LWR Stakeholder Survey Results and Gap Analysis

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Presentation Content

- Recent transient research activities
- Survey results
- Gap evaluation

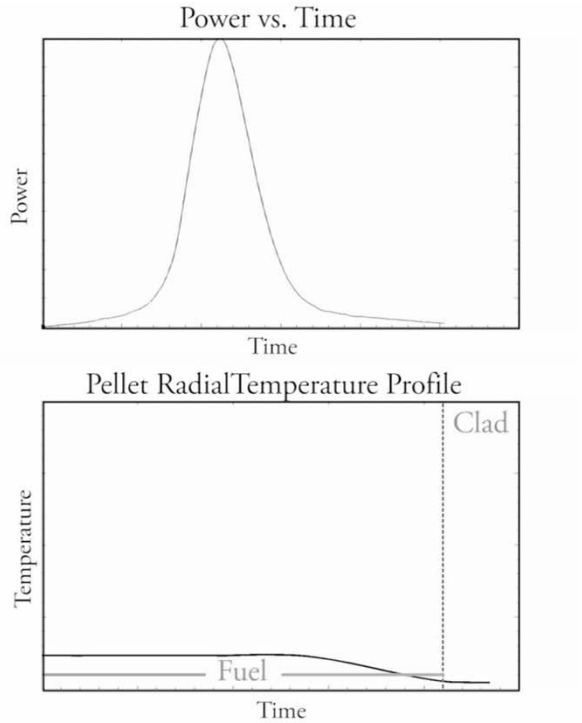
Background

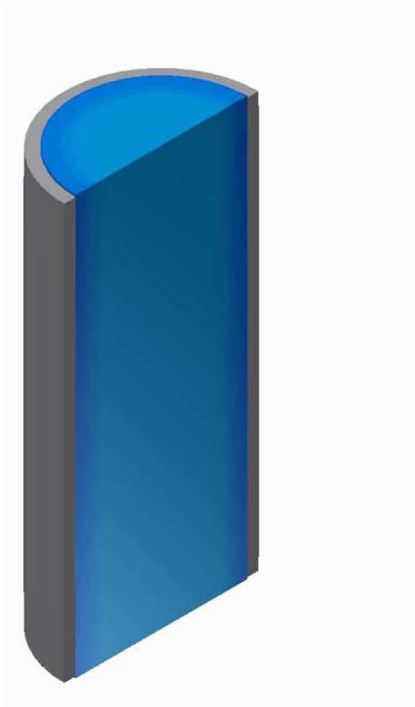
- Regulators became concerned with high burnup effects in the early '90s
  - Reactivity initiated accident (RIA) test programs
    - CABRI, NSRR, IGR/BIGR
  - LOCA research test programs
    - NRC ANL, JAEA, Halden IFA-650
- US NRC initiated LOCA rule making and issued draft regulatory guidance on RIA

Reactivity Initiated Accident

Fuel Response During a RIA

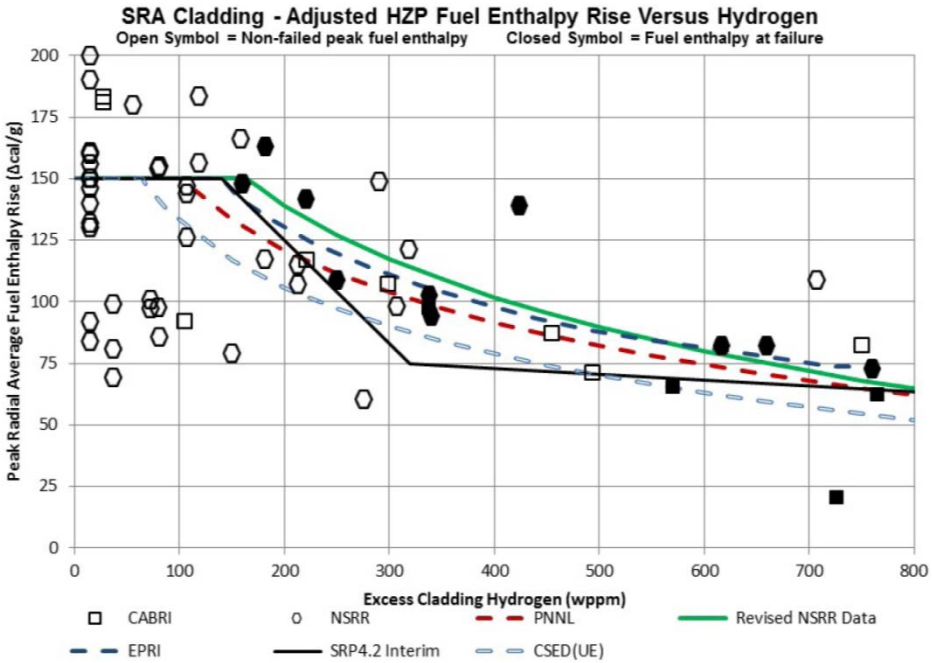
- Reactivity Initiated Accident – Sudden control rod ejection causes a brief power surge

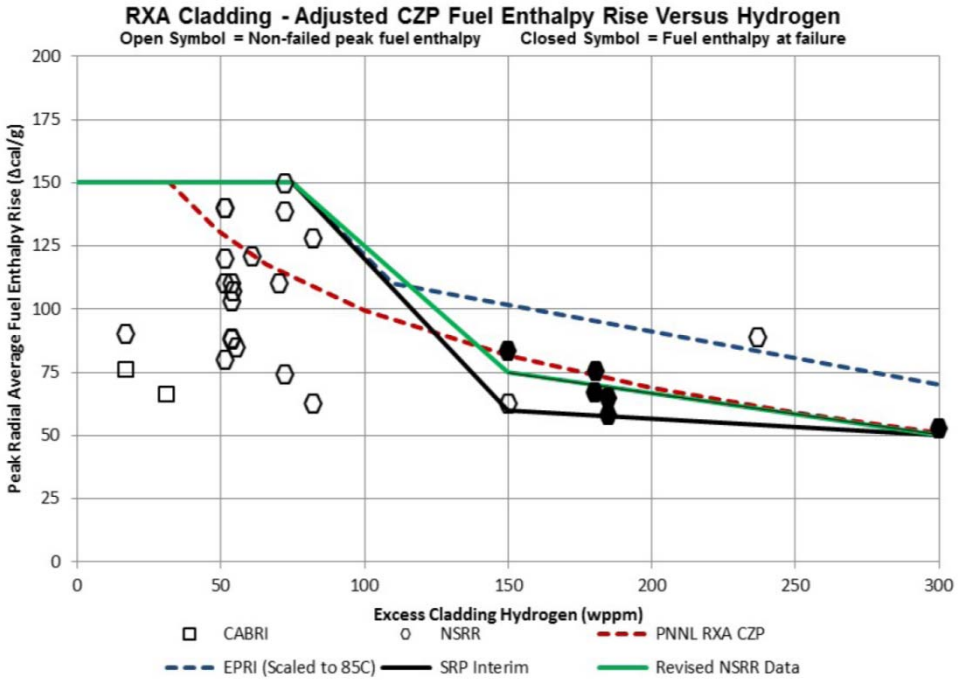




Proposed RIA PCMI Limits

- Limits based on NSRR test data (low temperature and short pulse width)





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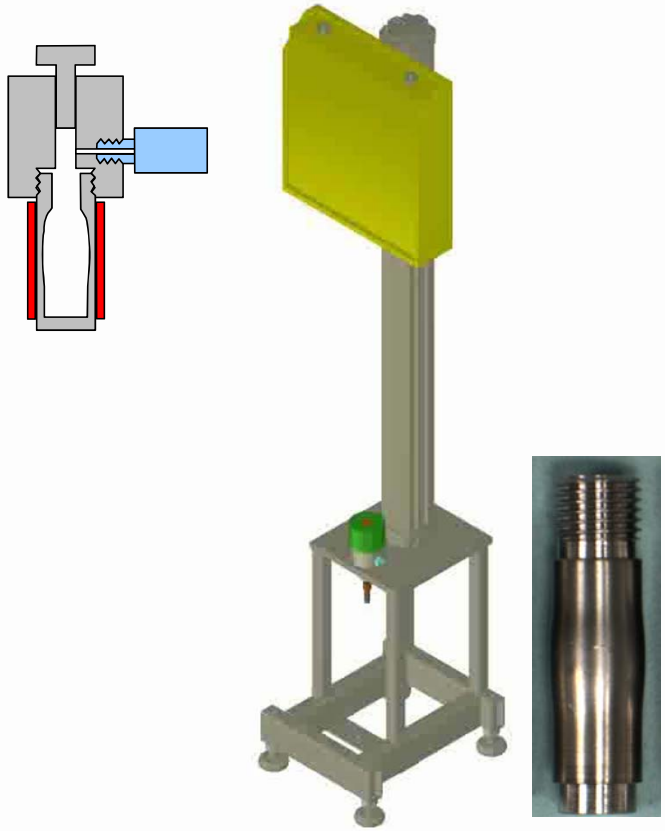
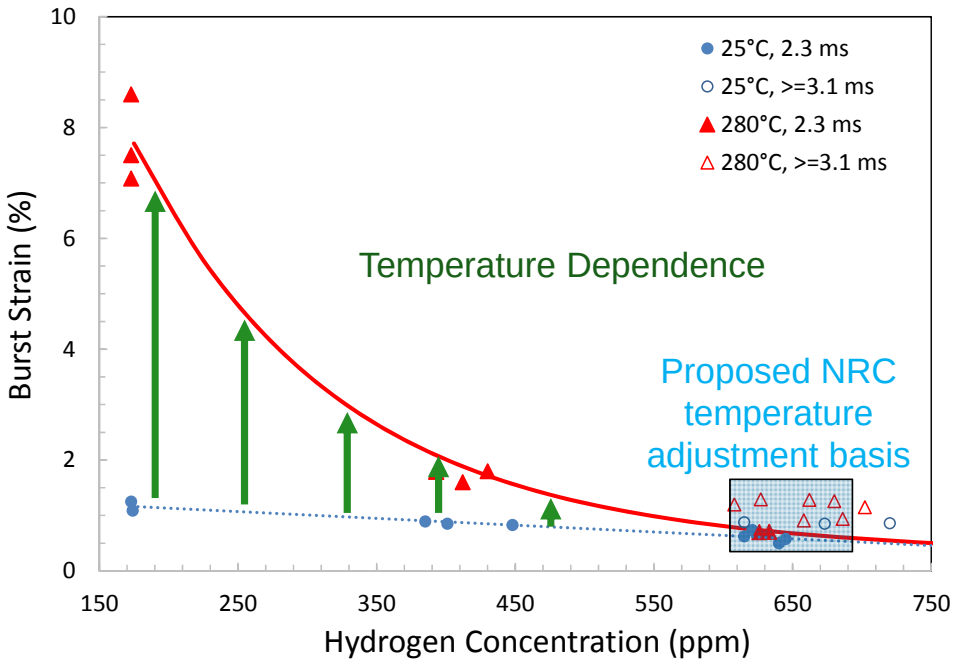
Modified Burst Test

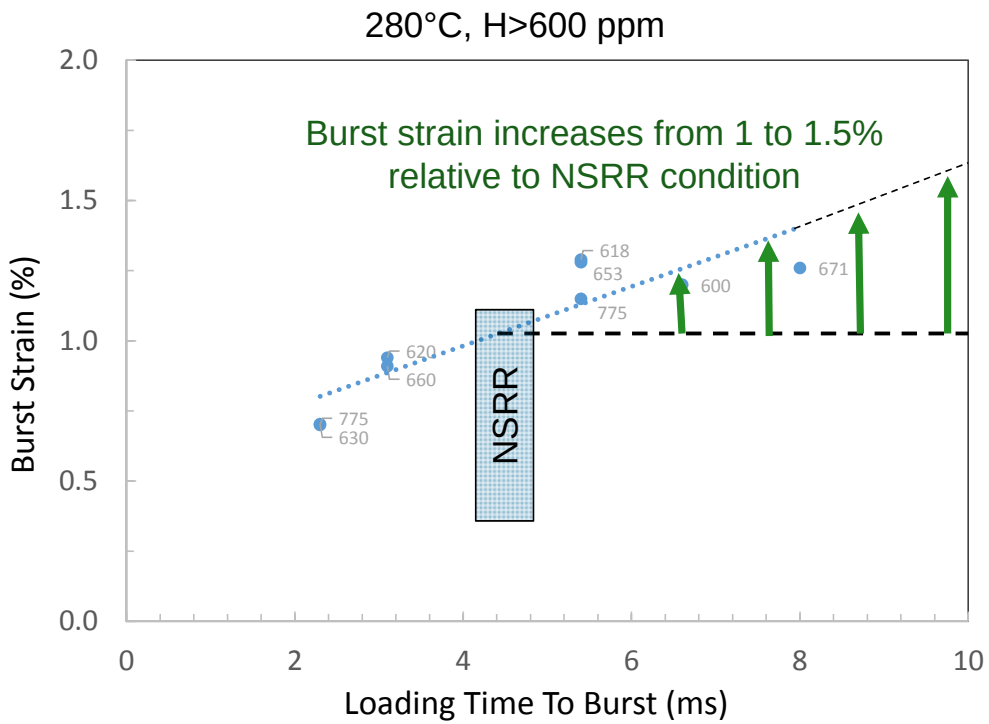
- NRC suggestion a “go/no-go” test
  - Support new alloy performance qualification
- Driver tube simulates pellet expansion
- Improvement over standard burst tests
  - Partial displacement driven deformation
  - Loading rate control by drop weight velocity/height
  - Desired deformation by piston travel
  - Live diameter measurements
  - Uses only 1” of cladding



Modified Burst Test Results – PWR SRA Cladding

- Test results indicate strong temperature and loading rate dependence

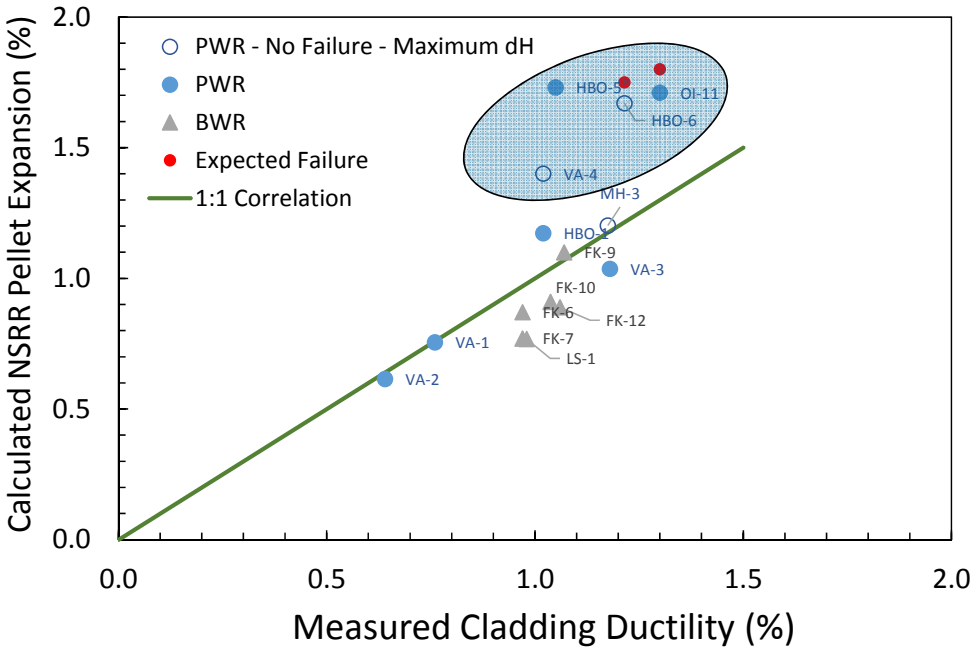




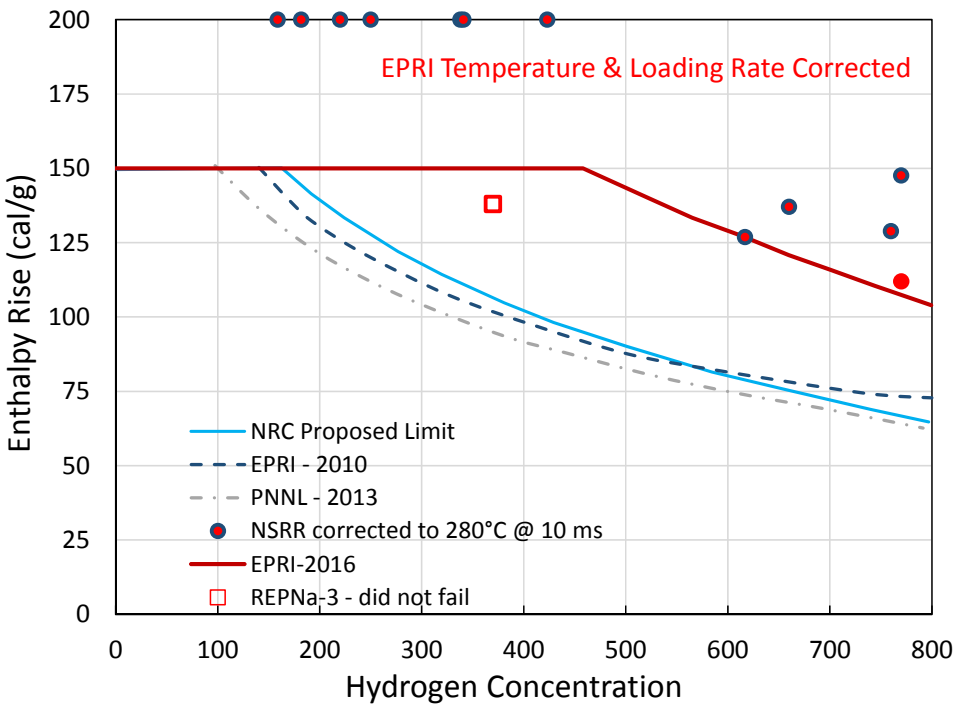
MBT Benchmark Results

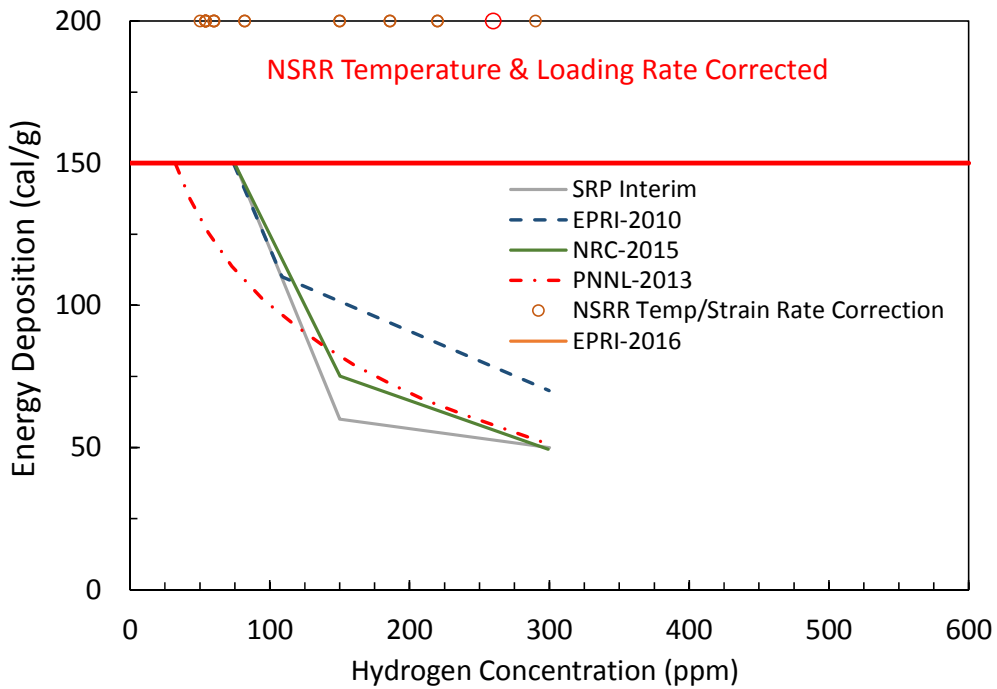
- Failed NSRR tests (and a few non-failed tests)
  - Known power history included in the benchmark

- MBT test data directly correlate with calculated NSRR failure strain
  - A few RXA BWR tests depart slightly (both parent rods operated at very low power in the last cycle)
- Some tests survived beyond cladding burst strain limits
  - Potential explanation with fuel flow at high temperatures



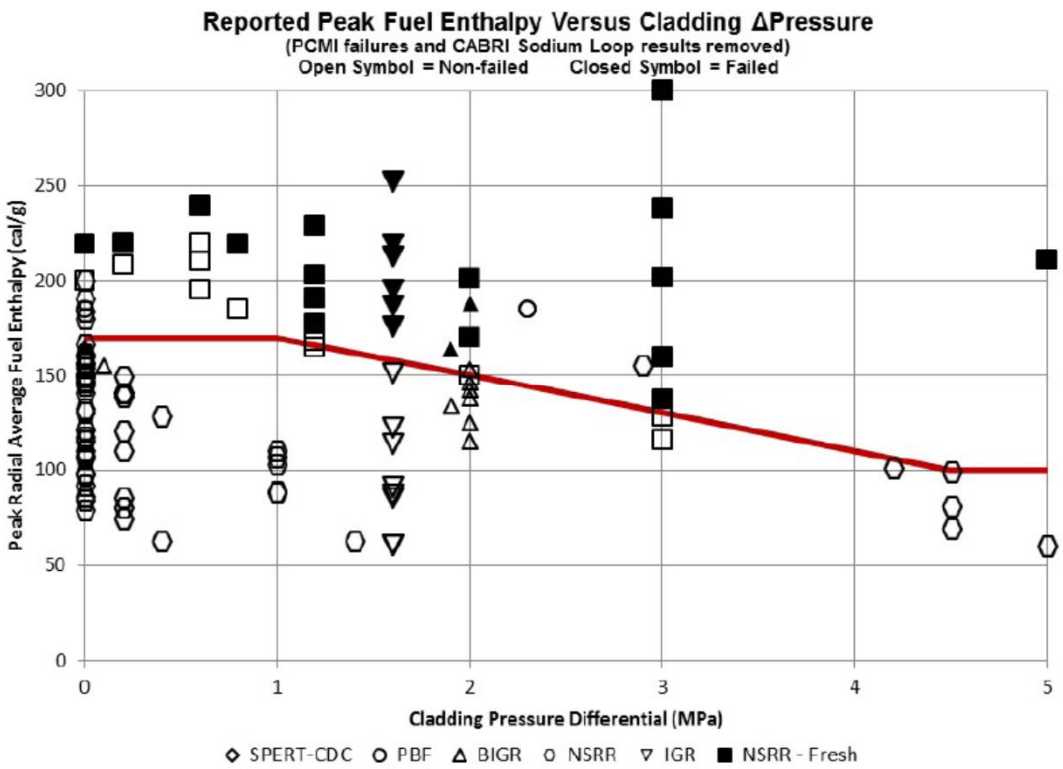
Technical Limits Suggested by Test Data





- Additional in-pile verification would be useful

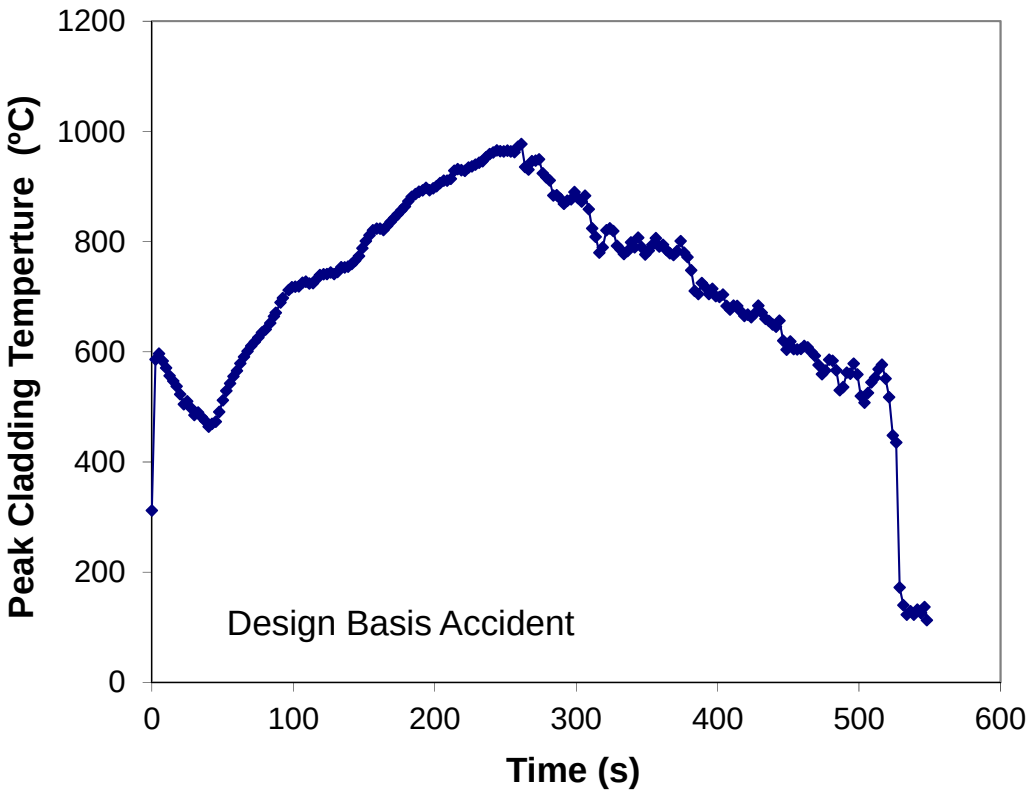
Proposed Over Pressure Failure Limit

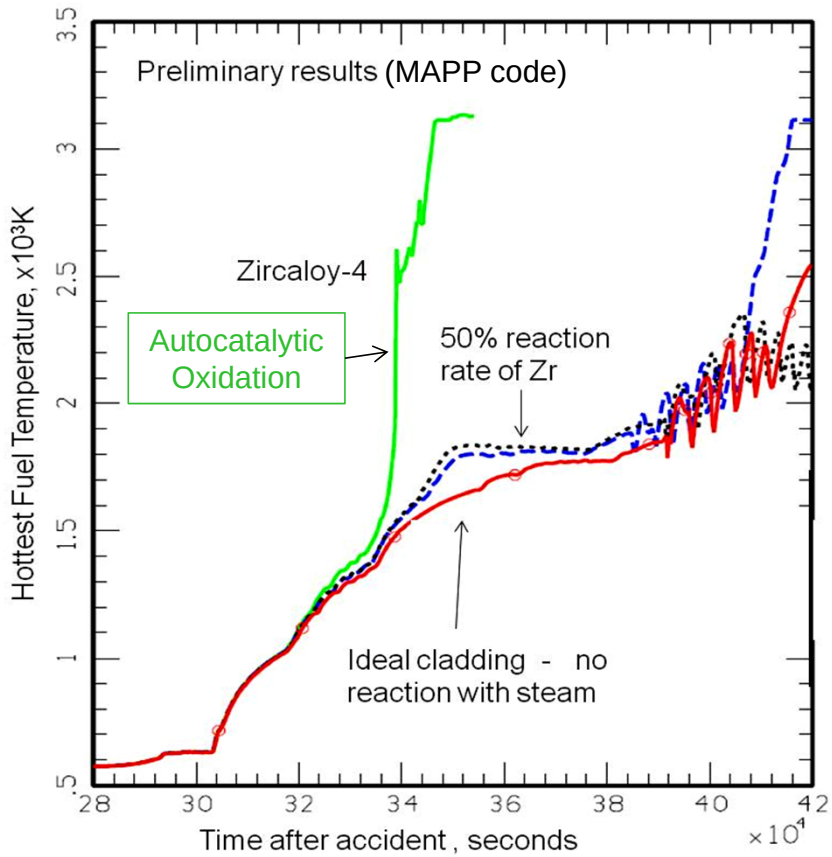


- Requires consideration of transient fission gas release ~20% depending on burnup
- No transient fission gas release data from prototypical rod pressure

Loss of Coolant Accident

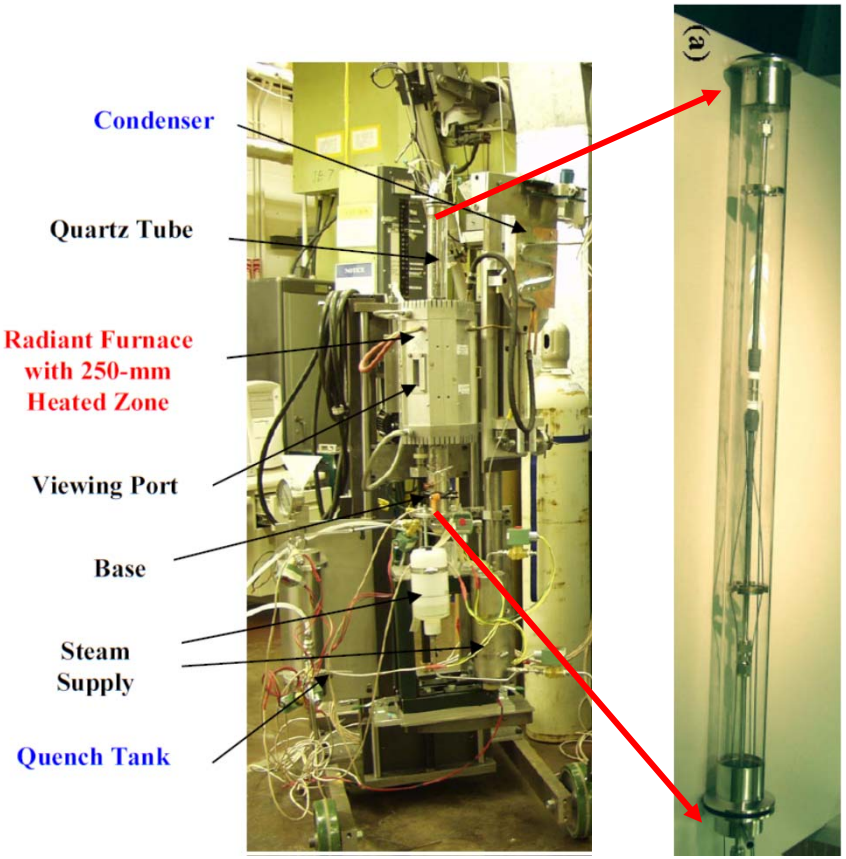
Phases of a LOCA

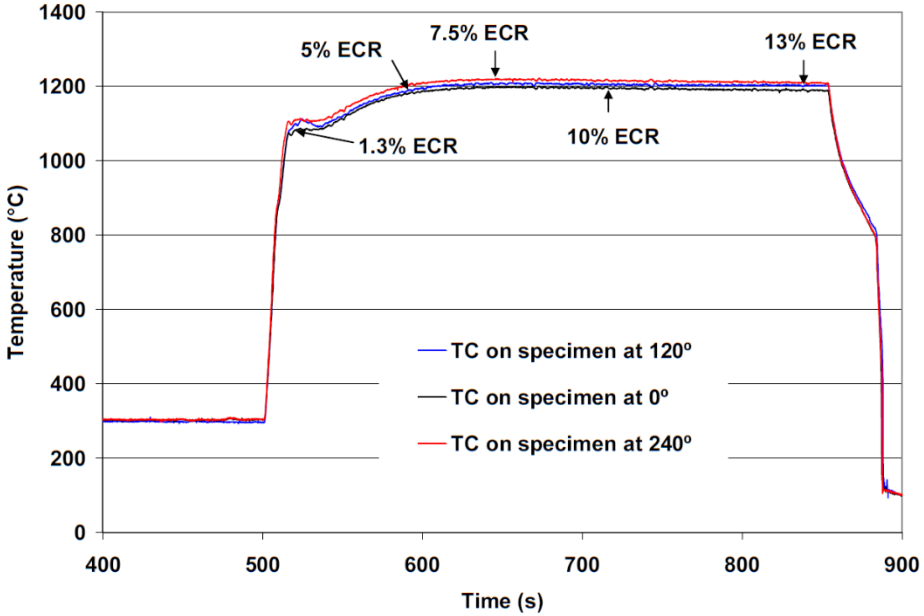




(Assume 72 hr passive cooling)

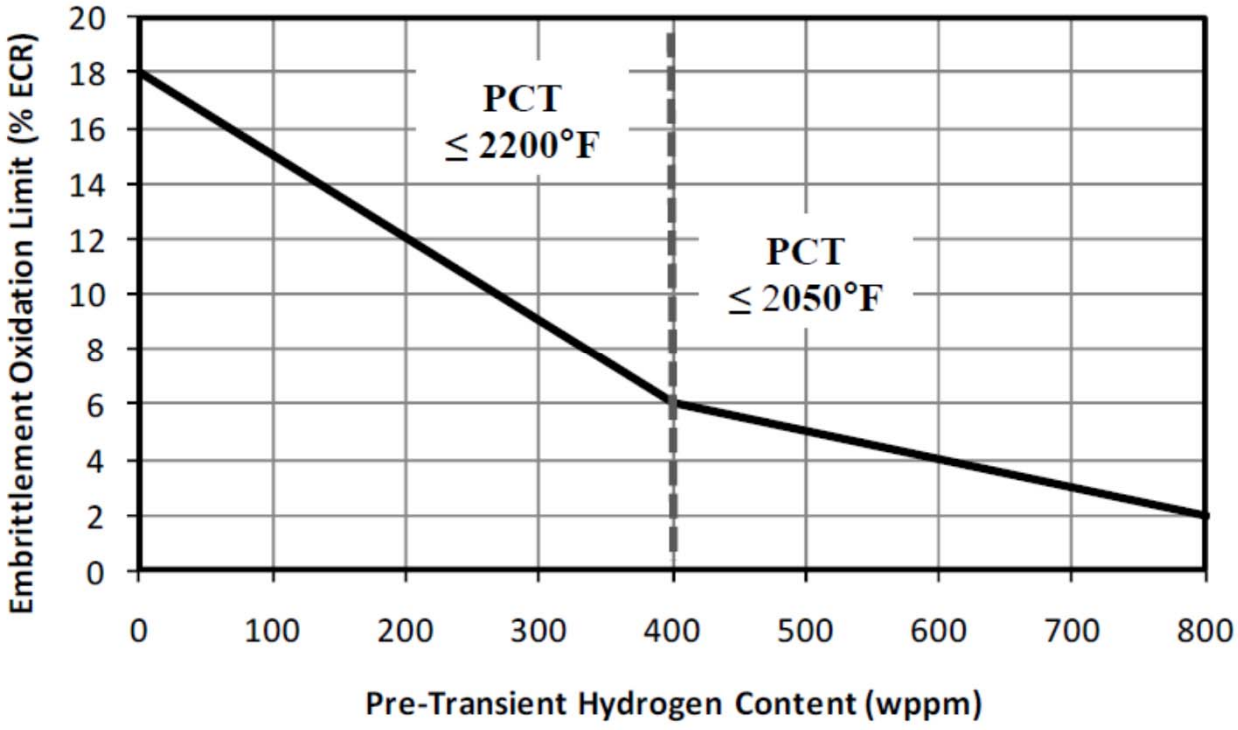
ANL LOCA Study



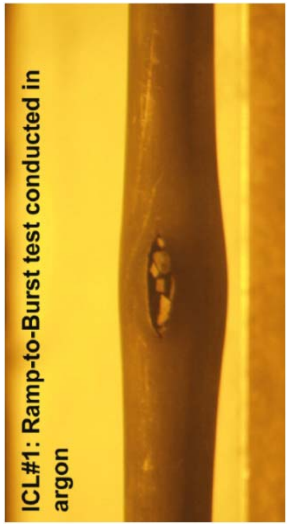


Proposed Ductility Limit

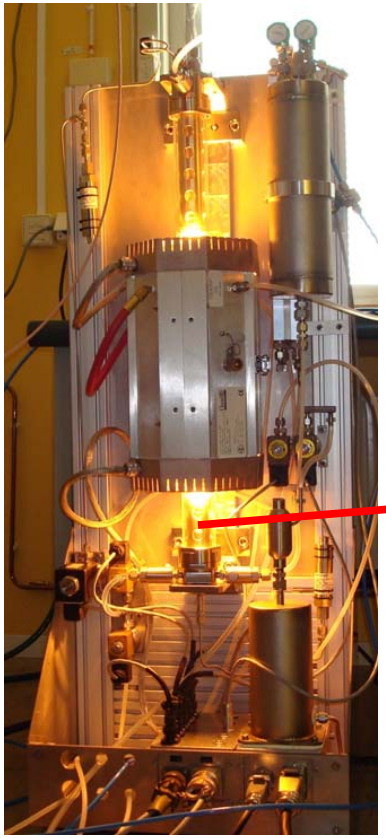
- Limiting time at temperature

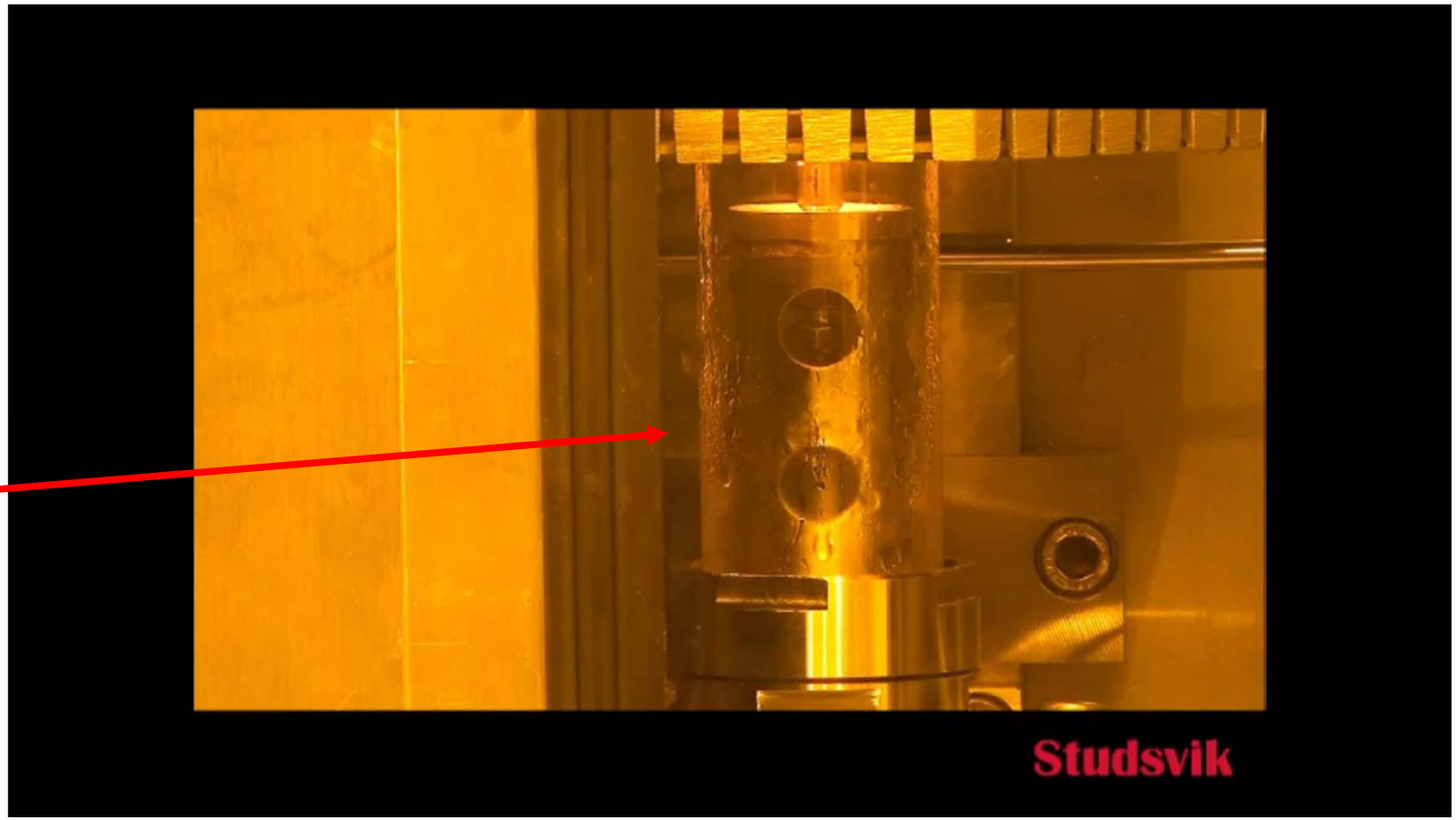


What about the ballooned and burst region?

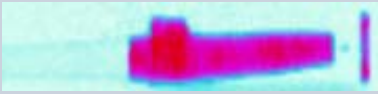
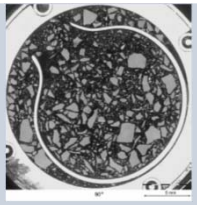
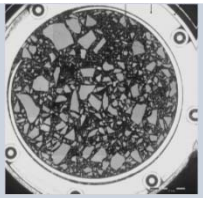
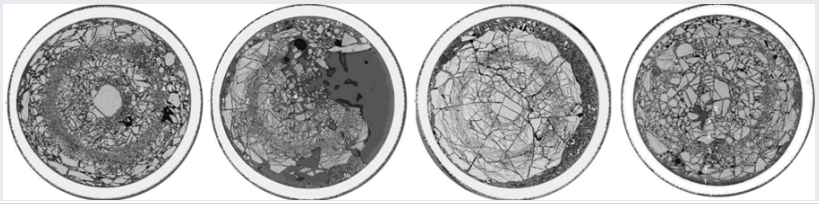
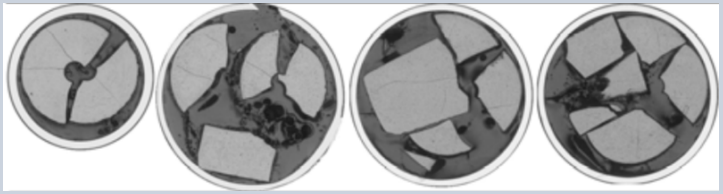
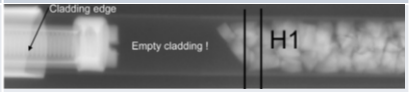
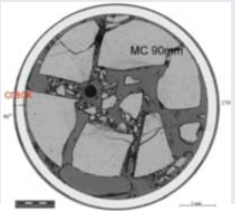
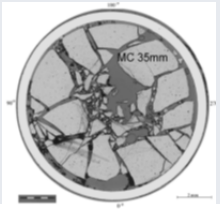


NRC LOCA and Bend Test – Severe Fuel Fragmentation





Sample Halden Tests

Test	BU		
4 800°C PCT PWR	92		 
5 1050°C PCT PWR	83		
6 830°C PCT VVER	56		
7 1150°C PCT BWR	44	 	 

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Severe Fuel Fragmentation Impact

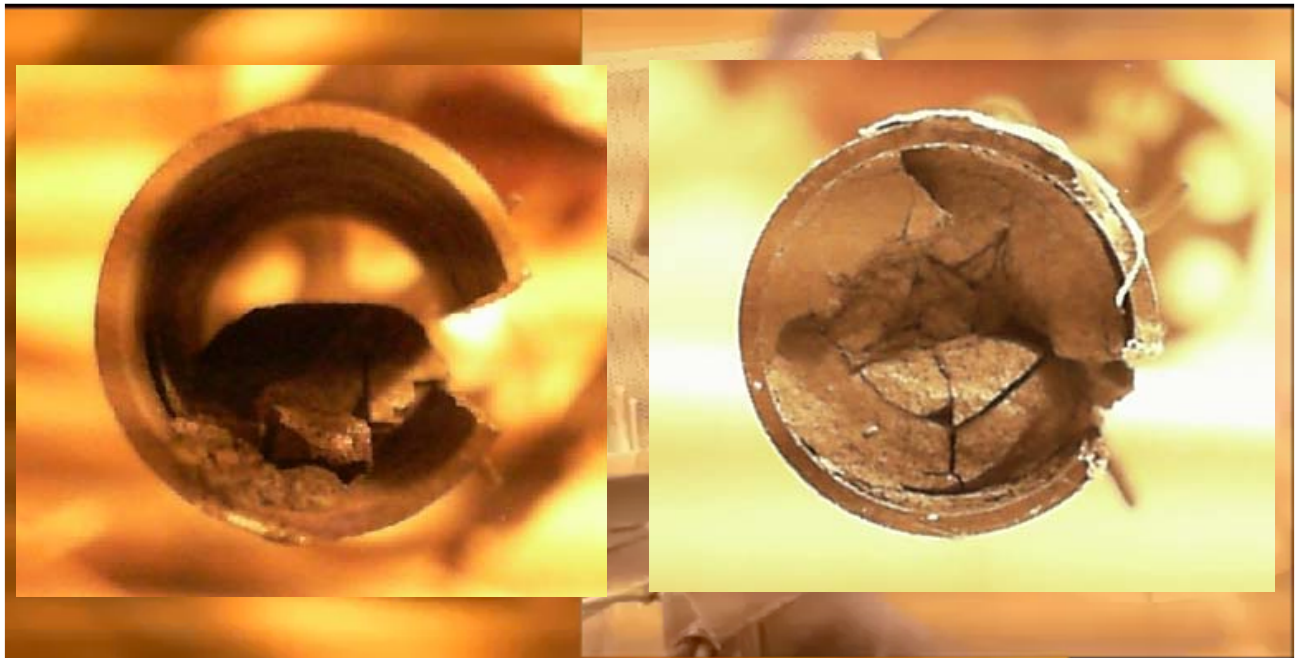
- NRC staff specifically identified a need to *"….define the boundary of safe operation for key fuel design and operating parameters, the staff is challenged to evaluate the acceptability of future fuel design advancements and fuel utilization changes."*
- Industry is interested in extending the burnup limit to reduce operating cost
  - 1/3 of the fleet is burnup limited
- Characterization of the fuel behavior is needed to enable disposition of the issue

Parametric Pellet Heating Test

- Test sample ~1” long
- Axial slit to remove radial restraint – to simulate ballooning condition

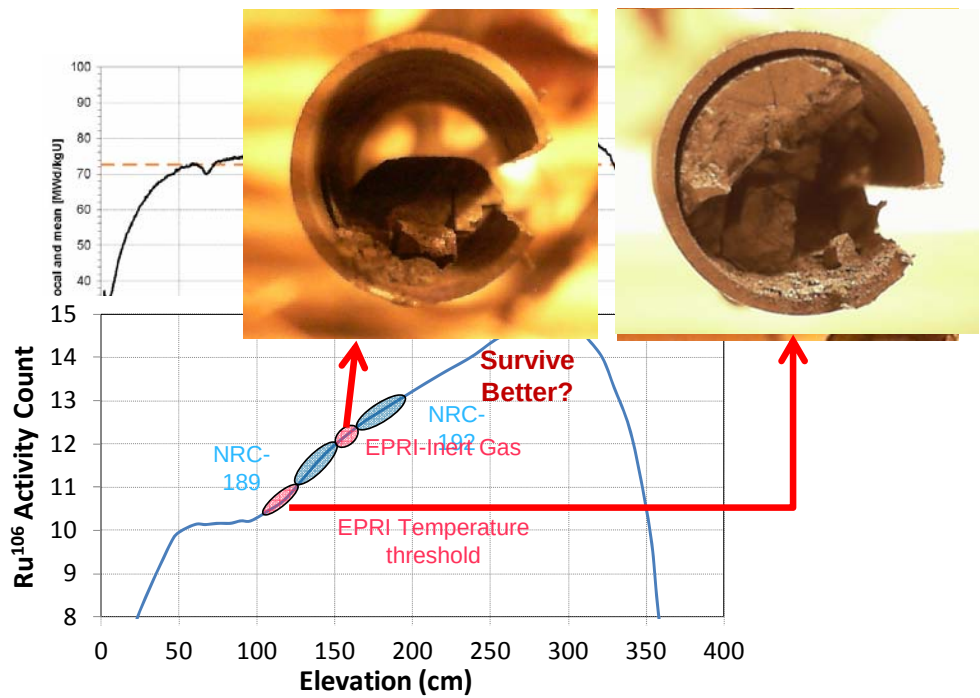
NRC Tested Rod
75 GWd/MTU
15 kw/m Last Cycle Power

Alternative Tested Rod
67 GWd/MTU
5 kw/m Last Cycle



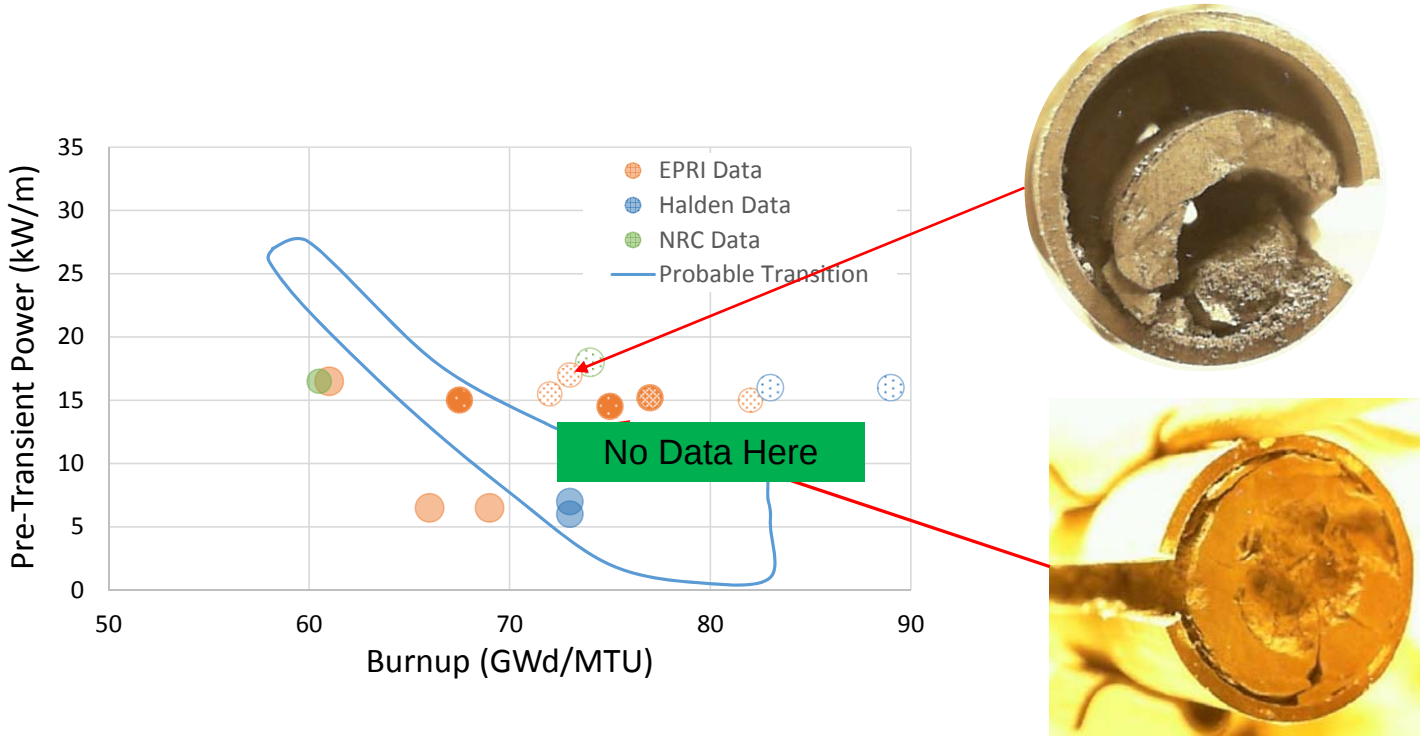
Pre-transient Power Effect

- Fuel rod operated with significant power tilt in the last cycle of operation
  - ^{106}Rh half-life ~1 year
  - Fuel rod irradiated for 3 cycles in the original host fuel assembly
  - Discharged and 3 years later transplanted to a fresher assembly and irradiated for a 4th cycle



Fuel Fragmentation Threshold

- Research is limited by availability of fuel with required pre-transient power history



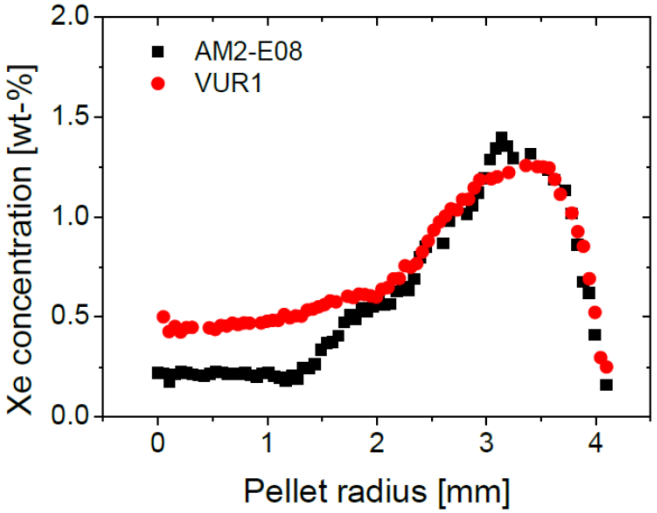
Fragmentation Mechanisms

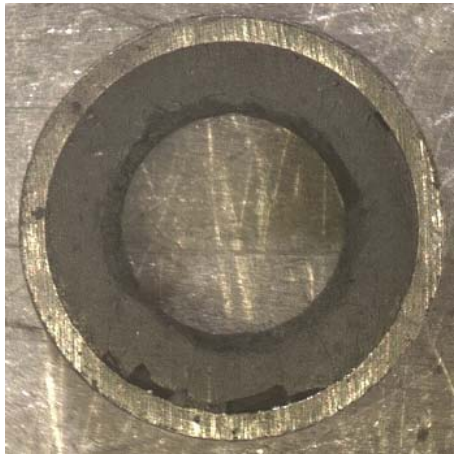
- Grain boundary fission gas generally accepted by scientific community

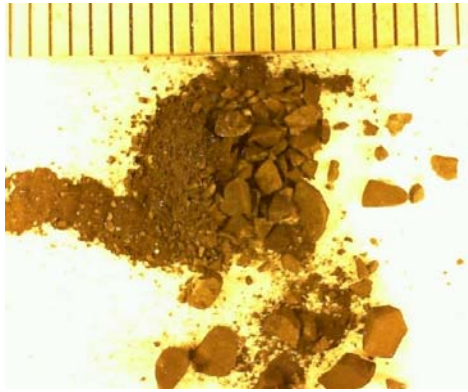
- Internal stress due to operational temperature gradient may also be a factor

Grain Boundary Fission Gas Measurement

- Oxidize fuel at low temperatures in the presence of oxygen
  - Preferential oxidation of grain boundaries
  - Pellet interior contains significant grain boundary fission gas

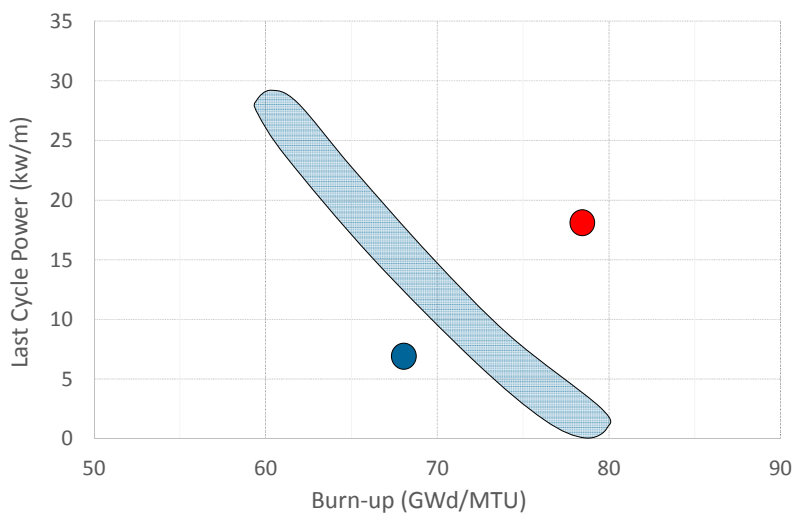


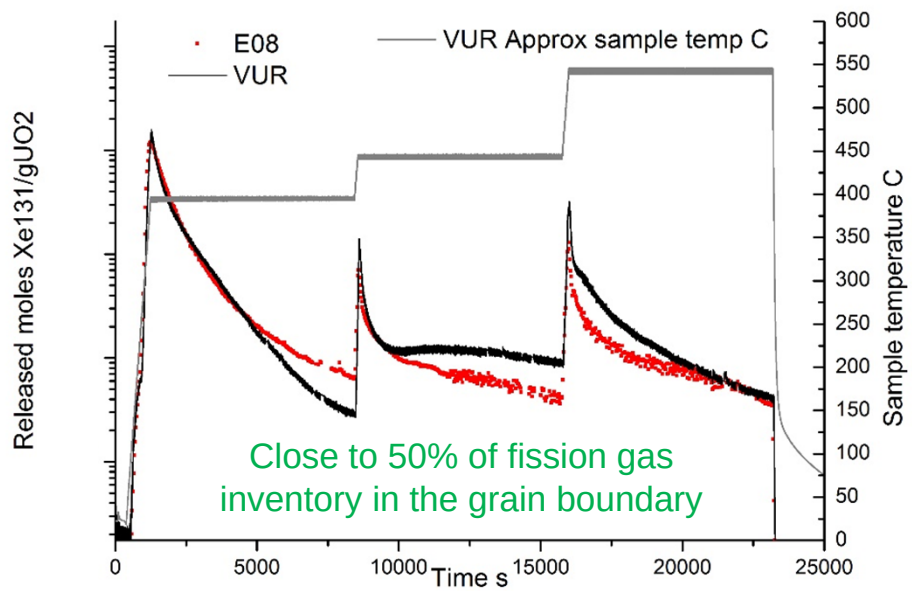




Fuel Fragmentation Mechanisms

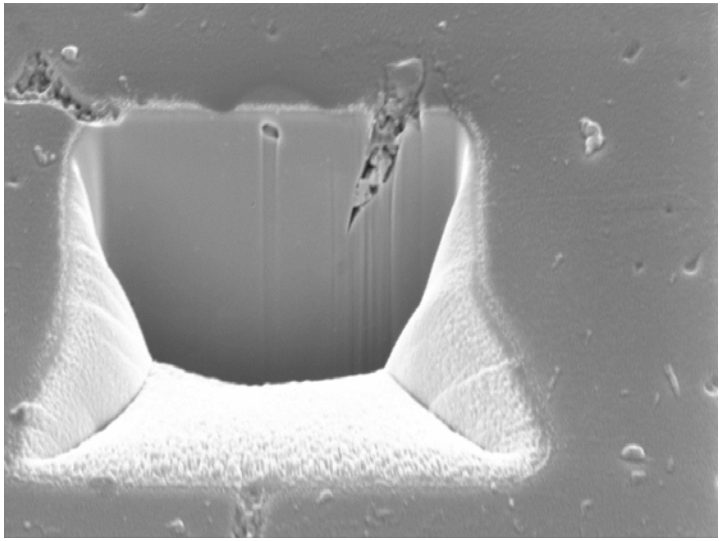
- No difference in the grain boundary fission gas content detected
  - Canadian Nuclear Laboratory (CNL) personnel indicates grain boundary fission gas saturation

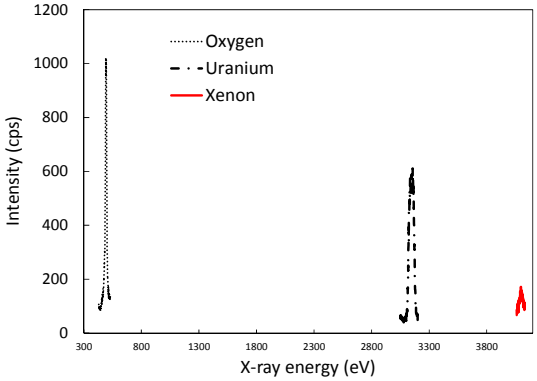




Intra-Grain Fission Gas Evaluation

- Focused ion beam milling to expose pores

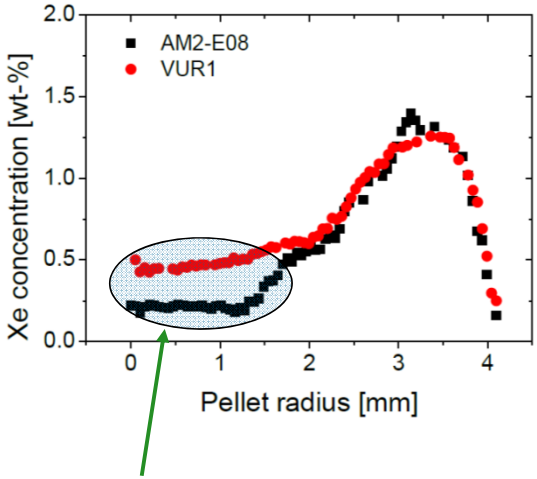




- Incremental Slice Building Pore Profile
- Use Software to Model X-ray Emission
- Adjust Gas Density to Match Measured X-ray Emission

Intra-Grain Fission Gas

- Verified expected lower intra-grain fission gas in the pellet interior
- Limited number of bubbles analyzed
  - Bubble pressure difference at differential radial positions is small



Consistent with higher operational fission gas release of E08 rod

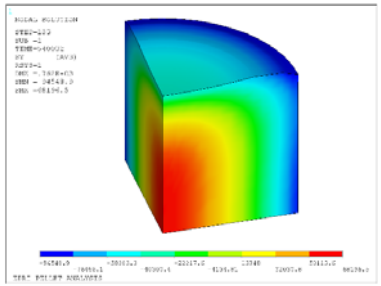
		Bubble pressure at STP	Bubble pressure at 700°C	
AM2-E08	**Position**	Ideal gas law	Ideal gas law	Ronchi
Bubble 1	Dark zone edge	16.1	57.3	61.3
Bubble 2	Dark zone edge	13.6	48.5	50.0
Bubble 3	Center	11.4	40.5	40.4
Bubble 4	Center	11.4	40.5	40.4
Bubble 5	Center	13.2	47.2	48.1
VUR1	**Position**	Ideal gas law	Ideal gas law	Ronchi
Bubble 1	Center	12.3	43.8	44.3
Bubble 2	Center	14.2	50.6	52.4
Bubble 3	Center	9.0*	32.0*	31.1*
Bubble 4	Dark zone edge	11.7	41.8	41.9

Thermal Stress 1/2

- Thermal stress arise because during operation the pellet interior is hotter than pellet periphery
  - In a LOCA fuel pellet would be at nearly uniform temperature
  - A 3-dimensional finite element analysis was performed

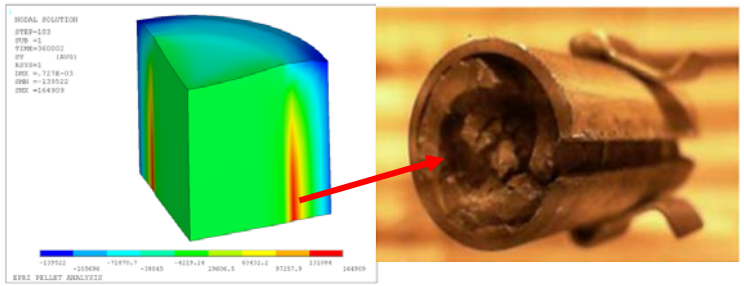
Solid Pellet Model

Pellet Interior in tension



Cracked Pellet Model

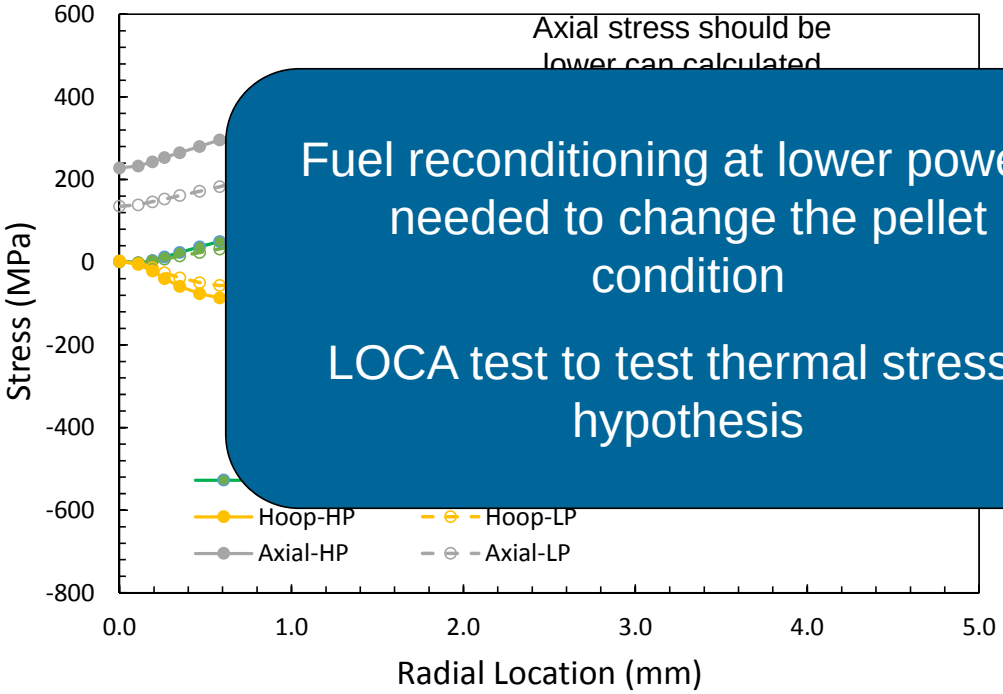
Localized stress near surface



  - Local surface stress concentration was indicated in the cracked quarter pellet model
  - Follow-up evaluation needed to determine if the local stress concentration could lead to crack propagation

Thermal Stress 2/2

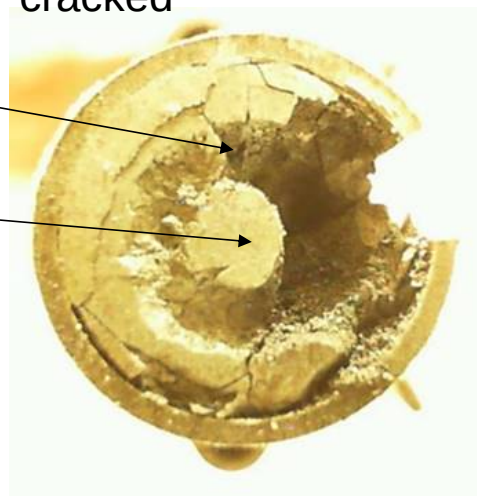
- Quarter pellet interior do not see local stress concentration
- Lower internal stress for lower pre-transient power



Fuel reconditioning at lower power needed to change the pellet condition

LOCA test to test thermal stress hypothesis

- Quarter pellet too conservative for axial stress calculation since pellet is cracked



Survey Results

Survey Questions 1/2

- What are your existing or emergent fuel transient performance issues that are not being adequately addressed?
- What methodology do you currently use to resolve fuel safety issues associated with
  - Emergent regulatory questions
  - Advanced fuel designs
  - Introduction of new operating regimes (i.e. power uprates, load following)
  - Optimize current regulatory/operating methods (i.e. apply risk informed methods)
  - Other, please explain
- What additional access to in-pile transient testing capability do you need to support timely resolution of issues?
- What capability should test devices have to meet your testing needs? (e.g., what thermal hydraulic environment (BWR/PWR static or flowing loops), pin configuration (single or multiple pins), and transient types (gradual power ramps, RIA/LOCA simulation)?

Survey Questions 2/2

- What complementary separate effects testing capability would be useful to first evaluate issues at a phenomenon level before committing to integral scale, in-reactor testing?
- What is the highest priority candidate separate effects study/studies that could be used to isolate phenomena of interest to improve codes and better design in-core testing?
- To enable/support fuel safety research described above,
  - What source material is required to conduct these experiments (fresh fuel, pre-irradiated fuel)?
  - What fuel pedigree/pre-characterization do you need to support evaluation?
  - What post-test examinations (PIE) are required to collect the desired data for NDE?
  - What PIE is required to collect the desired data for destructive examinations in a hot cell?
  - What small-sample PIE is required to collect the desired data?
- If you need access to historical reports and/or data, please list. Please add any additional information and/or questions.

Existing or Emergent Issues

Transients Conditions

- RIA/LOCA performance
  - U_2Si_3 fuel clad with SiC or SiC coated zirconium cladding
  - Fission gas release
  - Higher burnup
  - Doped pellets (Cr_2O_3 , BeO_2, Al_2O_3/SiO_2, Gd_2O_3, etc. doped pellets)
- Power ramp
  - No capability gap, ATR/TREAT/Halden
- Power cycling - load follow
  - EDF has extensive experience
  - Some data exist within the US industry but will require extensive evaluation

Normal Operation

- Crud phenomenon understanding and modeling
  - No gap, EPRI and CASL programs
- Feed-water nickel concentration
  - No gap, EPRI program
- Fuel degradation on failure
  - Data gap on advanced fuel
- Fission gas release
  - Data gap on advanced fuel

Methodology

What methodology do you currently use for				
Regulatory	Advanced fuel designs	New operating regimes	Optimizing reg/operating methods	Other, please explain
• Calculation • Fuel vendor • PWROG • CE reload methods as modified to use CASMO4/SIMULATE3	Calculation participating in EPRI, PWROG and CASL	• Halden test data with calculation • Licensed method • Vendors/EPRI/CASL • Talk to fuel vendors, transient thermal analyses	• Calculation • look for ways to gain process efficiencies while staying within our approved methods.	• Industry feedback with EPRI, reactor vendor • Using previous NRC guidance for LWRs
• fuel performance analysis using advanced computational techniques.				
• Studsvik codes coupled to T/H system codes (RELAP5/RETRAN/VIPRE) • We generally use calculations, based on previous testing when applicable/needed. When conditions are entirely new (e.g. advanced fuel designs) and testing has not been done in the past, we do testing			S3R core model integrated into a full scope simulator	

In-pile Testing Access and Capability

Additional In-pile Access	In-pile Test Capability
• LOCA and RIA	• Pressurized static capsule • Prototypical commercial reactor condition – flow loop • Water and steam cooling • Multiple pins and whole small bundle
• Normal operation and AOOs	• Power ramp and cycle • Fuel degradation from failure under normal conditions • Debris

Separate Effects Tests and Priority

Complementary Separate Effects Testing Capability	Highest Priority SE Testing
• Electrically heated test train - no gap, ANL, ORNL, Studsvik, etc)	Steam cooling of high performance metallic fuel, 550C peak fuel temperature assuming Zr cladding
• SiC creep and burst test – no gap, SiC creep too slow, MBT at ORNL used to test SIC	U_3Si_2 swelling, melting point and conductivity as a function of burnup
• U_3Si_2 interaction with water/steam	Modified burst testing on advanced cladding concept
• Fuel annealing studies (unclad fuel) to measure fission gas release – may be difficult	
• Fuel swelling measurement (U_3Si_2) – ATR	
• Measure effect of irradiation on U_3Si_2 melting point and conductivity	
• Modified burst testing on advanced cladding concept – Studsvik and ORNL	

Source Material and Pedigree

Source Material Required	Pedigree Need to Support Evaluation
Fresh and irradiated U_3Si_2/UO_2 fuel in SiC or SiC coated cladding	Fuel grain size distribution Cladding mechanical properties, hydrogen concentration, oxide thickness
Uranium nitride fuel	Cladding mechanical properties, hydrogen concentration, oxide thickness
	Power history, burnup, material composition and manufacturing process
	Complete characterization
	Standard pedigree per INL standard
	Late 2nd and 3rd cycle fuel from typical BWR/PWR

Post Irradiation Examination

Non-destructive Examinations
• Chemical and isotopic analysis
• Optical microscopy
• Electron microprobe
• X-ray diffraction
• Gamma scanner
• Alpha scanner
• TEM
• SEM with FIB

Small Sample Examination

Small Sample PIE	Destructive Examinations
Bow and length	Optical microscopy
Eddy current	Mechanical (tensile, compression, bend, micro-hardness)
Neutron radiography	Density
Gamma scanning	Composition
Radiation mapping	Fission gas measurement
High resolution visual	High temperature furnace (accident conditions)
Large plate/element checker	Blister annealing testing
Metrology	

Historical Report and Additional Information

Historical Report	Additional Information / Questions
• Complete set of exp results AND testing conditions used by Shimizu for U^3Si_2 testing (available literature has limited info) • Also, access to UN irradiation data in both thermal and fast spectrum is valuable.	• For current fuel, research needs to include a REALISTIC examination of the phenomena to ensure that it's of real world concern, rather than a change to a decimal point value in an analysis that is already grossly conservative.

Operational and PIE Gap Evaluation

- No capability gap on post irradiation examination
  - Additional capability may need be developed as need arise
- No capability gap on normal operational issues
- Data gap on operational issues
  - New fuel operational fission gas release
  - New fuel degradation in contact with coolant
  - New fuel / cladding power ramp performance
  - Fuel load follow limits/guidance

RIA Capability Gap

- Some tests could be conducted using pressurized static capsule
- Pressurized flow loop representative of commercial reactor conditions is needed in most tests
  - DNB potential at partial power
  - High temperature failure
  - Over pressure failure
  - Fuel-coolant interaction
  - Transient fission gas release
- Prototypical commercial reactor RIA pulse width is between 25 and 65 ms - Cladding ductility is pulse width dependent
  - TREAT pulse width is > 60 ms

RIA Data Gap

- PCMI performance of doped and new fuel designs
- PCMI performance of non zirconium cladding
  - Mechanical tests could generate most of the test data
- PCMI performance of zirconium based cladding under some conditions to verify mechanical characterization data
- Fuel-coolant interaction
- Transient fission gas release

LOCA Capability Gap

- Lack fully realistic test conditions
  - 50% external electrical heating used in Halden LOCA tests
  - 100% external heating utilized by others
  - TREAT could provide 100% nuclear heating
- Pressurized flow loop desirable
  - Remove heat from initial conditioning at pre-transient power to close fuel-cladding gap
  - Multiple rods to evaluate flow blockage due to balloon/burst and potential local temperature excursions
- In situ characterization of fuel relocation / dispersal

LOCA Data Gap

- Fuel fragmentation threshold and mechanisms
  - Fission gas and grain boundary role
  - Pellet stress contribution from operational temperature gradient
- Fuel relocation and dispersal
- Fuel cladding balloon and burst behavior
- No data on new fuel designs
  - Pellet behavior
  - Limited cladding characterization

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