Approach to Address Core Coolability Issues with Failed Fuel

RIA Workshop on RIA
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Presentation Overview

• Introduction
  – Experimental Justification for Separate Failure Threshold and Core Coolability Limit
  – Requirements for Demonstrating Coolability from Interim RIA Acceptance Criteria

• Industry Approach to Demonstrate Coolability
  – Flow blockage from fuel dispersal and clad ballooning
  – Mechanical energy generation from fuel dispersal
Justification for Maximum Enthalpy Limit Above Failure Threshold

- Experimental Observations
  - Majority of failures with peak fuel enthalpy above interim failure threshold maintained rod geometry
  - Consequences of fuel dispersal did not lead to damaging pressure pulses or loss of rod geometry

- Other Assessments Support Separate Criteria
  - Nuclear Safety Commission of Japan (NSCJ), Swedish Safety Authority (SKI), Switzerland (HSK), others
  - Technical evaluation included fuel dispersal

- Analytical Evaluations (RETRAN analysis, others)
  - Pressure pulse generation from dispersal of non-molten material will likely be within the reactor pressure vessel limits
  - Needs demonstration
Experimental Results for High Burnup Failures

Fuel Rod Average Burnup (GWd/MTU)

Maximum Radial Average Fuel Enthalpy (cal/gmUO₂)

- Maintain Rod Geometry
- Partial Clad Melting
- Loss of Rod Geometry
- EPRI Topical Report (melting)
- Japanese Coolability Limit
- RIL 0401 (Upper 95% Oxide)
- Swedish Regulatory Agency
Visual Appearance After Fuel Dispersal (Intermediate and High Burnup Fuel)

NSRR Experiments
Pulse widths: ~4 ms
Rod Length: 5 to 6 in
Uniform Axial Power

<table>
<thead>
<tr>
<th>Fuel Code</th>
<th>Burnup (GWd/tU)</th>
<th>Maximum Radial Average Peak Fuel Enthalpy</th>
</tr>
</thead>
<tbody>
<tr>
<td>JMH-5</td>
<td>30</td>
<td>220 cal/gm</td>
</tr>
<tr>
<td>TK-2</td>
<td>48</td>
<td>107 cal/gm</td>
</tr>
<tr>
<td>TK-7</td>
<td>50</td>
<td>95 cal/gm</td>
</tr>
<tr>
<td>OI-11</td>
<td>58</td>
<td>157 cal/gm</td>
</tr>
<tr>
<td>VA-1</td>
<td>78</td>
<td>127 cal/gm</td>
</tr>
</tbody>
</table>
Appearance of Unirradiated Test Rods After RIA Experiments

- Fuel Dispersal with Energy Release
- Current Coolability Limit
- No Fuel Dispersal or Energy Release
Mechanical Energy Generation after Cladding Failure – Experimental Results

CDC-SPERT and NSRR Failures
Mechanical Energy Generation

Consequences of PCMI failure for irradiated fuel are much lower than for molten fuel failure.
Particle Size in Dispersed Fuel

Sugiyama presentation, May 2007 FSRM - Tokia

Mean Particle Size:
- No endplug/cap failure – 15 – 20 microns
- With endplug failure - > 50 microns
- Small fraction of particles < 5 microns
- Particle size appears to be burnup independent
Interim Criteria for Core Coolability

1. Peak radial average fuel enthalpy < 230 cal/gm
2. Peak fuel temperature below incipient melting conditions
3. Mechanical energy generation effects on reactor pressure boundary, reactor internals, and fuel assembly structure from;
   – Non-molten fuel-coolant interaction (FCI)
   – Fuel rod burst
4. No loss of coolable geometry due to;
   – Fuel pellet and cladding fragmentation and dispersal
   – Fuel rod ballooning
Demonstrating Compliance to Core Coolability Criteria – Licensee Options

Option 1
• No cladding failures for all rods or beyond a burnup where high burnup rim structure formation occurs

Option 2
• No fuel dispersal upon failure based on power pulse characteristics and failure mode
  – May still need to address flow blockage by ballooning

Option 3
• Demonstrate consequences of fuel dispersal and ballooning have no impact on both short-term and long-term core coolability
Demonstrating Compliance to Core Coolability Criteria – Flow Diagram

- Fuel Rod Failure? No → Satisfy Safety Criteria
  - Mechanical Energy Generation
  - Structural Integrity? Yes → Core Coolability Ensured?
  - Flow Blockage Analysis
  - Adequate Cooling?
  - Sub-Critical? Yes → Reduce Max Allowable Fuel Enthalpy
- Fuel Dispersal? No → Core Coolability Ensured?
  - PCMI
- Fuel Rod Ballooning No → High Temp.
  - Yes → Fuel Rod Melting?
- Flow Blockage Analysis
  - Transport and Collection
Industry Approach: Separate Coolability Concerns into Two Parts

- Long-term coolability (t > 5 seconds)
  - Address effects of flow blockage due to fuel fragmentation and rod ballooning
  - Address effects of fuel particle transport in the primary coolant system
  - Bound these effects using another higher probability accident such as LOCA

- Short-term coolability (t < 5 seconds)
  - Address mechanical energy generation from non-molten Fuel-Coolant Interaction and release of rod pressure
Schematic of RIA Acceptance Criteria

- No fuel dispersal
- Dispersal of Coarse Fuel Particles - No Flow Blockage
- Potential reduction to dispose of fuel failure/dispersal consequences
- Total Fuel Enthalpy or Enthalpy Change
- 230 cal/gm or Melting Limit
- Fuel Rod Failure
- Rod Burnup
Overall Approach to Define Coolability Limit

• Vendors/Licensees to provide fuel design/plant design specific assessments
  – Incipient fuel melting enthalpy limit (#2)
  – Long-term coolability issues (#4)
  – Fuel dispersal/burst, mechanical energy generation, and RCS integrity assessment (#3)

• EPRI FRP-WG2 to provide example/generic methodology to address short-term coolability issues (#3)
  – Mass and energy of dispersed fuel
  – Mechanical energy generation from dispersed fuel and pressure release after burst
  – RCS integrity assessment
Industry Approach to Long-Term Coolability (PWR and BWR)

• Flow blockage from clad ballooning and fuel dispersal
  – Use LOCA to demonstrate flow blockage from clad ballooning and fuel dispersal will not lead to loss of coolable geometry

• Transport of fuel particles within the primary coolant system
  – Use LOCA to demonstrate that criticality and cooling of debris bed will not lead to loss of coolable geometry
Does LOCA Bound Flow Blockage from Clad Ballooning in RIA?

• How big is the affected region of the core?
  – Smaller region of the core experiences clad ballooning in RIA event

• Are the cladding deformations the same?
  – Balloon size will be smaller in RIA

• How do the flow blockage conditions compare?
  – Smaller affected region, less channel reduction, and full flow conditions lead to lower potential for flow blockage
Core Region with Clad Ballooning

• Calculations using NUREG-0630 criteria show 10 to 20% of the rods fail by clad ballooning in LBLOCA
  – Recent EU assessment

• Worst case estimates show <5% of fuel rods could experience clad ballooning in RIA event
  – Ballooning failure most likely in lower burnup fuel < 30 GWd/tU
  – DNB not likely in high burnup fuel (PCMI dominates)
Clad Balloon Characteristics in RIA

- High temperature burst in $\alpha+\beta$ phase leads to low burst strains
  - Experience from NSRR and IGR/BIGR tests

- High heating rates decrease burst strains
  - NUREG/CR-0344 tests

- High external pressure in PWRs and HZP BWRs prevent ballooning for low burnup fuel
  - Halden IFA-613 show clad collapse during post-DNB operation with coolant overpressure
  - CABRI and NSRR test results (2008-2012) will provide information on the role of fission gas release on clad ballooning
Low Burst Strain from RIA Test Data

Burst predominately in $\alpha+\beta$ temperature regime
Decrease Burst Strain and Increase Burst Temperature for Fast Heating Rates

Ref: Chung and Kassner, NUREG/CR-0344
Clad Collapse during Post-DNB Conditions

Halden IFA-613 Dryout Experiment

Coolant Pressure = 7 MPa

Rod Profilometry

Burnup 26 GWd/tU (initial pressure 1.7 MPa)
Potential Flow Blockage from Clad Ballooning

- Limited flow channel reduction compared to LOCA
  - Less fuel assemblies will experience ballooning
  - Lower cladding strains results in less channel blockage

- Full flow and coolant volume available to cool deformed fuel rods
  - Maintain heat transfer in upper region of the assembly

Flow Blockage in RIA is Bounded by LOCA Conditions
Flow Blockage from Fragmented Fuel Transport

• Similar scenarios addressed in BWR and PWR LOCA
  Long-term Cooling Assessments
  – BWR lower tie plate clogging tests
  – PWR sump clogging tests (W presentation)
  – Amount of material is small compared to the material expelled during a LOCA (fuel + sump debris)

Possible to demonstrate that flow blockage from fragmented fuel is bounded by LOCA
Other Consequences from Fragmented Fuel Transport

• Very low probability for a critical configuration and rubble bed overheating
  – Limited amount of material to form large rubble bed
  – Dispersed material will have low reactivity worth due to depletion of fissile atoms and fission products
  – Full flow conditions limits accumulation fuel material

Possible to demonstrate that consequences of fragmented fuel transport is bounded by LOCA
Industry Approach to Short-Term Coolability
BWR CRDA

• Pulse characteristics in BWR CRDA will mitigate fuel dispersal upon failure
  – Pulse width > 20 ms even at the highest rod worths
  – Significant fraction of deposited energy is in delayed power tail – mode of failure DNB
  – No need to calculate mechanical energy generation from fuel dispersal

• Mechanical energy generation from clad ballooning failure
  – Develop approach to calculate pressure pulse generation from rod pressure release upon failure
BWR Pulse Widths versus Control Blade Worth

Dynamic blade worth is defined as the peak reactivity during the transient.

GNF Presentation NRC RIA Workshop Nov 2006
Effect of Pulse Width on UO₂ Fuel Dispersal

Energy Deposition After Failure vs. Pulse Width

Fuel Dispersal

No Fuel Dispersal

Energy Deposition After Failure (cal/gm)

Pulse Width (msec)

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Industry Approach to Short-Term Coolability PWR REA

• Estimate consequences of fuel dispersal for PWR REA
  – Narrow pulse widths may not preclude fuel dispersal
  – Develop approach to calculate mass and energy of dispersed fuel
  – Develop approach to calculate pressure pulse generation and structural response of core internals

• Mechanical energy generation from clad ballooning failure
  – Develop approach to calculate pressure pulse generation from rod pressure release upon failure
Assessment of Fuel Dispersal Consequences

• Estimate mass and energy of dispersed fuel during an RIA event
  – Use 3-dimensional distribution of core power during rod ejection/rod drop accident
  – Function of maximum fuel enthalpy and the failure threshold

• Estimate mechanical energy generation and impact on reactor coolant system during an RIA event
  – Pressure and water hammer from fuel-coolant interaction leading to destructive forces on the fuel assembly, core components, and the reactor pressure vessel
Estimate the Amount and Energy of Dispersed Fuel

• Use results from 3-D neutron kinetics analysis and core burnup distribution to identify all failed nodes in core
  – Assume fuel enthalpy is proportional to power
  – Correlate local enthalpy, assembly/rod average burnup and postulated failure threshold to identify failed nodes

• Estimate amount of fuel dispersed and the thermal energy
  – Function of maximum allowable fuel enthalpy and failure threshold
  – Function of key assumptions related to the fuel dispersal kinetics
Core Power Distribution

Core Enthalpy Distribution for a PWR Control Rod Ejection

$H_{\text{max}} = 230 \text{ cal/gm}$

Core Power Distribution for a BWR Control Rod Drop Accident
Example of Fuel Dispersal Calculation for PWR Rod Ejection Accident

• Core Power and Burnup Distribution from Westinghouse 3-D Analysis
  – Radial (assembly) and axial relative power distribution
  – Assembly burnup distribution to determine failure threshold for each assembly

• Fuel Enthalpy Distribution Throughout the Core
  – Combine core radial peaking factor and axial peaking factor and multiply by maximum radial average peak enthalpy
    • Use three different max values - 230, 200, and 170 cal/gm
    • Hypothetical ejected rod worth values to reach maximum allowable enthalpy levels
  – Assume axial and radial power distribution is not function of maximum enthalpy (reactivity insertion)
Fuel Dispersal Kinetics Assumptions

• Estimated mass and energy of dispersed fuel using two methods
  – All failed nodes disperse fuel at maximum fuel enthalpy
  – Assemblies above 30 GWd/tU disperse fuel at failure enthalpy (only nodes that fail by PCMI)

• 20% of fuel in qualifying nodes dispersed into coolant
  – Upper limit of fuel dispersal amounts in NSRR tests without end/bending effects
Mass of Fuel Dispersal as Function of Failure Threshold and Maximum Allowable Enthalpy

Method 2 – Dispersal for Bu > 30 GWd/tU

Postulated Maximum Allowable Fuel Enthalpy Limits

- 230 cal/g
- 200 cal/g
- 170 cal/g

Assumed high burnup failure threshold (cal/gm)

- (16 ass, ~35 in)
- (13 ass, ~32 in)
- (12 ass, ~29 in)
- (9 ass, ~25 in)
- (8 ass, ~23 in)
- (7 ass, ~16 in)
- (6 ass, ~13 in)
- (5 ass, ~11 in)
- (1 ass, ~8 in)

Estimated Mass of Dispersed Fuel

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Fuel Dispersal Consequences - Mechanical Energy Generation

• Previous analysis results sensitive to assumed thermal equilibration time between fuel particles and coolant
  – Pressure pulse magnitude varied by factor of 10 for thermal equilibration times between 1 and 100 ms

• Modeling required to improve energy transfer kinetics between dispersed fuel and coolant
  – Coherency of dispersed material
  – Particle size distribution effect
  – Coolant voidage
Several Methods to Assess RCS Integrity

• Use maximum allowable pressure (120% of design pressure)
  – Evaluate transient pressure pulse using static pressure limit

• Use maximum absorbable energy of the reactor vessel (energy needed to yield the reactor vessel)
  – Japanese and EdF approach
  – No consideration given to damage of internal structures

• Assess damage to reactor internals (core barrel, fuel assembly, etc.)
  – Local pressure and flow velocities used to calculate structural response
  – Need structural limits to assess impact on coolability
Summary

• Experimental data and evaluations support maximum enthalpy limit well above failure threshold

• Consequences of fuel failure during RIA on long-term cooling bounded by LOCA event

• Short-term consequences of failure and fuel material dispersal can be addressed in coolability limit

• Industry looks forward to working with the staff on resolution of the coolability issues for RIA