Fuel Fragmentation Relocation and Dispersal - Status

Bob Baxter, Justin Byard, Lisa Gerken, Brandon Holden, Jerald Holm, John Klingensfus, Wyatt Sherer,

August 20, 2020
Meeting Objective

Inform the NRC of Framatome’s plans to address Fuel Fragmentation Relocation and Dispersal in support of increased burnup

• Plans are based on current understanding of the FFRD associated phenomena and expected results

Obtain NRC feedback
AGENDA

- Introduction and background
- FFRD workshop and roadmap
- AFM core design objective
- Summary of current knowledge
- Non-LOCA and LOCA
- FFRD Approach
- Summary
- Next Steps
Introduction and Background

Jerry Holm
Advanced Fuel Management

• Objective
FFRD Workshop and Roadmap

Bob Baxter
FFRD Workshop

Framatome Approach

- 3-Region Workshop, January 28 – 30, 2020
- Technical Presentations
- Idea Generation Sessions
- Input from George Washington University Professors
  - CFD Capabilities
  - Testing Capabilities
- Summarized List of Issues & Risks
AFM Core Design Objective

Brandon Holden
AFM Core Design Study
Summary of Current Knowledge

Bob Baxter
What are we going to talk about?

Definition:
Fuel dispersal refers to the ejection of fuel fragments through a rupture or opening in the cladding

Prerequisites for fuel dispersal in LOCA

Prerequisites for fuel dispersal in RIA

The amount of dispersed fragments depends on the burst opening size, on the fuel fragments size and on the capability of fragments to move to the rupture region (i.e. relocation)
Fuel fine fragmentation in LOCA conditions

Fuel fine fragmentation occurs if:

- The fuel pellet is predisposed to fragmentation
  Influence of the pre-transient state of the fuel rod, e.g.:
  - Burnup,
  - Fuel microstructure induced by irradiation,
  - Pellet-cladding bonding, etc.
- The LOCA transient induces thermomechanical loads triggering the fragmentation
  Influence of the LOCA transient, e.g.:
  - Thermal stresses,
  - Cladding deformation,
  - Pellet confinement (i.e. hydrostatic pressure),
  - Effect of rod depressurization at cladding burst, etc.
Influence of the pre-transient state
A burnup effect? (1/2)

Segment (local) average burnup (GWD/tU)

IFA-650.7
LK3/L - UO₂ - 44 GWD/tU

SCIP III – N05 LOCA
M5 - UO₂ - 64 GWD/tU

SCIP III – VUR1 LOCA
Zirlo - UO₂ - 66 GWD/tU

SCIP III – R2D5 LOCA 1
M5 - UO₂ - 68 GWD/tU

SCIP III – VUL2 LOCA 1
Zirlo - UO₂ - 74 GWD/tU

IFA-650.9
DX Zr 2.5Nb - UO₂ - 90 GWD/tU

Studsvik – NRC 198
Zirlo - UO₂ - 60 GWD/tU

SCIP III – N05 LOCA
M5 - UO₂ - 64 GWD/tU

Transition zone*

40 50 60 70 80 90

AFM FFRD Status – August 20, 2020
Influence of the pre-transient state
A burnup effect? (2/2)
Occurrence Conditions
Occurrence Conditions (continued)
**FFRD LOCA Rupture Material Loss**

NUREG-2160

- Studsvik Test 192
  - Rod Average Burnup 68.2 GWd/mtU
  - PCT 1185 C
  - Rupture Temperature 700 C
  - Rupture Pressure 81 bar (1174.8 psi)
  - Wire Probe Measurement
    - 85 mm Top
    - 73 mm Bottom

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*Figure 2-35 Gamma scan results for Test 192 with comparison to profilometry and initial wire probe measurements*
Fuel fine fragmentation in PCMI conditions

Fuel rod behavior under RIA is affected by:

- Characteristics of the power pulse, in particular the amplitude and pulse width
- Core coolant conditions (pressure, temperature, flow rate)
- Burn-up-dependent state of the fuel rod
  - Width of pellet-clad gap,
  - Cladding corrosion,
  - Internal gas overpressure of fuel rod,
  - Distribution of gaseous fission products in fuel pellets
- Fuel rod design
  - Internal fill gas pressure
  - Clad tube wall thickness
  - Fuel pellet composition
  - Fuel pellet geometrical design

Fuel fine fragmentation could occur if:

- PCMI occurs when the hydride-embrittled cladding cannot sustain the hoop strain produced by the pellet thermal expansion at a power transient:
  - Low-temperature failures by PCMI under the early heat-up stage of accident
    - Relevant to high-burn-up fuel rods with severely corroded cladding
    - Subjected to a narrow power pulse
    - Initiated from zero power conditions
  - High-temperature failures by cladding ballooning and burst
    - Failures occur as a consequence of film boiling and significant rod internal overpressure
    - Failures by disruption of the cladding upon quenching from high temperature (due to embrittlement from oxidation in film-boiling phase)
    - High-temperature failures by melting of cladding and fuel pellets

These factors control what kind of damage is inflicted to the fuel rod under the accident.
FFRD in PCMI, DNBR, FCM conditions

- RIA fuel rod test data

- RIA Fuel Rod failure
## FFRD in PCMI, DNBR, FCM conditions


![Axial profiles of cladding outer diameter before and after tests RH-1 and RH-2](image)

### RIA M5 Fuel Rod Test NEA 6847 (pg 170)

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Fuel Type</th>
<th>Clad tube material</th>
<th>Fuel burn-up [MWd(kgHM)$^{-1}$]</th>
<th>Clad oxide thickness [μm]</th>
<th>Fill gas pressure [Mpa]</th>
<th>Pulse Width [ms]</th>
<th>Peak fuel enthalpy [Jg$^{-1}$]</th>
<th>Failure enthalpy [Jg$^{-1}$]</th>
<th>Clad max hoop strain [%]</th>
<th>Transient FGR [%]</th>
<th>Fuel loss [%]</th>
<th>Coolant Temperature [K]</th>
<th>Coolant Pressure [Mpa]</th>
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<tbody>
<tr>
<td>REP-Na11</td>
<td>UO$_2$</td>
<td>M5</td>
<td>60</td>
<td>15-25</td>
<td>0.3</td>
<td>31</td>
<td>385</td>
<td>Survived</td>
<td>0.4</td>
<td>6.8</td>
<td>-</td>
<td>293</td>
<td>0.1</td>
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<tr>
<td>CIP0-2</td>
<td>UO$_2$</td>
<td>M5</td>
<td>76</td>
<td>15-25</td>
<td>0.3</td>
<td>28</td>
<td>343</td>
<td>Survived</td>
<td>0.3</td>
<td>NA</td>
<td>-</td>
<td>551</td>
<td>6.4</td>
</tr>
</tbody>
</table>
Non-LOCA

Bob Baxter
The following non-LOCA postulated accidents described in the standard review plan (SRP) may result in some amount of failed fuel.

<table>
<thead>
<tr>
<th>Standard Review Plan Event</th>
<th>Event Category</th>
<th>DNB</th>
<th>FCM</th>
<th>Enthalpy (PCMI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.1.5 Main Steam Line Break (MSLB)</td>
<td>Overcooling</td>
<td>X</td>
<td>X</td>
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<tr>
<td>15.2.8 Feed Line Rupture</td>
<td>Overheating</td>
<td>X</td>
<td>X</td>
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<tr>
<td>15.3.3 Locked Rotor (LR)</td>
<td>Loss of Flow</td>
<td>X</td>
<td>--</td>
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<tr>
<td>15.3.4 Reactor Coolant Pump (RCP) Shaft Break</td>
<td>Loss of Flow</td>
<td>X</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>15.4.3 Single Rod Withdrawal</td>
<td>Reactivity initiated</td>
<td>X</td>
<td>X</td>
<td>--</td>
</tr>
<tr>
<td>15.4.7 Fuel Assembly Misload</td>
<td>Reactivity initiated</td>
<td>X</td>
<td>X</td>
<td>--</td>
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<tr>
<td>15.4.8 Control Rod Ejection</td>
<td>Reactivity initiated</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Note: RCS overpressure from highly fragmented fuel released into the coolant may be a concern for any large dispersal of high burnup fragmented fuel and is evaluated after the fuel failures are assessed.
LOCA

Lisa Gerken
FFRD LOCA

- FFRD is generally linked to the LOCA transient
  - LOCA transients exhibit specific characteristics of swelling and rupture and propensity for material dispersal
  - LOCA transients induce core-wide heatup
- Dispersal-susceptible ruptures depend on burnup and rupture conditions
- Variety of postulated LOCA events create spectrum of post-rupture flow characteristics
  - Size
  - Location
  - Plant response
FFRD LOCA
FFRD LOCA
John Klingeneus
John Klingenhof
Summary

Jerry Holm
Summary

• FFRD workshop and roadmap
• AFM core design objective
• Summary of current knowledge
• Non-LOCA and LOCA
• FFRD Approach
Next Steps

Jerry Holm
Next Steps

Pre-Submittal meeting for AFM High Burnup TR
# Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tr>
<td>AFM</td>
<td>Advanced Fuel Management</td>
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<tr>
<td>ATF</td>
<td>Accident Tolerant Fuel</td>
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<tr>
<td>BU</td>
<td>Burnup</td>
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<tr>
<td>CVCS</td>
<td>Chemical and Volume Control System</td>
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<tr>
<td>DBA</td>
<td>Design Basis Accident</td>
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<td>DNB</td>
<td>Departure Nucleate Boiling</td>
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<tr>
<td>DNBFR</td>
<td>Departure Nucleate Boiling Ratio</td>
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<tr>
<td>ECCS</td>
<td>Emergency Core Cooling System</td>
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<td>EFPD</td>
<td>Effective Full Power Days</td>
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<tr>
<td>FA</td>
<td>Fuel Assembly</td>
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<tr>
<td>FCM</td>
<td>Fuel Centerline Melt</td>
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<tr>
<td>FdH</td>
<td>Radial Peaking</td>
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<tr>
<td>Fq</td>
<td>Total Peaking</td>
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<td>FFRD</td>
<td>Fuel Fragmentation Relocation and Dispersal</td>
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<td>Gad</td>
<td>Gadolinia</td>
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<tr>
<td>GSI</td>
<td>Generic Safety Issue</td>
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<td>HFP</td>
<td>Hot Full Power</td>
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<td>LBOCA</td>
<td>Large Break LOCA</td>
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<tr>
<td>LHGR</td>
<td>Linear Heat Generation Rate</td>
</tr>
<tr>
<td>LR</td>
<td>Locked Rotor</td>
</tr>
<tr>
<td>LOCA</td>
<td>Loss of Coolant Accident</td>
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<tr>
<td>MHA</td>
<td>Maximum Hypothetical Accident</td>
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<tr>
<td>MSLB</td>
<td>Main Steam Line Break</td>
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<tr>
<td>NPP</td>
<td>Nuclear Power Plant</td>
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<td>NRC</td>
<td>Nuclear Regulatory Commission</td>
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<tr>
<td>PCMI</td>
<td>Pellet Clad Metal Interaction</td>
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<td>PWR</td>
<td>Pressurized Water Reactor</td>
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<td>RCP</td>
<td>Reactor Coolant Pump</td>
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<td>RCS</td>
<td>Reactor Coolant System</td>
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<td>RG</td>
<td>Regulatory Guide</td>
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<td>RIA</td>
<td>Reactivity Initiated Accident</td>
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<td>RPD</td>
<td>Radial Power Distribution</td>
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<td>RV</td>
<td>Reactor Vessel</td>
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<td>SAFDLs</td>
<td>Safety Analysis Fuel Design Limits</td>
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<td>SBLOCA</td>
<td>Small Break LOCA</td>
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<td>SCIP</td>
<td>Studsvik Cladding Integrity Project</td>
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<td>SGTR</td>
<td>Steam Generator Tube Rupture</td>
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<tr>
<td>SRP</td>
<td>Standard Review Plan</td>
</tr>
<tr>
<td>TCS</td>
<td>Transient Cladding Strain</td>
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<tr>
<td>UO₂</td>
<td>Uranium dioxide</td>
</tr>
<tr>
<td>W4</td>
<td>Westinghouse 4-loop design plant</td>
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</tbody>
</table>
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