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)
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

Temperature Dependence

- Burst strain increases from 1 to 1.5% relative to NSRR condition

Proposed NRC temperature adjustment basis

- 280°C, H>600 ppm

Burst strain increases from 1 to 1.5% relative to NSRR condition
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

![Graph showing correlation between calculated NSRR pellet expansion and measured cladding ductility.](image-url)
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

![Graph showing peak cladding temperature over time](image1)

- **Design Basis Accident**

![Graph showing effects of various conditions](image2)

- **Preliminary results (MAPP code)**
  - Zircaloy-4
  - 50% reaction rate of Zr
  - Autocatalytic Oxidation
  - Ideal cladding - no reaction with steam

*(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

<table>
<thead>
<tr>
<th>Test</th>
<th>BU</th>
<th>Temperatures</th>
<th>Reactor Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>92</td>
<td>800°C, 1050°C</td>
<td>PCTPWR, PCTPWR</td>
</tr>
<tr>
<td>5</td>
<td>83</td>
<td>1050°C</td>
<td>PCTPWR</td>
</tr>
<tr>
<td>6</td>
<td>56</td>
<td>830°C</td>
<td>PCTVVER</td>
</tr>
<tr>
<td>7</td>
<td>44</td>
<td>1150°C</td>
<td>PCTBWR</td>
</tr>
</tbody>
</table>
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
  - $^{106}\text{Rh}$ half-life $\sim 1$ 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

![Graph showing Xe concentration vs. pellet radius](image1)

![Image of oxidized fuel](image2)
Fuel Fragmentation Mechanisms

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

Close to 50% of fission gas inventory in the grain boundary
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
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

- 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

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

Fuel reconditioning at lower power needed to change the pellet condition

LOCA test to test thermal stress hypothesis
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**

<table>
<thead>
<tr>
<th>Regulatory</th>
<th>Advanced fuel designs</th>
<th>New operating regimes</th>
<th>Optimizing reg/operating methods</th>
<th>Other, please explain</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Calculation • Fuel vendor • PWROG • CE reload methods as modified to use CASMO4/SIMULATE3</td>
<td>Calculation participating in EPRI, PWROG and CASL</td>
<td>• Halden test data with calculation • Licensed method • Vendors/EPRI/CASL • Talk to fuel vendors, transient thermal analyses</td>
<td>• Calculation • look for ways to gain process efficiencies while staying within our approved methods.</td>
<td>• Industry feedback with EPRI, reactor vendor • Using previous NRC guidance for LWRs</td>
</tr>
<tr>
<td>• fuel performance analysis using advanced computational techniques.</td>
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</tr>
<tr>
<td>• 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</td>
<td></td>
<td></td>
<td>S3R core model integrated into a full scope simulator</td>
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## In-pile Testing Access and Capability

<table>
<thead>
<tr>
<th>Additional In-pile Access</th>
<th>In-pile Test Capability</th>
</tr>
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<tbody>
<tr>
<td>• LOCA and RIA</td>
<td>• Pressurized static capsule</td>
</tr>
<tr>
<td></td>
<td>• Prototypical commercial reactor condition – flow loop</td>
</tr>
<tr>
<td></td>
<td>• Water and steam cooling</td>
</tr>
<tr>
<td></td>
<td>• Multiple pins and whole small bundle</td>
</tr>
<tr>
<td>• Normal operation and AOOs</td>
<td>• Power ramp and cycle</td>
</tr>
<tr>
<td></td>
<td>• Fuel degradation from failure under normal conditions</td>
</tr>
<tr>
<td></td>
<td>• Debris</td>
</tr>
</tbody>
</table>
## Separate Effects Tests and Priority

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

<table>
<thead>
<tr>
<th>Source Material Required</th>
<th>Pedigree Need to Support Evaluation</th>
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</table>
| Fresh and irradiated $\text{U}_3\text{Si}_2/\text{UO}_2$ 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 2\textsuperscript{nd} and 3\textsuperscript{rd} cycle fuel from typical BWR/PWR           |                                              |
## Post Irradiation Examination

### Non-destructive Examinations

<table>
<thead>
<tr>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical and isotopic analysis</td>
</tr>
<tr>
<td>Optical microscopy</td>
</tr>
<tr>
<td>Electron microprobe</td>
</tr>
<tr>
<td>X-ray diffraction</td>
</tr>
<tr>
<td>Gamma scanner</td>
</tr>
<tr>
<td>Alpha scanner</td>
</tr>
<tr>
<td>TEM</td>
</tr>
<tr>
<td>SEM with FIB</td>
</tr>
</tbody>
</table>
Small Sample Examination

<table>
<thead>
<tr>
<th>Small Sample PIE</th>
<th>Destructive Examinations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bow and length</td>
<td>Optical microscopy</td>
</tr>
<tr>
<td>Eddy current</td>
<td>Mechanical (tensile, compression, bend, micro-hardness)</td>
</tr>
<tr>
<td>Neutron radiography</td>
<td>Density</td>
</tr>
<tr>
<td>Gamma scanning</td>
<td>Composition</td>
</tr>
<tr>
<td>Radiation mapping</td>
<td>Fission gas measurement</td>
</tr>
<tr>
<td>High resolution visual</td>
<td>High temperature furnace (accident conditions)</td>
</tr>
<tr>
<td>Large plate/element checker</td>
<td>Blister annealing testing</td>
</tr>
<tr>
<td>Metrology</td>
<td></td>
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</tbody>
</table>
## Historical Report and Additional Information

<table>
<thead>
<tr>
<th>Historical Report</th>
<th>Additional Information / Questions</th>
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</thead>
</table>
| • Complete set of exp results AND testing conditions used by Shimizu for $\text{U}_3\text{Si}_2$ 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
Together...Shaping the Future of Electricity