Assessment of the V&V Challenges of Accident Tolerant Fuels

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Multiphysics Model Validation Workshop

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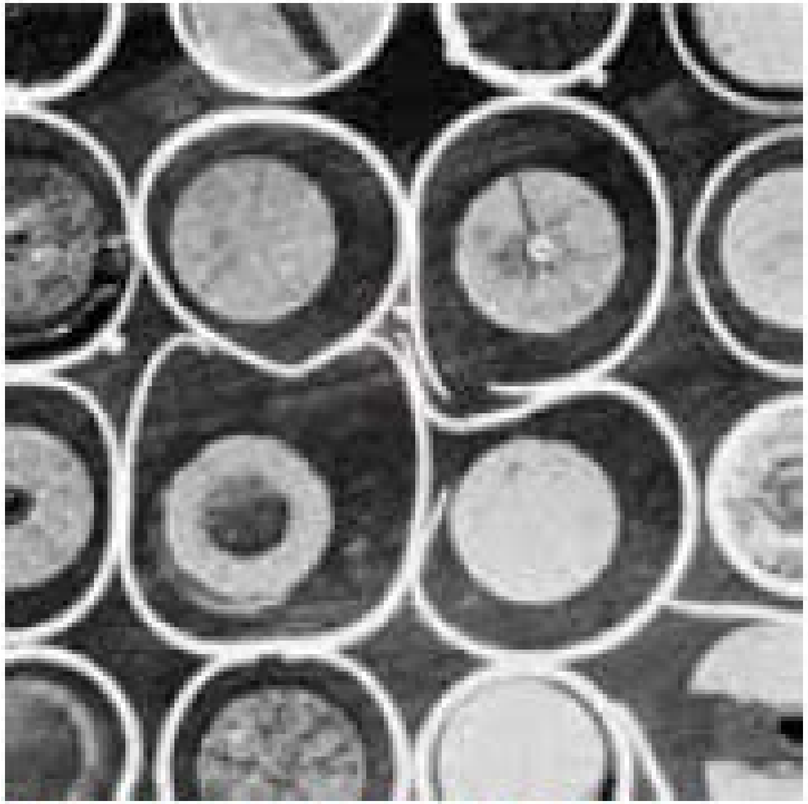
Outline

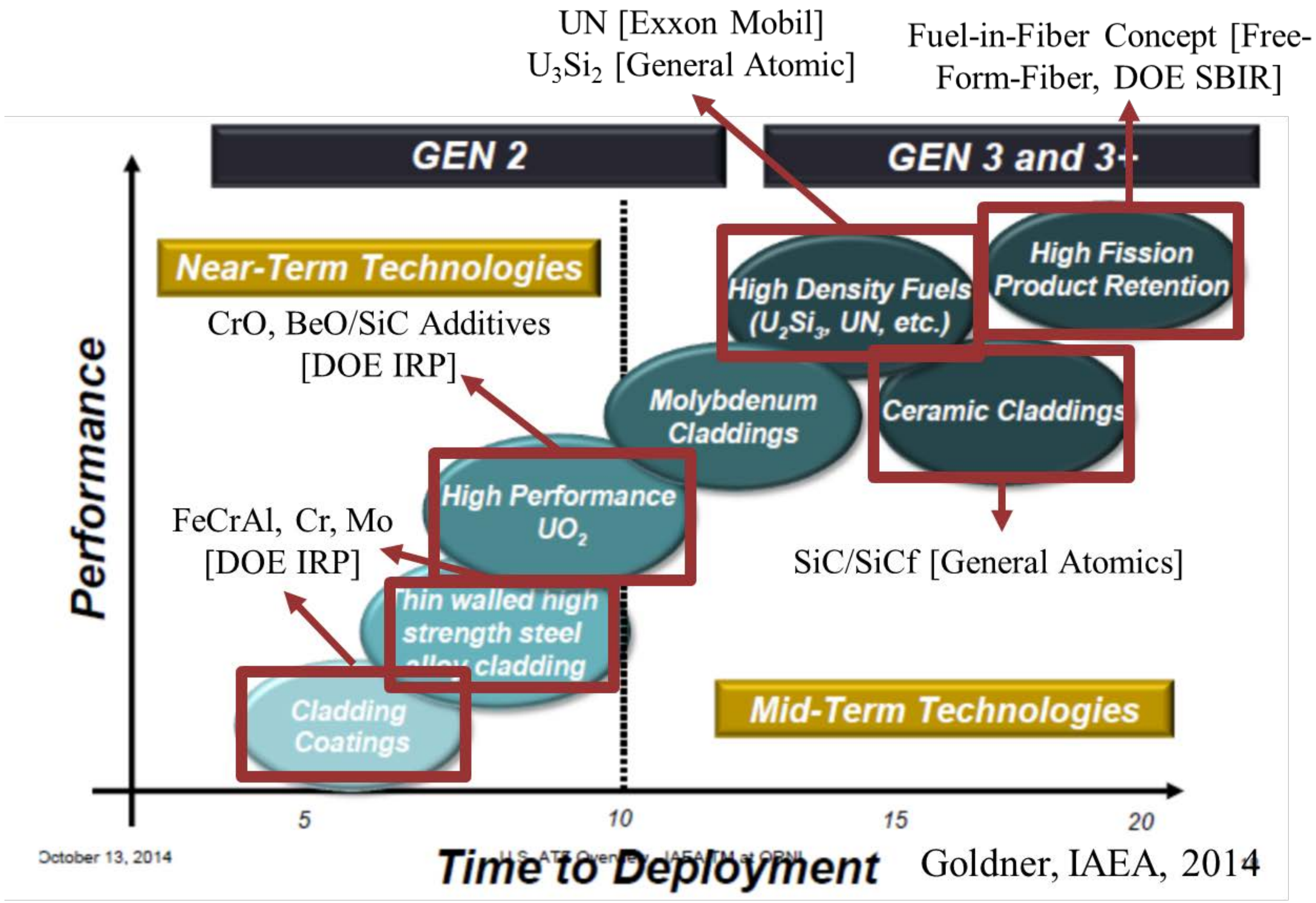
- ATF IRP Overview
- ATF Materials
  - Fabrication Technology
- Examples of V&V Needs
- Concluding Remarks

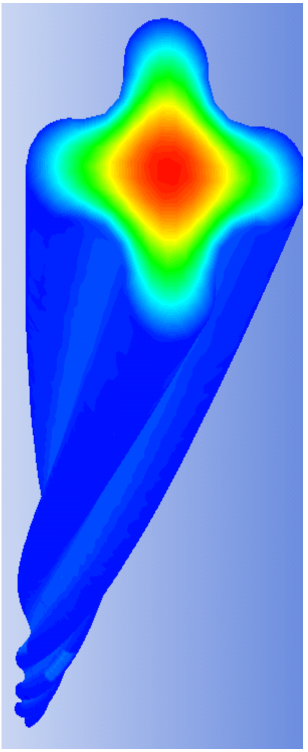


PHEBUS-LOCA (IRSN)

Acknowledgements: Funding for this work has been provided by DOE IRP contract # DE-NE0008416 and Center for Advanced Nuclear Energy Systems.

Accident Tolerant/Advanced Technology Fuel Program (Recent)





Shirvan K., et al., NED 270 (2014)

MIT LWR Simulation Experience

- Selected Tools Applicable to LWR Reactors with Prior Experience:
  - Red: Tools currently used for ATF
  - Green: CASL tools used in CASL Summer Institute for ATF
  - Orange: Modified Source Code

Category	Commercial Tools	Licensing Tools (NRC)	Academic/DOE Advanced M&S
Reactor Physics	CASMO SIMULATE	SCALE PARCS	SERPENT MPACT
Thermal-Hydraulics	VIPRE STARCCM	COBRA	COBRA-TF
Safety/System	S3K, RELAP5	TRACE	--
Fuel Performance	ABAQUS FALCON*	FRAPCON FRPTRAN	MOOSE/BISON FRAPCON-MIT
Severe Accident	MAAP*	MELCOR	--

MIT ATF Experimental Facilities

- Limited Sample Testing is Underway

Experimental Facilities

Upto 1500^{o}C Steam/Air Oxidation

400-500^{o}C Steam Oxidation

PWR CRUD Loop

Prototypic 4-Point Bend Test

Prototypic Pressure Tube Test

Burst Test (Plug & Liquid)

Mechanical/Thermal Creep

Full Surface Characterization

Upto 1500^{o}C Quench Test

SS/Transient CHF Testing

Ion Irradiation

MITR PWR Loop

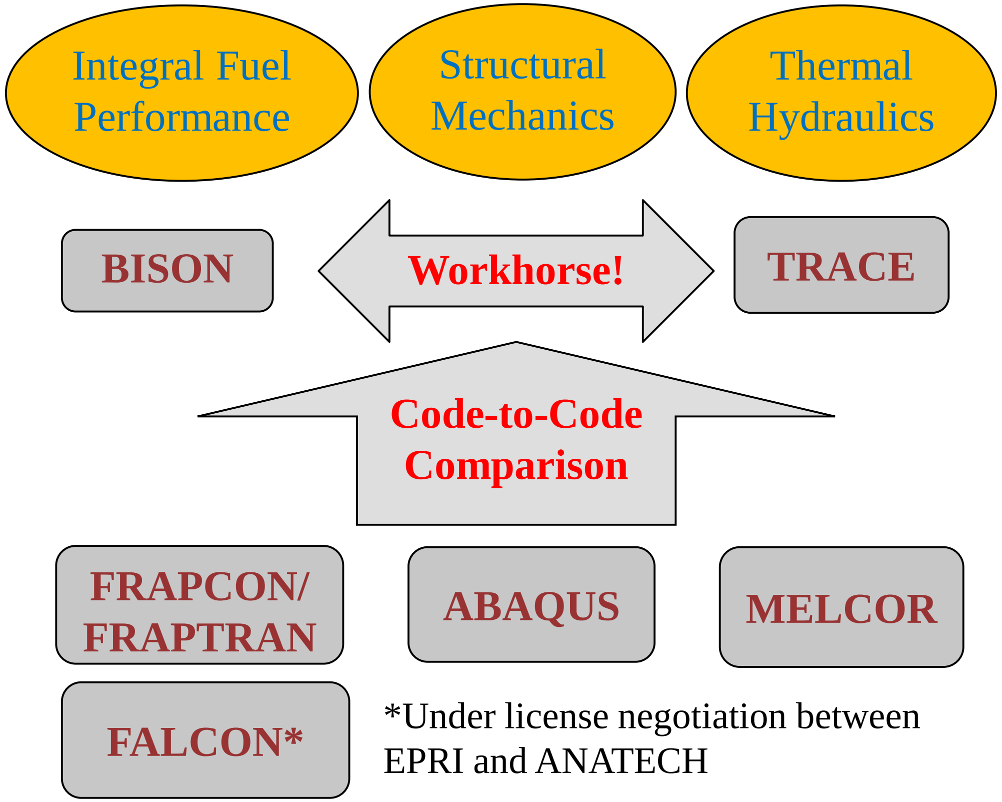
Post-Irradiation Examination (Dimension, SEM, Wettability)

DOE ATF Integrated Research Project

- Goal: Estimate Time-to-Failure → Failure Modes and a Framework
- Lead: MIT Co-Lead: UW, PSU, TAMU, ANATECH, AREVA
- Budget & Timeline: $3 million and 3 years (started Dec 2015)
- ATF Candidates: Clad: FeCrAl, Mo, Cr Fuel: Additives/Dopants

Strategy

- Steady State:
  - Minimal Neutronics Impact
  - Durability (SCC, Plasticity, Fatigue)
  - PCI (startup, power ramps)
- Design Basis Accident (DBA)
  - LOCAs, RIAs, LOFA
  - Oxidation, Fracture/Rupture, PCI
  - CHF, Quench Characteristics
- Beyond DBAs-Severe Accidents (SAs)
  - LBLOCA w/o SI, SBO (long/short term)
  - Oxidation, Fracture/Rupture of All Primary Components
  - Fuel PCI, Buckling & Quench Performance

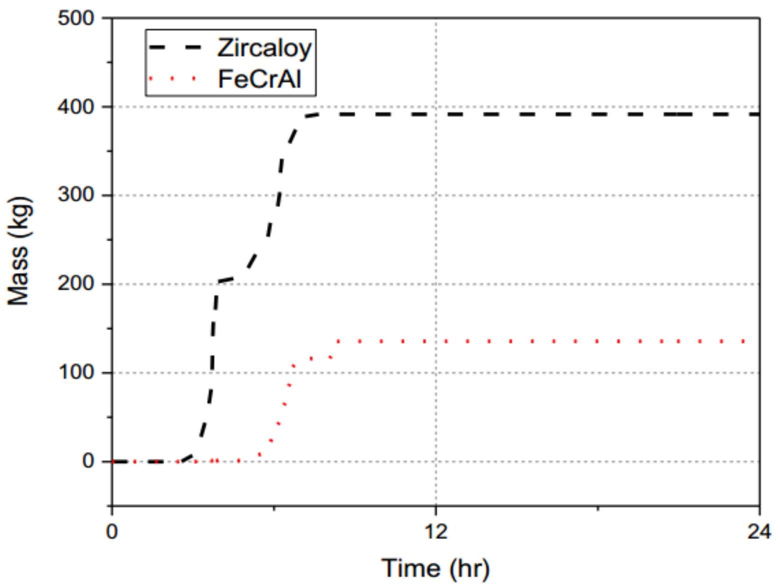


*Under license negotiation between EPRI and ANATECH

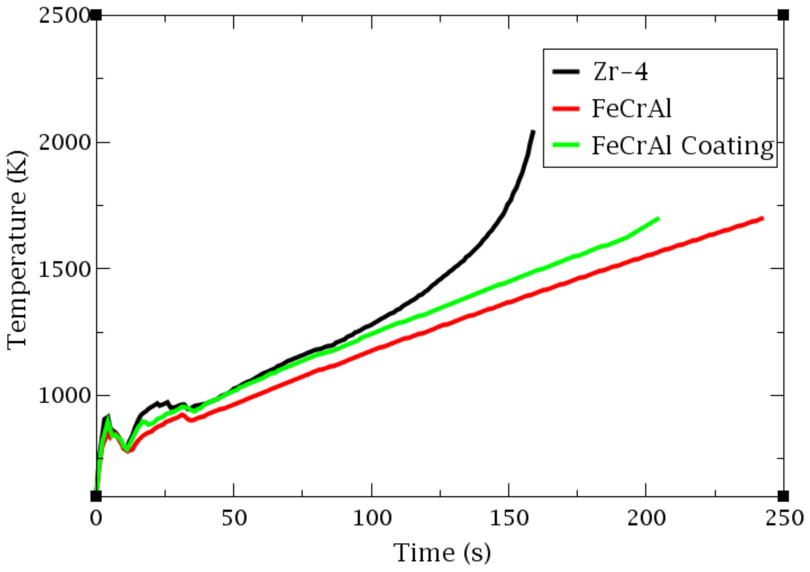
Estimation of Time-to-Failure

- Historically NRC has relied on MELCOR Type Severe Accident Tools
- TRACE may provide a more physics-based and accurate approach to time of fuel failure
- Historically, Fuel Performance (FP) tools development aimed to address the ability of the fuel to remain in a coolable geometry under accident,
  - Increase in computational power may allow FP to address coping time.
- ATF IRP approach is to use all three approaches!

From: Wang, J., et al., NED 313, 468 (2017)

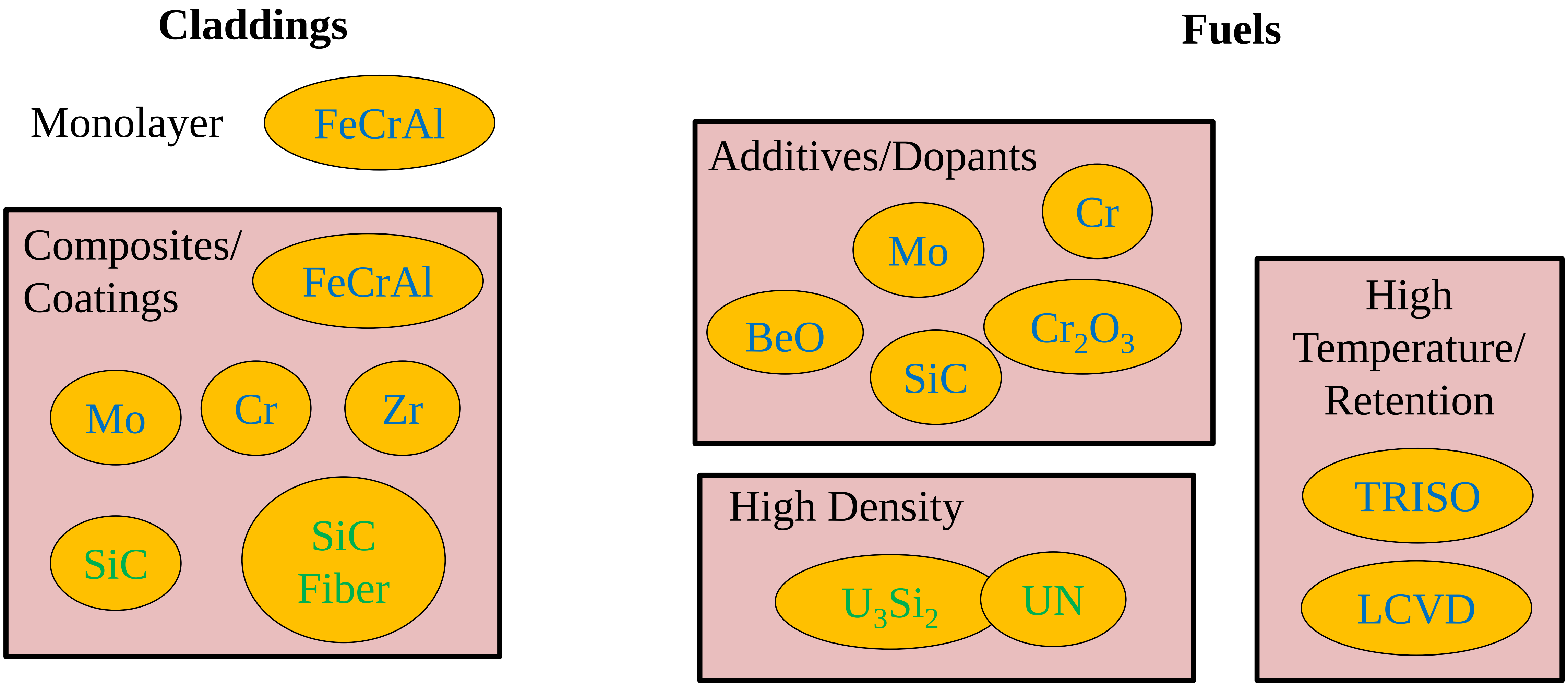


MELCOR [Left] Short Term Station Blackout and TRACE [Right] LBLOCA w/o Safety Injection



From: Gurgan, A., Shirvan, K., ANS Summer (2017)

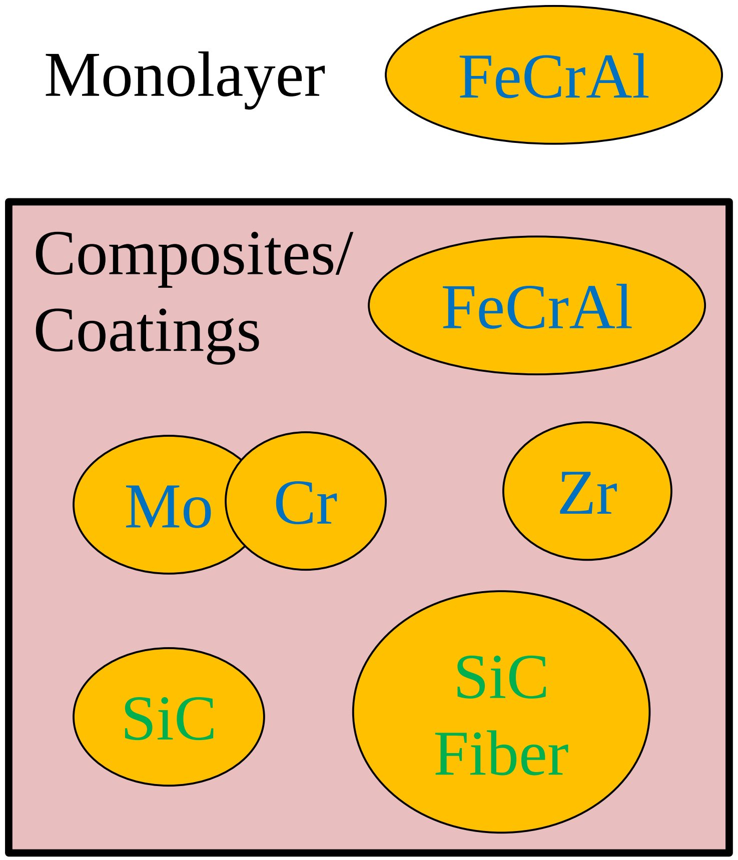
ATF Materials (Most Popular!)



Green: Fuel Cycle Cost Benefit

ATF Cladding Materials

Claddings



- Maximum Allowable Temperature (Max Temp.)
  - ✓ FeCrAl Cladding limit is the most certain
  - ✓ Zr/Cr limit is for slow transients
  - ✓ Mo limit depends on its structural role

Concept	Max Temp.	Comments
FeCrAl Monolayer Clad	~1500 ^{o}C	Melting Point
Zirc with Cr Coating	~1330 ^{o}C	Eutectic Melt Point
Zirc with Mo + Cr Coating	~ 1900 ^{o}C	Depends on Thickness and Inner Layer Oxidation
Zirc with Mo + FeCrAl/Zr	~1900 ^{o}C	Depends on Thickness and Inner Layer Oxidation
SiC with SiCf Composite	> 2000 ^{o}C	Depends on Architecture
SiCf with Cr Coating	~ 1900 ^{o}C	Cr is there for Normal Ops.
Zirc with SiCf with Cr	~1900 ^{o}C	Melt point of Zr and Cr

Metal Composite Fabrication Techniques (1)

- Commercial Scalability vs. Desired Quality/Tolerance

Physical Vapor Deposition

Image From: JC.BRACHET et al. | IAEA meeting on ATF, ORNL, Oct. 13-17, 2014

Cold-Spray

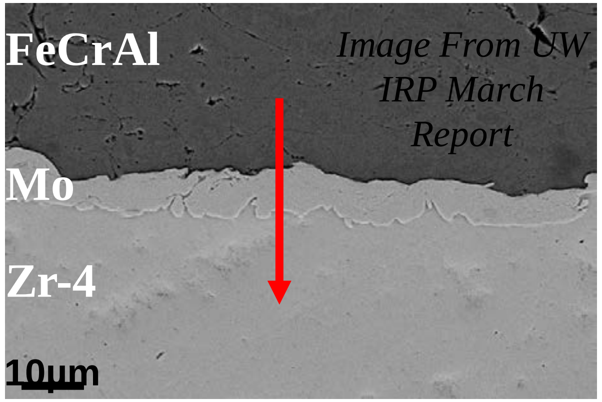
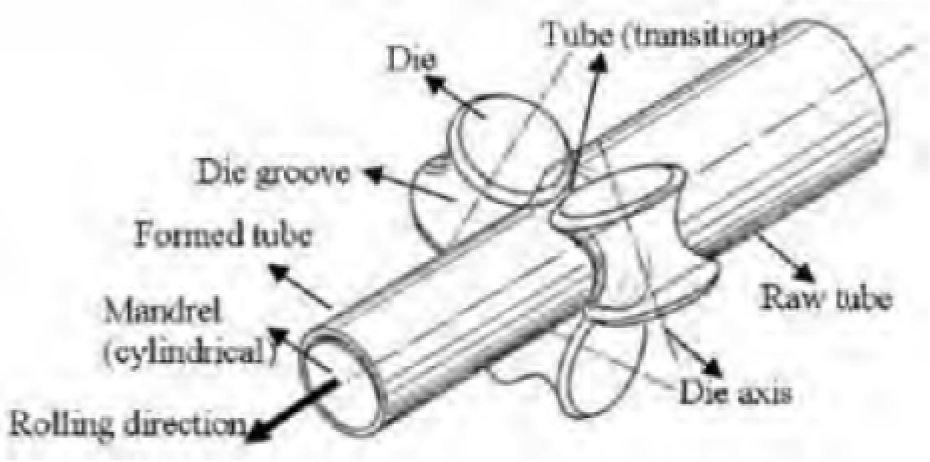


Image From UW IRP March Report

EB Welding → Hydraulic Pressurization → Co-Pilgering



Hot Hydrostatic Pressing

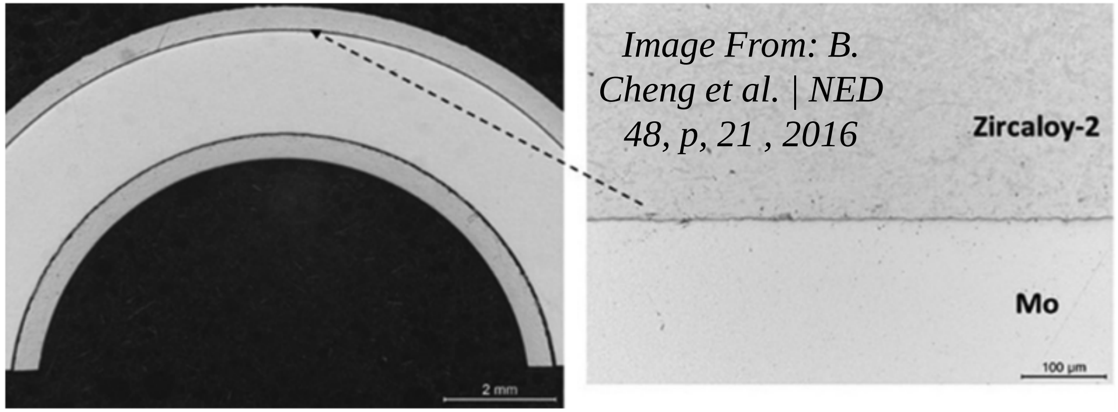
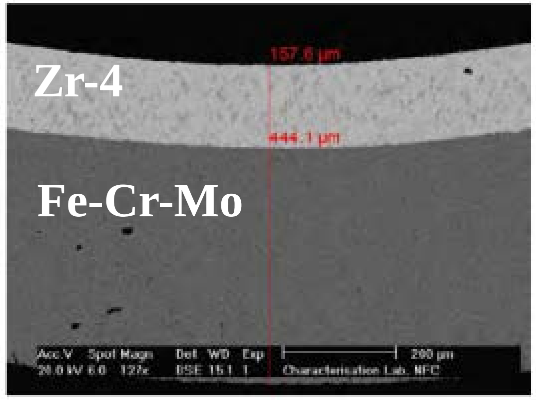


Image From: B. Cheng et al. | NED 48, p, 21 , 2016



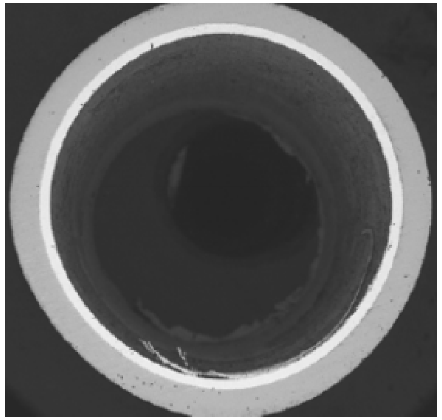
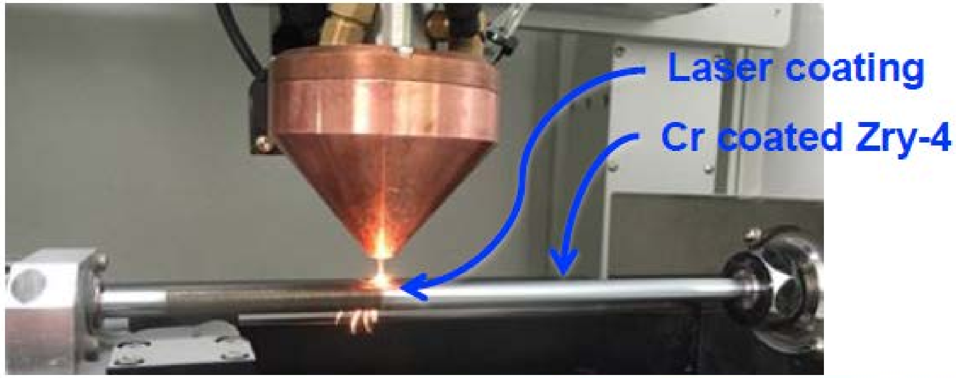
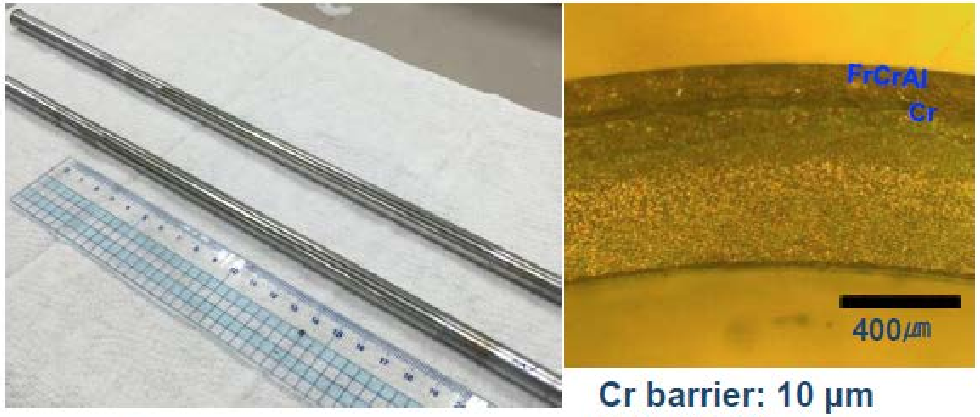


Image From: V.V Reddy et al. | IAEA Tech. Meeting, 2016.

Metal Composite Fabrication Techniques (2)

FeCrAl/Cr/Zry-4

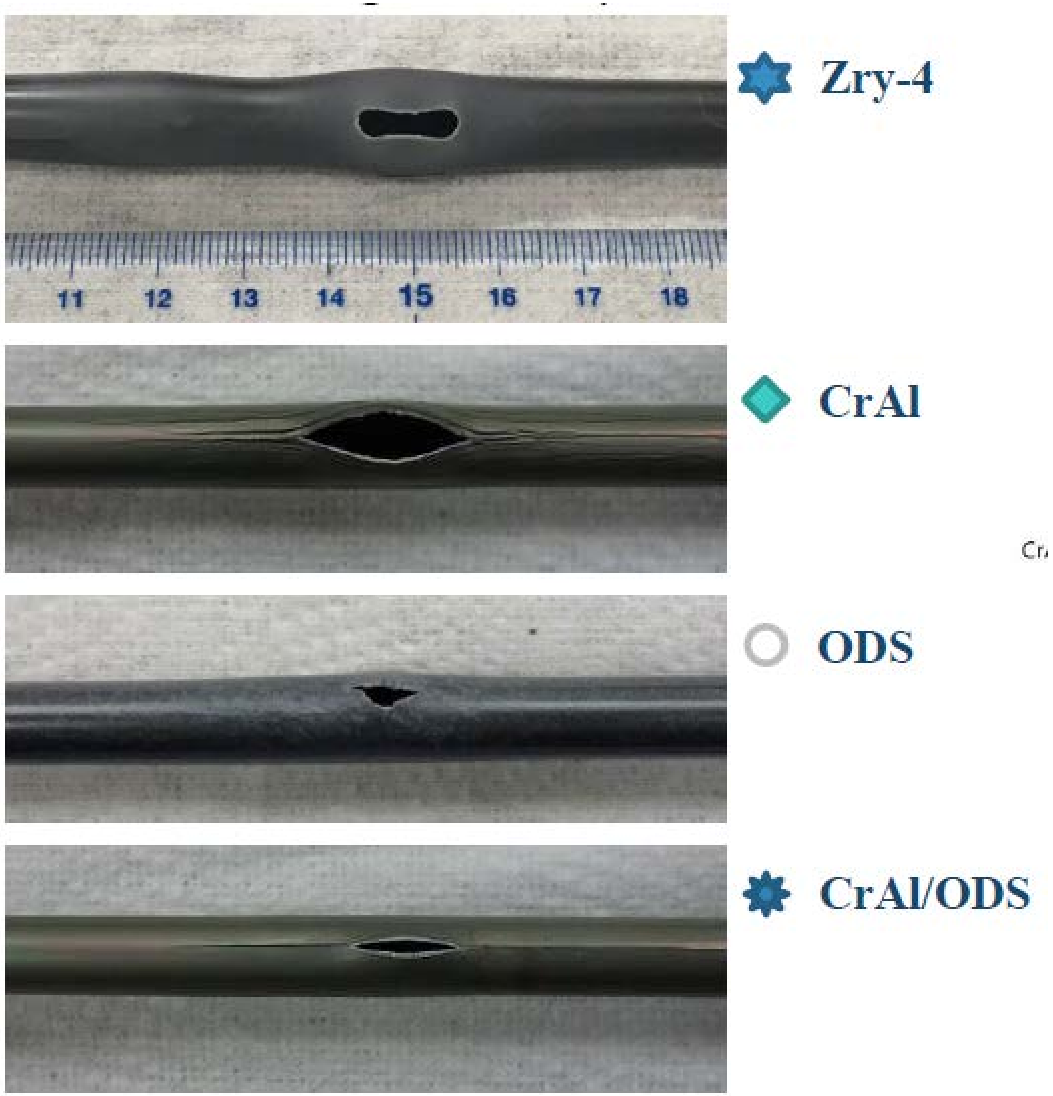




Cr barrier: 10 μm
FeCrAl: 75 μm

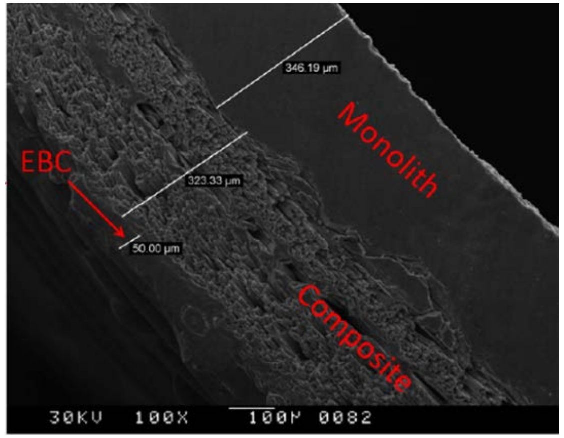
Korea Atomic Energy Research Institute (KAERI)

Images courtesy of Kim H.G, TopFuel 2016

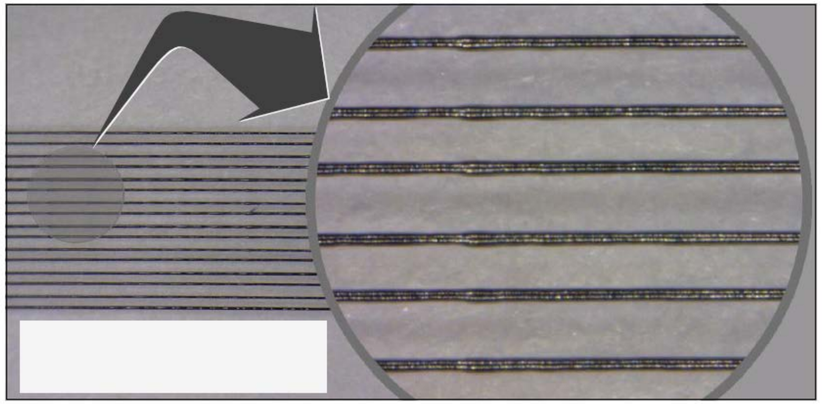


SiC Ceramic/Metallic Composite Fabrication Technique

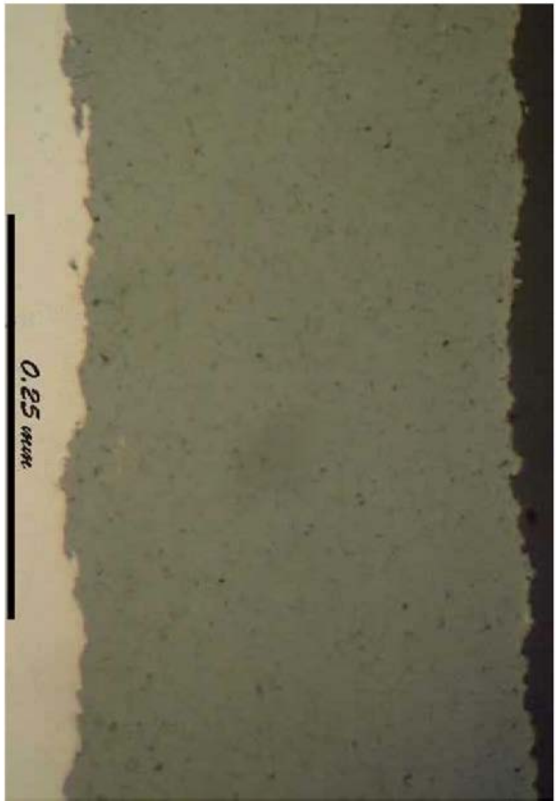
Start with Monolith SiC → Wind SiC Fibers → Infiltrate SiC Matrix → CVD Barier



Wind SiC Fibers → Infiltrate SiC Matrix → Thick CVD Barrier



Laser Driven Chemical Vapor Deposition Method (courtesy of Free-Form-Fiber)



Plasma Spray of Chromia (http://www.gordonengland.co.uk/xpmg23.htm)

Cladding Fuel Performance Simulation Metrics

- What information can we get from experiments?
- What information do we need to simulate time of failure?

Thermo-Mechanical
Density
Thermal Conductivity
Emissivity
Thermal Expansion
Elastic Modulus
Posisson Ratio
Swelling/Growth
Thermal Creep (primary, etc)
Irradiation Creep
High Temperature Creep
Plasticity/Irradiation Hardening
Meyer Hardness
Cladding Damage Mechanisms

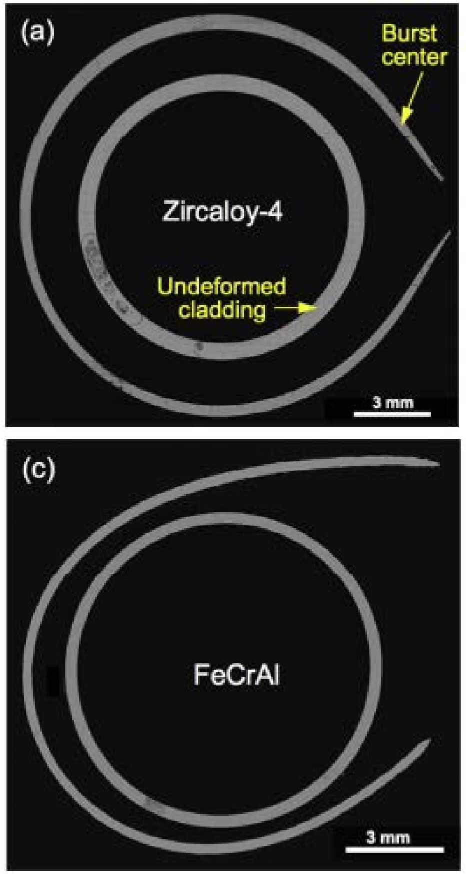
Waterside Corrosion
Corrosion Layer Growth/CRUD (phase/stage dependent)
Thermal conductivity of Corrosion Layer
Phase Transformation
Radiation Induced Segregation
Stress Corrosion Cracking (i.e. Intergranular)
Hydrogen Pickup Fraction
Hydrogen Migration
Hydride Formation
Strength/Ductility Degradation from Hydrogen

Fuel Integral
Pellet to Cladding Mechanical Interaction (PCMI)
Pellet-to-Cladding Chemical Interaction (Especially w/HBS)
Fuel Burst (LOCAs)
Fuel Assembly Structural Interaction
Lift-off
Fuel-Clad Gap Evolution and Heat Transfer
Mechanical Shock/Seismic
Grid-to-Rod Fretting/Wear
Tritium Release

M&S Tools Challenges

Images From: C.P. Massey et al., JNM 470 (2016) 134

Metrics	Tools	Address
Plasticity/Large Deformation	BISON/FRAPTRAN	FEA/Empirical
Fracture Failure/Post Burst Behavior	ABAQUS/BISON	FEA + Empirical
Critical Heat Flux/Post-CHF/Quench	TRACE/BISON	Empirical
Stress Corrosion Cracking	BISON/FRAPCON	Empirical
Corrosion/CRUD Deposition	BISON/FRAPCON	Empirical
Mechanical Shock/Impact	ABAQUS	FEA/Emperical
Multi-Layer Interaction	BISON/FRAPCON	FEA/Improved Model
Extended Gap Opening	BISON/FRAPCON	Improved Model/Empirical
Non-Fuel Structure Performance during SA	TRACE	Empirical/Improve Model



Note: TRACE has capability for time-dependent geometric feedback of fuel cladding.

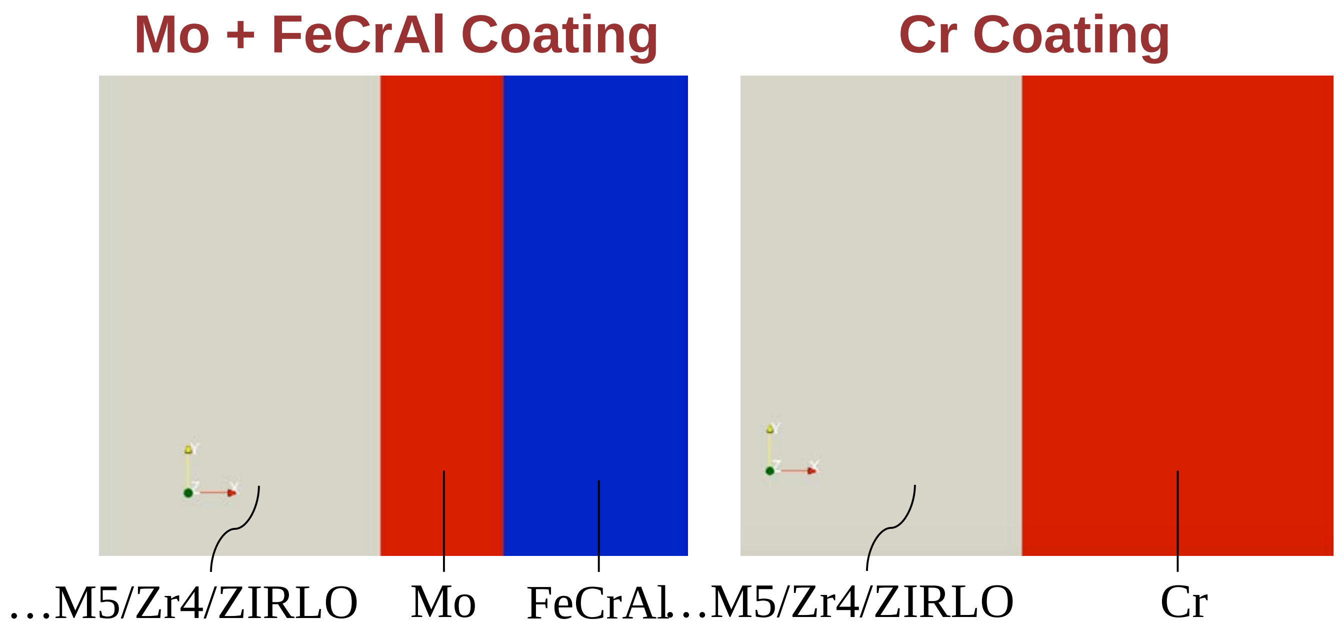
Examples

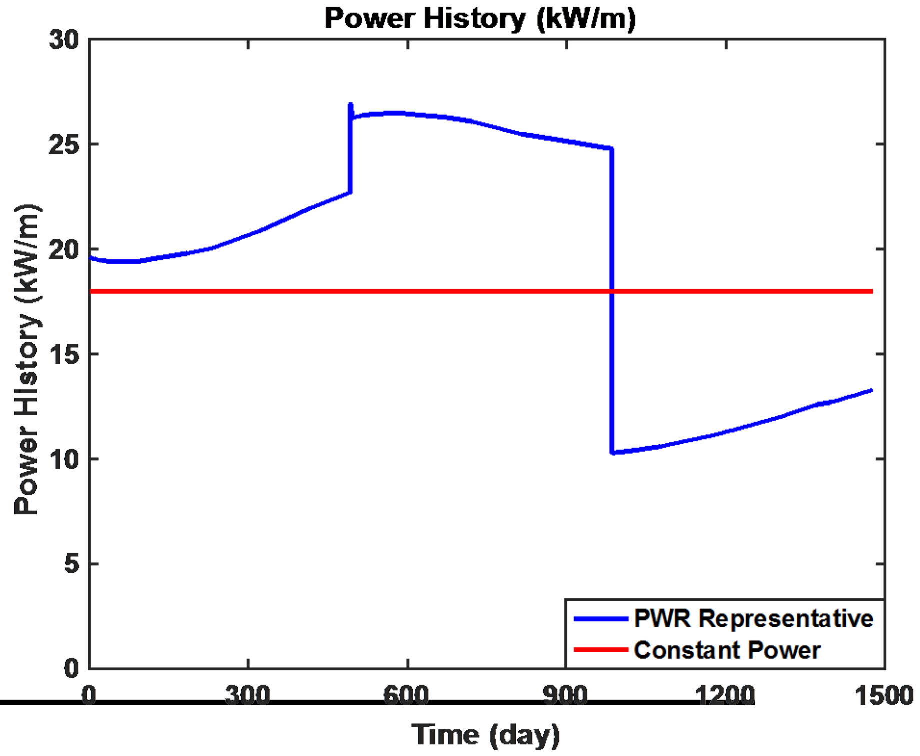
- Coated Cladding Fuel Performance
- SiC Cladding Failure Mode
- SiC Integral Fuel Performance
- Cladding Water-Side Heat Transfer

Coated Cladding Fuel Performance

Cladding/Coating Material & Thickness

	Cladding	Coating(s)			Power History
	M5 / Zr4 / ZIRLO	Cr	Mo	FeCrAl	
Case 1. M5/Zr4/ZIRLO + Cr Coating	521.5μm	50 μm	-	-	Constant @ 18 kW/m
Case 2. M5/Zr4/ZIRLO + Cr Coating	521.5μm	50 μm	-	-	PWR Power History
Case 3. M5/Zr4/ZIRLO + Mo/FeCrAl Coating	521.5μm	-	20 μm	30 μm	Constant @ 18 kW/m
Case 4: M5/Zr4/ZIRLO + Mo/FeCrAl Coating	521.5μm	-	20 μm	30 μm	PWR Power History





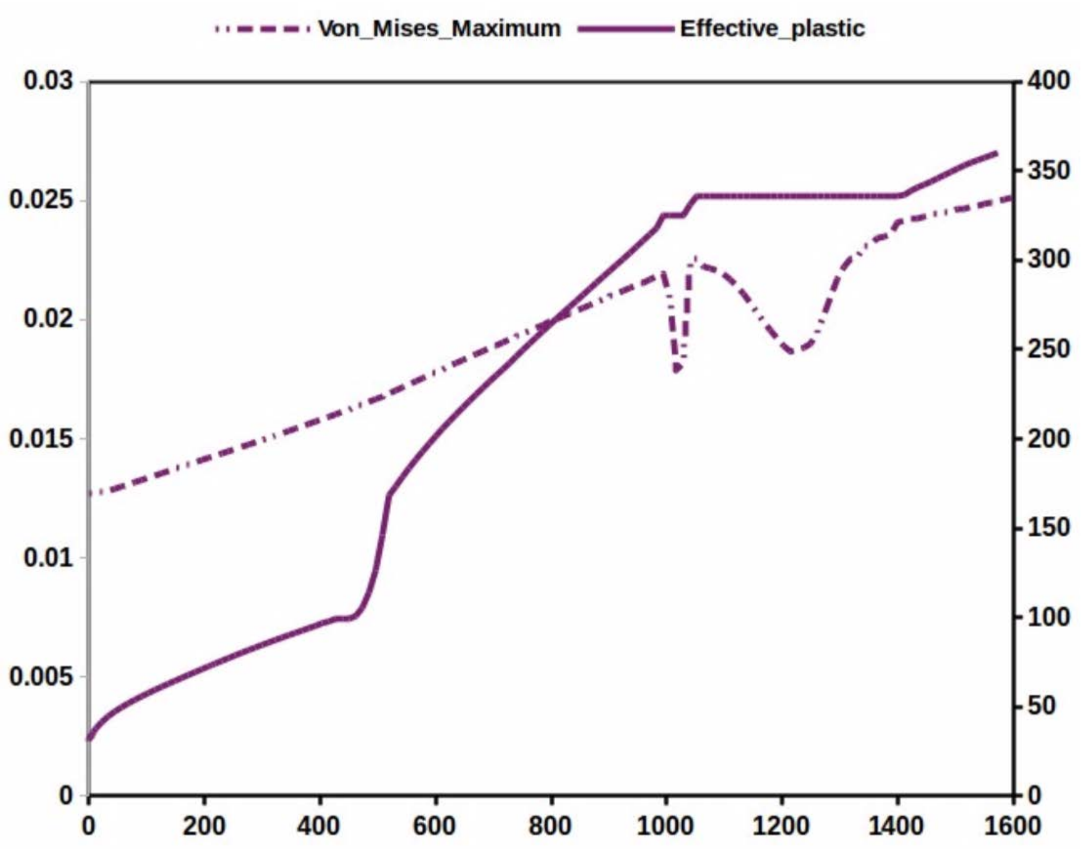
Coated Cladding Fuel Performance (2)

f (T, fluence)	Zr	FeCrAl	Cr	Mo
Elastic (E, ν)	🟩 🟩	🟩	🟩	🟩
Thermal Conductivity	🟩	🟩	🟩	🟩
Thermal Expansion	🟩	🟩	🟩	🟩
Swelling	🟩	🟨	🟥	🟨
Thermal Creep	🟩	🟨	🟥	
Irradiation Creep	🟩	🟨	🟥	
Yield Strength	🟩 🟩	🟩 🟨	🟩 🟥	🟩 🟨
Failure Strength	🟩	🟩 🟨	🟩 🟥	🟩 🟨

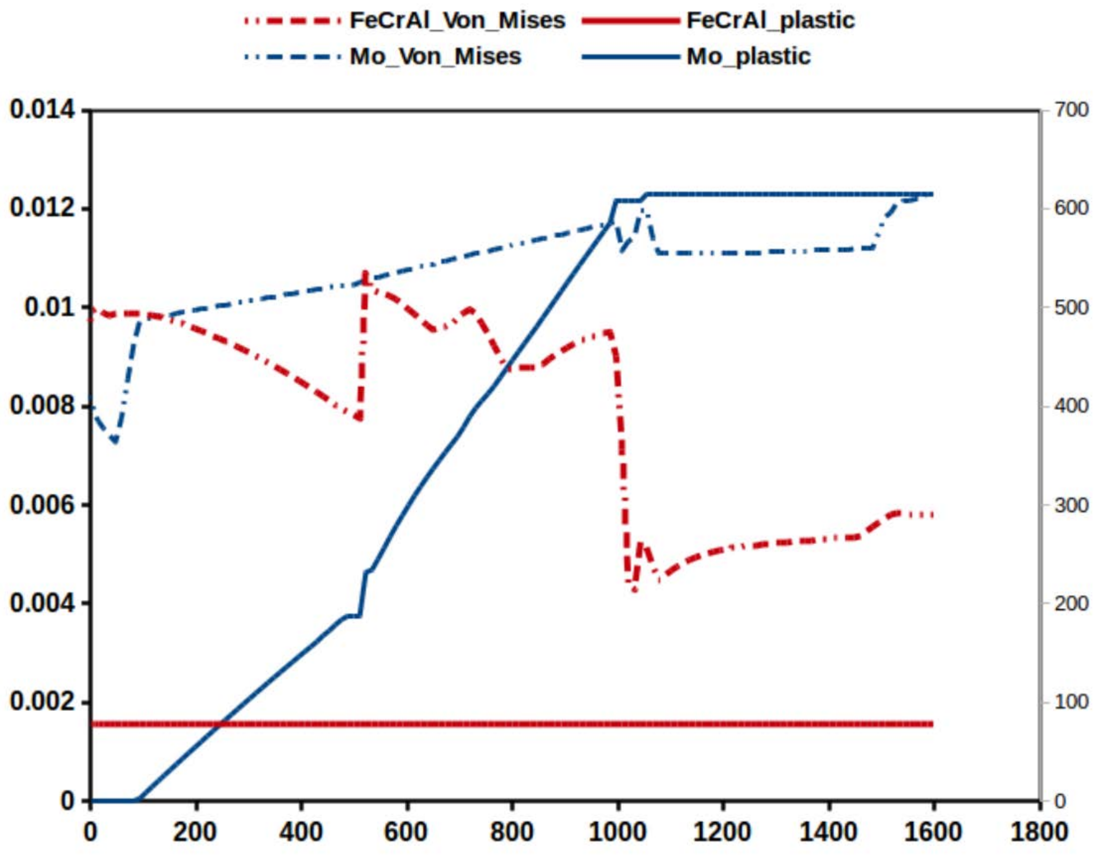
🟩 Available 🟨 Limited/In Progress 🟥 Very limited/ Unavailable

Coated Cladding Fuel Performance (3)

- Steady-State Plasticity = Uncertainty in Performance



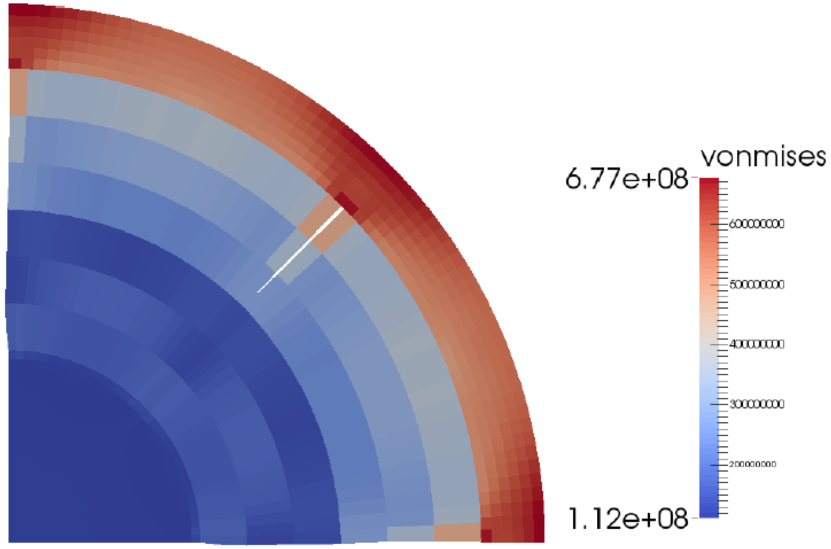
Cr-Coated

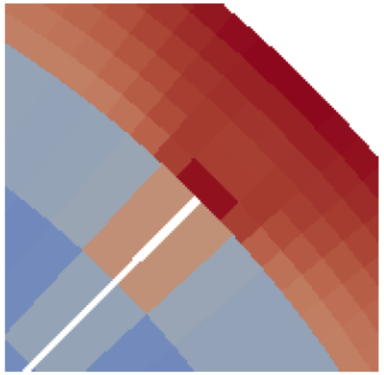


FeCrAl-Mo-Coated

Coated Cladding Fuel Performance (4)

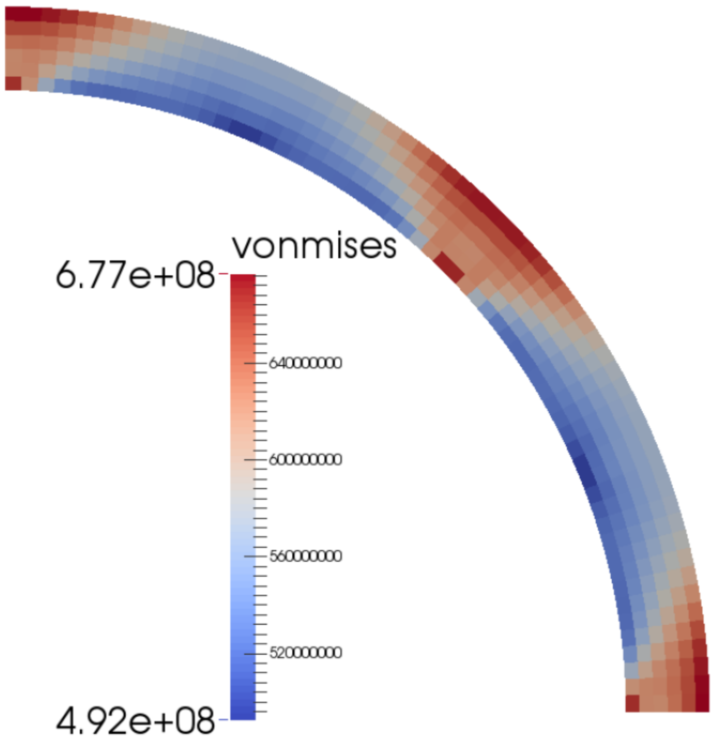
- Currently not part of any regulatory limit:
  - Likely if Credit to ATF is Requested



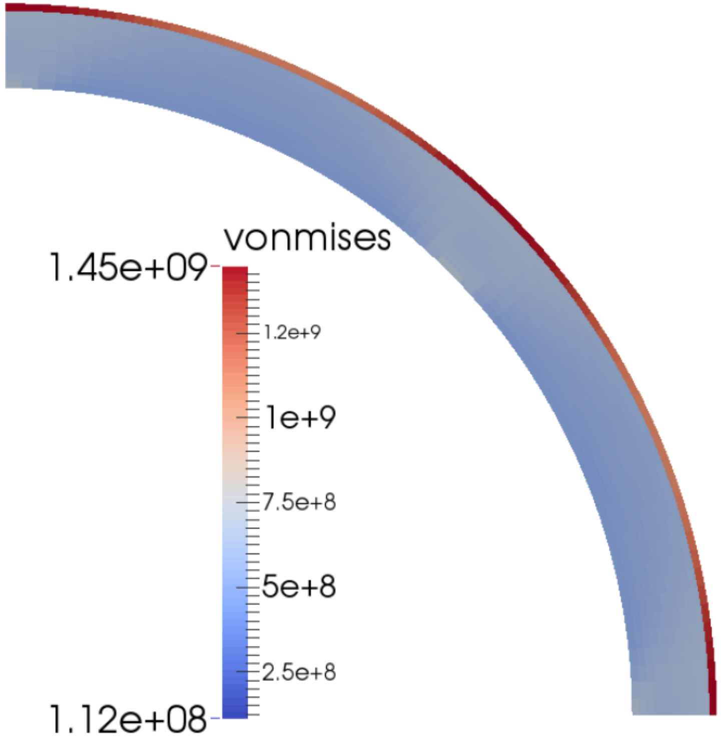


First ramp

Zr-4

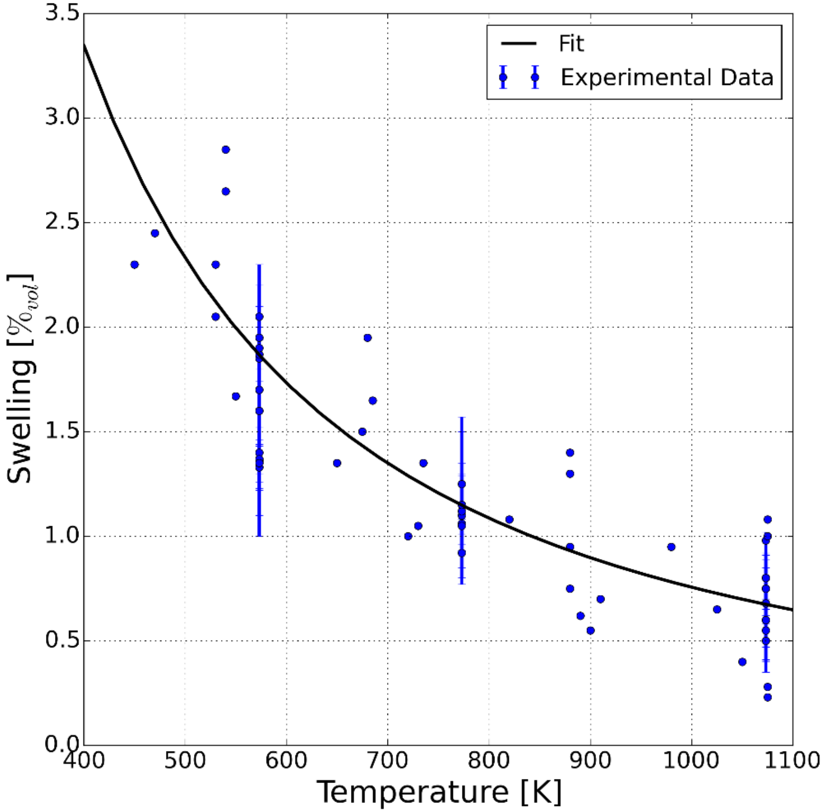


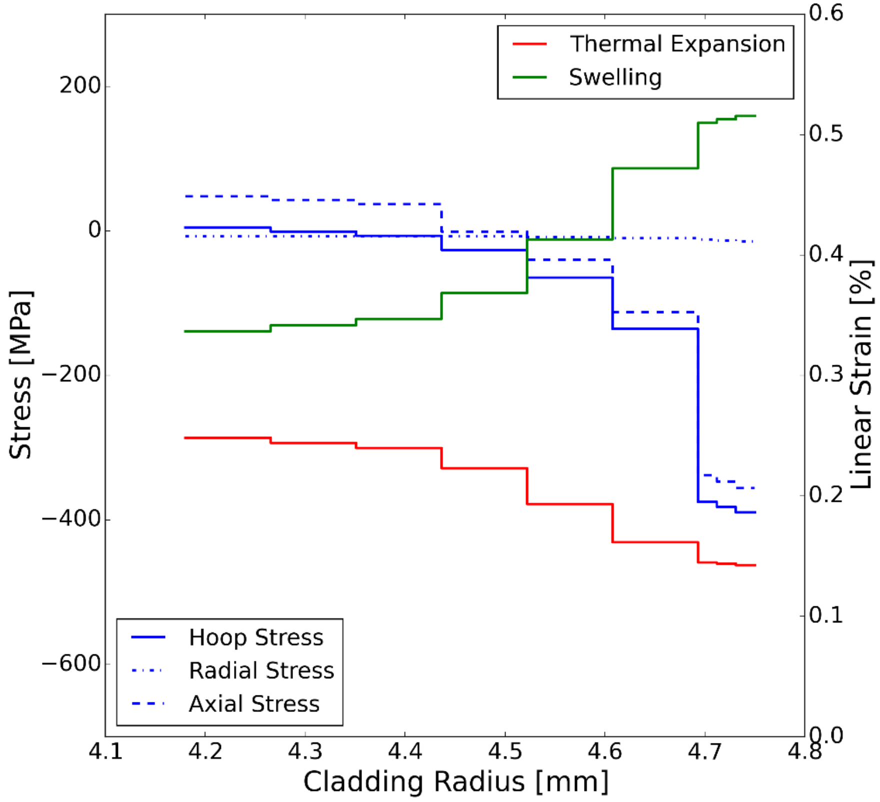
Zr-4/Cr



SiC Cladding Failure Mode

- Different layers (Monolith vs. Composite) have different thermo-mechanical property
  - Irradiation swelling strain is in opposite direction to thermal strain.

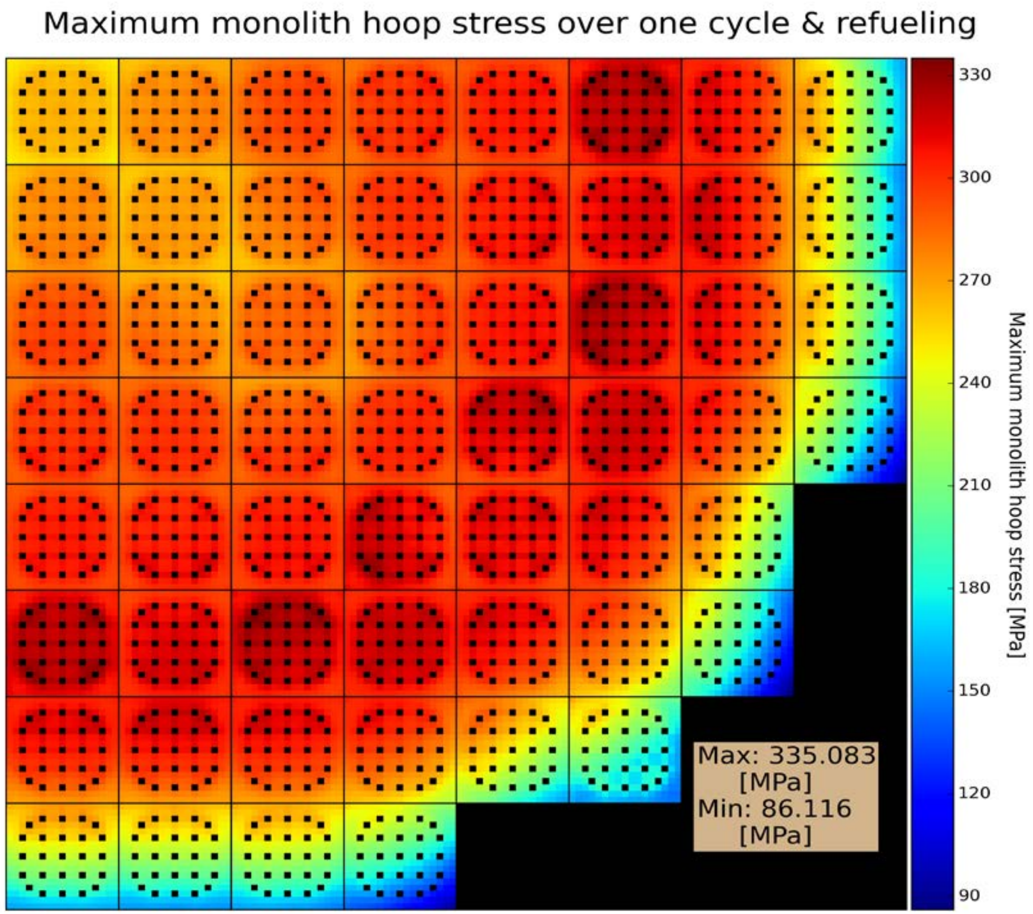


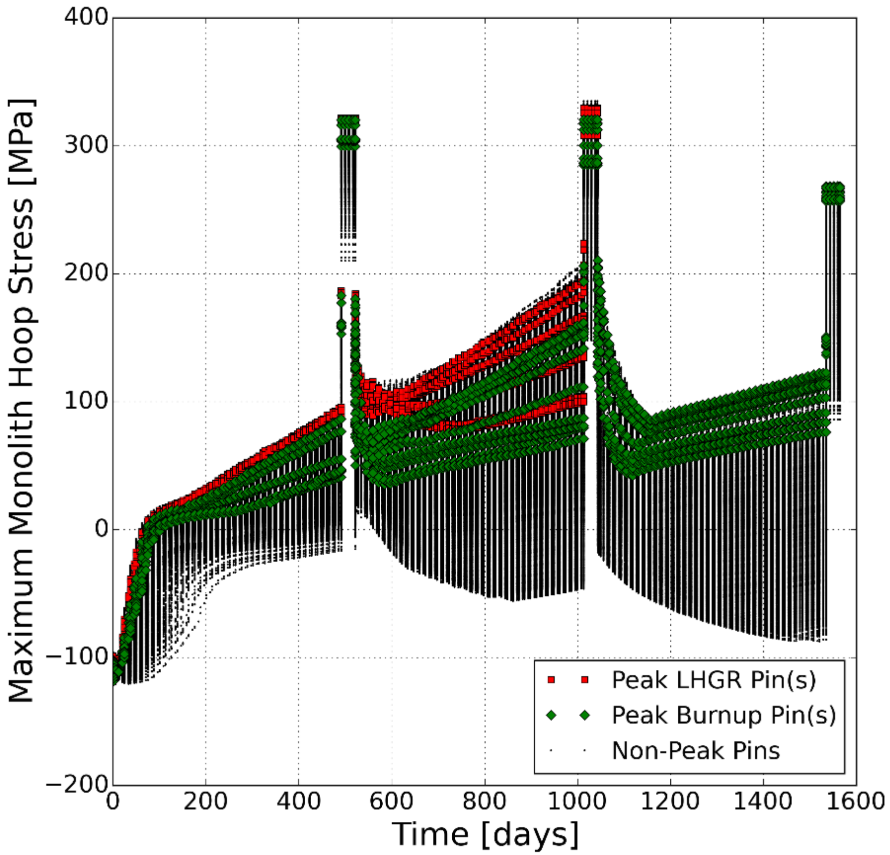


Stress @ Shutdown: Thermal strain that is going against radiation induced swelling strain is very small at shutdown.

SiC Cladding Failure Mode (2)

- Can stress-induced failures meet current fuel failure standards (1 ppm)?





From: Mieloszyk, **Shirvan** et al., ANFM, 2015

SiC Cladding Failure Mode (3)

- Important lesson learned from 2014 MIT SiC Modeling Workshop

Weak Modeling & Simulation

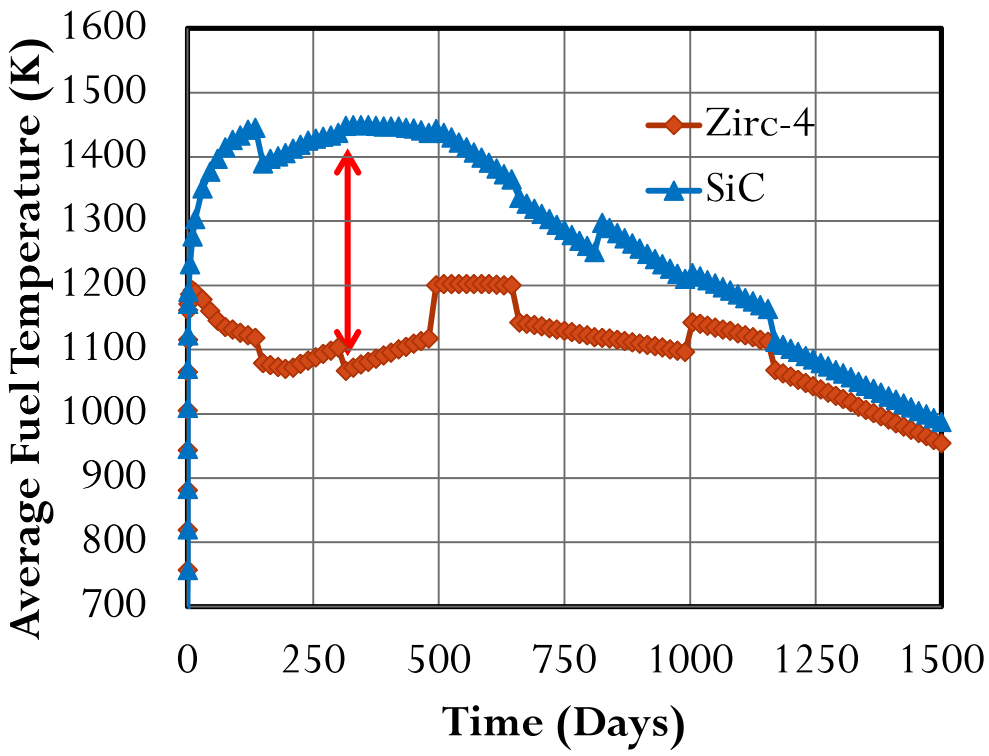
PIE Figure From Morris et al., ORNL-24 (4-00), 2014

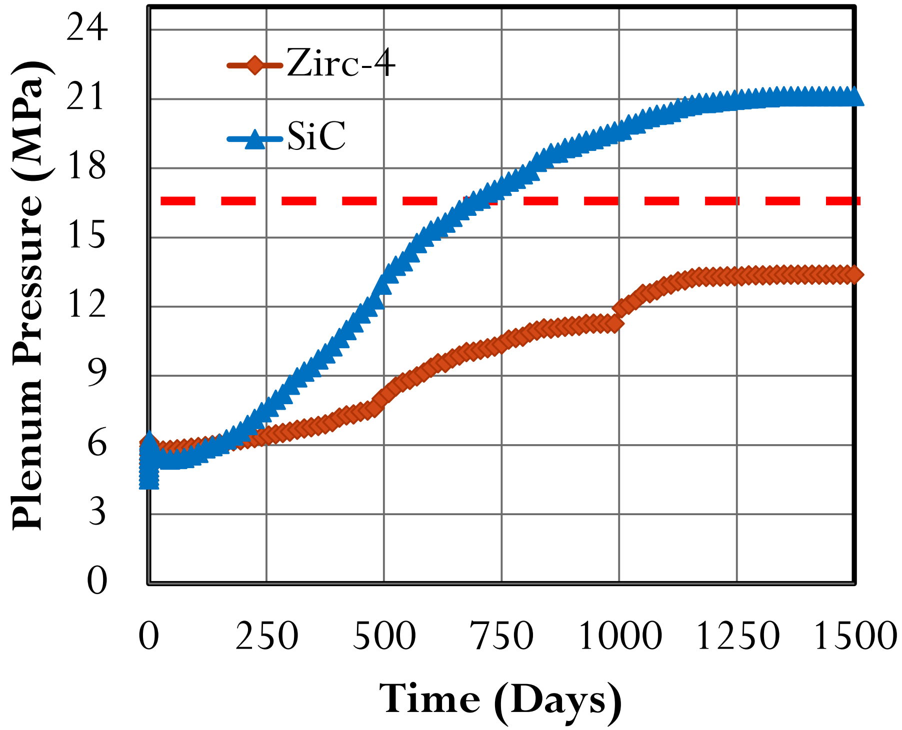
Strong Modeling & Simulation

Image From: https://atrnsuf.inl.gov/documents/review2016/161102_Katoh_NSUF-APR_Rad-HHF-synergism%20R1.pdf

SiC Integral Fuel Performance

- SiC cladding results in significant increase in UO_2 temperature.
  - SiC irradiated thermal conductivity is almost 1/3 of Zircaloy.
  - SiC lack of creep down also contributes to this higher fuel temperature.





* Simulation Performed with FRAPCON-MIT, 2014

SiC Integral Fuel Performance (2)

- How can we reduce the fuel temperature:
  - Fuel w/additives or gap fillers
- How confident are we in fuel temperature predictions:

Zr-4 Fuel Performance	FRAPCON	BISON
Max Beginning of Life T (K)	1367	1352
Max End of Life T (K)	1574	1656
Max Plenum Pressure (MPa)	11.1	11.1
Max FGR (%)	11.9	8.6

SiC Fuel Performance	FRAPCON	BISON
Max Beginning of Life T (K)	1631	1606
Max End of Life T (K)	1852	2288
Max Plenum Pressure (MPa)	14.2	35
Max FGR (%)	28.6	53.6

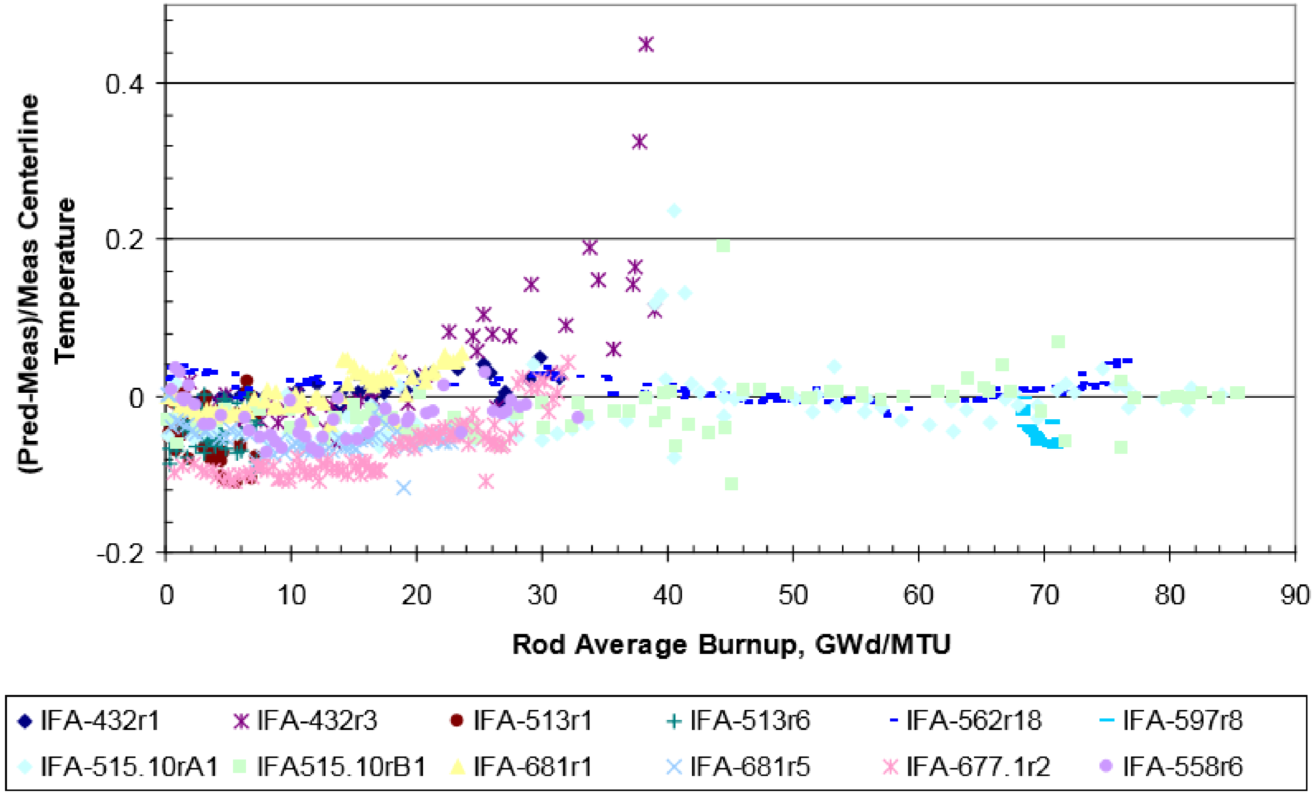
Table from: **Shirvan**, ICAPP '14

SiC Integral Fuel Performance (3)

- Gap remains open for extended period of time for SiC case.
  - Typical fuel performance validation data are integral

Cracking models could account for over 50% of gap closure

Michel et al., Eng. Frac. Mech., **75**, 3581 (2008)

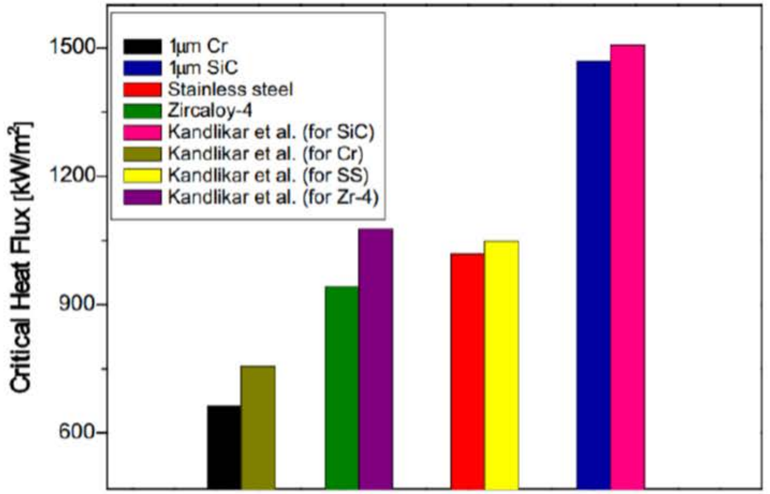


UO_2 FRAPCON assessment cases as a function of burnup [Fig. from https://www.nrc.gov/docs/ML1110/ML11101A006.pdf]

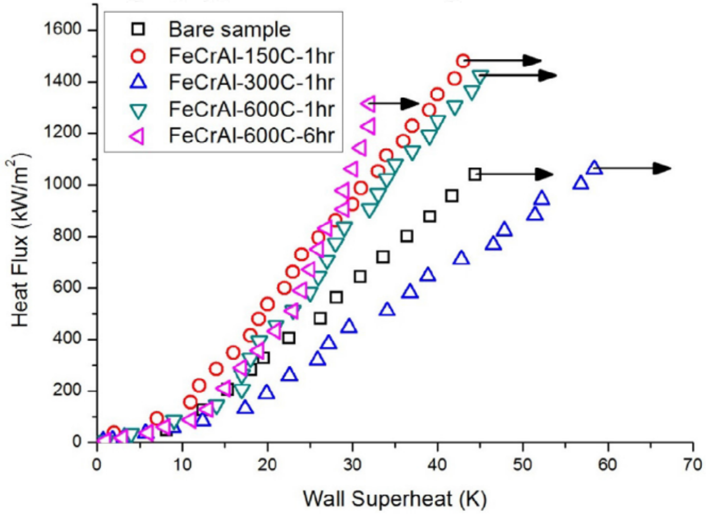
Cladding Water-Side Heat Transfer

- Departure from nucleate boiling (and dryout) during steady-state and fast/slow transients needs to be measured for different ATF surfaces
  - Large V&V challenge without prototypic size testing (e.g. Scaling)

Recent Pool Boiling Data show Zr and Cr to be similar



From: Kam D.H., Et al., An. of Nuc. Energy 76 (2015)



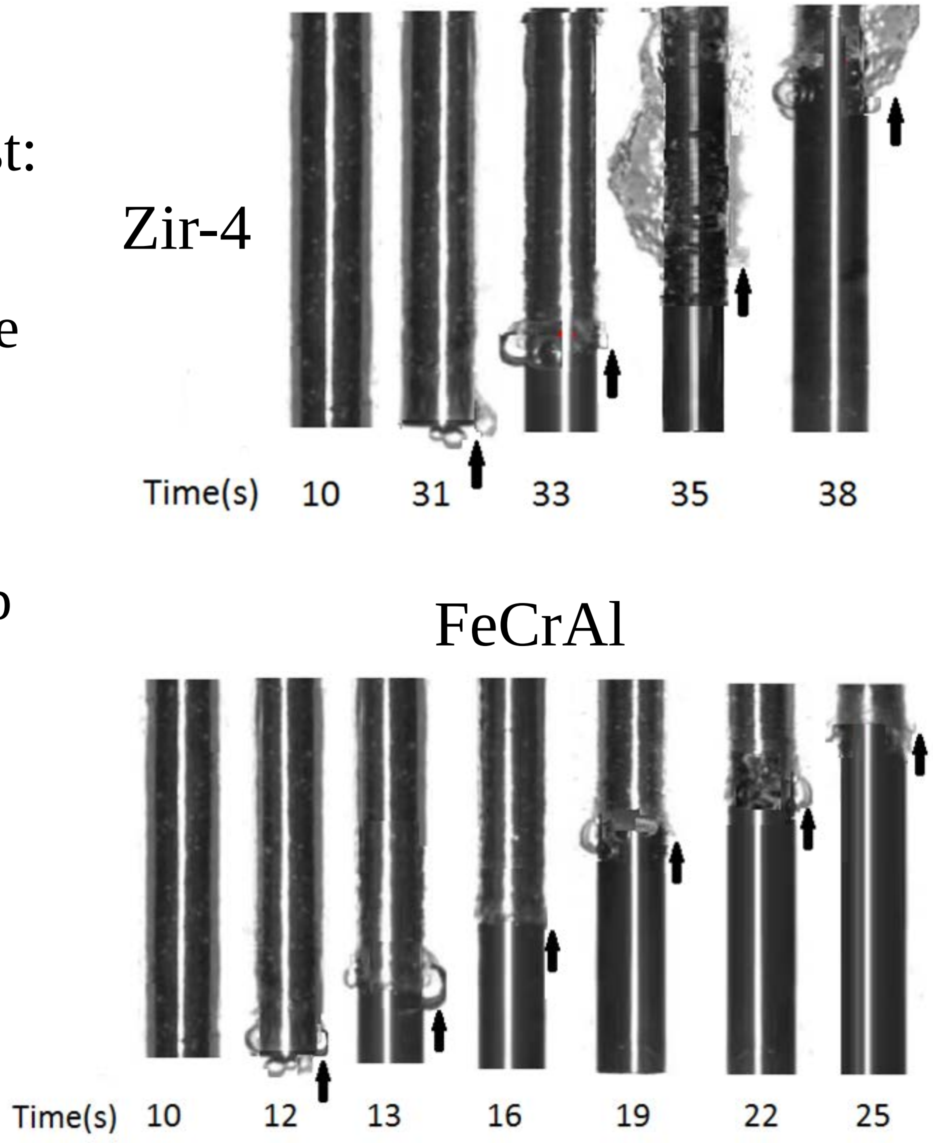
From: Seo et al., JHMT, 102, 2016

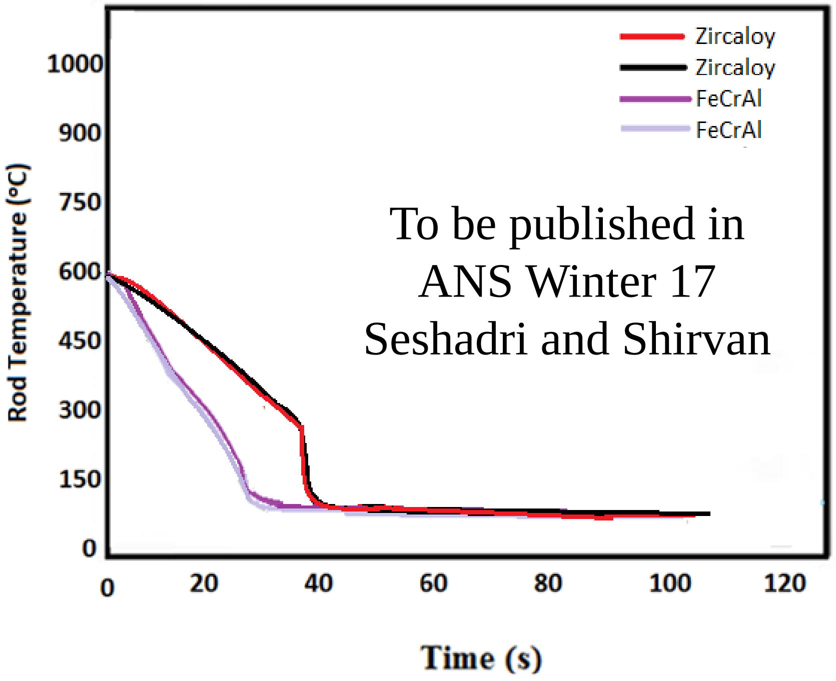
	Roughness (μm)		Contact Angle	
Sample Condition	**Zirc-4**	**FeCrAl**	**Zirc-4**	**FeCrAl**
As Machined	0.352	0.651	83.5°	79.7°
Oxidized	0.424	0.712	48.2°	39.4°
Quench Sample	0.312	0.384	83.1°	81.1°

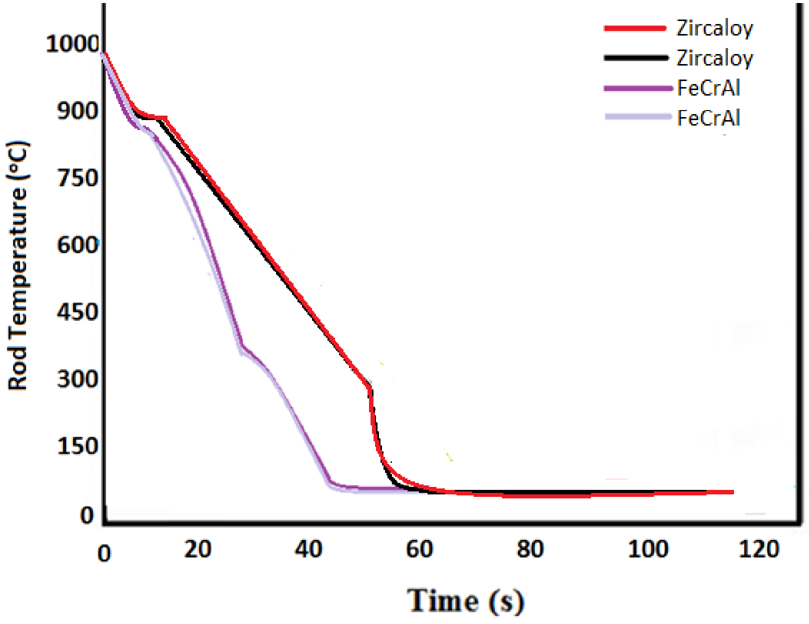
What are the effect of gammas and neutrons?

Cladding Water-Side Heat Trans

- Parameters and Physics of interest:
  - Roughness
  - Contact Angle
  - Wickability
  - Emissivity
  - Quench Temp
  - Water Temp
  - Quench velocity
  - Fluid Regime

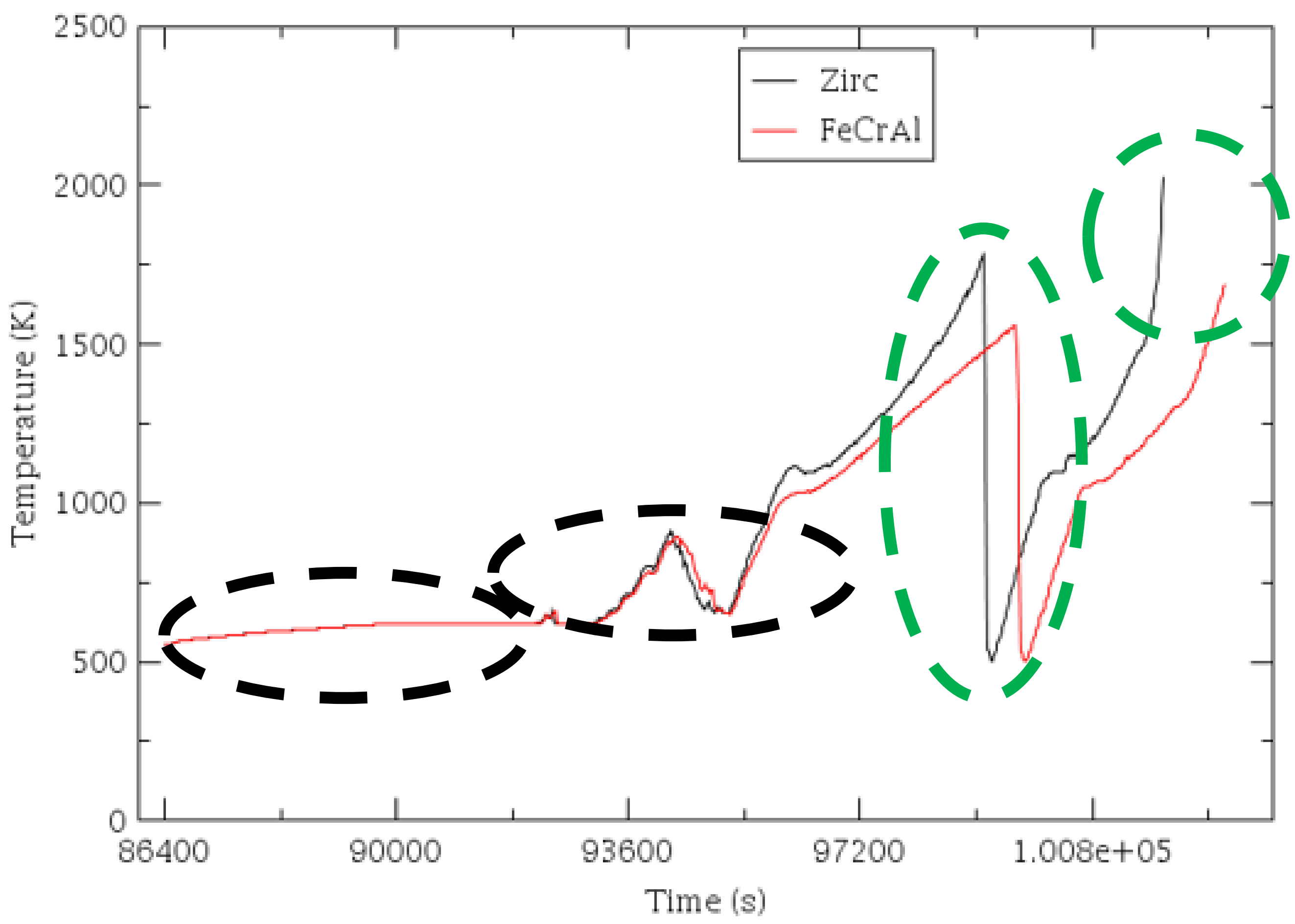






Severe Accident Progression

- Accident Sequence:
  - Steady State (leading up to accident)
  - Blowdown/Boil off/Rod Burst
  - Heat up to Primary System Failure (e.g. hot log creep rupture) → Depressurize
  - Heat up and Core Melt If Nothing is Done!
- If extended grace period is credited then <u>New Failure Modes</u> during the BDBA sequence need investigation.



TRACE PWR Simulation of SBO

Concluding Remarks

- State-of-Art high fidelity simulation resources are needed to design smart out-of-pile/in-pile experiments and assess ATF time-to-failure

- Much research needs to still focus on failure modes to allow for an informed UQ analysis.

- Despite tremendous progress in M&S, V&V of many key parameters still requires proto-typical geometry and conditions (e.g. irradiation/Temp/P).

- Close collaboration of all organization involved in nuclear R&D is critical for ATF development.
  - ➢ Lets Join Forces to Tackle the ATF Challenge Problem!