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

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Abstract

The United States Nuclear Regulatory Commission (USNRC) has conducted a series of integral Loss-of-Coolant Accident (LOCA) tests on high-burnup, fueled rod segments at Studsvik Laboratory in Sweden. In total, six integral LOCA tests have been completed using rod segments fabricated from ZIRLO rods provided by Westinghouse and irradiated in commercial nuclear power plants in the United States. Four of these segments were taken from irradiated rods with a rod average burnup of ≈70 GWD/MTU and a measured hydrogen content of ≈200 wppm. Two of these segments were taken from irradiated rods with a rod average burnup of ≈55 GWD/MTU and a measured hydrogen content of ≈200 wppm. During the test program, significant observations related to fuel fragmentation, mobility and release were recorded. The observations of the test program related to fuel fragmentation, mobility and release will be presented and discussed in this paper. Hypotheses to explain the observed behavior will be offered, and experiments and examinations to further investigate the hypotheses will be proposed. Recommendations for the Halden LOCA program will be included.

1 Introduction

As part of USNRC's ongoing integral LOCA research program, four integral LOCA tests were conducted at Studsvik Laboratory on high burnup, fueled rods to investigate the mechanical properties of ballooned and ruptured cladding. These fuel rods had a rod average burnup near 70 GWD/MTU. In these tests, significant fuel release was observed. The burnup of the first four rods tested at Studsvik was still above U.S. licensed burnup limits of 62 GWd/t, however they were closer to the current limit than that of previous Halden experiments, and therefore arguably generated greater concern that the findings of IFA-650.4. In addition, the fuel fragmentation size of the dispersed fuel could be readily observed in the Studsvik tests, and the fuel fragments were observed to be fine.

In response to these observations, a range of historical data was reviewed and two additional tests were planned on samples segmented from lower burnup fuel rods. The historical review is documented in a USNRC publication titled "Fuel Fragmentation, Relocation, and Dispersal during the Loss-of-Coolant Accident" [1]. That report discusses trends and observations available in existing data, when evaluated as a whole and in light of more recent findings. The two additional tests were completed at Studsvik in November 2011.

In this paper, the results of all six integral LOCA tests at Studsvik that relate to fuel fragmentation, mobility and release are presented and discussed. The terms fuel fragmentation, mobility and release are defined as they are used in this paper and the experimental procedures and measurements of this program are described. Hypotheses are offered to explain the observations in the experiments and further examinations are proposed to investigate the hypotheses.

There are differences in the experimental setup used in this program, and in fact in all integral LOCA experimental programs, compared to an in-reactor LOCA scenario. It is not always clear how these deviations from reactor conditions affect the experimental results. This paper focuses on understanding the observations in the experiments. Even though the experiments may deviate from reactor conditions, valuable observations can be made which result in better understanding of the conditions that exacerbate fuel fragmentation, mobility and release.

2 Fuel Fragmentation, Mobility and Release Defined

During normal reactor operation, oxide fuel pellets develop cracks due to thermal stresses. At higher values of burnup, fission gas production and migration, combined with very high local burnup, are postulated to generate a "rim" region in fuel pellets that is highly porous. In addition, during LOCA conditions, additional fragmentation is postulated to occur because of the thermal-mechanical response to the transient. The measurements of fuel fragment size reported in this paper were made after all of the experimental procedures and it is not possible to attribute the observations to initial or transient conditions. Therefore, in this paper, *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.

If fuel pellets are fragmented and separated from each other, they could be free to move relative to their neighbors. In this experimental program, the fuel segments were subjected to a postulated LOCA transient as well as other experimental steps that do not necessarily have a correlate in the LOCA transient (see section 3). In this paper, *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. In this paper, *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." By using the terms fuel mobility and release, rather than the perhaps more established terms *relocation* and *dispersal*, the author intends to distinguish between the fuel that moves and falls out of a rod during the LOCA simulation (considered relocation and dispersal in this paper) from the fuel that moves and falls out under any circumstance, during the LOCA simulation or after active experimental steps such as inverting the severed rod (considered mobility and release in this paper). The 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.

3 Experimental Procedures and Measurements

The integral loss-of-coolant accident (LOCA) tests conducted at Studsvik were originally designed to develop an understanding of the impact of LOCA conditions on the mechanical behavior of ballooned and ruptured fuel rods. A test train and experiment design were developed that could generate data for this purpose. There are aspects of the test train and experiment design that are typical of conditions expected in a reactor during a LOCA, and there are aspects that are not typical. This section will discuss the test train and experimental design.

The tests in this experimental program at Studsvik are conducted in a hot cell facility. Fuel rod segments are encapsulated in a quartz tube and external heating is provided by a clam-shell, radiant furnace. There is no nuclear heating in these tests. In each experiment, single rod segments of pressurized, irradiated and fuelled cladding, approximately 300 mm in length, were ramped in steam from 300^{o}C to a target temperature of about 1200°C at a rate of 5^{o}C/sec. Internal pressures were consistent with end of life rod internal pressure, although likely on the high end, and were chosen to induce ballooning and rupture with rupture strains in the range of 30% - 50%. Hold times were selected to achieve various oxidation levels (ECR). The test train and furnace used to conduct these experiments are shown in Figure 1a. A report titled "NRC LOCA Tests at Studsvik, Design and Construction of Test Train Device and Tests with Unirradiated Cladding Material" [2] provides extensive details and drawings of the test train used in these tests.

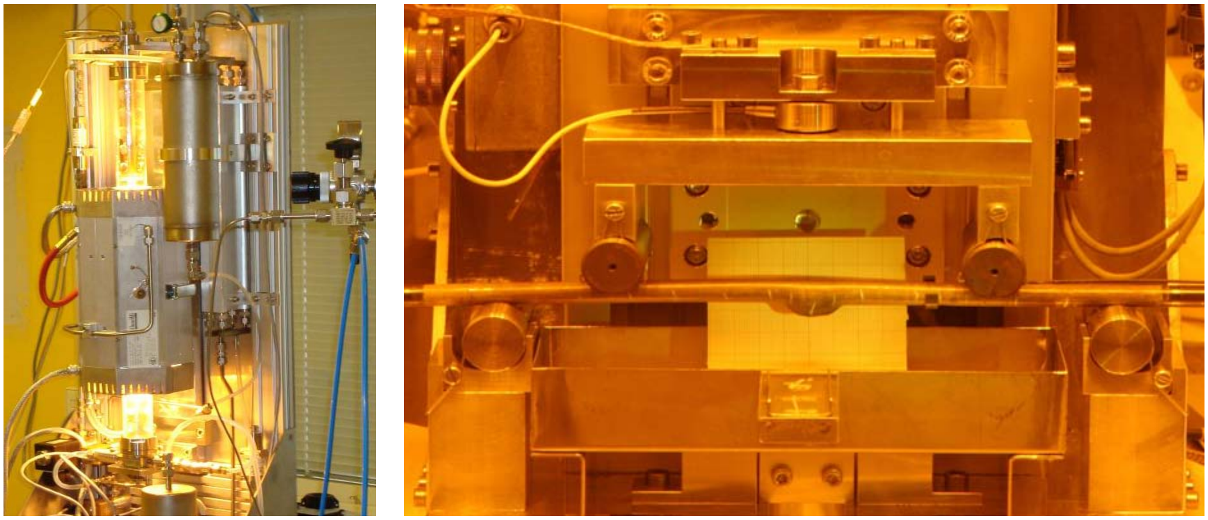
(a) (b)

Figure 1. (a) The single-rod, integral test train and (b) the four-point bend device used at Studsvik.

Following the LOCA simulation, four-point bend tests (4PBTs) were conducted to measure the residual mechanical behaviour of the ballooned and ruptured region, as shown in Figure 1b. After the 4PBT, a shake test was performed to determine the mobility of fuel particles that remained in the fuel rod. The shake test consisted of an inversion of the two halves of the broken fuel rod followed by minor shaking to dislodge any loose fuel particles. This test was conducted approximately two days after the LOCA simulation.

During these tests, significant fuel release was observed at various stages of the experimental procedures and multiple measurements and observations were made to characterize the fuel release. Wire probe measurements, as illustrated in Figure 2, were performed to measure the length of cladding that was "empty[1]" of fuel for each segment. Mass measurements were made before and after the LOCA simulation, after the 4PBT and after the shake test to determine the fuel release at each stage. Photos were taken to document the appearance of the fuel and cladding at all stages. Particle size measurements were completed by processing fuel fragments through a series of six sieves to determine the distribution of the fuel particles by size.

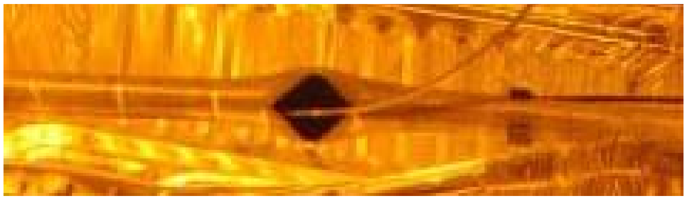

Figure 2. A wire probe is inserted into the fuel rod to measure the empty cladding length.

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[1] This technique is a rough characterization of how far the fuel release has extended and does not necessarily indicate if the fuel release is complete along the measured length. The measured length will be referred to as "empty" for simplicity.

4 Observations

In this experimental program, a total of six integral LOCA tests were performed on segments of high burnup, fueled rods. While the experimental procedures for each test remained largely the same (except for one variation in fill pressure and variations in ECR through adjustments in the duration of high temperature oxidation), there were important differences between the test segments, the observed burst response, fragmentation size and fuel release. Table 1 below consolidates some of the characteristics of each test and the remaining subsections will expand on the observations of fuel fragmentation, mobility and release. In Table 1, PCT is peak cladding temperature and IFBA is Integral Fuel Burnable Absorber.

Table 1 - Summary of Test Characteristics and 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

4.1 Observations and Discussion: Fuel Release

Earlier in this paper, fuel release was defined as any fuel material found outside of the fuel rod that results from any step within the experimental procedures. The amount of fuel lost after the LOCA simulation, after the 4PBT and after the shaking was determined from mass measurements. The “empty” length was measured following the completion of all of these experimental steps (and in some cases, also measured following the LOCA simulation). Measurements of fuel lost for each test are included in Table 1. The total mass release and final measurements of the “empty” length are remarkably similar for each test, despite differences in test parameters (such as rod internal pressure, peak temperature, oxidation time). On average, about half of the fuel mass in each of the 300-mm-long fuel rod segments was lost during the testing, either during the LOCA simulation itself, during the bend test or subsequent shaking of the broken rod. However, a distinct difference was apparent between the fuel release observed in tests 189-193 and 196 and 198. During tests 189-193, a significant amount of fuel was lost during the LOCA simulation. Figure 3 shows the rupture opening after LOCA testing for tests 189-193. It can be seen that the rupture region is completely void of fuel. In contrast, during tests 196 and 198 essentially no fuel was lost during the LOCA simulation. Figure 4 shows the rupture opening after LOCA simulation for tests 196 and 198. In these tests, the rupture opening was significantly smaller than those in tests 189-193. The test segment from test 196 was not subjected to a 4PBT, but was cut in half and then subjected to the shake test. The test segment from test 198 was subjected to a 4PBT and a shake test. In both cases, a significant amount of fuel was lost during the shake test.

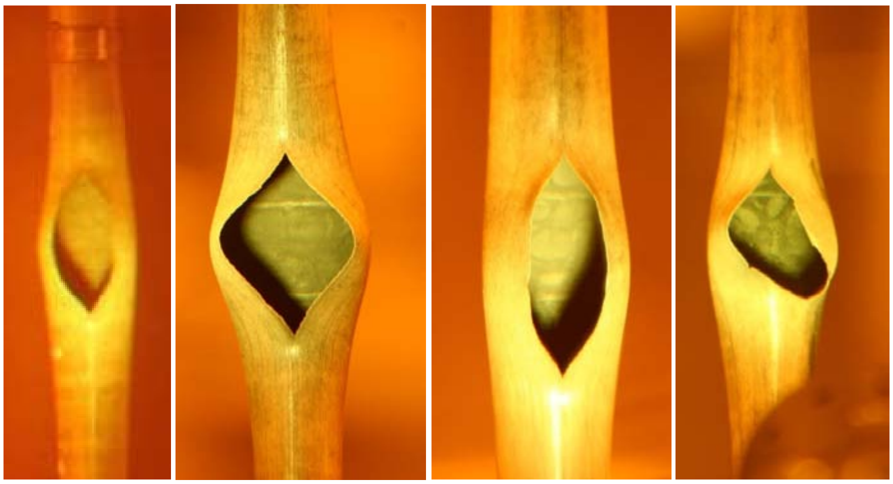

Figure 3. Rupture opening in Studsvik LOCA tests 189, 191, 192, and 193 (left to right), showing the absence of fuel in the rupture plane.

Figure 4. Rupture opening in Studsvik LOCA tests 196 and 198 (left to right)

4.2 Observations and Discussion: Fragmentation

Fuel fragment size measurements were made for the total mass of fuel material found outside of the fuel rod after all steps of the experimental procedures for each of the six tests. The fragments were processed through a series of six sieves to determine the distribution of the fuel particles by size. Figure 5 depicts the results of this examination. One of the first observations that are apparent is a significant difference in distribution between tests, 191-193[2] and tests 196 and 198. In tests 191-193, the fuel was finely fragmented and all fragments measured less than four millimeters (except a small amount from test 193). The mass of fuel fragments from these tests was approximately evenly distributed between the size groups separated by the six sieves used. In contrast, the fuel in tests 196 and 198 was not finely fragmented and the fragments measured predominately larger than 4 millimeters.

Although it is not obvious by examination of Figure 5, Table 1 indicates that the total mass found outside of the fuel rod for tests 191-193 was about the same that measured in tests 196 and 198, so the difference in size distribution is not due to a skewing of limited sample size.

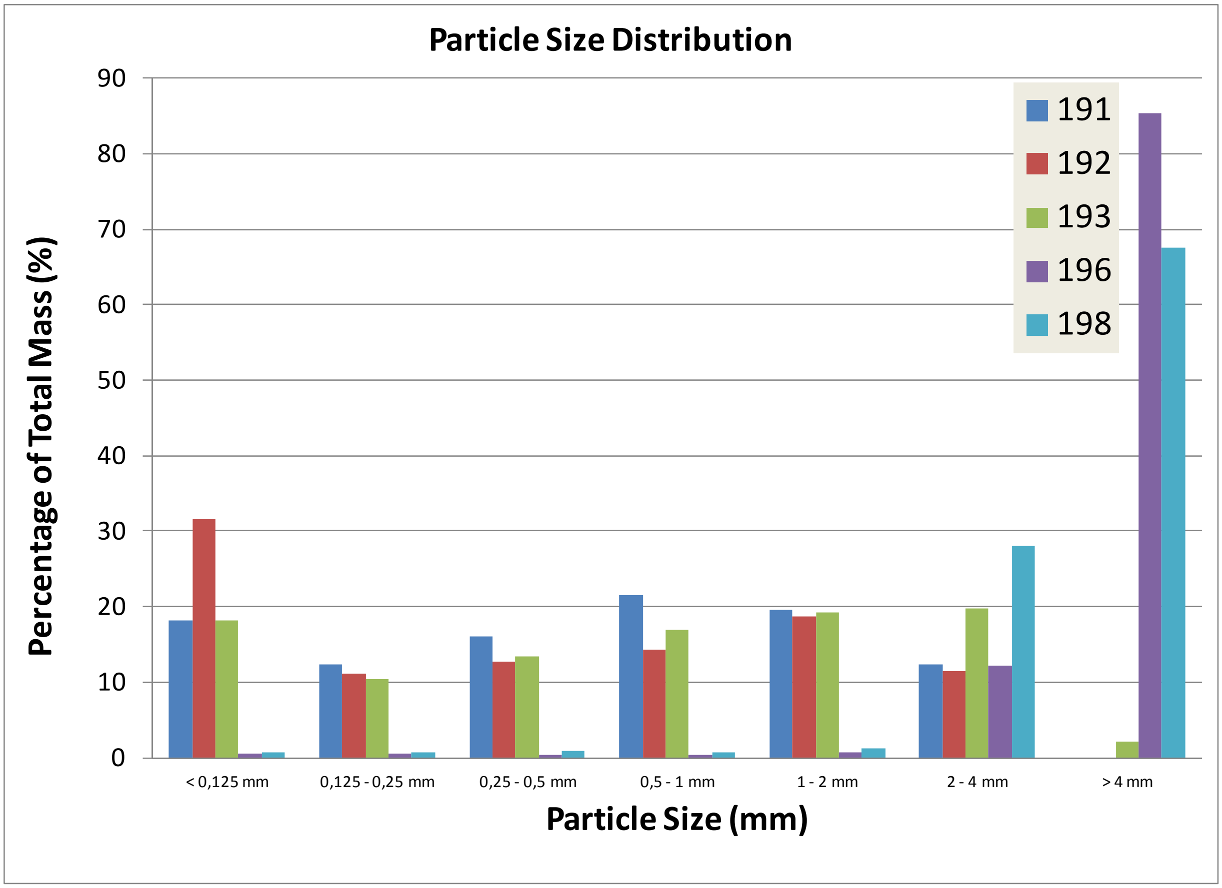

Figure 5. Particle size distribution from six integral LOCA tests

To further illustrate the difference in the fragmentation of fuel observed in tests 191-192 and tests 196 and 198, Figure 6 and Figure 7 provide images of fuel particles collected from four tests. Figure 6 includes images of fuel particles from tests 192 and 193 and the images reveal the sand-like quality of the

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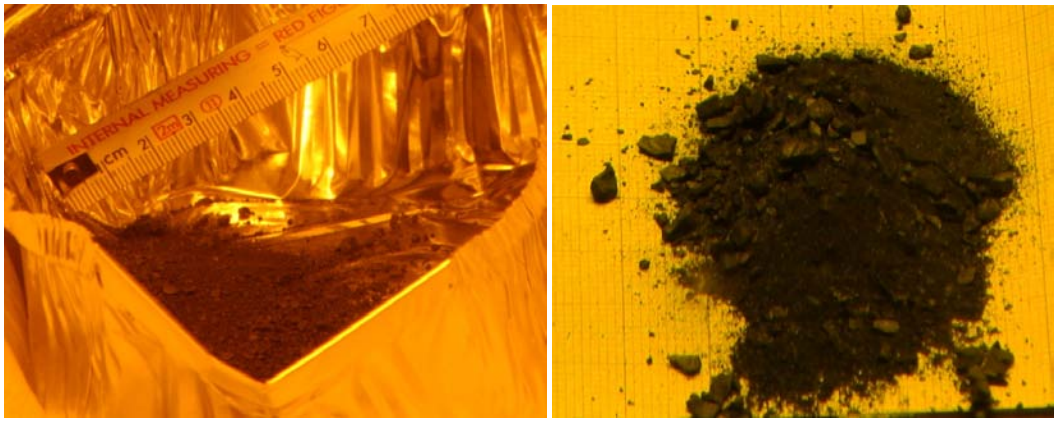
[2] Disposal of fuel from test 189 took place prior to the decision to undertake further examinations of the fuel particles, and therefore particle size measurements are not available for fuel from tests 189.

fuel fragments collected from these tests. In contrast, Figure 7 includes two images of fuel particles from tests 196 and 198 and the images reveal much larger fuel fragments. In some cases the fragments appear to be as large as half a pellet.



(a) (b)

Figure 6. Images of fuel particles collected from test rod (a) 192 and (b) 193 revealing a very small, sand-like fragmentation size

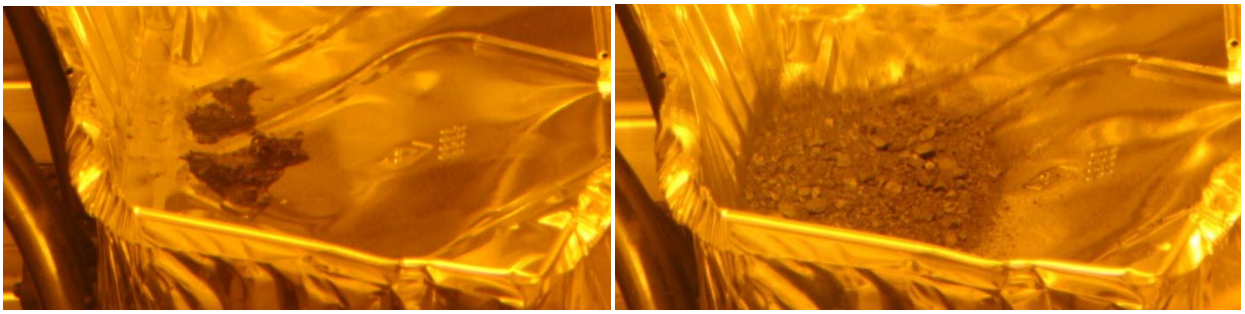
(a) (b)

Figure 7. Images of fuel particles collected from test rod (a) 196 and (b) 198 revealing large fragments

4.3 Observations and Discussion: Mobility

Earlier in this paper, fuel mobility was defined as any physical movement of fuel pellets or fuel fragments within the cladding that takes place at any point during the experimental procedures. This includes fuel that is mobile and lost during the LOCA simulation and fuel that is mobile and lost during the shake test conducted a few days after the LOCA simulation. A few observations related to the timing and magnitude of fuel mobility will be presented here.

First, observations of these experiments suggest that fuel mobility may be influenced by the wetness of the fuel. When the fuel rod is first removed from the test train, leaving a small hole at the bottom of the train, a small amount of wet, black fuel sludge fell out. An image taken just after a test segment was removed can be seen in Figure 8a. After two days, a larger amount of fuel is found beneath the test train, even though no disturbance or activity took place in or near the test train. An image taken two days after the segment was removed can be seen in Figure 8b. This observation could indicate that as the fuel dries out, it becomes more mobile and gradually empties out of the test train, perhaps after losing adherence to the test train surfaces. Other observations from the shake tests revealed a similar phenomenon: more fuel was mobile after two or three days had passed since the LOCA simulation.



(a) (b)

Figure 8. Fuel collected beneath the LOCA test train (a) just after the fuel segment was removed, and (b) two days after the fuel segment was removed.

Another observation of the shaking test, is that the fuel which fell out during the shaking step flowed out readily as soon as the rod was inverted and before any shaking. A video of the shaking step was recorded. In this video, the shaking does not appear to dislodge any almost-mobile fuel fragments; rather, the inversion allows already mobile fuel to spill out readily. So while the experimental procedure refers to the “shake” test, very little physical shaking was required to lead to fuel mobility. It appeared that any fuel that was going to fall out was mobile due to gravity alone.

The magnitude of fuel mobility was examined by measuring the mass of lost fuel, as well as by a wire probe measurement indicating the length of “empty” cladding material. The length of “empty” cladding material was compared to the measured final strain in each test. Figure 9 – Figure 14 illustrate this comparison. In these figures, the fueled length extends from approximately 45mm (bottom) to 345 mm (top) on the x-axis as labeled. In all figures, a region of the graph is shaded purple to indicate the final measurement of the axial extent of fuel release. The intersection of this length with the values of local, final strain are noted. The values range from 1% to 9% strain. Results are similar to those from Halden (See Section 4.1.7 of Ref. 1).

For tests in which the wire probe was used to measure the length of “empty” cladding just after the LOCA simulation, a blue region indicates the axial extent of fuel release just after the LOCA simulation. In tests 191-193, there was significant fuel release during the LOCA simulation and further fuel release took place during the shaking test. There was no significant agitation of the fuel rod between the LOCA simulation and the shaking tests, so the additional fuel lost could be a result of the dry out phenomenon discussed above.

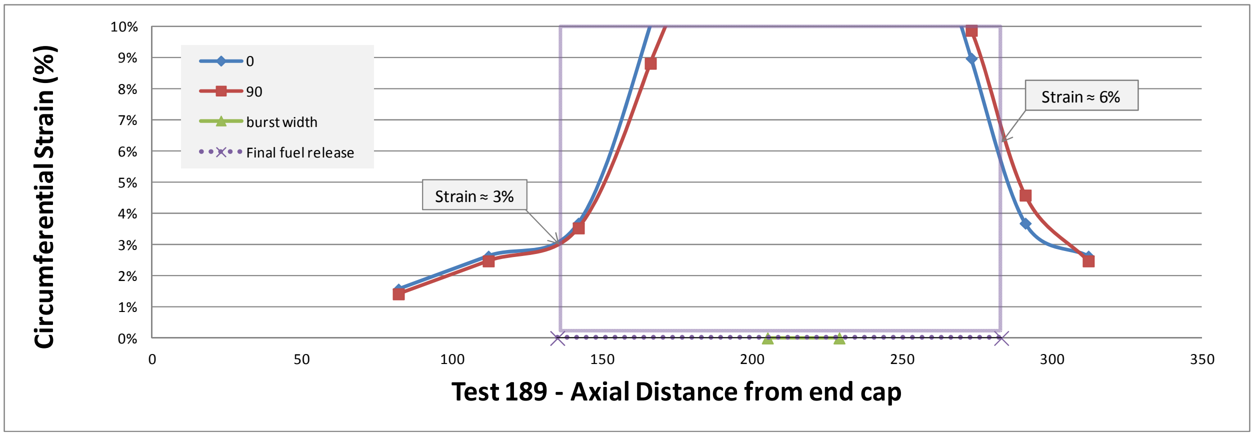


Figure 9. Axial extent of fuel release in comparison to measured final strain in test 189

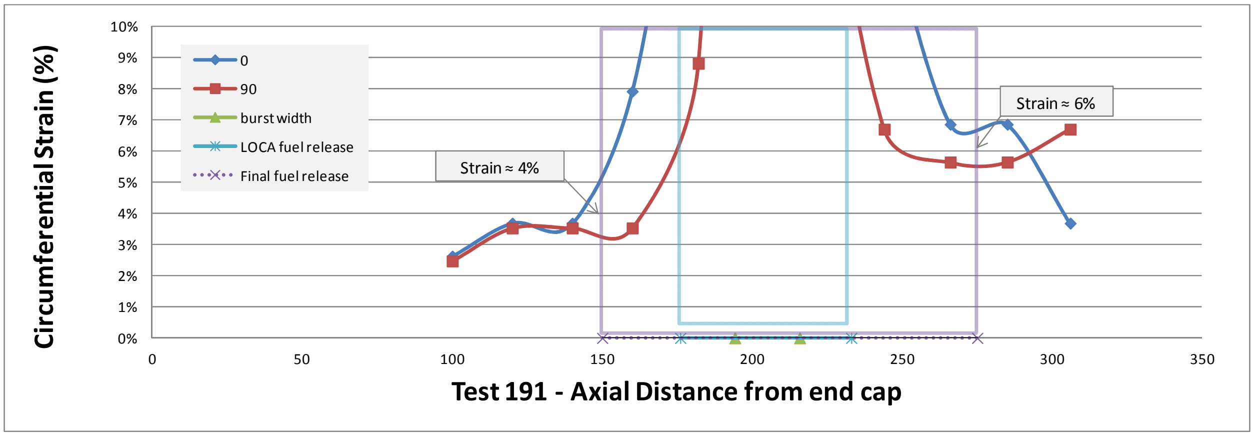


Figure 10. Axial extent of fuel release in comparison to measured final strain in test 191

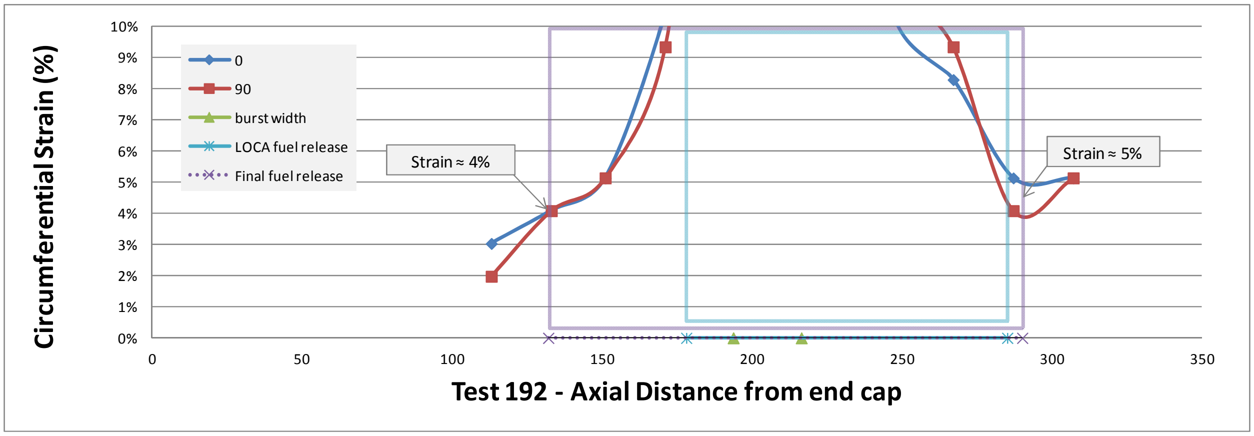


Figure 11. Axial extent of fuel release in comparison to measured final strain in test 192

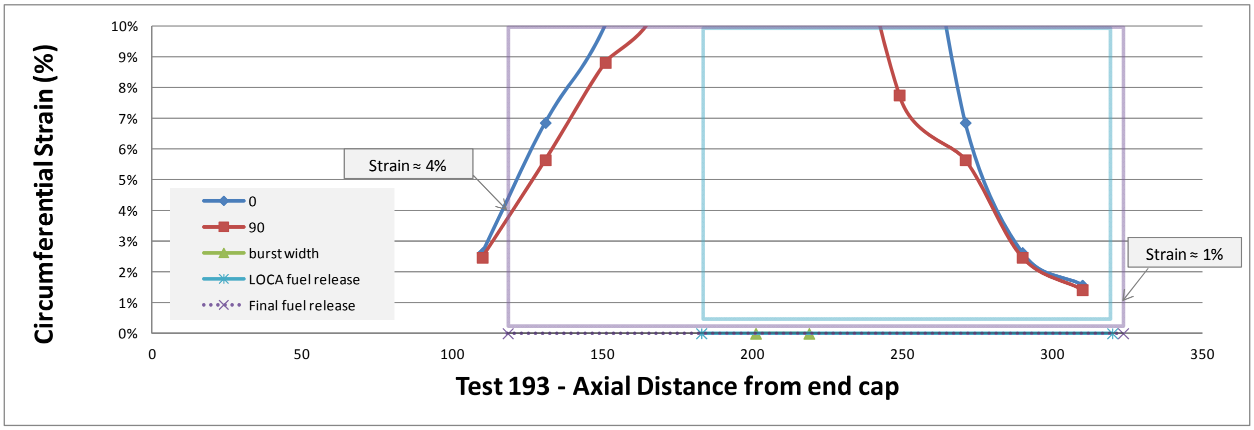


Figure 12. Axial extent of fuel release in comparison to measured final strain in test 193

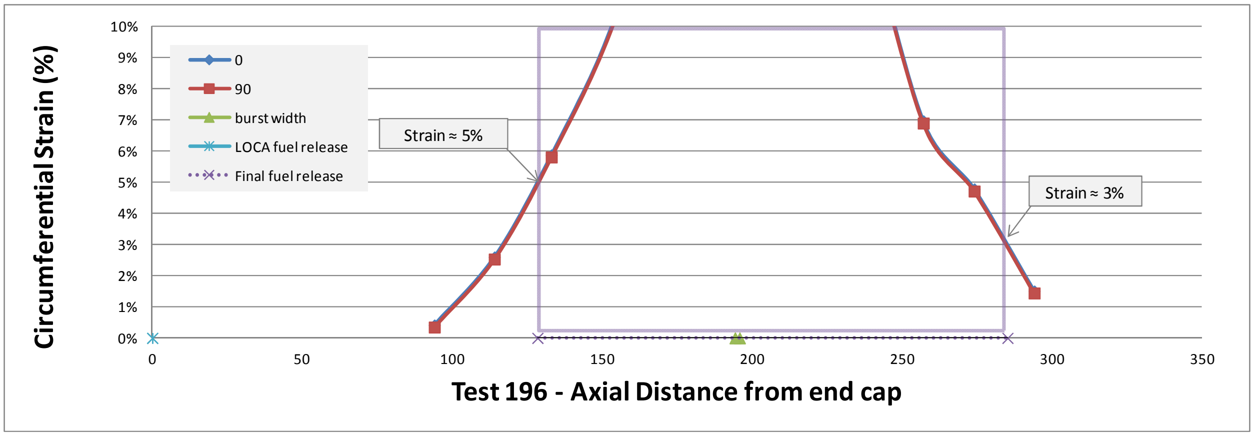


Figure 13. Axial extent of fuel release in comparison to measured final strain in test 196.

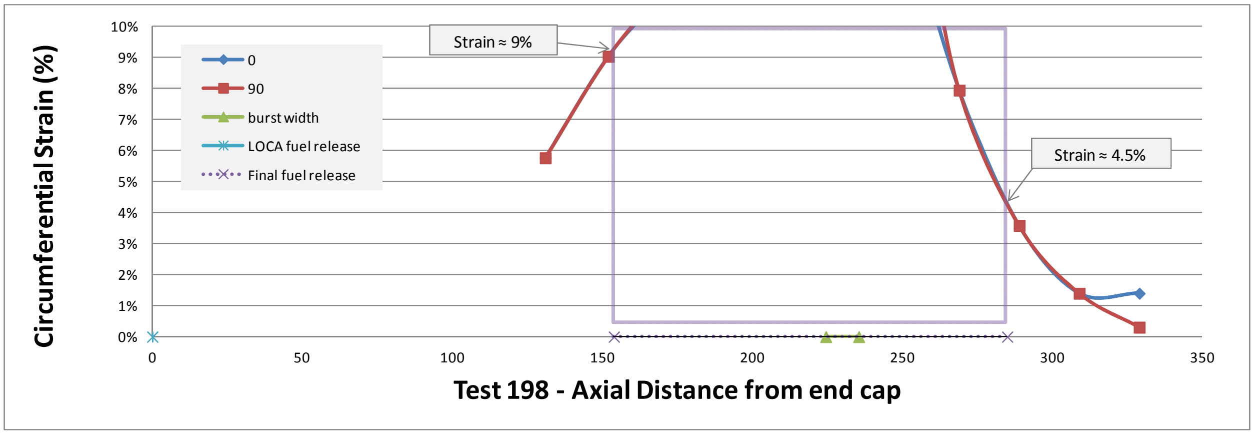


Figure 14. Axial extent of fuel release in comparison to measured final strain in test 198

5 Hypotheses and Proposed Investigation

By examining the observations of fuel fragmentation, mobility and release in these six experiments, a few hypotheses have been developed. These hypotheses will be presented, along with experiments and examinations that could test the validity of each hypothesis.

When examining the observations of fuel release, one thing that may seem obvious, but is worth highlighting, is that fuel release can only occur if the fuel particles are smaller than the fuel rod opening. In tests 191-193, very fine fuel fragments were observed and this was coincident with very large ballooning and rupture features. In tests 196 and 198, no fuel release was observed during the LOCA simulation, and this was coincident with very small rupture features. However, after the rods from tests 196 and 198 were severed, a significant amount of fuel was lost as a result of inversion and shaking. The collected fuel fragments were measured to be much larger than the rupture feature of these two tests. Considering the relationship between fuel fragment size and fuel rod opening size is important when trying to predict the occurrence of fuel release in a reactor scenario. If fuel dispersal will only occur in a reactor scenario when the fuel fragments are smaller than the rupture opening, experiments and examinations to improve the confidence in predicting the occurrence of fuel release could be targeted to understand the controlling variables for fuel fragmentation size and rupture opening size.

Regarding the observations of fuel mobility, it could be hypothesized that some threshold of local cladding strain is required before fuel can be mobile. The cladding strain threshold may be influenced by fuel fragment size. In the six tests run at Studsvik, the observed strain threshold varied from 1% up to 9%. Experiments and examinations that could test the validity of a strain threshold hypothesis include additional integral LOCA tests as well as more detailed examination at the location where the boundary of “emptied” fuel was measured. The wire probe technique reveals the first point at which a traveling probe is obstructed, and is therefore a very rough measurement of the “emptied” fuel region. Detailed images of the boundary of “emptied” fuel may reveal a more consistent relationship between local cladding strain and fuel mobility.

The observation that post-test fuel mobility is accentuated by dryness of the fuel fragments was consistent throughout the test procedures and between tests. This observation could be important when trying to predict the occurrence of fuel release in a reactor scenario. Experiments and examinations that could improve the confidence in predicting fuel mobility in a reactor scenario would then be designed to simulate the post-quench environment of a fuel rod. Removing the fuel rod from the test train and examining fuel mobility following two or three days of sitting in the hot-cell is not prototypical of the post quench environment.

When comparing the observations of fuel fragmentation in tests 191-193 and tests 196 and 198, a clear difference in particle size distribution is observed. Recalling Table 1, the LOCA simulation was almost identical for these two sets of tests. Because the parameters of the LOCA simulation were similar for each of the six tests, explanations for the difference may arise from a difference in the father rods. As identified in Table 1, the rod average burnup of the father rods for test 191-193 was 70-72 GWd/MTU, while the burnup of the father rods for tests 196 and 198 was 55 GWd/MTU. The pellet type was also different between the fuel rods; standard UO_2 pellets in the case of 191-193 and zirc-diboride coated pellets in the case of 196 and 198. The cladding wall thickness was the same for the two test sets; however, the outer diameter of the fuel rods for tests 191-193 was larger than the outer diameter for tests 196 and 198. Another difference between the tests 191-193 and 196 and 198 was the ballooning and rupture response during the LOCA simulation.

Again, because the parameters of the LOCA simulation were similar for each of the six tests, one hypothesis to explain the fragmentation observations is that the final measured fragmentation was different due to a significant difference in initial state of the fuel. In other words, one hypothesis is that the pellets of the rods tested in tests 191-193 were already finely fragmented and little or no further fragmentation resulted from the LOCA simulation. Nothing to suggest this was the case was observed during cutting and re-fabrication of the test segments; however, that does not necessarily rule out initial fine fragmentation. Post-irradiation examination of the pellets in the father rods from these six test rods and further integral LOCA tests on fuel rods with well characterized end-of-life pellet fragmentation could be used to investigate this hypothesis.

A slightly different hypothesis to explain the fragmentation observations is that the driving mechanism for fuel fragmentation is a tensile stress on the fuel pellet that is induced by the cladding strain when a strong fuel-cladding bond exists. Post-irradiation examination of the fuel-cladding bonding layer of the father rods from these six test rods and further integral LOCA tests on fuel rods with well characterized fuel-cladding bonding layers could be used to investigate this hypothesis.

Finally, another hypothesis to explain the fragmentation observations is that the heat up and expansion of the fission gas bubbles in the fuel pellet causes fuel fragmentation during the LOCA simulation. This hypothesis could also be investigated with post-irradiation examination of the pellets in the father rods from these six test rods to characterize their initial state. Quantifying the expected fission gas release behavior in the test rods through calculations could also be used to investigate this hypothesis. Additional experiments could be conducted which attempt to induce the postulated fission gas phenomena, but leave the segment in a state that can be examined for evidence of these phenomena. For example, experiments could be conducted which simulate the temperature transient used in these tests, but without rod internal pressure, and post-test examination of the pellets could reveal if fuel fragmentation was induced. Alternatively, experiments could be conducted which simulate the beginning of the temperature transient, but hold at a temperature just short of rupture temperature. Post test examination of the pellet could reveal if fuel fragmentation was induced and fission gas analysis (by puncturing and gas mass spectrometry) could characterize the fission gas released by the transient.

6 Conclusions

The USNRC has completed a total of six integral tests at Studsvik on high-burnup fuel rods, four with a burnup around 70 GWd/MTU and two with a burnup around 55 GWd/MTU. By examining the observations of fuel fragmentation, mobility and release from these six tests, a number of hypotheses can be conceived to predict if fuel release should be expected under LOCA conditions in reactor scenarios; however the supporting evidence for each is inadequate. 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 induced by operation. The difference could be attributed to transient phenomenon such as pellet tensile strain caused by a strong fuel cladding bond or retained fission gas expansion. The particular father rods used in tests 189-193 had a unique operating history (mean LHG of ≈ 24 kW/m for cycle 1, ≈ 23 kW/m for cycle 2, ≈ 5 kW/m for cycle 3, and ≈ 15 kW/m for cycle 4) and claims have been made that this induced non-typical, end-of-life fragmentation; however, without characterization of the initial condition, this claim remains unsupported. Fuel mobility appears to require cladding strain; however, the available measurements are rough and the scatter in the strain threshold is high. Fuel fragments appear to be more mobile when the fragments are dry, and this could be advantageous when considering fuel relocation and release in a reactor scenario. Fuel release occurs only when the fragmentation size is smaller than rupture opening size, however fragmentation size and rupture size are both phenomena that are not well predicted and therefore this observation does not readily lead to an ability to predict the occurrence of fuel dispersal in reactor conditions.

There are differences in the experimental setup used in this program, and in fact in all integral LOCA experimental programs, compared to an in-reactor LOCA scenario. It is not always clear how these deviations from reactor conditions affect the experimental results. More work is needed to evaluate the extent to which the experimental results are representative of fuel response in-reactor to a LOCA scenario.

Examinations of the father rods for these six integral LOCA tests at Studsvik have been proposed which could test a number of hypotheses presented in this paper. More detailed observations and measurements may be available from other sources, particularly from some of the more recent programs such as the IFA-650 LOCA test series, which could also test the hypotheses presented in this paper. Comparing and resolving findings of the various experimental programs in which fuel release was observed is a valuable next step to develop and ability to better predict the extent of fuel release during and following a LOCA.

Conducting additional tests could also be pursued to develop a more complete understanding of the likelihood of fuel fragmentation, mobility and release in response to LOCA conditions. The test setup at Studsvik is simple and easily accessible, making it well suited for a test matrix evaluating the impact of separate effects such as rod internal pressure, void volume, peak cladding temperature and rod burnup. Operating in a hot cell offers the benefit of capturing testing with video and photos. The LOCA test set up at Halden simulates many in-reactor conditions that the Studsvik test setup does not, and understanding the influence of these in-reactor conditions is critical to interpreting results. A cooperative test program between Halden and Studsvik may provide comparisons and insights to develop an understanding of the conditions and critical variables controlling fuel fragmentation and release under LOCA conditions.

This paper focused on understanding the observations in the experiments and even though the experiments deviate notably from reactor conditions, valuable observations can be made which move towards greater understanding of the conditions that exacerbate fuel fragmentation, mobility and release. Further work was proposed to investigate residual questions and test hypotheses. 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 paper is to encourage and provoke research initiatives in pursuit of such an understanding.

7 Recommendations for Halden Testing

There are three tests planned in the current Halden three-year program in the IFA-650 series. The call for papers for the workshop on LOCA identified “the definition for the future direction of the HRP LOCA testing” as one of the purposes of the workshop. Specifically, definition for the future direction of the HRP LOCA testing with the aim of closing gaps in the current state of understanding of key LOCA phenomena. The workshop announcement proposed the questions: “How do the Halden results compare to other results and what has been learned from other programs in this area?” and “Can additional relevant information be extracted from tests already completed by making further examinations?” The following recommendations are provided in response to these questions and workshop objectives.

1. IFA 650.13 could be conducted as planned as a so-called non-burst test, as a repeat of IFA 650.12 but terminating slightly earlier. This will provide valuable insight into the influence (or lack of influence) of the rupture event on fuel fragmentation and mobility.

2. IFA 650.14 could be conducted on an irradiated rod with rod characteristics (a segment from the same father rod if possible) and transient characteristics similar to those of Studsvik tests 196 or 198. This will provide valuable insight into the influence (or lack of influence) of more realistic

conditions on fragmentation, mobility and release phenomenon. It may also provide insight into the influence of zirc diboride on fragmentation, mobility and release phenomenon.

3. IFA 650.15 could be conducted on an irradiated rod with rod characteristics (a segment from the same father rod if possible) and transient characteristics similar to those of Studsvik tests 192 or 193. This will provide valuable insight into the influence (or lack of influence) of more realistic conditions on fragmentation, mobility and release phenomenon.

4. Metallography and ceramography examinations of un-tested material from the father rods of 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. The information on fuel-cladding bond layers could be synthesized with an effort to determine if there is a relationship between bond layer features and fuel fragmentation and mobility. The information on initial pellet cracking could be synthesized with an effort to determine what fragmentation (if any) takes place due to the LOCA simulation.

5. 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.

6. The geometry of the test chamber could be reconsidered. The space for fragment mobility in both the Halden and Studsvik setups is not typical, and the test chamber could be redesigned to more realistically simulate the space available around a fuel rod in an assembly geometry.

7. At this time, introducing additional variables such as MOX and Gd fuel pellets is not recommended. Based on experience with multiple test variables at Studsvik (see Table 1), to the extent possible, future test should be run with only one variable changing relative to a previous test. Introducing multiple test variables makes it difficult to hypothesize the cause of test observations.

8. Alternatively, a large test matrix could be developed and commissioned which addressed many postulated variables all at once, executed as a multi-party cooperative effort—possibly at other research institutions in addition to the Halden Project.

8 References

1. USNRC staff report, “Fuel Fragmentation, Relocation and Dispersal during the Loss-of-Coolant Accident,” Manuscript completed Feb 2012, to be published

2. 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 Feb 2012, to be published