Observations of Fuel Fragmentation, Mobility and Loss in Integral, High-Burnup, Fueled LOCA Tests

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Presentation Overview

- Results of six integral LOCA tests will be presented and discussed
- Hypotheses to explain the observations will be offered
- Experiments and further examinations will be proposed
- Present NRC's next steps and recommendations related to the Halden Program

Pursing a more complete understanding of the phenomena observed in these tests will allow for better predictions of fuel response to LOCA conditions in-reactor and assure that LOCA consequences continue to be acceptable. One intention of this presentation is to encourage and provoke research initiatives in pursuit of such an understanding.

Overview of six test segments and transient conditions

- All tests were fabricated from ZIRLO rods, irradiated in US commercial plants

- Initial four test segments:
  - Tests 189-193
  - Burnup ≈ 70 GWd/MTU
  - Initial hydrogen content ≈ 200 wppm
  - Standard UO_2 fuel
  - Fill pressure = 110 bar for first two, 82 bar for second two
  - Ramp rate from 300° C to PCT = 5° C/sec, quench at 800° C
  - PCT ≈ 950° C for the first test, 1160° C for the other three

- Final two test segments:
  - Tests 196-198
  - Burnup ≈ 55 GWd/MTU
  - Initial hydrogen content ≈ 200 wppm
  - UO_2 fuel coated with ZrB_2 burnable absorber
  - Fill pressure = 82 bar
  - Ramp rate from 300° C to PCT = 5° C/sec, quench at 800° C
  - PCT ≈ 950° C for one, 1160° C for the other

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Overview of experimental and measurement procedures

Re-fabricated rod segment with welded, “open” end cap

Initial weight recorded

Rod segment heated to reach equilibrium at 300° C and then pressurized and sealed. Subjected to a heat up (rod rupture occurs during heat up) and high-temperature oxidation, followed by quench

Rod segment cools and is removed from the test train

Fuel fragments collected, post-LOCA weight recorded, wire probe measured empty length

Rod segment is subjected to four-point bend test.

Fuel fragments collected, post-bend weight recorded, wire probe measured empty length

Both halves of broken rod segment are inverted and shaken

Fuel fragments collected, final weight recorded, wire probe measured empty length

Fuel fragments processed through six sieves to determine the fragment size distribution

Reminder, the primary purpose of these experiments was not to study fuel dispersal, but rather mechanical behavior of ballooned and ruptured fueled rods.

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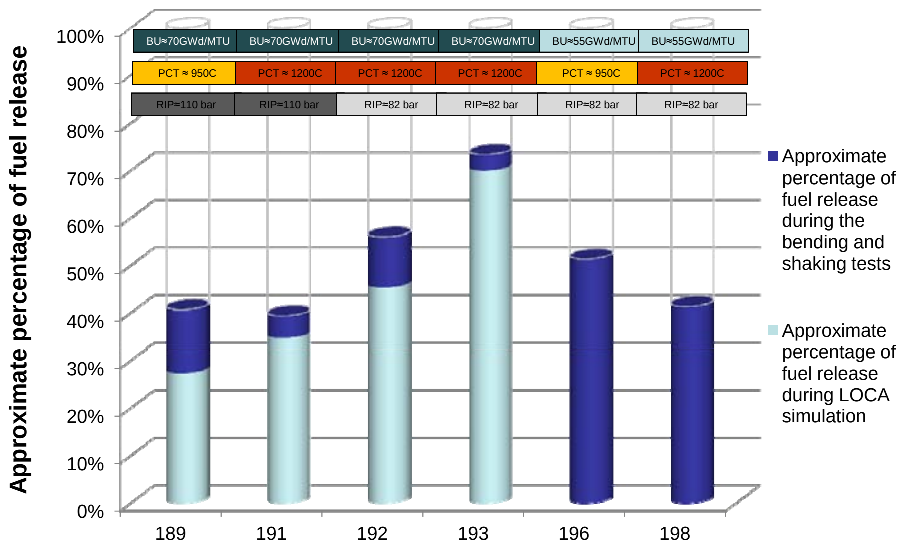
Observations of fuel release: Total fuel release was similar in each test, however a distinct difference is apparent between tests 189-192 and tests 196 and 198.



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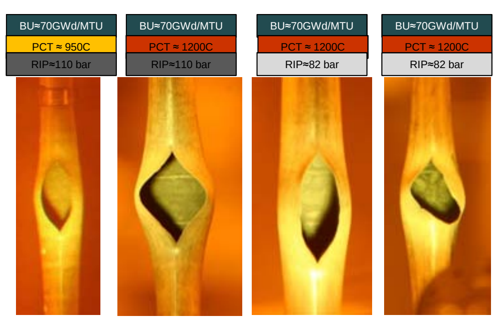
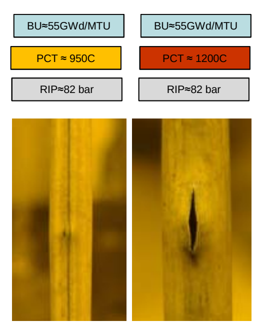
Observations of fuel release: The rupture characteristics, including the total strain and burst width and length, were markedly different in tests 189-192 and tests 196-198.



Rupture opening in Studsvik LOCA tests 189, 191, 192, and 193 (left to right), showing the absence of fuel in the rupture plane.



Rupture opening in Studsvik LOCA tests 196 and 198 (left to right)

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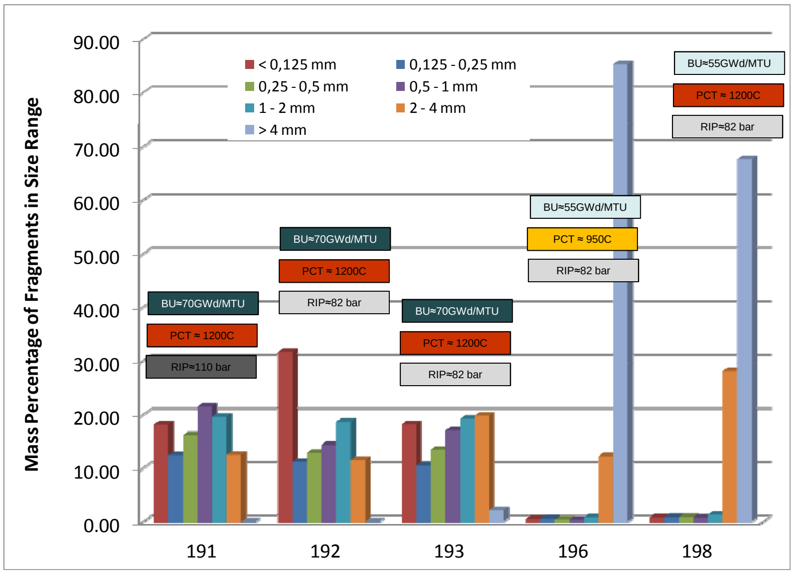
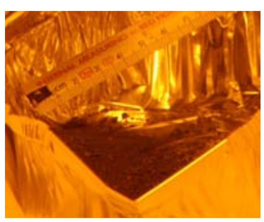
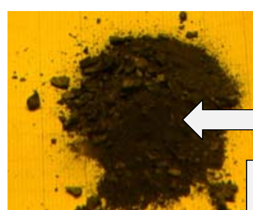
Observations of fuel fragmentation: The particle size distribution was markedly different in tests 189-192 and tests 196-198.



Observations of fuel fragmentation: The fuel fragmentation was markedly different in tests 189-192 and tests 196-198.



(a)



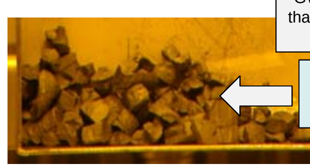
(b)

BU≈ 70GWd/MTU

Images of fuel particles collected from test rod (a) 192 and (b) 1[...] revealing a very small, sand-like fragmentation size

Fragmentation appears to be a function of burnup, however the difference between the fragmentation size distribution between fuel rods of 55 and 70 GWd/MTU seems larger than a linear continuum of fragmentation.

(a)

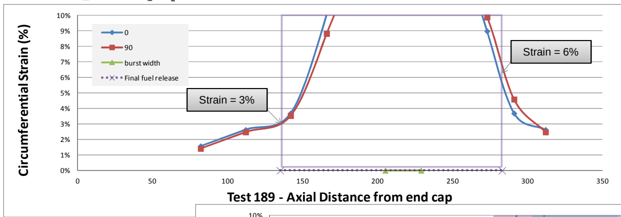


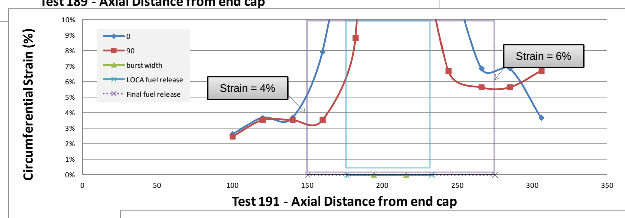
(b)

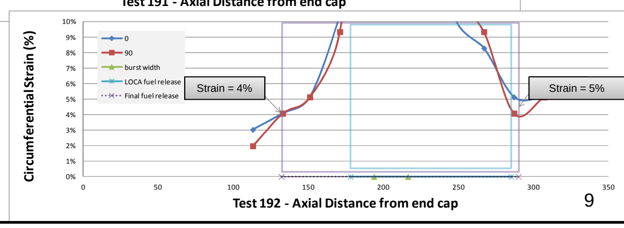
BU≈ 55GWd/MTU

Images of fuel particles collected from test rod (a) 196 and (b) 198 revealing large fragments

Observations of fuel mobility: Fuel mobility is coincident with some degree of cladding strain.







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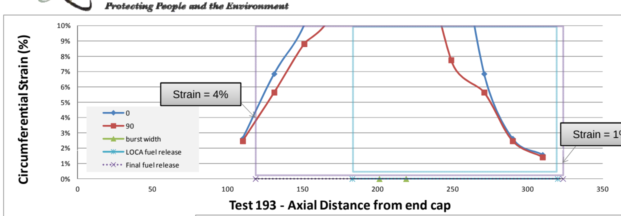
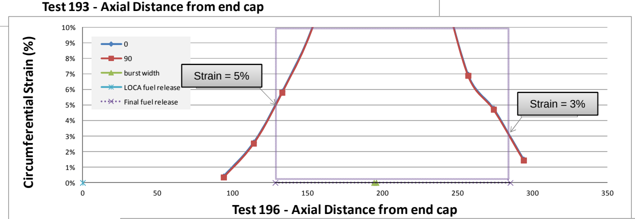
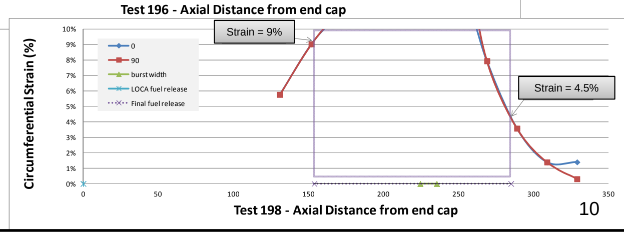
Observations of fuel mobility: Fuel mobility is coincident with some degree of cladding strain.







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Hypotheses to account for the observations and proposed **research** to verify or refute the hypotheses

Hypothesis	Research
Fuel Fragmentation	
• Unique properties (BU, additives, ballooning behavior, etc) of the father rods in the two tests sets account for the difference in final particle size distribution	• PIE of the father rods combined with breakdown of post-test results by father rod unique properties.
• Differences in the initial pellet fragmentation of the father rods in the two tests sets account for the difference in final particle size distribution.	• PIE of the father rods to characterize end-of-life (i.e., initial state for transient testing) pellet fragmentation.

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Hypotheses to account for the observations and proposed **research** to verify or refute the hypotheses

Hypothesis	Research
Fuel Fragmentation	
• Fragmentation is driven by a tensile stress on the fuel pellet that is induced by the cladding strain when a strong fuel-cladding bond.	• PIE of father rods to characterize the fuel-cladding bond and identify any relationship between bond layer and fragmentation
• Fragmentation is driven by the heat up and expansion of the fission gas (FG) bubbles in the fuel pellet causes fuel fragmentation during the LOCA simulation.	• PIE of the pellets in the father rods to characterize their initial state ***and/or*** FGR behavior calculations ***and/or*** experiments specifically designed to induce postulated FG phenomenon, but leave fuel in state to be further examined.

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Hypotheses to account for the observations and proposed **research** to verify or refute the hypotheses

Hypothesis	Research
Fuel Release	
• Fuel release can only occur if the fuel particles are smaller than the fuel rod opening	• Experiments and examinations targeted to understand the controlling variables for fuel fragmentation size and rupture opening size.
Fuel Mobility	
• Some threshold of cladding strain is required before fuel can be mobile	• Additional integral testing, varying the cladding strain, and more detailed examination at the location where the boundary of "empty" fuel was measured

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NRC's Next Steps

Near-term research under evaluation

- A focused PIE campaign to establish a relationship (or lack thereof) between fuel fragmentation to pre-test state, burnup, bond layer and rim structure in available integral test samples.
- Analytical scoping efforts related to rod burst population (with population identified by operation cycle)
- Analytical efforts to quantify the potential thermal-hydraulic consequences of fuel dispersal using available SA methodologies.

Collaboration with Halden

- Contribute specific recommendations (see next slide)
- Facilitate partnership and communication between Halden and complimentary research programs when appropriate.

Regulatory considerations under evaluation

- Will be addressed by my colleague Paul Clifford.

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Recommendations related to the Halden Program

1. IFA 650.13 conducted as planned
2. IFA 650.14 & IFA 650.15 could be designed as sister tests (a segment from the same father rod if possible) to Studsvik tests 192/193 (very high burnup, standard fuel) & 196/198 (mid-to-high burnup, IFBA fuel), respectively.
3. PIE of father rods for each test in the IFA 650 series could be made available (if already completed) or could be initiated in order to characterize the initial fuel-cladding bond and the extent of initial pellet cracking.
4. A comparative study could be conducted, examining fragmentation observations from the neutron radiographs of all IFA 650 series tests which look for a relationship between the observed fragmentation and fuel rod characteristics and the experimental conditions.
5. The geometry of the test chamber could be reconsidered.
6. Minimize test variables when possible.
7. Alternatively, a larger test matrix could be developed and commissioned which addresses many postulated variables all at once, executed as a multi-party cooperative effort—possibly at other research institutions in addition to the Halden Project.

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Conclusions

- Presented and discussed results of six integral LOCA tests
- Offered hypotheses to explain the observations
- Proposed experiments and further examinations that could elucidate those hypotheses
- Presented NRC's next steps and recommendations related to the Halden Program

Pursing a more complete understanding of the phenomena observed in these tests will allow for better predictions of fuel response to LOCA conditions in-reactor and assure that LOCA consequences continue to be acceptable. One intention of this presentation was to encourage and provoke research initiatives in pursuit of such an understanding.

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For more information

Available publications:

- "Observations of Fuel Fragmentation, Mobility and Loss in Integral, High-Burnup, Fueled LOCA Tests", Full Paper prepared for the Halden Workshop on LOCA, Lyon, France, May 29-30, 2012
- NUREG-2121, "Fuel Fragmentation, Relocation and Dispersal during the Loss-of-Coolant Accident," Published March 2012

Upcoming publications:

- Helin, M., Flygare, J., STUDSVIK/N-11/130, "NRC LOCA Tests at Studsvik, Design and Construction of Test Train Device and Tests with Unirradiated Cladding Material," Manuscript completed, to be published

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Backup Slides

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Summary of Results

Test ID	189	191	192	193	196	198
Rod ID	AM2-E08-2-1	AM2-F10-2-2	AM2-E08-2-2	AM2-F10-2-1	M14-L3	M14-L2
Comments	Ramp to rupture test	Ramp to PCT, held for 25 s at PCT	Ramp to PCT, held for 5 s at PCT	Ramp to PCT, held for 85 s at PCT	Ramp to rupture test	Ramp to PCT, held for 85 s at PCT
Cladding	ZIRLO	ZIRLO	ZIRLO	ZIRLO	ZIRLO	ZIRLO
Rod Type	UO_2	UO_2	UO_2	UO_2	IFBA - ZrB_2 coating	IFBA - ZrB_2 coating
Burnup (GWd/MTU)	≈ 72	≈ 71	≈ 72	≈ 71	≈ 55	≈ 55
Adjacent Hydrogen Measurement (wppm)	176	271	288	187	149	<149
Cladding OD (mm)	9.5	9.5	9.5	9.5	9.14	9.14
Cladding thickness (mm)	0.57	0.57	0.57	0.57	0.57	0.57
PCT (°C)	950 ± 20	1160 ± 20	1160 ± 20	1160 ± 20	960 ± 20	1160 ± 20
Max. Burst Strain (%)	48	50	56	51	25	25
Fill Pressure (bar)	110	110	82	82	82	82
Rupture Pressure (bar)	113	104	77	77	72	74
Rupture Temperature (°C)	700	680	700	728	686	693
Rupture Opening Width (mm)	10.5	17.5	9.0	13.8	0.2	1.6
Rupture Opening Axial Length (mm)	23.9	21.6	22.7	17.8	1.5	11.0
Fuel Mass Released During LOCA (g)	>41	52	68	105	0	0
Fuel Mass Release TOTAL (g)	>61	59	84	110	77	62
Measured "Empty" Length (mm)	148	125	165	205	157	131

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Terms defined

- ***fuel fragmentation*** refers to any separation of the fuel pellet into more than one piece that is observed after all experimental procedures are complete, regardless of when or why it occurred.
- ***fuel mobility*** refers to any physical movement of fuel pellets or fuel fragments within the cladding that takes place at any point during the experimental procedures.
- ***fuel release*** refers to any fuel material found outside of the fuel rod that results from any step within the experimental procedures

These terms have been chosen specifically, in order to distinguish phenomenon that could be termed ***"active"*** from phenomenon that could be termed ***"passive."*** We acknowledge that ***"active"*** experimental steps (e.g., inverting the severed rod) do not necessarily have a correlate in a postulated reactor scenario and this should be understood when considering the mobility and release observed in these experiments

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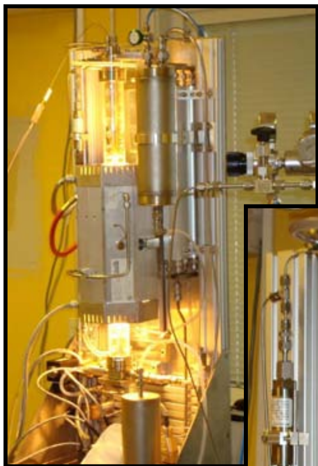
Experimental Procedures and Measurements



- o Experiment features:
  - Conducted in a hot cell facility.
  - External heating provided by a clam-shell, radiant furnace
  - Segments encapsulated in a quartz tube
- o Test specimen features:
  - Single rod
  - fueled
  - pressurized
  - 300 mm in length
- o Transient features
  - Ramped in steam from 300ºC to a target temperature of about 1200° C at a rate of 5ºC/sec.

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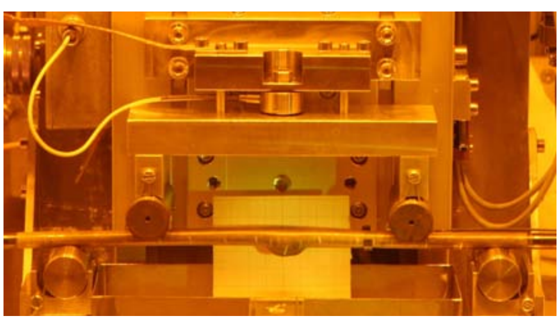
Experimental Procedures and Measurements



A four point bend device applied bending force on integral test segments after the LOCA simulation. This was followed by a “shake” test in which the two halves of the broken fuel rod were inverted and lightly shaken to dislodge any loose fuel particles.

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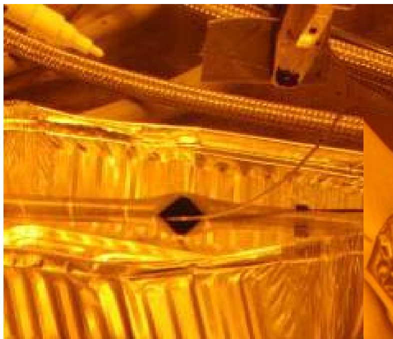
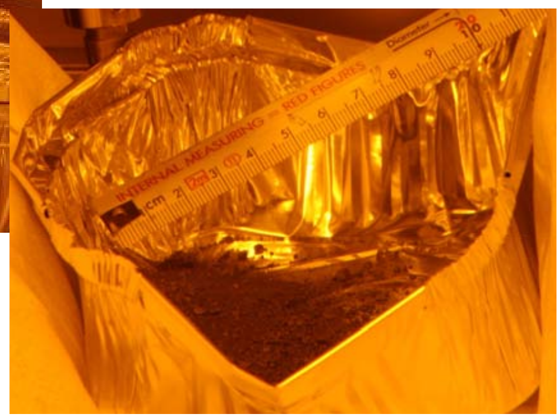
Experimental Procedures and Measurements



A wire probe is inserted into the fuel rod to measure the voided cladding length.



An image of the fuel fragments collected from the LOCA test train

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