Extensive research has been conducted on fuel fragmentation, relocation, and dispersal (FFRD) during a loss-of-coolant accident (LOCA). This research has shown that FFRD phenomena are correlated with burnup. As the U.S. nuclear industry pursues the operation of plants with higher fuel burnup levels, it is important to understand and account for FFRD-related phenomena and their impact on regulatory figures of merit (e.g., peak cladding temperature) in licensing applications. Recently, the U.S. Nuclear Regulatory Commission’s Office of Nuclear Regulatory Research (RES) published a research information letter to communicate the staff’s interpretation of findings from experimental programs on FFRD and to define conservative, empirical boundaries for FFRD-related phenomena.

The RIL provides a basis for limiting the analysis of FFRD to regions of the core with specific characteristics. Data from experimental programs conducted to date suggests that fine fragmentation is limited to fuel above 55 gigawatt days per metric ton of uranium (GWd/MTU) pellet average burnup. Axial fuel relocation is limited to regions of the fuel rod that have a local cladding strain greater than 3 percent. Relocated fuel fragments can occupy between 60 percent and 85 percent of the fuel rod cross-sectional area in the balloon region. The propensity for fuel dispersal is correlated with fuel fragment size and burst opening size; however, cladding burst and fuel relocation are prerequisites. This effectively limits fuel dispersal by the same parameters as fine fragmentation and relocation (i.e., pellet average burnup greater than 55 GWd/MTU and cladding strain greater than 3 percent). Finally, data from experimental programs conducted to date suggests that significant quantities of fission gas may be released during a LOCA transient. Transient fission gas release becomes increasingly significant with increasing burnup, with releases as high as 20 percent observed from a fuel rod segment with an average burnup of 70 GWd/MTU. Fission gas released during a LOCA may impact fuel rod ballooning and burst behavior and, thus, fuel relocation and dispersal.

INTRODUCTION

Emergency core cooling systems, core, and fuel must be designed to ensure that the fuel rods maintain a coolable geometry following postulated loss-of-coolant accidents (LOCAs). Over the last 10 or more years, research has indicated that high-burnup fuel can finely fragment, relocate axially, and disperse into the coolant under certain LOCA conditions. Transient conditions may cause trapped gaseous fission products to be released from the pellet, increasing rod internal pressure and impacting burst timing. Finely fragmented fuel may easily relocate axially within the fuel rod following ballooning of overheated cladding, impacting local heat distribution along the fuel rod, and potentially disperse through the breach in the cladding. If fuel disperses out of a burst fuel rod, it could compromise coolable geometry, impact the accident progression, complicate the safety demonstration, and alter cooling for long-term decay heat removal for both the fuel rods in the core and the dispersed fuel particles.

In 2012, the U.S. Nuclear Regulatory Commission (NRC) published NUREG-2121 [1] summarizing research related to fuel behavior during a LOCA. Later, it published SECY-15-0148 [2] evaluating FFRD in the context of a draft final rule on emergency core cooling system performance under a LOCA. SECY-15-0148 concluded that immediate regulatory action was not needed to address FFRD phenomena at that time. However, this conclusion was closely linked with existing fuel design limits and assumptions on how high-burnup fuel would be operated.

Since the publication of SECY-15-0148 in 2015, the NRC has continued to participate in multilateral research activities related to FFRD, including the Studsvik Cladding Integrity Project (SCIP) and the OECD Nuclear Energy Agency’s Working Group on Fuel Safety [3]. In light of recent interest by the U.S. nuclear industry to increase rod-average burnup limits beyond 62 GWd/MTU, staff published Research Information Letter (RIL) 2021-13 to offer its interpretation of research on the subject. RIL 2021-13 was subjected to an external peer review by an international panel of experts who have been heavily involved in some of the experimental programs discussed in the RIL. The RIL was also reviewed by NRC’s Advisory Committee on Reactor Safeguards [4]. The final version of the RIL includes changes based on these peer reviews, as described in Appendix B of RIL 2021-13 and in Ref. [5].

RIL 2021-13 addresses five elements of the RES staff’s interpretation of FFRD research and describes the technical basis for these elements:

1. Establish an empirical threshold at which fuel pellets become susceptible to fine fragmentation.
2. Establish a local cladding strain threshold below which fuel relocation is limited.
3. Examine experimental results of the mass of “dispersible” fuel as a function of burnup.
4. Provide evidence of significant transient fission gas release (tFGR) that may impact ballooning and burst behavior of high-burnup fuel under LOCA conditions.
5. Establish the basis for a range of packing fractions of relocated but nondispersant fuel in the balloon region.

This paper will summarize the evaluation of these five elements presented in the RIL. But first, it will describe the experimental programs considered in the RIL.

EXPERIMENTAL PROGRAMS CONSIDERED IN RIL 2021-13

The behavior of fuel rods under LOCA conditions has been studied for decades. Experiments have often focused on the timing and degree of ballooning and burst, the mechanical behavior of the cladding following the LOCA transient, and the cooling effectiveness around ballooned fuel rods.

In 2006, the Halden Reactor Project (HRP) ran a test (IFA-650.4) on a fuel rodlet with a segment average burnup\(^1\) of 92.3 GWd/MTU \([6]\). Following the test, significant fuel relocation and dispersal were observed. Even though fuel fragmentation and relocation had occurred in tests before IFA-650.4 and, in some cases, minor fuel loss had even been observed,\(^2\) there had been little effort to quantify or specifically study the fragmentation or relocation of fuel pellets. The results of IFA-650.4 were considered so significant that they caused a refocus of international LOCA research to better understand FFRD. Experimental methods were designed to anticipate FFRD and better capture relevant experimental features. Posttest examinations were developed to quantify the degree of fragmentation and relocation. In addition, experiments began to largely focus on irradiated material above 50 GWd/MTU. For these reasons, RIL 2021-13 focuses on insights gained from experiments conducted after 2006.

Experimental programs on FFRD since 2006, such as those conducted in the HRP and the Studsvik Cladding Integrity Project (SCIP), include tests on refabricated, 30-to-50-centimeter (cm)-long, internally pressurized rodlets \([6, 7, 8]\). Rodlets were pressurized to a range of pressures to induce the various ballooning characteristics. The majority of tests imposed thermal-hydraulic boundary conditions to simulate a large-break LOCA, including heatup that induced ballooning and burst and, in some cases, high-temperature steam oxidation as well as reflood and quench. Tests performed in the Halden reactor utilized nuclear heating while tests performed at Studsvik and at Oak Ridge National Laboratory utilized furnace heating. Elsewhere, analysis has been performed for different heating methods, nuclear- and furnace-heated, concluding that the radial temperature profile in the fuel (and therefore the thermally induced pellet stresses) resulting from both methods should be similar \(\text{(Capps, et al., 2021)}\).

Experimental programs on FFRD and tFGR have also included separate effects tests, including heating tests on small sections of fuel rods a few pellets in height, as well as fuel pellet disks \([7, 9, 10, 11]\).

Many of the tests described above have included posttest examinations to quantify the degree of fuel fragmentation. Examinations have included sifting fuel fragments using a sieve stack with different mesh sizes, allowing for mass measurements of fuel collected for each fragment size group.

RES STAFF’S INTERPRETATION OF FFRD RESEARCH

Element 1: Fine Fuel Fragmentation Threshold

Combining Halden, NRC, SCIP, and ORNL integral experiments, more than 35 tests were conducted on rodlets with burnups ranging from approximately 45 to 90 GWd/MTU segment average, for which detailed observations on fragmentation are available. These tests can be examined to define an empirical threshold at which fuel pellets become susceptible to fine fragmentation and fuel dispersal becomes a concern.

The mass fractions of all mobile fuel fragments smaller than 1 millimeter (mm) and 2 mm, shown in Fig. 1, were examined to evaluate trends in fine fragmentation. The mobile fuel mass fractions include both the mass dispersed during the LOCA tests and that “shaken” out of the test segments following the LOCA test. This figure shows that fuel can have a notable portion of fragments below 1 mm and 2 mm at 60 GWd/MTU.\(^3\)

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1 Unless otherwise noted, the burnup of rodlets used in the experimental programs cited in this paper is the average burnup of the rod segments. Because the test segments used in the cited test programs are relatively short, the variation of burnup along the axial length was often minimal, and thus segment average burnup can be used interchangeably in an analysis with pellet average burnup.

2 A loss of fuel mass equivalent to about one fuel pellet was observed in integral LOCA tests performed at Argonne National Laboratory on boiling-water reactor (BWR) fuel rods with local burnup of 64 GWd/MTU. NUREG-2121 \([1]\) contains further discussion.

3 Segment burnup values in SCIP III are determined from gamma scanning and are characterized by a relative uncertainty of ±5% \([44]\). Work is ongoing in SCIP IV to reduce the uncertainty of
The data in Fig. 1 suggest that the onset for fine fragmentation may occur below 60 GWd/MTU pellet average burnup; however, no tests have quantified fragment size for comparison between 45 and 60 GWd/MTU. Extrapolating from the large amount of data above 60 GWd/MTU, the data suggests an empirical threshold for the onset of fine fuel fragmentation near a pellet average burnup of 55 GWd/MTU.

**Element 2: Cladding Strain Threshold for Relocation**

Another aspect of quantifying the amount of fuel dispersal associated with a burst of high-burnup fuel rods is related to the axial length of the fuel rod predicted to experience fuel relocation. Experimental results from the NRC’s LOCA test program at Studsvik, presented in Fig. 2, show that in regions of very low cladding diametrical strain, fuel does not relocate axially, even when agitated. Fig. 3 provides an image of the fuel fragments collected after shaking, indicating that this test segment experienced fine fragmentation.

The gamma scan shown in Fig. 2 was made after the test segment was broken in half and both the upper and lower segment halves were “shaken” to dislodge any fuel. While the “shaking” action was not designed to represent any particular load experienced during a LOCA, the observation that fuel remained in the test segment after shaking is an indication that fuel pellets in low strain regions away from the burst location tend to resist axial relocation, even in fuel rods that have experienced fine fragmentation. The local strain from this test was approximately 4 percent in the lower part of the fuel segment and 5 percent in the upper part of the fuel segment at the locations where the gamma scan indicates fuel remains. A wire probe was also used to examine the extent of empty cladding following the LOCA and following the “shaking.” The comparison of wire probe measurements before (i.e., “after LOCA”) and after shaking in Fig. 2 shows that additional fuel was dispersed during shaking, and the gamma scan confirms that some fuel remained in the upper and lower halves. TABLE presents the boundary of relocated fuel, as determined by wire probe measurements from the NRC’s LOCA tests at Studsvik [12].

Similar measurements were taken in the SCIP III program on 10 segments after LOCA testing to investigate the relationship between cladding strain and relocation. In SCIP III, posttest gamma-scan data were evaluated to determine where the fuel column was intact. The position of the intact fuel column was then compared against the local cladding strain. STUDSVIK-SCIP III-253, “SCIP III—Subtask 1.1: Fuel fragmentation, relocation and

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**Table:**

<table>
<thead>
<tr>
<th>Segment</th>
<th>Cladding Strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower</td>
<td>4%</td>
</tr>
<tr>
<td>Upper</td>
<td>5%</td>
</tr>
</tbody>
</table>

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**Fig. 2.** Gamma scan, profilometry, and wire probe measurements from NRC test 192 [12].

**Fig. 3.** Fuel fragments collected from the top end of rod 192 after gentle shaking and just before gamma scan [12].
dispersal, Final Summary Report,” issued 2019 [7], reports and discusses the results. When the results of the 10 SCIP III tests are combined with the NRC’s 6 LOCA tests presented above, the data indicates an average value of a “strain threshold” for relocation is 3.7 percent, with a standard deviation of 1.7 percent [13].

The observations discussed above suggest that fuel relocation is limited in regions of the fuel rod experiencing less than 3-percent cladding strain.

TABLE I. Estimates of relocation strain thresholds from the NRC’s LOCA tests at Studsvik [12].

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Strain threshold, top (%)</th>
<th>Strain threshold, bottom (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>189</td>
<td>6.0</td>
<td>3.0</td>
</tr>
<tr>
<td>191</td>
<td>6.0</td>
<td>4.0</td>
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<tr>
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<td>5.0</td>
</tr>
<tr>
<td>198</td>
<td>4.5</td>
<td>9.0</td>
</tr>
</tbody>
</table>

Element 3: Mass of Dispersible Fuel

Another objective of RIL 2021-13 is to use available research to document insights that could be used to develop a model quantify the amount of fuel dispersal associated with burst of high-burnup fuel rods. The Halden, NRC, SCIP, and ORNL experiments were examined to inform the model.

In developing the RIL, the staff considered various approaches to interpret the available data for an empirical model. Six approaches are discussed in an appendix to the RIL, but ultimately the most conservative approach was proposed in the RIL in recognition of three sources of uncertainty.

First, the posttest examination of several rodlets revealed that fuel in the segment was finely fragmented, even when limited dispersal was observed during the test. Handling of these rods showed that this finely fragmented fuel could readily relocate within the rod and fall out after the test. It would be difficult to rule out the possibility that forces acting on the fuel in a design-basis LOCA could result in greater dispersal than observed during these experiments.

Second, the burst opening size is a key determinant of the amount of fuel that can disperse (i.e., smaller burst openings could limit the particle size and total mass of dispersed fuel, while a larger burst opening could allow larger particles and more mass to disperse). Burst opening size can vary stochastically with respect to fuel rod characteristics such as rod internal pressure. Data collected through various LOCA and cladding balloon-burst test programs also indicate wide variability in burst opening size with respect to burnup (Capps, et al., 2021; NRC, 2012).

Finally, the mass of the short fuel rod segments used in these experiments and the relatively short balloon (resulting from a relatively steep temperature gradient induced by furnace heating) may not be representative of the mass dispersed in a full-length rod with a different strain profile.

Based on these observations, it is reasonable to assume that all fuel above a burnup of 55 GWd/MTU in the length of the rod with greater than 3-percent cladding strain could disperse.

Element 4: Transient Fission Gas Release

The amount of fission gas released during normal operating and accident conditions is important to understanding the behavior of a nuclear fuel rod. FGR introduces adverse fuel performance effects that include the degradation of the thermal conductivity within the fuel-clad gap and an increase in cladding hoop strains when rod internal pressure exceeds the reactor coolant system pressure [14]. During steady-state normal operation, fission gas release (FGR) into the rod void volume is governed by diffusion. Modern fuel performance codes predict normal-operation FGR well. However, observations in experimental programs, such as the HRP, SCIP, and the French GASPARD program, indicate that FGR can be exacerbated by LOCA-like transients. This phenomenon is termed “transient fission gas release” (tFGR).

Fission gas released during a transient may further increase rod internal pressure, which may lead to cladding failure that would not have been expected if tFGR was neglected [15].

To initiate tFGR in the experiments referenced below, a fuel pellet or segment is subjected to a temperature transient. The tFGR tests generally consist of three phases:

1. a thermal equilibrium phase
2. a temperature transient phase
3. a cooling phase

Most of the temperature ramp rates observed in the experiments varied between 0.2 °C per second and 20 °C per second. Once the target temperature is reached, the fuel segment is either held at temperature for a specified time followed by cooling, or the fuel segment is immediately cooled by turning off the furnace. To simulate the blowdown phase of a LOCA, some experiments were performed in a steam environment or with water introduced within the test environment [16].

Fig. 4 presents a compilation of more than 15 tFGR tests from several experimental programs. tFGR results presented in Fig. 4 exclude fission gas released during base irradiation and account only for the fission gas released during the LOCA-like transient. This is because experiments are conducted on refabricated fuel rod
segments and samples, meaning the gas released during normal operation is no longer present.

Fig. 4 shows that tFGR tends to increase with increasing fuel segment burnup. However, the simple plot of tFGR versus burnup does not account for many test variables that may significantly impact tFGR behavior. For instance, the Studsvik tests were performed with a low-fill pressure (i.e., low hydrostatic pressure and constraint), while the single-pellet tests were unpressurized. Studies have shown that tFGR decreases with increasing hydrostatic pressure [17, 9]. Thus, performing tFGR tests at low-fill pressures may be conservative (i.e., little to no hydrostatic pressure).

Furthermore, the terminal temperature in many of the tests shown in Fig. 4 is greater than 1,000 °C. This may be higher than best estimate predictions of peak temperatures for high-burnup fuel rods, and it is almost certainly higher than the temperature at which high-burnup rods would be expected to burst. The GASPARD program showed that tFGR occurred in two temperature regimes: a burst release at lower temperatures (~600-800 °C) and a larger release at high temperatures (>1,000 °C) [10]. Only the lower temperature burst release would be expected to influence ballooning and burst behavior based on observed burst temperatures for high-burnup fuel rods. This suggests that the Studsvik and single-pellet (i.e., GASPARD) data in Fig. 4 may be conservative when considering the impact of tFGR on ballooning and burst behavior. On the other hand, Halden LOCA test IFA-650.14 (i.e., the Halden (In-Pile) point in the figure) was subjected to more prototypical LOCA conditions and did not burst, yet significant FGR of 18.6 percent was observed during the test. Thus, it is not clear whether results from single-pellet and furnace tests are truly conservative compared to in-pile LOCA conditions.

Finally, it is worth noting that these tests have been performed on short (about 30-cm) segments or single pellets. It is unclear how extensive tFGR would be in a full-length rod during a LOCA.

Researchers have developed tFGR models applicable to LOCAs that account for these known dependencies [18, 15]. However, these models have received little validation to date and are therefore not ready for regulatory applications.

**Element 5: Packing Fraction of Relocated Fuel**

Axial fuel relocation and fuel packing within regions of a fuel rod that experience ballooning can significantly affect LOCA analyses. When fuel redistributes axially within the rod, it changes the axial power distribution and local cladding temperature. Pulverized fuel in a “packed” crumbled configuration will have an increased void fraction when compared to its undamaged state, impacting the overall heat removal from the fuel rod. This will, in turn, affect temperatures in the fuel and cladding, potentially driving microstructural changes, FGR, differences in cladding ductility, ballooning and burst behavior, and cladding oxidation. Fig. 5 illustrates axial fuel relocation and packing.

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4 However, PCTs for high-burnup rods are significantly impacted by pre-transient linear heat generation rates, so predicted PCTs are heavily influenced by the fuel loading pattern.
This phenomenon has been observed in multiple programs and facilities such as Halden, SCIP, and the Power Burst Facility [1, 19, 6, 20]. In the various programs, the packing fraction, sometimes referred to as the filling ratio, is defined as the ratio of the volume of fuel to the total available local volume. Early tests performed at the Power Burst Facility and at Forschungsreaktor 2 (Research Reactor 2 or FR2) in Germany on unirradiated or low-burnup fuels (up to 35 GWd/MTU) showed packing fractions in a range from roughly 60 to 80 percent [21, 20].

Axial fuel relocation and packing were also observed during Halden’s IFA-650.9 test, which consisted of a high-burnup PWR rod, subjected to LOCA conditions. Fig. 6 shows the posttest gamma scans of IFA-650.9. As can be seen, a significant portion of the fuel stack was missing due to axial fuel relocation and dispersal. The relocated fuel had dropped to the lower portion of the rod near the burst opening, where the diameter nearly doubled. In this ballooned area, the cesium (Cs)-137 and the ruthenium (Ru)-103 count rates were respectively 30–70 percent and 20–30 percent higher than the general level of the rod [1]. Later work at Halden on test IFA-650.12 estimated the average packing fraction in the balloon region to be approximately 55 percent based on cladding strain measurements and a fuel mass balance [6].

In SCIP, the packing fraction has been estimated from posttest gamma scans and profilometry measurements. After the LOCA test, gamma scans were performed on the fuel segment, measuring the Cs-137 signal in the vertical direction. Measurements were made of fuel rods that burst, as well as fuel rods that ballooned but did not burst.

The Cs-137 measurement was normalized so that the non-fragmented and nonrelocated fuel at the top end of the fuel column has a value of 1. This was then divided by the cross-sectional area at the given position, yielding the packing fraction, shown in Fig. 7. For this test, the average packing fraction in the lower portion of the balloon varied between 0.7 and 0.85, with an average value of approximately 0.78. In the upper part of the balloon, the packing fraction is lower (0.4–0.7), likely because of a lack of fuel available to pack this region.

Fig. 6. Post-test gamma scans of IFA-650.9, a high-burnup PWR fuel rod subjected to a LOCA simulation at the Halden reactor [12].

Fig. 7. Packing fraction of 3V5-Q13 [7].

Fig. 8 shows the average packing fraction of many of the SCIP III LOCA tests calculated as described above. The packing fraction reported by SCIP III is based on the densely packed region typically below the burst in the lower balloon area. Packing fraction in the upper balloon area is typically lower due to fuel mass limitations. Fig. 8 shows that there is a slight correlation between segment burnup and packing fraction. This may be due to the increase in fine fragmentation at higher burnups. It is possible that the finer fragments relocate more easily and increase the packing fraction in the balloon region just below the burst location while decreasing the packing fraction above the burst location. This is consistent with recent discrete element modeling work [22]. However, the effect of burnup on packing fraction is not large; most measured packing fractions are near the average packing fraction of 0.78. The exception is the lowest burnup test, which has a packing fraction of approximately 0.6. This is consistent with discrete element modeling calculations for cases with no fine fragmentation [22].
Previous tests on lower burnup fuel showed lower packing fractions (as low as approximately 0.6), which is consistent with the lower burnup SCIP III test. It is reasonable to use packing fraction values in this range for LOCA calculations. In general, a larger packing fraction will increase the local decay heat, which may increase the local cladding temperature. At the same time, a smaller packing fraction may reduce local heat transfer and increase fuel temperatures, which in turn would impact FGR and thus ballooning and burst behavior. It is important to examine a range of packing fractions to account for these competing effects on integral rod behavior.

LIMITATIONS OF THE EMPIRICAL DATABASE

The thresholds presented in RIL 2021-13 are purely empirical. All of the tests were performed on uranium dioxide fuel in zirconium alloy cladding, so the observed behavior may not apply to new fuel or cladding designs. Furthermore, the interpretations in the RIL focus on burnup as the factor most important to FFRD behavior. However, it is likely that characteristics that evolve with burnup, such as porosity, stresses within the fuel pellet, grain growth, and subgrain formation, are more directly correlated with FFRD behavior. Other parameters – such as temperature, pressure, and heat-up rate – may also significantly impact observed behavior. More experimental data would be needed to better understand the impacts of the aforementioned parameters on FFRD and transient fission gas release behavior.

Fig. 8: Average packing fraction in the lower portion of the balloon in the SCIP III tests
Light Water Reactors program. CRAFT is developing a LOCA test plan to be conducted in the Transient Reactor Test (TREAT) facility at Idaho National Laboratory and the Severe Accident Testing Station (SATS) at Oak Ridge National Laboratory. The goal of the test plan is to address knowledge gaps in fuel fragmentation and relocation phenomenology.

Defining when fuel pellets become susceptible to fragmentation is the first step and a key piece of information which could be used to design fuel, cladding and operating regimes that limit or prevent FFRD. However, it is only part of understanding the overall safety implications of FFRD. Analyses to define the thermal hydraulic conditions that fuel rods would be subjected to during a LOCA would also be needed. If some fuel is predicted to be dispersed, the impacts of the dispersed fuel in the reactor and reactor cooling system would also need to be evaluated. These aspects are not covered by RIL 2021-13 but are being addressed as part of other NRC research activities. For example, RES staff are currently developing a methodology to quantify the mass of fuel that may be dispersed from a high burnup core during a loss of coolant accident, based on a core loading pattern developed by the Nuclear Energy Advanced Modeling and Simulation (NEAMS) program [23]. The methodology uses the SCALE and PARCS codes for reactor physics, the FAST code for steady-state and transient fuel performance, and the TRACE code for thermal hydraulic systems analyses. RES staff has also evaluated potential impacts of FFRD on the accident source term [24]. Further analysis would be needed to address other potential consequences of dispersed fuel identified in the RIL and in NUREG-2121 (e.g., energetic fuel-coolant interactions, core coolability, and long-term decay heat removal).

REFERENCES