo-tube to endcap welded
  - Coating formed on tube and endcaps
  - 40 coated tubes under preparation
- Tube burst and creep test setup is in progress



Collaborative Development of ATF Cladding

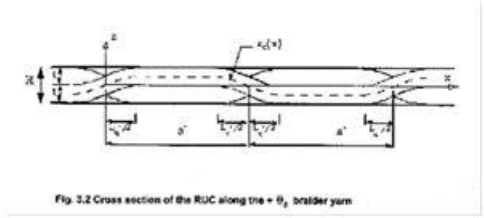
Tasks	2013	21014	2015	2016
Fabrication of 8 mil Mo-alloy Tubes				
- Mo and Mo + La_2O_3				
- New Mo alloys				
Coating on Mo Tubes				
- PVD, HVAF processes				
- Hybrid co-reduction				
Feasibility Tests				
- Corrosion in simulated LWR Water				
- Oxidation in 1000°C Steam				
- Oxidation in 1200-1700°C Steam				
- Welding				
- Tube Burst and Creep Test				
- Coating chemical stability				
Irradiation & Propety Testing				
- ATR				
- Halden				
- BOR-60				
Analysis				
- Neutronic on core design/economics				
- Effect on plant degradation in accident				
- Thermal-mechanical design				

Good progress **Initiated** **In preparation** **Developing**

- Working closely with DOE FCRD program (INL, LANL, ORNL)
- Collaborating with AREVA
- Seeking expanded collaboration with DOE, fuel vendors, and int'l R&D organizations

EPRI SiC Composite BWR Channel Program

- SiC fiber reinforced SiC matrix composite fabricated for impact testing (4”x4”x24”, 0.05-0.06” wall)



  - Hi-Nicalon Type-S fiber
  - Chemical vapor deposition process

EPRI SiC Composite BWR Channel Program: Scope

- Initial design screening (complete)
  - Fragmentation resistance and Irradiation induced swelling issues resolved
  - Eliminated polymer infiltration pyrolysis (PIP) process
- Material property characterization and issue resolution
  - Generate data to support the insertion of a commercial lead channel
  - Resolve remaining issues
- 1/3 Scale integral sample demonstration in Oak Ridge National Laboratory HFIR reactor
- Post irradiation mechanical testing
- Data evaluation and commercial demonstration decision

EPRI SiC Composite BWR Channel Program: Summary

- Evaluations conducted thus far suggest SiC composite could meet BWR Channel mechanical requirements
  - Excellent high temperature performance
- Material recession in BWR water chemistry identified
  - Oxygen potential suspected (needs verification)
  - Strategies to protect SiC in BWR environment are being explored
- SiC property data generation is continuing but material recession issue will cause a delay in overall program
  - Resumption of MIT testing expected in 6 months

EPRI/INL/DOE Joint Workshop on Accident Tolerant Fuel
27 – 28 February 2014 (San Antonio, TX)

EPRI/INL/DOE Joint Workshop on ATF

- EPRI and INL have organized and hosted joint workshops on ATF R&D since 2012
- Third EPRI/INL/DOE workshop held on 27-28 February 2014 in San Antonio, TX
- Broad international, multi-sector participation, including USDOE/national labs, international utilities, vendors, and R&D institutions

2014 EPRI/INL/DOE Joint Workshop on ATF: Workshop Topics

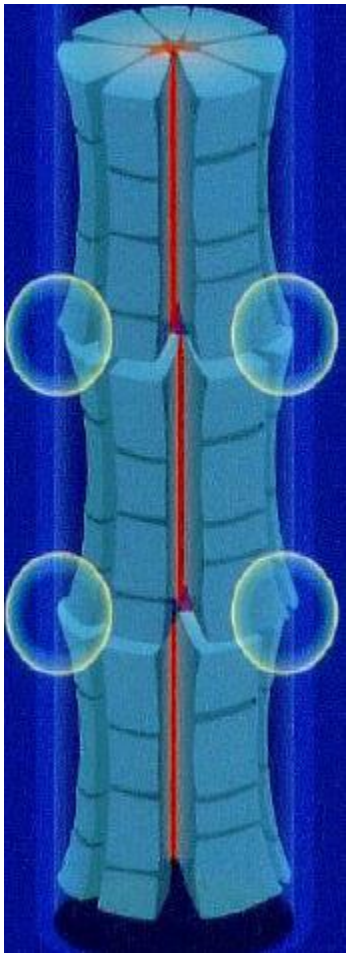
- Industry Perspectives on ATF
  - Utility perspectives (Exelon, TVA)
  - Lessons from BWR barrier fuel development (GE, ret.)
- Modeling and Simulation Applications
  - MELCOR (INL)
  - MAAP (TEPCO, EPRI)
- USDOE ATF Program (DOE, INL)
  - Advanced stainless steel cladding (GNF)
  - Coated cladding and modified fuel (AREVA)
  - SiC and coated cladding, UN fuel (Westinghouse)
  - Molybdenum alloys for cladding (LANL)
- Halden Testing Capabilitie for ATF (Halden Project)
- SiC Composite Technology
  - BWR fuel channel application (EPRI)
  - Historical overview and context for SiC composite development (ORNL)
  - SiC composite testing (ORNL)
- Control Materials for ATF Applications (CRIEPI)
- International Developments in ATF (INL for NEA Secretariat)

2014 EPRI/INL/DOE Joint Workshop on ATF: Perspectives from Participants

- **Utilities**
  - Safety must always be the highest priority
  - New technologies must have minimal additional cost and operational impact while achieving maximum and verifiable benefits
  - Impact of ATF on plant life extension also warrants consideration
  - ATF should be applicable to next generation nuclear plants
- **Vendors**
  - Ability to manufacture and qualify and return on investment (ROI)
- **Government**: Funding and focus often constrained by non-technical factors; need for industry initiative and participation
- **EPRI**
  - Exploring viable technologies to meet ATF targets
  - Will coordinate technical collaborations with all parties
- **All:** Broader collaboration needed to succeed – long R&D timeframes

Lessons from Barrier Fuel Development (S. Armijo, ACRS/GE Ret.)

- Paramount: define problem being solved
- Strong organizational commitment, clear responsibilities, and stable leadership is essential
- R&D spanned ~15 years through Quad Cities irradiation
- Portfolio R&D approach helps to avoid dead ends
- **Expect surprises**
- Early introduction of concepts (as segmented rods) into power reactors is important
- Test aggressively (numbers and severity)
  - statistics are not favorable
  - mild testing risks missing low frequency problems



Reactor Facilities for Barrier Fuel Development (S. Armijo, ACRS/GE Ret.)

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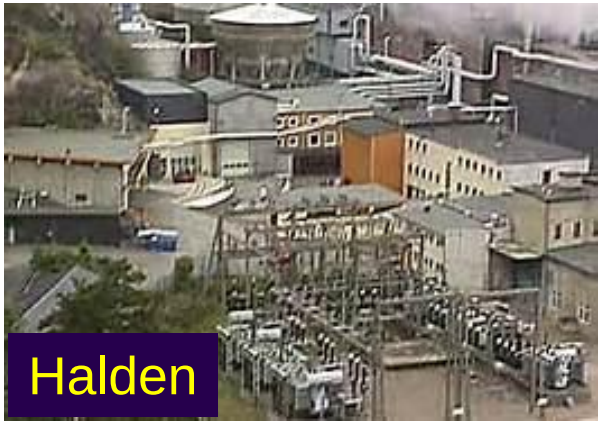
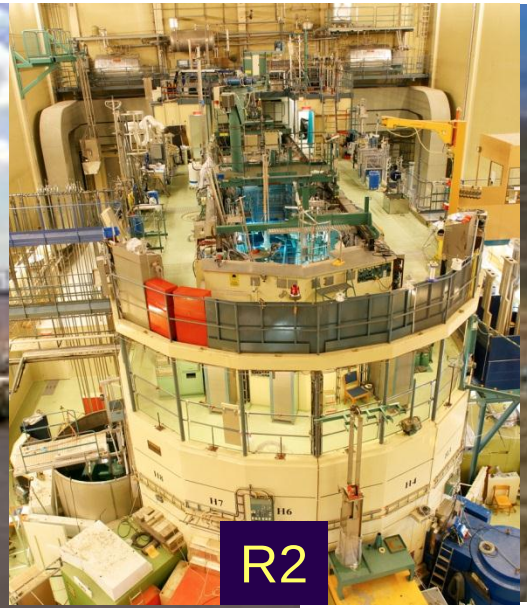
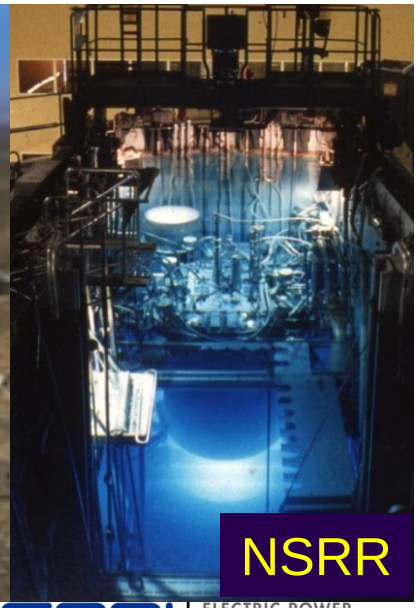

Halden


EBR II


Quad Cities 1 & 2


R2


PBF


NSRR

Other Workshop *Highlights*

- Real but incremental progress on ATF R&D
- Definition of the “ATF” problem remains incomplete
  - reduce or eliminate hydrogen generation
  - maintain coolable core geometry
  - maintain or improve performance
- Decline in global infrastructure for characterization and testing
- Modeling and simulation capabilities should be exploited
- Value of lessons from nuclear fuel R&D and other applications
- Pursuing multiple paths essential to success
  - parallel technology options (surprises happen)
  - non-fuel components (low hanging fruit)
- Strong organizational commitment, clear responsibilities, and stable leadership are pre-requisites

International Collaboration for ATF R&D

EPRI Consultations in 2013 with International ATF Stakeholders

- EPRI 30 October 2013 Coordination Meeting (Paris)
  - Follow up discussion after OECD/NEA ATF meeting to help EPRI assess gaps and needs in international ATF RD&D
  - NEA provided a brief summary of 28 – 29 October meeting
  - IAEA provided brief overview of 2014 cooperative research program
- General consensus on value and need for sharing of work plans and results (as appropriate) to avoid unnecessary overlap
- General recognition of EPRI's value and role in providing interface with utilities and vendors

EPRI Consultations in 2013 with International ATF Stakeholders: Themes

- Fundamental studies of properties are needed – data is lacking
- Modeling and simulation can improve/optimize testing design and down selection efforts
- Strong utility and vendor community pull needed for successful deployment of ATF technologies
- EPRI strengths include coordination of material characterization and fuel testing programs that are:
  - industry driven
  - international in scope
  - sustainable over decades

Closing: EPRI Perspective on International Collaboration: NEA Expert Group on ATF

- Coordination among international stakeholders under NEA auspices represents an opportunity for:
  - Sharing status of R&D plans and technology maturity
  - Establishing common understanding of metrics and criteria
  - Identifying barriers and gaps in knowledge and R&D activities
  - Sharing of basic material property data
  - Modeling and simulation exercises and benchmarking of codes
- **EPRI supports OECD/NEA activities in ATF and has committed to partial funding of Expert Group startup administrative costs**

Closing: EPRI Perspective on International Collaboration (cont'd)

- Later stages of R&D will likely benefit from (require?) greater coordination of limited resources, *especially facilities for characterization and testing of new materials and pre-commercial ATF concepts*
- EPRI is considering development of an ATF R&D program focused on in-core behavior of new materials, designs, and concepts for fuel, control materials, and other core components

Together…Shaping the Future of Electricity