U.S.NRC
United States Nuclear Regulatory Commission
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RIL 2021-13

Interpretation of Research on Fuel Fragmentation, Relocation, and Dispersal at High Burnup

Date Published: December 2021

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Research Information Letter
Office of Nuclear Regulatory Research

Disclaimer

Abstract

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. The purpose of this research information letter is to communicate the Office of Nuclear Regulatory Research (RES) staff's interpretation of findings from experimental programs on FFRD and to define conservative, empirical boundaries for FFRD-related phenomena.

This letter 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.

Foreword

Research Information Letters (RILs) are documents issued by the NRC's Office of Nuclear Regulatory Research (RES) to the NRC regulatory and regional offices that summarize, synthesize, and/or interpret significant research information relevant to a given technical area, provide new or revised information, and discuss how that information may be used in regulatory activities. RILs can improve regulatory efficiency and effectiveness by providing important, pertinent information to the regulatory office in a timely, concise, and comprehensive summary. While publicly available, a RIL is not intended to communicate an official NRC position or regulatory guidance to external stakeholders. The RIL provides the RES staff's interpretation of fuel, fragmentation, relocation and dispersal (FFRD) research available to date in a way that is timely and easy to interpret.

The nuclear industry is pursuing increases in allowable fuel burnup levels (beyond the current 62 gigawatt days per metric ton of uranium GWd/MTU) and the Office of Nuclear Reactor Regulation (NRR) has already received applications from fuel vendors. The RIL identifies 55 GWd/MTU as the likely onset of fine fragmentation; however the possibility that fuel could finely fragment during a loss of coolant accident (LOCA) does not, by itself, present a safety concern. Fuel relocation and fuel dispersal may impact regulatory figures of merit, and the RIL describes additional factors (other than burnup) that influence fuel relocation and dispersal. NRR staff reviewers can use the information in this RIL to inform and focus their reviews on FFRD related topics in these high burnup applications.

Research on FFRD is still ongoing. RES staff are participating in the fourth phase of the Studsvik Cladding Integrity Program (SCIP IV) and closely follow plans for additional FFRD research at U.S. national laboratories. As significant new data becomes available, the RIL could be supplemented.

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.

As stated above, the RIL is written for NRR. While the intended audience is internal, the staff is committed to disseminating the information in the RIL through public forums and conferences. By compiling, interpreting, prioritizing, and assessing all available empirical data, it was possible to identify key data gaps. These data gaps will help inform future research activities needed to better understand FFRD phenomena and the sensitivity of these phenomena to fuel design, operating, and transient parameters. The proactive dissemination of the RIL is essential to upholding NRC's commitment to transparency.

Contents

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.

This research information letter (RIL) summarizes the Office of Nuclear Regulatory Research (RES) staff’s interpretation of research related to fuel fragmentation, relocation, and dispersal (FFRD) used to help define conservative, empirical thresholds for the burnup level when fuel pellets become susceptible to fine fragmentation and the fraction of fuel that may be dispersed from a failed rod. This RIL describes the results of research on the relationship of local cladding strain to fuel fragmentation and relocation, to establish a conservative threshold of cladding strain below which fine fragmentation and axial fuel relocation are not significant. This RIL also summarizes the RES staff’s interpretation of research related to transient fission gas release (tFGR). Finally, this RIL presents empirical observations on the degree of fuel relocation into a ballooned region of the cladding and provides a range of packing fraction values that could be used in LOCA analysis. The RIL does not define an amount of fuel dispersal that is small enough to have acceptable safety consequences; however, it includes a brief discussion of the consequences of dispersal.

Background

In 2012, the U.S. Nuclear Regulatory Commission (NRC) published NUREG-2121, “Fuel Fragmentation, Relocation, and Dispersal During the Loss-of-Coolant Accident” (NRC, 2012), which provided a comprehensive review of past research programs for observations related to FFRD. NUREG-2121 captured the results of over 90 LOCA tests performed in eight different programs over 35 years. The staff concluded from this review that the occurrence of FFRD could not be precluded during a LOCA and required additional research.

The staff’s understanding of FFRD phenomena continued to advance after the publication of NUREG-2121 because of new experimental research and detailed analysis. In 2015, the staff published SECY-15-0148, “Evaluation of Fuel Fragmentation, Relocation and Dispersal Under Loss-of-Coolant Accident (LOCA) Conditions Relative to the Draft Final Rule on Emergency Core Cooling System Performance During a LOCA (50.46c)” (NRC, 2015). SECY-15-0148 summarized the research efforts completed since 2012 and outlined the state of knowledge through 2015. Most significantly, 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. SECY-15-0148 stated the following:

> Research has shown that as burnup exceeds 62 [gigawatt days per metric ton of uranium] GWd/MTU, fuel becomes increasingly susceptible to FFRD. Advancements in fuel design and available fuel management flexibility could lead to FFRD that may present a safety concern.
>
> [T]he industry continues to develop advanced fuel designs and more economical fuel loading patterns. The research findings described [in SECY-15-0148] indicate that changes in fuel design and plant operations may have an adverse impact with respect to FFRD phenomena.

SECY-15-0148 noted that additional research on FFRD was ongoing. A significant international experimental program, the Studsvik Cladding Integrity Program III (SCIP III), has since been completed and yielded substantial new information on FFRD phenomena. The program included investigation of the effects of various parameters related to FFRD and added approximately 10 experiments on fuel rods above current U.S. burnup limits to the previous database. More recently, Oak Ridge National Laboratory (ORNL) has conducted testing directly comparable to the tests run at the Studsvik Nuclear Laboratory in Sweden, adding three additional experiments to the previous database (Capps, et al., 2020). Additional work related to tFGR has also been completed to understand the potential impact on fuel rod burst timing. The impact of tFGR on the radiological source term assumed in onsite and offsite dose consequence calculations or on existing guidance is beyond the scope of this RIL. Separate efforts are ongoing on this subject within the NRC.[1] Recently, researchers at ORNL and Idaho National Laboratory published “A Critical Review of High Burnup Fuel Fragmentation, Relocation, and Dispersal under Loss-of-Coolant Accident Conditions” (Capps, et al., 2021).

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1 The impact of FFRD and tFGR on accident source term is being addressed as part of an update to Regulatory Guide 1.183, “Alternative Radiological Source Terms for Evaluating Design Basis Accidents at Nuclear Power Reactors.” More information on this topic may be found in Draft Regulatory Guide DG-1389 (U.S. Nuclear Regulatory Commission, 2021).

This review included an extensive discussion of the publicly available experiments related to FFRD and served as an important reference in the development of this RIL.

Motivation for This Research Information Letter

As anticipated in SECY-15-0148, the U.S. industry continues to develop advanced fuel designs and more economical fuel loading patterns. Recently, the U.S. industry indicated it would like to seek approval to operate fuel to rod average burnup levels well above 62 gigawatt days per metric ton of uranium (GWd/MTU). Fuel vendors are starting to outline their licensing approaches for operation above 62 GWd/MTU including consideration of FFRD, so it is timely to communicate the RES staff's interpretation of research related to FFRD—most notably, to clarify that 62 GWd/MTU should not be considered the burnup when FFRD *begins*. Rather, available research indicates that FFRD phenomena can be observed at rod average burnups below 62 GWd/MTU and that fuel fragmentation and the potential for dispersal increase as burnup increases. The motivation for this RIL is to address five elements of the RES staff's interpretation of FFRD research and describe 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 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 nondispersed fuel in the balloon region.

The RIL recognizes that there are still many questions about the parameters impacting FFRD. Ongoing research may alter the understanding of these parameters in the near future and may allow for reexamination of some of the conservative assumptions made in this RIL. The section "Limitations of the Empirical Database" at the end of this document discusses additional research that could allow for refinement of the insights presented in this RIL. However, the RES staff considered the timeline of the U.S. industry's pursuit of operation above 62 GWd/MTU in writing this RIL, even though the understanding of FFRD is incomplete, to provide NRC technical reviewers with important and timely interpretations of a complex technical issue. Based on the present state of information and the potential for new data to offer more insights, the RES staff made a conservative interpretation of the available research.

While the NRC's current regulatory framework under Title 10 of the *Code of Federal Regulations* 50.46(a)(1)(i) allows for emergency core cooling system performance evaluations using realistic models, the current state of knowledge related to FFRD phenomena suggests that the conservative interpretations offered in this RIL is appropriate at this time. Quantification of uncertainties associated with FFRD is beyond the scope of this RIL.

Definitions and Terms

This document contains terms of art that are unique to this RIL or not yet well established within the nuclear fuel community. To be precise with the intended concept for each of the terms in this RIL, the following definitions are offered:

High burnup—This is a relative term, implying burnup values higher than some "standard" burnup. Approved licensing limits for burnup vary internationally, but within the United States, current limits are approximately 62 GWd/MTU rod average. For the purpose of this RIL, "high burnup" is defined as burnup greater than 62 GWd/MTU rod average.

> *Rod average burnup*—In a large light-water reactor, power varies across the core and within a fuel assembly. The variations in power mean that specific fuel rods can operate to different burnup values relative to the core average power or their assembly average power. There can also be measurable deviations in burnup along the axial length of a particular fuel rod. Rod average burnup is the average value of burnup along the axial length of a specific fuel rod.
>
> *Segment average burnup*—In the test programs discussed in this RIL, tests are conducted on segments cut from full-length rods. The test segment lengths vary but are generally between 25 and 50 cm. Segment average burnup is the average burnup along the axial length of a specific test segment. Because the test segments used in the cited test programs are relatively short, the variation along the axial length was often minimal. The empirical thresholds presented in this RIL were developed based on segment average burnup values. Because the test segments were short and characterized by minimal axial burnup variation, they can be used in an analysis interchangeably with pellet average burnup.

Fuel fragmentation and fine fragmentation—Fuel fragmentation refers to any separation of a fuel pellet into more than one piece, regardless of when or why it occurred. During normal operation, oxide fuel pellets develop many large cracks because of thermal stresses. Additional cracks may form during transient scenarios. For lower burnup fuel, the resulting fragments tend to be large. In contrast, this RIL presents research in which fuel examined following transient testing was fragmented more than would be expected due to normal operation or for lower burnup fuel under transient conditions. Fuel fragments were smaller and fragmentation was more extensive. To distinguish this finer and more extensive fragmentation behavior from the fragmentation expected due to operation or observed in transient testing on lower burnup fuel, this RIL will use the term "fine fragmentation" to refer to the finer, more extensive fragmentation observed in some tests following transient testing.

Fuel relocation, axial versus radial fuel relocation and mobile fuel—If fuel pellets are fragmented and separated from each other, they could be free to move relative to their neighbors. Simply stated, fuel relocation can be described as any physical movement of fuel pellets or fuel fragments within the cladding. Generally, radial fuel relocation is described as distinct from axial fuel relocation.

> *Radial* fuel relocation is the movement of the fuel outward toward the cladding. Examination of postirradiation images shows that fuel pellets crack during operation and cracked pellet pieces can move towards the cladding, complicating the modeling of the "gap" volume between the fuel and cladding. This process is widely recognized in fuel

performance analysis. It starts at beginning of life and quickly reaches equilibrium—by 5 GWd/MTU, according to the Fuel Analysis under Steady-state and Transients (FAST) computer code (Geelhood, et al., 2021).

Axial fuel relocation is the vertical movement of fuel fragments within the cladding. Under normal operation, this process is usually limited by the fuel pellet immediately above or below the pellet in question. For the purpose of this RIL, axial fuel relocation is said to have occurred if postirradiation examination reveals that fuel fragments have moved axially relative to their original location. Evidence that would support this determination includes empty regions of the cladding rod or the observation of additional fuel material in the enlarged volume of the balloon region, or both. In the remaining discussion, "fuel relocation" refers to "axial fuel relocation."

Mobile fuel—Some of the test programs discussed in this RIL aimed to characterize the total amount of fuel that could relocate, even if the relocation did not occur during transient testing. The total amount of fuel that was mobile was often investigated experimentally by minor shaking of the test segment after testing, including inverting the test segment to shake loose fuel fragments from the portion below any ballooned or burst region. Even after shaking, some fuel remained in the test segments, indicating that not all of the fuel fragments were able to move. The fuel that was able to move during this shaking procedure was added to any fuel dispersed during transient testing to understand more about the mobility of fuel fragments.

Fuel dispersal—Fuel dispersal is the ejection of fuel fragments or particles through a burst or opening in the cladding into the coolant. As this RIL will discuss, the amount of fuel dispersed during testing varied greatly, and a number of factors influenced dispersal. The RIL will discuss not only fuel that dispersed during the test and was collected from the bottom of the test equipment immediately following transient testing, but also mobile fuel as fuel that could be dispersed under different conditions. It is the position of this RIL that all mobile fuel is susceptible to dispersal and that actual fuel dispersal will depend on several factors.

Experimental Programs Considered in This Research Information Letter

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 an average burnup of 92.3 GWd/MTU (Wiesenack, 2013). 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

[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 (NRC, 2012) contains further discussion.

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, this RIL focuses on insights gained from experiments conducted after 2006.

Experimental programs on FFRD since 2006, such as those conducted at the HRP and SCIP, include tests on refabricated, 30-to-50-centimeter (cm)-long, internally pressurized rodlets (Wiesenack, 2013; Magnusson, et al., 2020; Capps, et al., 2021). 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 (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 (Magnusson, et al., 2020; Turnbull, et al., 2015; Pontillon, et al., 2004; Bianco, et al., 2015).

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, similar to the apparatus shown in Figure 1, allowing for mass measurements of fuel collected, as in Figure 2, for each fragment size group.

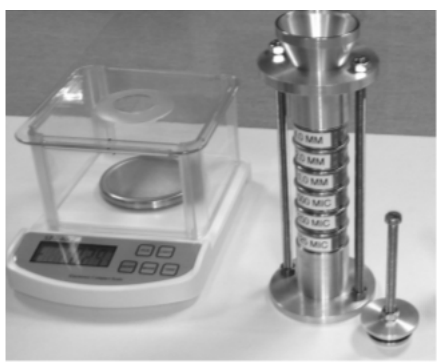

Figure 1. A sieve stack apparatus is used to examine fuel fragment size distribution in the programs referenced in this RIL. The image is of Halden's sieving apparatus used in the IFA-650 experiments (Wiesenack, 2015).

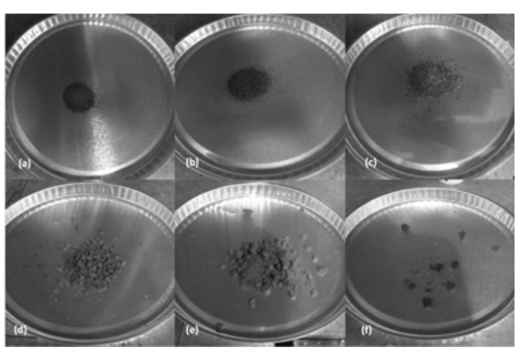

Figure 2. Example of fuel fragment collections following sieving (Capps, et al., 2020).

The five elements of the RES staff's interpretation of FFRD research are largely based on experiments conducted through the HRP, an NRC-sponsored test program at Studsvik Nuclear Laboratory, the third phase of the SCIP (SCIP III), and at ORNL. The following sections summarize these experimental programs. Many of the experimental techniques and examination procedures were similar across these programs, with a few exceptions noted below.

Halden Reactor Project IFA-650 Series

From 2005 to 2017, 13 LOCA tests were conducted with fuels irradiated in commercial nuclear power stations. Seven of the tests were on pressurized-water reactor (PWR) fuel rodlets (IFA-650.3/4/5/9/10/15/16), four tests were on BWR rodlets (IFA-650.7/12/13/14), and two tests were on Russian water-water energetic reactor (VVER) fuel rodlets (IFA-650.6/11). Rodlet burnup values ranged from 44 to 92 GWd/MTU. Halden researchers have written in detail about the IFA-650 series experimental setup (Wiesenack, 2013).

The IFA-650 series involved single rod experiments conducted in a pressurized flask connected to a water loop. The experiments were conducted in the Halden reactor, where a low level of nuclear power is generated in the fuel rod to simulate decay heat, and electrical heaters surrounding the rod simulate the heat from neighboring rods. The experimental setup includes multiple thermocouples to capture cladding and coolant conditions, as well as a cladding extensometer and a pressure sensor to measure rod internal pressure throughout the experiment. During a test, the loop is initially filled with circulating water and then a loss of coolant is initiated. From there, the fuel rod increases in temperature and ballooning and burst proceed, according to the dynamic behavior of the system. The heatup rate varied from 2 to 6 degrees Celsius (C) per second during the tests.[3] In some cases, the heater power was slightly adjusted during the transient to obtain the desired target peak cladding temperature (PCT). The PCTs in the IFA-650 series ranged from 800 to 1,200 degrees C. In other words, the rods in the IFA-650 test series experienced cladding temperatures and coolant boundary conditions reasonably prototypical of a LOCA postulated to occur at an operating power reactor.

Following the LOCA simulation in four of the 650-series tests (IFA-650.12/13/14/15), fuel fragments were shaken out of the rods and examined to determine the size distribution.

The NRC's Loss-of-Coolant Accident Testing at Studsvik

From 2009 to 2011, the NRC sponsored a LOCA experimental program at Studsvik Nuclear Laboratory in Sweden. The experimental program included six single-rodlet integral LOCA tests; four on rodlets with segment burnup ranging from 72 to 78 GWd/MTU and two on rodlets with segment burnup around 60 GWd/MTU (NRC, 2012; NRC, 2013).[4] In the NRC experiments, a

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[3] In the IFA-650 test rig, heatup rate and PCT cannot be chosen independently of each other. In LOCA experiments with irradiated fuel, the desired target PCT determines the required rod power and thus also the heatup rate. "Approaching 800°C, where ballooning and burst would occur in pressurized rods, the heat-up rate is about 2 K/s at the lowest powers and 6 K/s at the highest power" (Wiesenack, 2013).

[4] The full length rods cut to create the four rodlets with segment burnup values between 72 and 78 GWd/MTU had an integral fuel burnable absorber (IFBA) design in which a thin layer of zirconium diboride is applied to the outer pellet surface. In comparison to standard uranium dioxide (UO_2) fuel designs, IFBA fuel can have higher end of life rod internal pressure. However, it is not obvious that IFBA fuel would otherwise behave differently from standard UO_2 with respect to fuel fragmentation, relocation, and dispersal. Therefore, as results are presented in this RIL, no distinction is made between the results of the NRC's LOCA test program and those of the other programs discussed.

pressurized, high-burnup, fueled rod segment was subjected to a temperature transient in a steam environment to induce ballooning, burst, and high-temperature steam oxidation. The tests were conducted in a hot-cell facility; therefore, the rodlets were not subject to any degree of nuclear heating. An infrared furnace externally heated a 30-cm rodlet to a target cladding surface temperature. The rodlets were heated in a flowing steam environment from 300 degrees C to the target temperature (either 950 degrees C or 1,185 degrees C, depending on the test) at a rate of 5 degrees C per second. Internal pressures were consistent with a typical end of life rod internal pressure, although likely on the high end, and were chosen to induce ballooning and burst, with burst hoop strains in the range of 25 to 55 percent. The test conditions led to rod cladding temperatures and coolant boundary conditions that were reasonably prototypical of a LOCA.

Following the LOCA simulation, four-point bend tests were conducted to measure the residual mechanical behavior of the ballooned and burst region. After the four-point bend test, a “shake test” determined the mobility of fuel fragments 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 fragments. During these posttest steps, significant fuel loss occurred at various stages, and multiple measurements and observations characterizing the fuel loss are reported elsewhere (NRC, 2012; NRC, 2013).

Studsvik Cladding Integrity Program

The experimental methods developed for the NRC were later used in the third phase of the Studsvik Cladding Integrity Program (SCIP III) and are continuing to be used in the SCIP IV international research project. Some tests in SCIP III used the same equipment built for the NRC, while other tests utilized a newly designed test device with similar features (Karlsson, et al., 2016). The SCIP III project generated 18 tests, designed similarly to the NRC’s 6 tests, to further evaluate how various parameters affect FFRD. These parameters include fuel burnup and microstructure, cladding strain, temperature, internal gas pressure and gas flow at the time of burst, and magnitude of tFGR. SCIP IV continues to generate additional tests to deepen the understanding of the parameters that affect FFRD.

Oak Ridge National Laboratory

In 2019, three hot-cell integral LOCA tests were conducted in the Severe Accident Test Station (SATS) at ORNL (Capps, et al., 2020). The segment average burnup of the three tests conducted at ORNL ranged from 69 to 77 GWd/MTU; the segments were harvested from parent rods with average burnups ranging from 63 to 68.5 GWd/MTU (burnup values from corrigendum to Capps, et al., 2020). The details of the SATS experimental setup are covered extensively elsewhere (Snead, et al., 2015; Linton, et al., 2017), but the experimental equipment and methods are effectively comparable to those used at Studsvik. Following the LOCA simulation, fuel fragments were shaken out of the rods and examined to determine the size distribution.

RES Staff's Interpretation of Fuel Fragmentation, Relocation, and Dispersal Research

This RIL addresses five elements of the RES staff's interpretation of FFRD research, including the technical basis for these elements.

Element 1: Empirical threshold at which fuel pellets become susceptible to fine fragmentation

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, 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 Figure 3, 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.

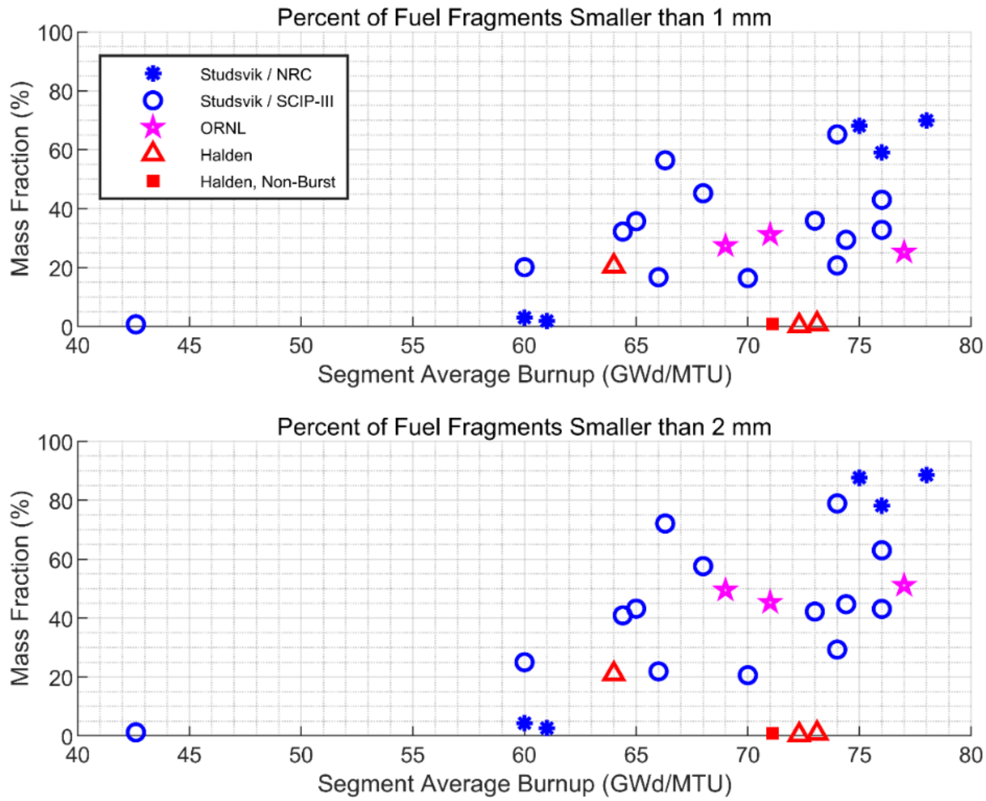

Figure 3. Measurements of percent of fuel fragments smaller than 1 mm [5] and 2 mm as a function of burnup (Wiesenack, 2013; Wiesenack, 2015; NRC, 2013; Capps, et al., 2020; Magnusson, 2017; Magnusson and Sheng, 2017; Magnusson, 2018; Magnusson, et al., 2020; Mileshina and Magnusson, 2019a, b, c, d, e; Mileshina et al., 2019; König, 2021a, b, c) [6].

The data in Figure 3 suggest that the onset for fine fragmentation may occur below 60 GWd/MTU; 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: A local cladding strain threshold below which relocation is limited

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 Figure 4, show that in regions of very low cladding diametrical strain, fuel does not relocate

5 The Studsvik measurements include "lost mass." Studsvik researchers define "lost mass" as the difference between the total mass of fragmented fuel and the total mass of all fuel fragments collected for sieving and weighting. The lost mass is assumed to be smaller than 1 mm, based on the fact that larger fragments can easily be identified during the collection process from the test chamber (Magnusson, et al., 2019).

6 Segment burnup values in SCIP III are determined from gamma scanning and are characterized by a relative uncertainty of ±5% (Karlsson, et al., 2016). Work is ongoing in SCIP IV to reduce the uncertainty of burnup values derived from gamma scan measurements, however the findings remain within the ±5% previously stated uncertainty.

axially, even when agitated. Figure 5 provides an image of the fuel fragments collected after shaking, indicating that this test segment experienced fine fragmentation.

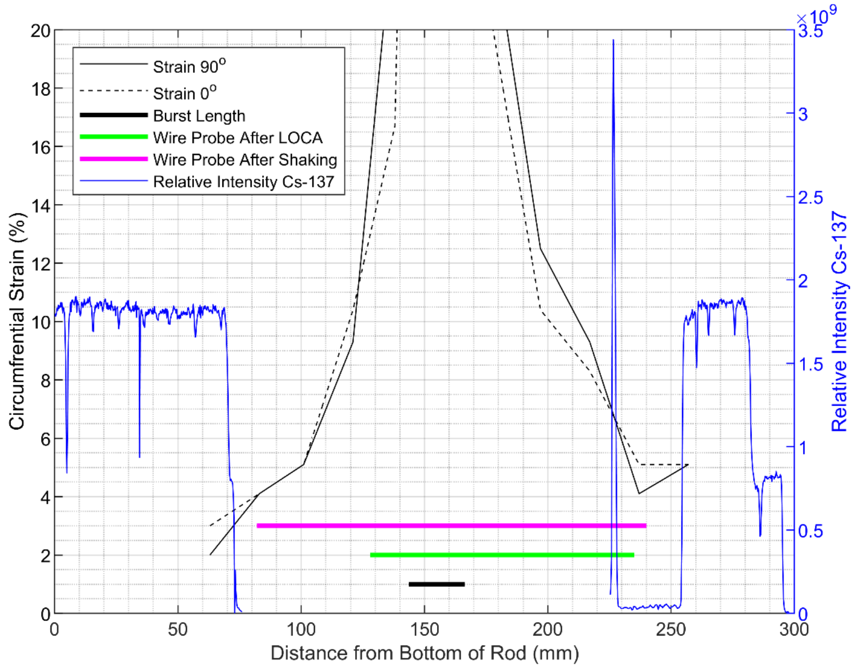

Figure 4. Gamma scan, profilometry, and wire probe measurements from NRC test 192 (NRC, 2013).

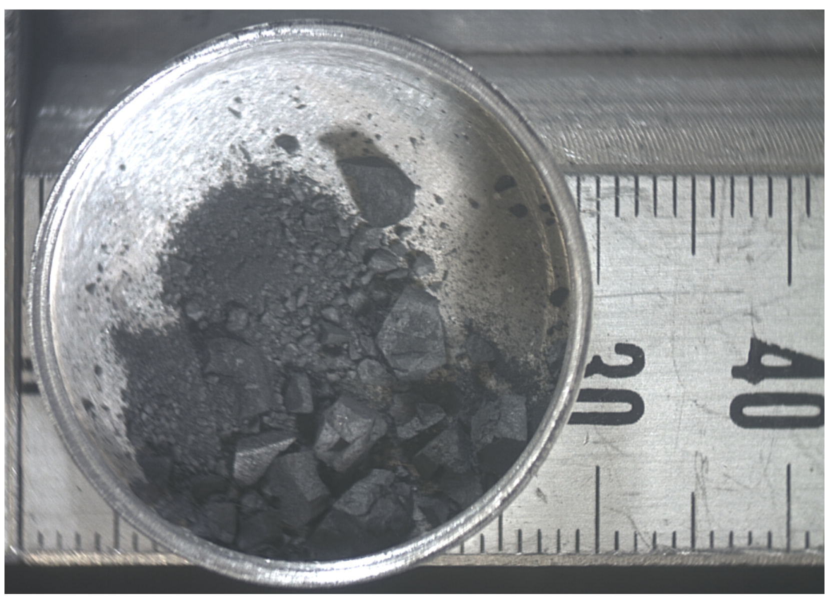

Figure 5. Fuel fragments collected from the top end of rod 192 after gentle shaking and just before gamma scan (NRC, 2013).

The gamma scan shown in Figure 4 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 Figure 4 shows that additional fuel was dispersed during shaking, and the gamma scan confirms that some fuel remained in the upper and lower halves. Table 1 presents the boundary of relocated fuel, as determined by wire probe measurements from the NRC's LOCA tests at Studsvik (NRC, 2013).

Table 1. Estimates of relocation strain thresholds from the NRC's LOCA tests at Studsvik.

Test Number	Strain threshold, top (%)	Strain threshold, bottom (%)
189	6.0	3.0
191	6.0	4.0
192	5.0	4.0
193	1.0	4.0
196	3.0	5.0
198	4.5	9.0

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 dispersal, Final Summary Report," issued 2019 (Magnusson, et al., 2020), 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 (Studsvik Cladding Integrity Program, 2019).

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

Element 3: Mass of "dispersible" fuel as a function of burnup

Another objective of this RIL 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.

The experimental data and RES staff's engineering judgment led to the development of six empirical models to define a dispersible fragment size and a strain threshold for mobility. Appendix A discusses these models in detail. Other empirical models could be developed based on other engineering approaches or additional experimental data. A model can be selected based on the desired conservatism and consideration of corewide dispersal predictions. As discussed in the appendix, the RES staff has interpreted the total mass of mobile fuel, rather than the mass of fuel dispersed during a test, to be the most meaningful metric to evaluate the model. This is based on the staff's perception that the dispersal observed during experiments may not be conservatively representative of design-basis LOCA conditions in an operating reactor. Based on the analysis documented in Appendix A, 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: Provide evidence of significant tFGR that may impact ballooning and burst behavior of high-burnup fuel under LOCA conditions

During steady-state normal operation, fission gas release (FGR) into the rod void volume is governed by diffusion, characterized by approved fuel rod thermal-mechanical models, and validated by a large empirical database. However, observations in experimental programs, such as the HRP, SCIP, and the French GASPARD program, indicate that increases in FGR can be exacerbated by LOCA-like transients. This phenomenon is termed “transient fission gas release” (tFGR).

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 (Rest, et al., 2019). 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 (Khvostov, 2020).

tFGR remains a complex phenomenon with many dependencies (e.g., burnup, irradiation history, temperature ramp rate, degree of fragmentation, hydrostatic pressure). This RIL does not propose a hypothesis for why tFGR occurs but rather focuses on when it has been observed in experimental test programs relevant to the LOCA event.[7]

To initiate tFGR in the experiments referenced below, a fuel pellet or segment is subjected to a temperature transient. Figure 6 illustrates an example tFGR test. Three distinct phases are seen:

(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 degrees C per second and 20 degrees 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 experimental tests were performed in a steam environment or with water introduced within the test environment (Tejland and Sheng, 2019).

[7] Many studies have examined tFGR behavior during reactivity-initiated accidents. Regulatory Guide 1.236, “Pressurized-Water Reactor Control Rod Ejection and Boiling-Water Reactor Control Rod Drop Accidents,” establishes a model for transient FGR as a function of burnup and deposited energy under reactivity-initiated accident conditions. However, the models in Regulatory Guide 1.236 and the aforementioned studies are not directly applicable to the LOCA-type scenarios described in this RIL.

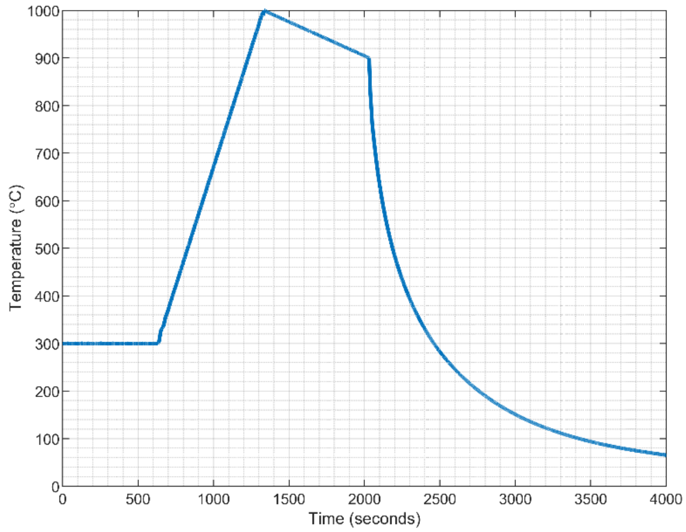

Figure 6. Example time and temperature transient for a tFGR test performed at Studsvik.

Figure 7 presents a compilation of more than 15 tFGR tests (in percentages).[8] from several experimental programs (e.g., Studsvik, Halden, GASPARD). tFGR results presented in Figure 7 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. (As noted earlier, refabricated rod segments are refilled with an inert gas.)

8 tFGR results are presented as the percentage of fission gas generated during irradiation that is released during the transient.

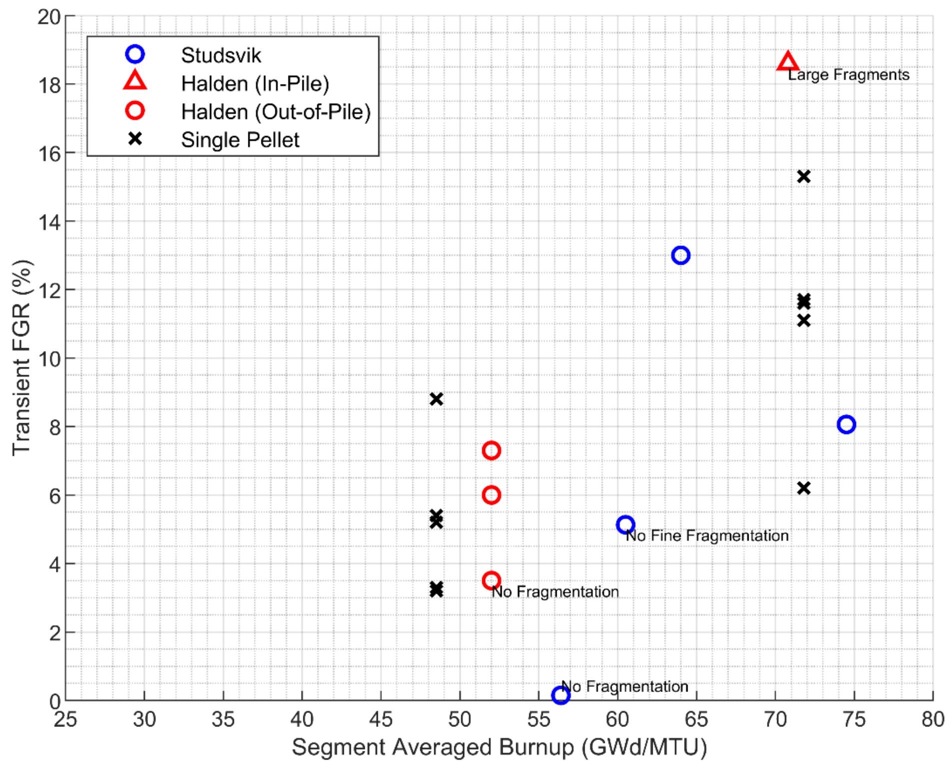

Figure 7. Measured tFGR as a function of burnup. Circle symbols represent out-of-pile LOCA tests (Magnusson, et al., 2020; Magnusson, et al., 2016; Tejland and Sheng, 2019a; Tejland and Sheng, 2019b; Bianco, et al., 2015). The triangle represents an in-pile LOCA test (Tradotti, 2014), and crosses represent single pellet-clad nonwelded samples (Pontillon, et al., 2004).

Figure 7 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 (Une, et al., 2002; Turnbull, et al., 2015). 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 Figure 7 is greater than 1,000 degrees 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.[9] The GASPARD program showed that tFGR occurred in two temperature regimes: a burst release at lower temperatures (~600–800 degrees C) and a larger release at high temperatures (>1,000 degrees C) (Pontillon, et al., 2004). 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 Figure 7 may be conservative when considering the impact of tFGR on ballooning and burst behavior. On the

9 However, PCTs for high-burnup rods are significantly impacted by pretransient linear heat generation rates, so predicted PCTs are heavily influenced by the fuel loading pattern.

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 (Jernkvist, 2019; Khvostov, 2020). However, these models have received little validation to date and are therefore not ready for regulatory applications.

Element 5: Establish the basis for a range of packing fractions of relocated but nondispersed fuel in the balloon region

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. Figure 8 illustrates axial fuel relocation and packing.

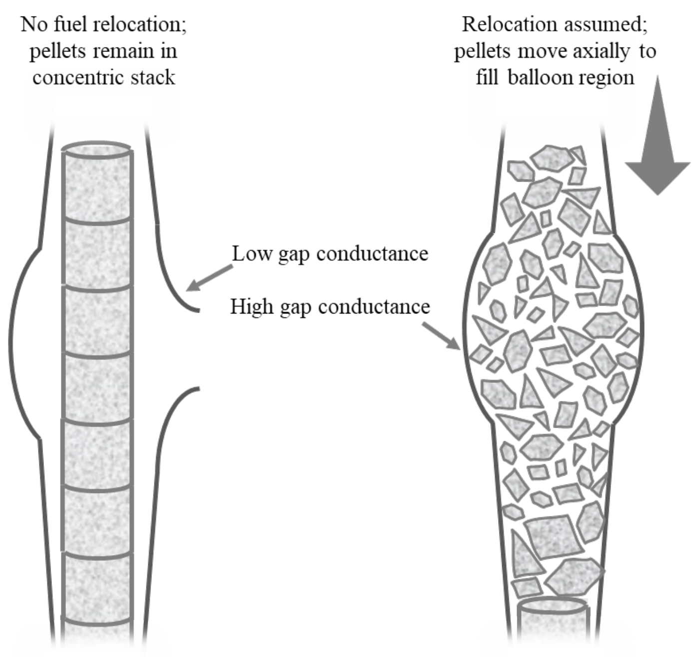

Figure 8. Illustration of fuel relocation and packing in the ballooned region.

This phenomenon has been observed in multiple programs and facilities such as Halden, SCIP, and the Power Burst Facility (NRC, 2012; Magnusson, et al., 2019; Wiesenack, 2013; Parsons, et al., 1986). 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 (Moreno, et al., 2005; Parsons, et al., 1986).

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. Figure 9 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 (NRC, 2012). 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 (Wiesenack, 2013).

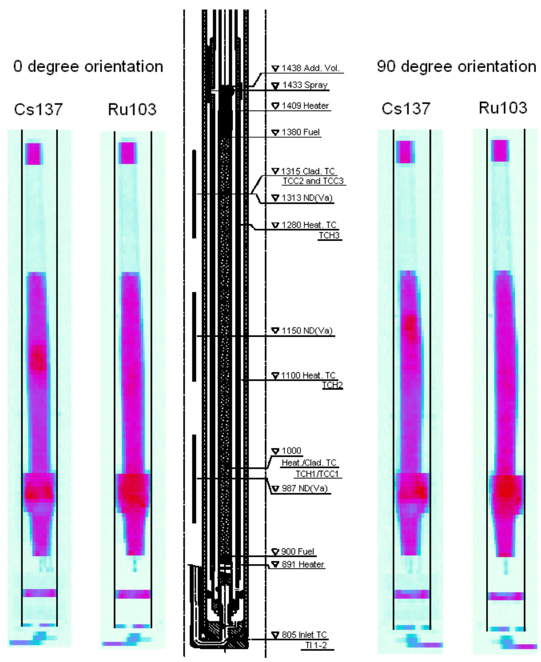

Figure 9. Posttest gamma scans of IFA-650.9, a high-burnup PWR fuel rod subjected to a LOCA simulation at the Halden reactor (NRC, 2012).

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.

Figure 10 presents the Cs-137 signal and local cladding strain as a function of the axial position relative to the burst center. From the figure, extensive fuel relocation can be observed in the vicinity of the ballooned region. Figure 10 shows that the fuel relocated downwards, in the lower balloon region, where the larger volume allows for fuel fragments to settle in a crumbled packed configuration, resulting in an elevated Cs-137 measurement.

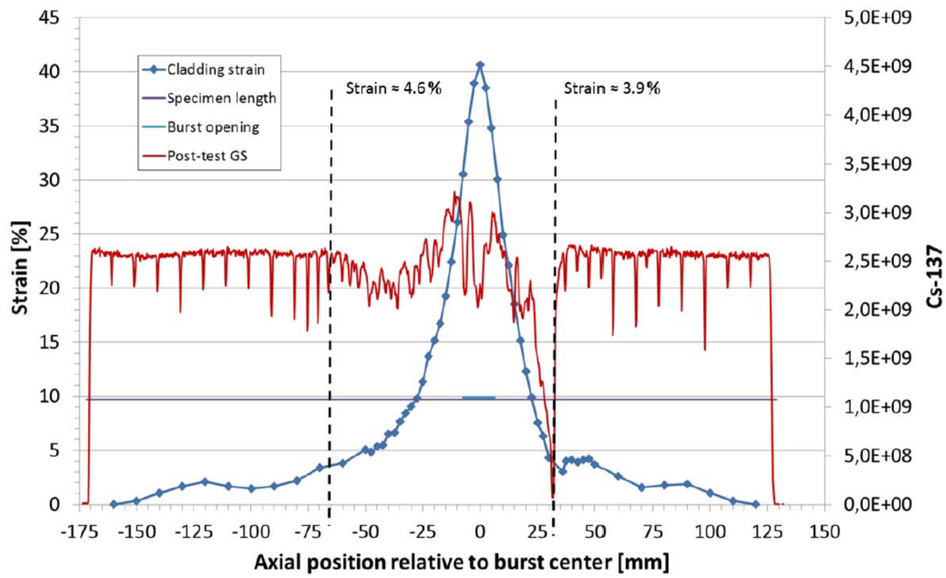

Figure 10. Posttest Cs-137 signal and profilometry of SCIP III's 3V5-Q13 (Magnusson, et al., 2020).

The Cs-137 measurement, shown in Figure 10, was normalized so that the nonfragmented 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 Figure 11. 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. Here, the cross-sectional area of the cladding is assumed to be circular along the specimen length, and the Cs-137 signal does not account for self-shielding effects.

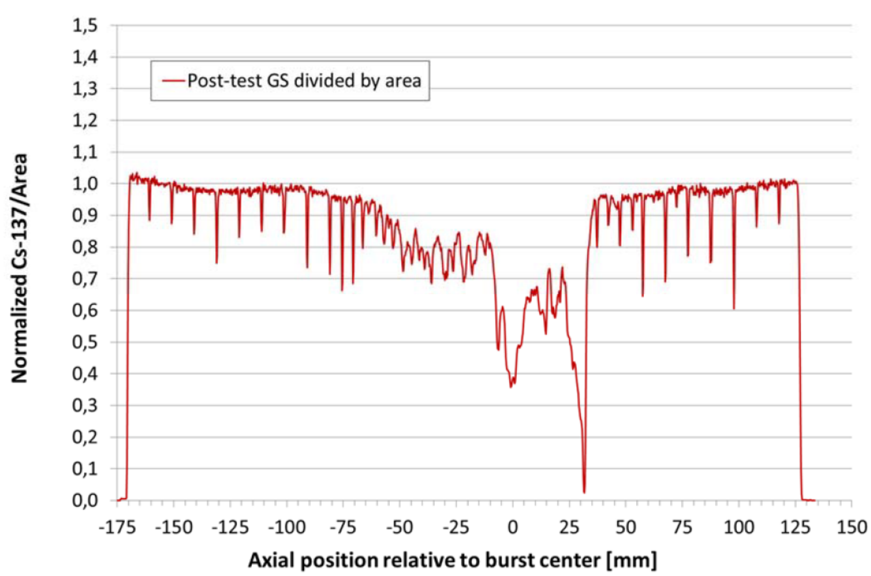

Figure 11. Packing fraction of 3V5-Q13 (Magnusson, et al., 2020).

Figure 12 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. Figure 13 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 (Ma, et al., 2020). 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 (Ma, et al., 2020).

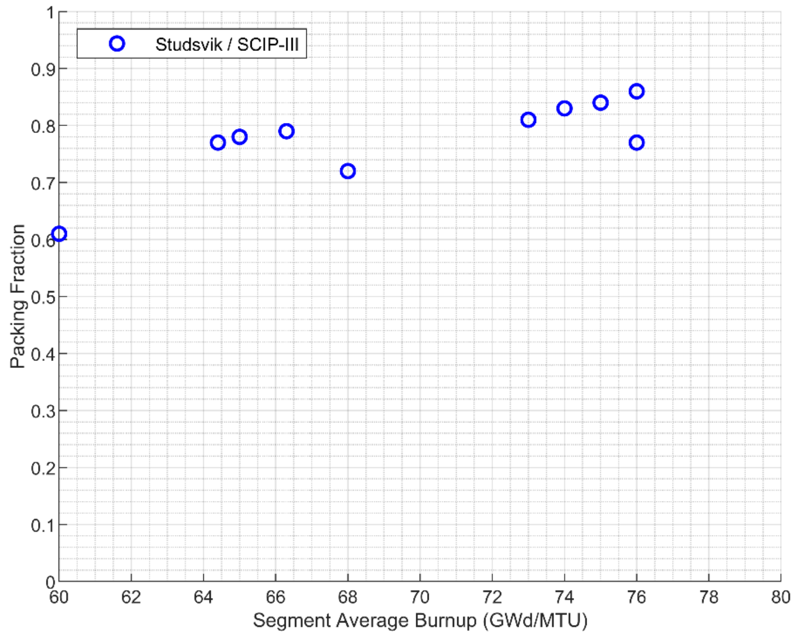

Figure 12. Average packing fraction in the lower portion of the balloon in the SCIP III tests (Magnusson, et al., 2020).

Figure 12 summarizes the packing fractions determined in the SCIP III tests. Most of the data show packing fractions ranging from 70 to 85 percent for the lower portion of the balloon region. Note that lower packing fractions are observed in the upper portion of the balloon region because of downward relocation and fuel mass limitations. 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.

Prototypicality and Representativeness of Empirical Database

Confirmation of the representativeness of important test parameters and conditions used to generate the experimental database referenced in this RIL is necessary to ensure that the conclusions made here are relevant to the assessment of burnup extension requests and other fuel-related licensing applications for operating reactors.

In reviewing the test conditions in the empirical database against parameter ranges representative of operating reactors, the NRC staff considered typical ranges for key fuel parameters of interest to the FFRD phenomena addressed by the RIL. Table 2 summarizes key fuel parameters considered in the review. The RES staff generally found that the test parameter values in the empirical database align with the basic set of generic parameters considered in the review.

While the information in Table 2 is considered generically representative of operating reactors, the RES staff recognizes that these specific inputs may not be sufficient to characterize the actual plant- and fuel-specific conditions at each individual operating reactor. Furthermore, a complete set of potentially relevant parameters would encompass numerous additional parameters beyond the scope of the present review. For example, the empirical database and conclusions in this RIL do not necessarily apply to new fuel technologies, such as non-uranium-dioxide fuel pellets, new dopants or absorber materials added to fuel pellets, new cladding materials, or coated fuel claddings. Therefore, while the present generic review is sufficient to confirm the overall representativeness of the empirical database used in the RIL to the current operating fleet, reliance on the data or conclusions in this RIL in specific licensing applications submitted to the NRC will require further plant-specific justification.

Additionally, while the empirical database considered in this RIL directly pertains to FFRD phenomena, the RES staff recognizes that many tests within the database also involve interrelated phenomena associated with cladding ballooning and burst. While interrelated, such phenomena extend beyond the scope of this RIL, and the RES staff has deliberately refrained from applying the test database supporting the RIL directly to their characterization. Cladding ballooning and burst phenomena, such as the degree of circumferential ballooning experienced by fuel rod cladding, the axial extent of the ballooned region, and the size of the burst opening, have been the subject of numerous past test programs, which generally remain relevant to modern fuel designs. When compared to recent tests primarily concerned with FFRD phenomena, past test programs addressing cladding ballooning and burst may consider wider ranges of input parameters relevant to cladding ballooning and burst, may involve significantly larger datasets, and may contain test features more prototypical for estimating cladding ballooning and burst (e.g., representative cladding heating methods, multirod geometries). Therefore, the characterization of phenomena associated with cladding ballooning and burst may require consideration of a broader range of test data than has been included in the empirical database for FFRD phenomena supporting this RIL.

Finally, the RES staff is issuing this RIL to summarize recent test data and insights pertaining to FFRD phenomena as part of the agency’s preparations for the review of anticipated industry requests for burnup extensions. To support the agency’s readiness to perform regulatory reviews on a schedule commensurate with the industry’s proposed submittal dates, the RES staff is issuing the RIL now, even though significant research concerning FFRD phenomena remains ongoing. While this RIL has attempted to interpret the existing FFRD database conservatively, particularly in areas subject to data limitations or elevated uncertainty, the RES staff recognizes that new information obtained subsequent to the issuance of this RIL may affect the conclusions expressed here. For this reason, the RES staff intends to continue to follow the progress of ongoing research programs associated with FFRD phenomena, applying, as appropriate, new insights and conclusions from this research in future regulatory reviews.

Table 2. Comparison of Experimental and Typical Commercial Parameters.

Parameter	Experimental Range	Typical BWR*	Typical PWR*
Cladding outer diameter (inches)	0.360–0.440	0.395	0.370–0.440
Cladding inner diameter (inches)	0.330–0.384	0.343	0.322–0.382
Cladding Thickness (inches)	0.024–0.028	0.026	0.024–0.029
Cladding Alloy	Zry-2, Zry-4, ZIRLO, M5, E110	Zry-2	ZIRLO, Opt. ZIRLO, M5
Rod Internal Pressure (hot, psia)	600–1,616	400–2,100	800–3,200
Initial Cladding delta pressure (hot, psia)	585–1,601	(-650)–1,050	(-1,400)–1,000
Rod Average burnup (GWd/MTU)	0–90	0–62	0–62
LOCA Cladding Heating Rate (°C/sec)	2–9	0–10**	0–10**

* Typical values for current fuel designs up to 62 GWd/MTU rod average.

** Maximum cladding heating rates during refill/reflood portion of LOCA. Heating rates during LOCA blowdown phase may be significantly larger.

Discussion of Consequences and Consequence Modeling

This RIL summarizes the RES staff's interpretation of research related to FFRD as it can be used to define conservative, empirical thresholds related to FFRD and define when dispersal of fuel into the coolant *begins*. This RIL also summarizes the RES staff's interpretation of available research to define empirical thresholds that could be used to quantify the amount of fuel dispersal associated with the burst of high-burnup fuel rods. This information can be combined with full-core LOCA modeling efforts to estimate total fuel mass dispersal and tFGR from a LOCA or other transient where fuel failure is driven by cladding ballooning and burst (Raynaud, 2013; Raynaud and Porter, 2014). Such efforts could serve as the starting point for evaluating the consequences of FFRD.

A robust discussion of the consequences of fuel dispersal is beyond the scope of this RIL. However, the NRC has made statements about FFRD consequences in past publications. SECY-15-0148 briefly discussed the potential safety concerns for dispersal. NUREG-2121 included a slightly more detailed discussion of the consequences of dispersal in Chapter 5. These documents identified the following potential safety concerns associated with FFRD:

- energetic fuel-coolant interactions
- recriticality of dispersed fragments
- core coolability and long-term decay heat removal
- radiological impacts, including control room dose and equipment qualification

These safety concerns should be addressed if full-core analysis models predict significant fuel dispersal, based on the thresholds identified in this RIL.

Limitations of the Empirical Database

The thresholds presented in this RIL are completely empirical and applicable only to the materials and conditions tested in the cited research. The cited research did not include testing of doped fuel or coated cladding, and therefore, the thresholds in the RIL do not apply to these fuel and cladding materials. Additional research on doped fuels, which can be characterized by different microstructure changes as they accumulate burnup, could demonstrate that the thresholds in the RIL are also applicable to doped fuel or present the need for a more mechanistic threshold tied to fuel microstructure features. Since doped fuel may also have different transient fission gas behavior, additional research to understand how fission gas is retained and released under operating and transient conditions for doped fuel could alter the tFGR threshold in this RIL. Additional research on coated claddings may also allow for a reduction in the conservatism of FFRD thresholds. Fuel fragmentation, relocation, and dispersal behavior has all been shown to have some relationship to local cladding strain, and some coated claddings are reported to have less significant strain than standard cladding under postulated LOCA conditions (Geelhood and Luscher, 2019).

The thresholds presented in this RIL are also simplistic, developed mostly on an observed relationship between each phenomenon and burnup. However, burnup is not likely the sole determinant of behavior in any of the thresholds discussed in this RIL. It is more probable 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. These fuel pellet features may in turn be influenced by operating history and perhaps the operating power just before the postulated transient. Further, some research has confirmed that transient characteristics, such as temperature ramp rate, peak temperature and burst pressure could also affect FFRD behavior. However, at this time, the authors did not consider the available information to be sufficient to offer empirical thresholds related to variables other than burnup. Additional research could provide the necessary basis for multiparameter thresholds, or the basis for exchanging burnup for a more mechanistically important variable. Further research is also needed to better quantify the impacts of rod internal pressure, cladding restraint, fuel temperature, and other parameters on tFGR. Such research could also be used to validate semiempirical or mechanistic models for fine fragmentation and tFGR that have recently been implemented in fuel performance codes (Jernkvist, 2019; Khvostov, 2020).

Finally, the thresholds in this RIL presume that fuel performance models accurately predict the cladding strain along the axial length of a fuel rod. Most LOCA ballooning models were initially developed to assess flow blockage and core coolability and are calibrated to predict the maximum cladding strain in the balloon. They are not necessarily calibrated to accurately predict the axial length of the balloon region. Further, LOCA models can be validated against data from experiments that used a variety of heating methods, and the degree of ballooning can be very sensitive to how the samples are heated. Without a validated model for the prediction of axial strain values, conservative assumptions may be needed in combination with the proposed model for predicting fuel dispersal. Additional research on ballooning behavior, as well as validation of ballooning models for the prediction of balloon axial length, could allow for less conservative assumptions when applying the models. The RIL also takes the position that there is no direct relationship between burst opening area and burnup but acknowledges that burst opening area has a significant impact on the amount of fuel that can be dispersed. The proposed dispersal model assumes that any burst rod may have a large burst opening. In fact, a significant past work has been done on cladding burst (Powers and Meyer, 1980; Chung and Kassner, 1978). Although burst opening size was not the main objective of the past research, differences have generally been observed in cladding swelling and burst behavior based on test setup (e.g., heating methods, heat method setup and associated temperature variation, ramp rate, rod pressure, fuel simulator or lack thereof, single versus multiple rods). Burst opening area has also been postulated to be dependent on the phase of the zirconium cladding at burst (Chung and Kassner, 1978). Additional research or analysis on predicting burst area may allow for further refinement of the dispersal model. Researchers are beginning to develop models for burst opening size as a function of various parameters (Capps, et al., 2021), however more work is needed in order to validate and integrate similar models into LOCA analysis.

Summary and Conclusions

This RIL summarizes the RES staff's interpretation of research related to FFRD and presents a conservative, empirical threshold for when significant fuel fragmentation *begins* as 55 GWd/MTU pellet average burnup for standard UO_2 fuel. The research described herein indicates that below this burnup value, fine fragmentation is *not* a concern.

This RIL also summarizes the RES staff's interpretation of available research to define empirical thresholds that could be used to quantify the amount of fuel dispersal associated with burst of high-burnup fuel rods. The RIL defines a cladding strain threshold of 3 percent as a value below which fuel relocation is *not* a concern. The staff considered multiple empirical models to quantify fuel dispersal and concluded that predicting all fuel above 55 GWd/MTU in the region of the fuel rod with cladding strain above 3 percent represents a conservative prediction of fuel dispersal.

This RIL also summarizes the RES staff's interpretation of research related to tFGR. Research has shown that tFGR increases with burnup, with releases as high as about 20 percent observed for fuel at a pellet average burnup of about 70 GWd/MTU. Such releases could have a significant impact on cladding ballooning and burst behavior during a LOCA and should be accounted for in fuel performance models.

Lastly, this RIL investigates and summarizes the RES staff's interpretation of the research related to the packing fraction. Most of the data show packing fractions ranging from 60 to 85 percent. Packing fraction also varies axially, with high packing fractions in the lower portion of the balloon and lower packing fractions in the upper portion of the balloon. Because of competing phenomena controlling the fuel and cladding temperatures in a region of ballooned cladding and packed fuel during a LOCA, it is important to model a range of packing fractions to evaluate the effects of the packing fraction on cladding temperature and other fuel rod performance metrics.

Acknowledgments

Several organizations, individuals, and resources were instrumental in supporting the development of this RIL. Although the authors of the RIL maintained an independent and separate perspective, they gratefully acknowledge the help received from the following individuals and organizations.

Discussions and review

Staff in the Nuclear Systems Performance Branch within the NRR Division of Safety Systems provided technical review during the development of this RIL. Their comments significantly improved the document. The authors are particularly grateful for thoughtful comments and discussion with Paul Clifford, Benjamin Parks, John Lenning, and Ricardo Torres on the results and conclusions documented in this RIL.

External expert peer review

The authors would like to acknowledge the five external experts who provided peer review for this RIL. They each offered detailed comments that significantly improved the final product and helped clarify complex concepts presented in the RIL. The authors truly appreciate the time and thought the panel applied to this review.

The peer reviewers were selected based on their expertise in FFRD phenomena and familiarity with the research captured in the RIL. It must be clarified that the reviewers were asked to provide personal viewpoints based on their experience. The comments do not necessarily represent the views of their organization.

- Nathan Capps, ORNL
- Tatiana Taurines, Institut de radioprotection et de sûreté nucléaire, France
- Fabiola Cappia, Idaho National Laboratory
- Ken Yueh, Electric Power Research Institute
- Daniel Jädernäs, Studsvik Nuclear AB

Appendix B to this RIL includes a summary of the comments received from the peer review group, as well as how they were resolved.

Studsvik, SCIP III members and management board

The authors would also like to thank Studsvik and the membership of the SCIP III program. Their financial and technical investment in the SCIP III program enabled a huge leap in understanding of FFRD phenomena. The authors also thank the members of the SCIP III management board. All SCIP III data cited in the RIL were previously restricted under the terms of the SCIP III agreement. The NRC asked permission to publish these results in service of this effort to provide transparency for the agency’s regulatory materials. The SCIP III management board granted this request, allowing the detailed technical basis for the authors’ interpretations on FFRD to be publicly available. It should be noted however that the interpretations and views stated in the RIL are those of NRC only and do not necessarily reflect the interpretations of the SCIP-III membership.

References

Bianco, A., et al., 2015. “Experimental investigation on the causes for pellet fragmentation,” *Journal of Nuclear Materials,* pp. 260–267.

Billone, M., Y. Yan, T. Burtseva, and R. Daum, 2008. NUREG/CR-6967, “Cladding Embrittlement During Postulated Loss-of-Coolant Accidents,” Washington, DC, June 2008 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML082130389).

Capps, N., et al., 2021. ORNL/SPR-2021/2218, "Engineering Assessment of UO2 and Cladding Behavior under High-Burnup LOCA Conditions," Oak Ridge National Laboratory, Oak Ridge, TN.

Capps, N., et al., 2021. “A Critical Review of High Burnup Fuel Fragmentation, Relocation, and Dispersal under Loss-of-Coolant Accident Conditions,” *Journal of Nuclear Materials*, Vol. 546, p. 152750.

Capps, N., et al., 2020. “Integral LOCA fragmentation test on high-burnup fuel,” *Nuclear Engineering and Design,* p. 110811.

Chung, H.M., and T.F. Kassner, 1978. NUREG/CR-0344, “Deformation Characteristics of Zircaloy Cladding in Vacuum and Steam under Transient-Heating Conditions: Summary Report,” Washington, DC, July 1978. (ADAMS Accession No. ML20062H050).

Esmaili, H., 2021. “Letter Report on Evaluation of the Impact of Fuel Fragmentation, Relocation, and Dispersal for the Radiological Design Basis Accidents in Regulatory Guide 1.183,” Memorandum from H. Esmaili (NRC) to K. Hsueh (NRC), July 20, 2021 (ADAMS Accession No. ML21197A067).

Geelhood, K., et al., 2021. PNNL-31160, “FAST-1.0.1: A Computer Code for Thermal-Mechanical Nuclear Fuel Analysis under Steady-state and Transients,” Pacific Northwest National Laboratory, Richland, WA.

Geelhood, K.G., and W.G. Luscher, 2019. PNNL-28437, Rev. 1 “Degradation and Failure Phenomena of Accident Tolerant Fuel Concepts; Chromium Coated Zirconium Alloy Cladding,” Pacific Northwest National Laboratory, Richland, WA (ADAMS Accession No. ML19172A154).

Jernkvist, L.O., 2019. “Modelling of fine fragmentation and fission gas release of UO2 fuel in accident conditions,” *EPJ Nuclear Sciences & Technologies,* Vol. 5, p. 11.

Karlsson, J., et al., 2016. “SCIP III—Test Method Descriptions Studsvik/N-15/315 Studsvik-SCIP III-196,” Studsvik Nuclear AB, Nykoping, Sweden.

Khvostov, G., 2020. “Analytical criteria for fuel fragmentation and burst FGR during a LOCA,” *Nuclear Engineering and Technology,* 52(10), pp. 2402–2409.

König, M., 2021a. “STUDSVIK-SCIP III-236 Rev. 2, Integral LOCA test to study the resistance to axial loads during quench or post transient: WZtR165 LOCA1,” Studsvik Nuclear AB, Sweden.

König, M., 2021b. “STUDSVIK-SCIP III-237 Rev. 2, Integral LOCA test to study the resistance to axial loads during quench or post transient: WZtR165 LOCA 2a and 2b,” Studsvik Nuclear AB, Sweden.

König, M., 2019c. “STUDSVIK-SCIP III-238 Rev. 2, Integral LOCA test to study the resistance to axial loads during quench or post transient: 01E7 LOCA3,” Studsvik Nuclear AB, Sweden.

Linton, K., Y. Yan, Z. Burns, and Terrani, K., 2017. ORNL/SPR-2017/434, “Hot Cell Installation and Demonstration of the Severe Accident Test Station,” Oak Ridge National Laboratory, Oak Ridge, TN.

Ma, Z., K. Shirvan, Y. Wu, and G. Su, 2020. “A three-dimension axial fuel relocation framework with discrete element method to support burnup extension,” *Journal of Nuclear Materials,* Vol. 541, p. 152408.

Magnusson, P., et al., 2016. “A study of transient FGR by integral LOCA tests,” *Top Fuel 2016.*

Magnusson, P., 2017. “STUDSVIK-SCIP III-209, Integral LOCA test to study fuel fragmentation of the high burnup fuel rod 3V5-Q13,”Studsvik Nuclear AB, Nykoping, Sweden.

Magnusson, P., et al., 2020. “STUDSVIK-SCIP III-253—Subtask 1.1: Fuel fragmentation, relocation and dispersal, Final Summary Report,”Studsvik Nuclear AB, Nykoping, Sweden.

Magnusson, P., Sheng, C., 2017. “STUDSVIK-SCIP III-214, Integral LOCA test to study fuel fragmentation of the high burnup fuel rod R2D5-LOCA1,” Studsvik Nuclear AB, Sweden.

Magnusson, P., Sheng, C., 2018. “STUDSVIK-SCIP III-227, Integral LOCA test to study fuel fragmentation of the high burnup and low last cycle local power fuel rod VUR1,” Studsvik Nuclear AB, Sweden.

Mileshina, L. and P. Magnusson, 2019a. “STUDSVIK-SCIP III-230, Integral LOCA test to study effect of pressure on fuel fragmentation: VUL2 LOCA3,” Studsvik Nuclear AB, Sweden.

Mileshina, L. and P. Magnusson, 2019b. “STUDSVIK-SCIP III-235, Integral LOCA test to study burnup threshold on fuel fragmentation: 09-OL1L04 LOCA2,” Studsvik Nuclear AB, Sweden.

Mileshina, L. and P. Magnusson, 2019c. “STUDSVIK-SCIP III-240, Integral LOCA test to study burnup threshold on fuel fragmentation: WZR0067 LOCA1,” Studsvik Nuclear AB, Sweden.

Mileshina, L. ,and P. Magnusson, 2019d. “STUDSVIK-SCIP III-232, Integral LOCA test to study effect of pressure on fuel fragmentation: VUL2 LOCA4,” Studsvik Nuclear AB, Sweden.

Mileshina, L. and P. Magnusson, 2019e. “STUDSVIK-SCIP III-241, Integral LOCA counterpart test on rodlets from fuel rod 36U-N05,” Studsvik Nuclear AB, Sweden.

Mileshina, L. and P. Magnusson, 2018. “STUDSVIK-SCIP III-216, Integral LOCA test to study cladding strain and non-depressurization effects on fuel fragmentation: R2D5 LOCA3,” s.I.: Studsvik Nuclear AB.

Mileshina, L., Tejland, P., Magnusson, P., 2019. “STUDSVIK-SCIP III-254, Integral LOCA test to study effect of plenum gas volume on fuel fragmentation: 09-VUR1 LOCA2,” Studsvik Nuclear AB, Sweden.

Moreno, R.O., I.G. Cabezón, P.J.G. Sedano, and Y.T. Gómez, 2005. “Fuel Relocation Effects in BWR LOCA Conditions,” 2005 Water Reactor Fuel Performance Meeting, Kyoto, Japan,

Parsons, P., E. Hindle, and C. Mann, 1986. “The Deformation, Oxidation and Embrittlement of PWR Fuel Cladding in a Loss-of-Coolant Accident: A State-of-the-Art Report,” Committee on the Safety of Nuclear Installations, OECD Nuclear Energy Agency, Paris, France.

Pontillon, Y., et al., 2004. “Experimental and Theoretical Investigation of Fission Gas Release from UO2 up to 70 GWd/t under Simulated LOCA Type Conditions: The GASPARD Program,” *Proceedings of the 2004 International Meeting on LWR Fuel Performance.*

Powers, D., and R.O. Meyer, 1980. NUREG-0630, “Cladding Swelling and Rupture Models for LOCA Analysis,” Washington, DC, April 1980 (ADAMS Accession No. ML053490337).

Raynaud, P., 2013. “Core-Wide Estimates of Fuel Dispersal During a LOCA,” Proceedings of TOPFUEL, Charlotte, NC, American Nuclear Society, pp. 636–643.

Raynaud, P., and I. Porter, 2014. “Predictions of fuel dispersal during a LOCA,” Proceedings of WRFPM, Sendai, Japan, pp. 14–17.

Rest, J., et al., 2019. “Fission gas release from UO2 nuclear fuel: A review,” *Journal of Nuclear Materials,* Vol. 513, pp. 301–345.

Snead, M., et al., 2015. ORNL/TM-2015/556, “Severe Accident Test Station Design Document,” Oak Ridge, TN: Oak Ridge National Laboratory.

Tejland, P., and C. Sheng, 2019a. “Studsvik-SCIP-III-243, Integral BWR H3 overheating test of the fuel rod 12-R1E10,” Nykoping, Studsvik Nuclear AB, Sweden.

Tejland, P., and C. Sheng, 2019b. “Studsvik-SCIP-III-233, Integral overheating test to study TFGR of the fuel rod 09-OL1L04,” Nykoping, Studsvik Nuclear AB, Sweden.

Tradotti, R., 2014. “LOCA Testing at Halden, The BWR Fuel Experiment IFA-650.14,” OECD Halden Reactor Project, Halden, Norway.

Turnbull, J.A., et al., 2015. “An Assessment of the Fuel Pulverization Threshold During LOCA-Type Temperature Transients,” *Nuclear Science and Engineering,* pp. 477–485.

Une, K., S. Kashibe, and K. Hayashi, 2002. “Fission gas release behavior in UO2 fuels with developed rim structure,” *Journal of Nuclear Science and Technology,* 39, pp. 668-674.

U.S. Nuclear Regulatory Commission, 2012. NUREG-2121, “Fuel Fragmentation, Relocation and Dispersal During the Loss-of-Coolant Accident,” Washington, DC, March 2012 (ADAMS Accession No. ML12090A018).

U.S. Nuclear Regulatory Commission, 2013. NUREG-2160, “Post-Test Examination Results from Integral, High-Burnup, Fueled LOCA Tests at Studsvik Nuclear Laboratory,” Washington, DC, August 2013 (ADAMS Accession No. ML13240A256).

U.S. Nuclear Regulatory Commission, 2015. SECY-15-0148, “Evaluation of Fuel Fragmentation, Relocation and Dispersal under Loss-of-Coolant Accident (LOCA) Conditions Relative to the Draft Final Rule on Emergency Core Cooling System Performance During a LOCA (50.46c),” Washington, DC, November 30, 2015 (ADAMS Accession No. ML15230A200).

U.S. Nuclear Regulatory Commission, 2020. Regulatory Guide 1.236, "Pressurized-Water Reactor Control Rod Ejection and Boiling-Water Reactor Control Rod Drop Accidents" Washington, DC, June 2020 (ADAMS Accession No. ML20055F490).

U.S. Nuclear Regulatory Commission, 2021. Draft Regulatory Guide DG-1389, " Proposed Revision 1 to Regulatory Guide 1.183, Alternative Radiological Source Terms for Evaluating Design Basis Accidents at Nuclear Power Reactors" Washington, DC, November 2021 (ADAMS Accession No. ML21292A319).

Wiesenack, W., 2013. “HRP-380, Summary of the Halden Reactor Project LOCA Test Series IFA-650,” Halden Reactor Project, Halden, Norway.

Wiesenack, W., 2015. “HPR-383, Summary and Comparison of LOCA Tests with BWR Fuel in the Halden Reator Project Test Series IFA-650,” Halden Reactor Project, Halden, Norway.

Appendix A
A Model for Predicting Dispersal

Combining integral experiments from the Halden Reactor Project, the U.S. Nuclear Regulatory Commission (NRC), the Studsvik Cladding Integrity Program (SCIP), and Oak Ridge National Laboratory (ORNL), more than 35 tests were conducted on rodlets with segment average burnups ranging from approximately 45 to 90 gigawatt days per metric ton of uranium (GWd/MTU) of uranium dioxide (UO_2) fuel, for which detailed observations on fuel fragmentation, relocation, and dispersal (FFRD) are available. One goal of the research information letter (RIL) is to establish a simplified model for the expected mass of fuel dispersal from a rod if burst occurs. The staff examined the available data and considered a variety of approaches to develop a model for predicting mass of fuel dispersal.

Observed trends

Experimental results of the mass of fuel dispersed during loss-of-coolant (LOCA) testing were examined for trends. Figure A-1 includes mass values measured from LOCA tests at Studsvik through the NRC's LOCA program and in SCIP III. Table A-1 includes complementary qualitative observations from Halden and ORNL. Figure A-1 shows a correlation between dispersed mass and burnup, with higher burnup rods dispersing more fuel following cladding burst.

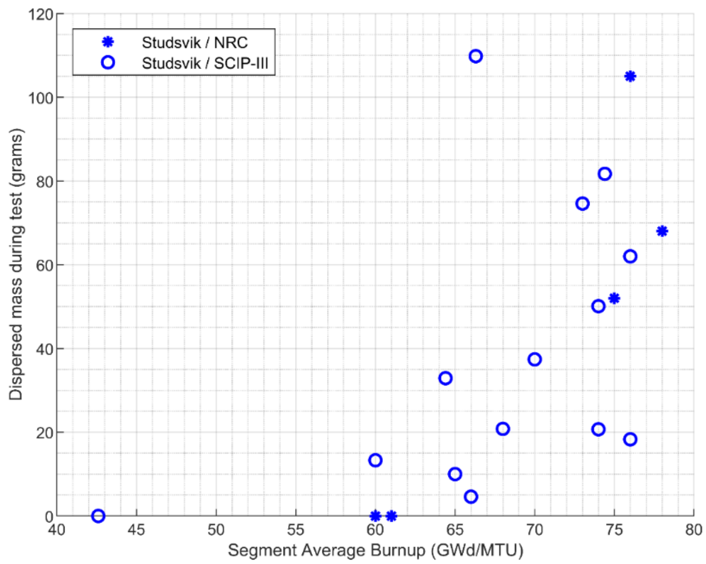

Figure A-1. Mass of fuel dispersed during the LOCA experiment as a function of burnup (NRC, 2013; Magnusson, 2017; Magnusson and Sheng, 2017; Magnusson, 2018; Magnusson, et al., 2020; Mileshina and Magnusson, 2019a, b, c, d, e; Mileshina et al., 2019; König, 2021a, b, c).

Table A-1. Qualitative observations of dispersal during LOCA testing (Wiesenack, 2013; Wiesenack, 2015; NRC, 2013; Capps, et al., 2020).

Test series	Test number	Segment Average Burnup (GWd/MTU)	Dispersed Mass (grams)
Halden	650.02	0.0	none
Halden	650.07	44.3	none
Halden	650.06	55.5	none
Halden	650.11	56.0	none
Halden	650.10	60.0	minor
Halden	650.12	72.3	minor to medium
Halden	650.13	73.1	minor
Halden	650.03	81.9	none
Halden	650.05	83.0	medium
Halden	650.09	90.0	very strong
NRC	198	60.0	none
NRC	196	61.0	none
ORNL	NA #1	69.0	none
ORNL	HBR #1	71.0	none
ORNL	NA #2	77.0	none
Halden	650.04	92.3	very strong

The dispersed mass observed during these experiments may not be conservatively representative of design-basis LOCA conditions in an operating reactor for at least three reasons. 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, and 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.

Acknowledging these limitations of the experimental design, in many cases, a rodlet was cut following the LOCA test and shaken to allow loose fuel fragments to be emptied and examined. The fuel that was dispersed during the test was combined with the fuel that was later shaken out of the test samples and processed through a series of sieves to separate fuel fragments by size. This allowed for measurement in specific size groups: <0.125 millimeters (mm), 0.125–0.25 mm, 0.25–0.5 mm, 0.5–1 mm, 1–2 mm, 2–4 mm, and >4 mm. The mass fractions of fragments smaller than 1 mm and 2 mm were examined to evaluate trends in fine fragmentation. Figure A-2 shows the mass fraction of fragments smaller than 1 mm, as well as the mass fraction of fragments smaller than 2 mm. The fraction of finely fragmented fuel increases with higher burnup.

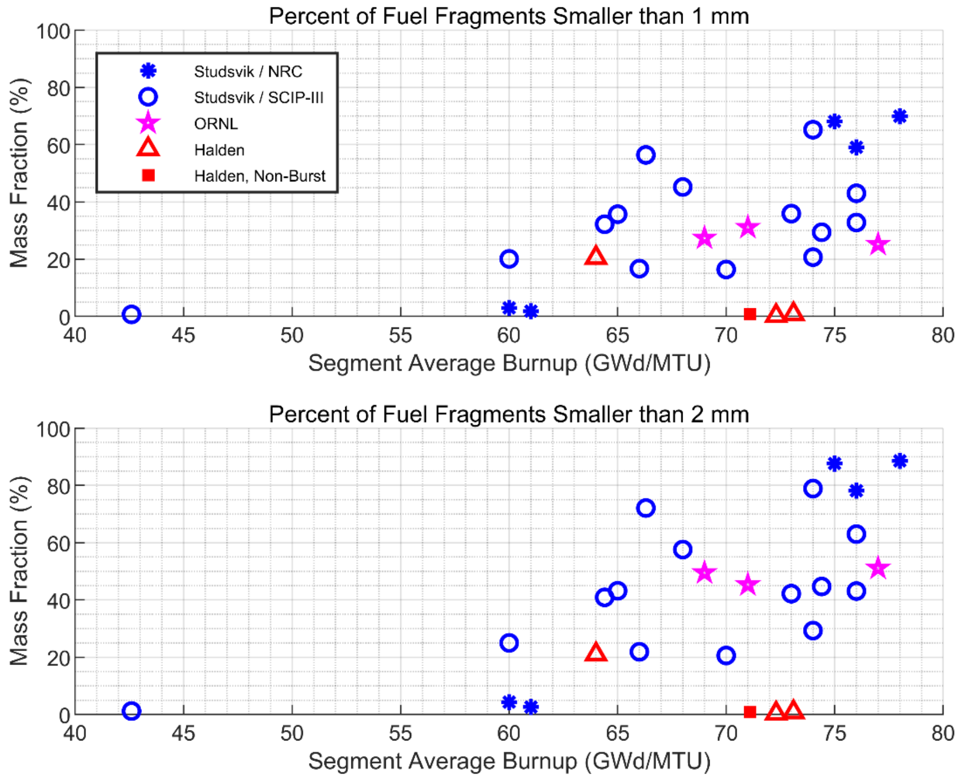

Figure A-2. Mass fraction of fuel fragments smaller than 1 mm[10] and 2 mm (Wiesenack, 2013; Wiesenack, 2015; NRC, 2013; Capps, et al., 2020; Magnusson, 2017; Magnusson and Sheng, 2017; Magnusson, 2018; Magnusson, et al., 2020; Mileshina and Magnusson, 2019a, b, c, d, e; Mileshina et al., 2019; König, 2021a, b, c).

As discussed in the RIL, experimental results reveal that fuel relocation is limited in regions of the fuel rod experiencing low cladding strain. There is some variability between tests, and observed strain thresholds for fuel relocation ranged from 1–10 percent. It might be obvious to consider that fuel above the burst opening could relocate into the ballooned region under the force of gravity and possibly disperse. However, experiments have also shown that fuel can be swept out of high strained regions of the cladding below the burst opening. Figure A-3 shows a posttest gamma scan of SCIP III test VUR1-LOCA1. The x-axis in Figure A-3 is marked with the zero at the center of the burst opening; therefore, the burst opening extended from about -13 mm to +13 mm in the figure. The relative cesium (Cs)-137 activity suggests that almost 40 mm below the bottom of the burst opening was empty of fuel. While this was not observed in every test, it suggests that fuel could be swept out of high strained regions of the cladding below the burst opening under certain conditions. This phenomenon likely depends on the differential pressure between the rod and coolant at the time of burst, effectiveness of axial gas communication, burst opening size, and average fragment size. These variables were not isolated in the cited experiments, so it is not possible to define conditions for when sweeping of fuel below the burst will and will not occur based on available results.

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10 The Studsvik measurements include “lost mass.” Studsvik researchers define “lost mass” as the difference between the total mass of fragmented fuel and the total mass of all fuel fragments collected for sieving and weighting. The lost mass is assumed to be smaller than 1 mm, because larger fragments can easily be identified during the collection process from the test chamber (Magnusson, et al., 2019).

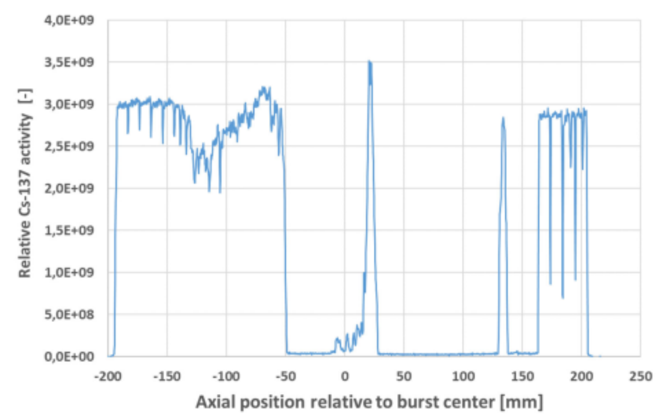

Figure A-3. Posttest gamma scan of SCIP III test VUR1-LOCA1 (Magnusson and Sheng, 2018).

Finally, the influence of burst opening was examined. A comparison between two high-burnup tests in SCIP III demonstrates that burst opening size has a large influence on the relative mass of fuel dispersed during the test compared to the total mass of fragmented and mobile fuel. Figure A-4 presents fragmentation size distribution values for tests at 73 and 60 segment average burnup. On the right side of Figure A-4, scaled representations of the burst opening size for each test are shown. The first test had a relatively large burst opening, while the second test had a smaller burst opening. The tests showed somewhat comparable amounts of mobile fuel (i.e., the total of all fragments collected during the LOCA test and following shaking after the test). Mobile fuel totaled 91.6 grams (g) for WZR0067-LOCA and 83.7 g for OL1L04-LOCA2. The two tests also had a similar breakdown of fuel larger than 1 mm: 58.7 g versus 66.9 g for WZR0067-LOCA and OL1L04-LOCA2, respectively. However, the test with the larger burst opening had approximately 4 times more fuel dispersed during the test.

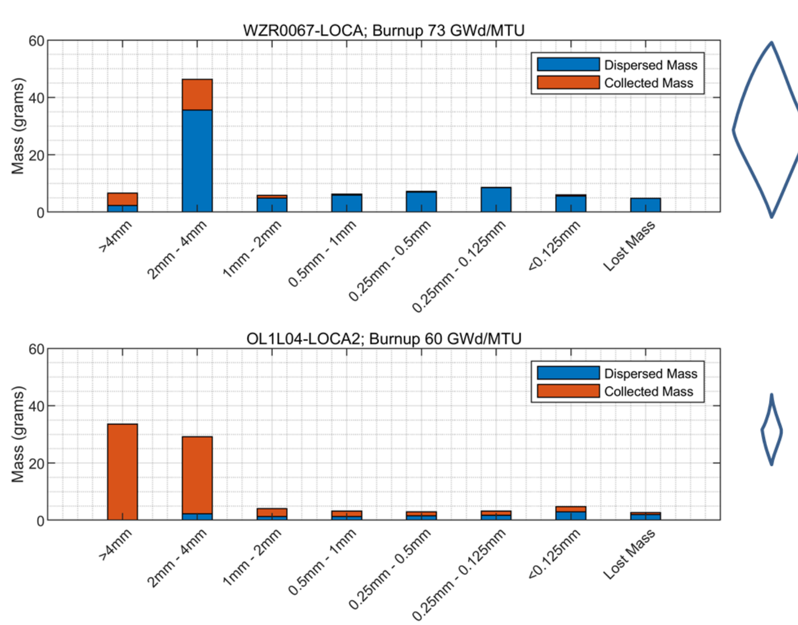

Figure A-4. Fragment size distribution for SCIP III test at 60 and 73 GWd/MTU, with relative burst opening size (Mileshina and Magnusson, 2019b, c).

Looking closer at the burst opening area from tests conducted at Studsvik for the NRC, at Studsvik for SCIP III, at Halden, and at ORNL, Figure A-5 shows that there is no direct relationship between burnup and burst opening area,[11] burst width, or burst length. A more comprehensive review of burst dimensions measured in other experimental programs can be found elsewhere (Capps, et al., 2021) and is beyond the scope of this RIL.

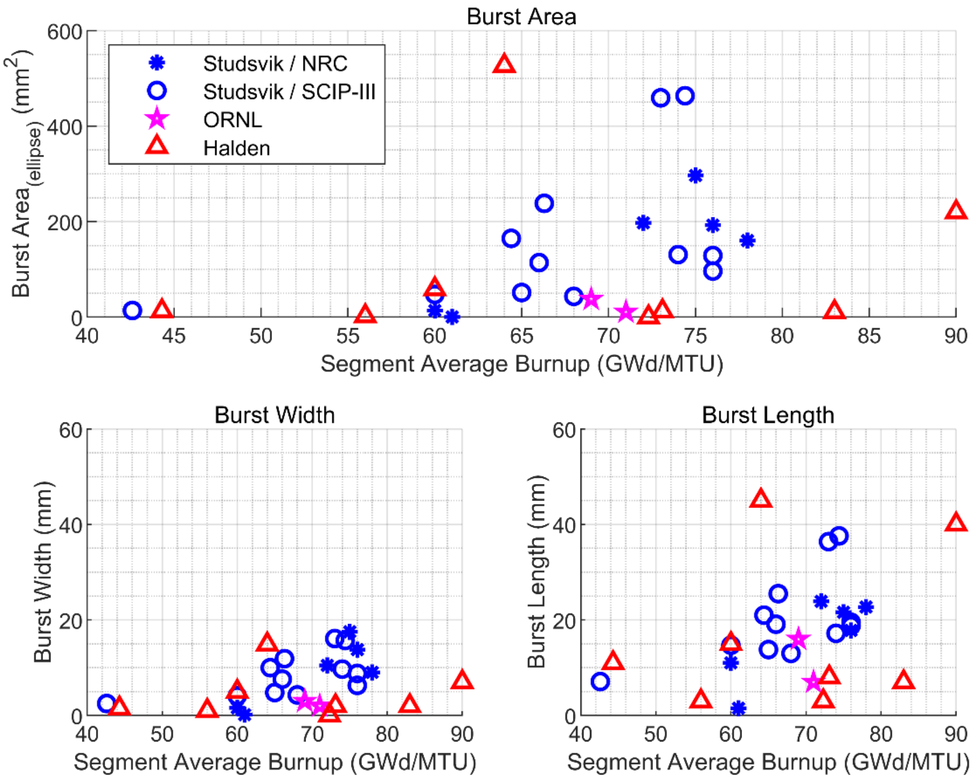

Figure A-5. Burst area, length, and width as a function of burnup (Wiesenack, 2013; Wiesenack, 2015; NRC, 2013; Capps, et al., 2020; Magnusson, 2017; Magnusson and Sheng, 2017; Magnusson, 2018; Magnusson, et al., 2020; Mileshina and Magnusson, 2019a, b, c, d, e; Mileshina et al., 2019; König, 2021a, b, c).

Desired Model Characteristics

Taking these observations together, the staff looked to design a model that captured the observations that (1) higher burnup rods have more dispersal, (2) fragmentation was more significant as burnup increased, (3) fuel in regions of low strain was relatively intact and not mobile (and therefore could not readily disperse), and (4) burst opening size could influence dispersal but varied randomly. Recognizing that the rodlets used for testing in all of the available research programs were far shorter (30–40 centimeters) than rods in a reactor, the staff looked to design a model that would allow for the experiment values to be extrapolated to full length rods. To do this, the model should be calibrated to variables with observed influence, namely burnup and strain, and should disassociate any dependence on stochastic variables, namely burst opening size.

11 Burst area was calculated as an ellipse based on burst length and width measurements.

Models Examined

Two types of models were examined. The first class of models uses a surrogate fragment size to define "dispersible" fuel and is calibrated to the observed quantities of fuel fragments of that size as a function of burnup. The first class combines the burnup trend of the surrogate with a strain threshold. The second class of models defines fuel of any size as dispersible and depends only on the strain threshold.

With respect to the first class of proposed models, the Office of Nuclear Regulatory Research (RES) staff examined two surrogates for "dispersible" fuel:

(1) All *mobile fuel* fragments smaller than 1 mm are dispersible.
(2) All *mobile fuel* fragments smaller than 2 mm are dispersible.

The quantity of "*mobile fuel*" is determined experimentally based on the total of all fuel collected during testing and after the rods were broken and fuel was shaken out. Calibrating a model to quantities of all mobile fuel collected, including after breaking and shaking the rods, ensures that the model is independent of burst opening size. Figure A-6 and Figure A-7 present the measured value of the mass fraction of fuel fragments smaller than 1 mm and 2 mm, respectively, as well as a corresponding conservative model for the mass fraction as a function of burnup.

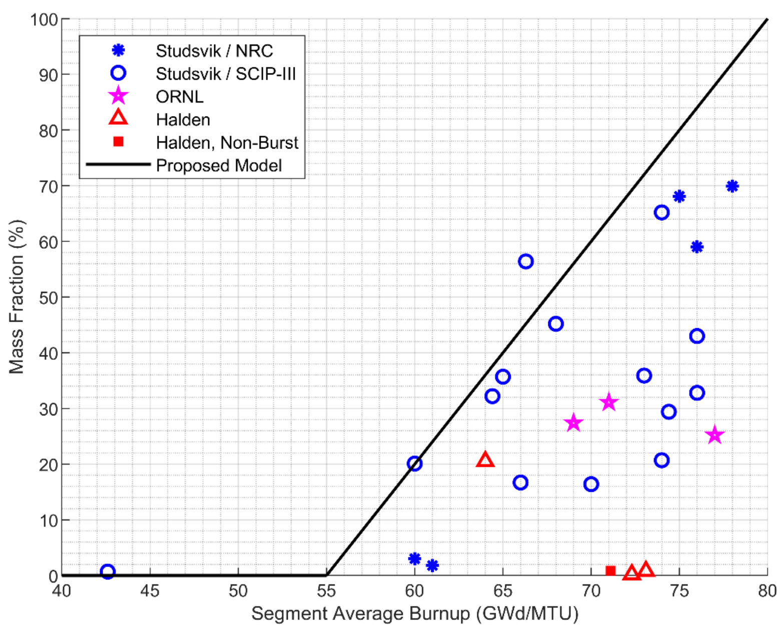

Figure A-6. Mass fraction of all collected fuel smaller than 1 mm as a function of burnup.

The proposed model in Figure A-6 for mass fraction less than 1 mm as a function of burnup is as follows:

$$Mass\ fraction = \begin{cases} 0, BU \leq 55 \\ .04(BU - 55), 55 < BU < 80 \\ 1, BU > 80 \end{cases}$$

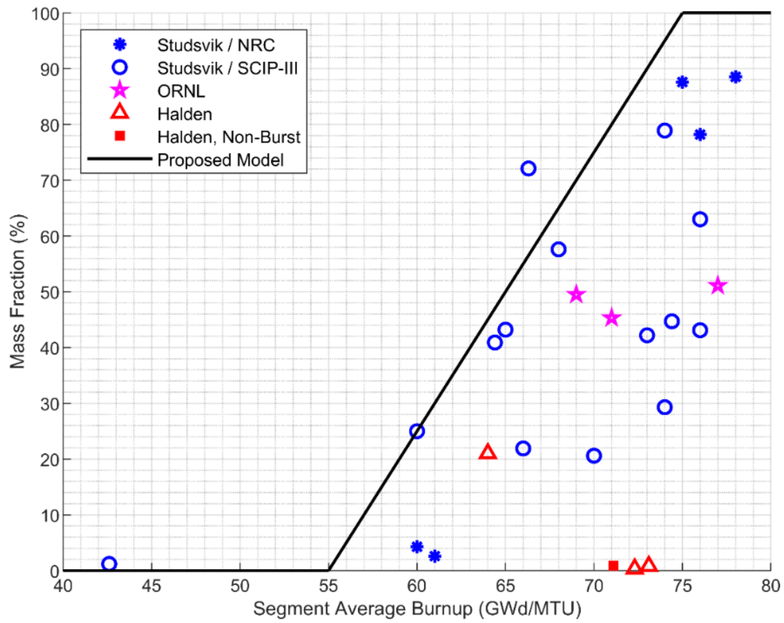

Figure A-7 Mass fraction of all collected fuel smaller than 2 mm as a function of burnup.

The proposed model in Figure A-7 for mass fraction less than 2 mm as a function of burnup is as follows:

$$Mass\ fraction = \begin{cases} 0, BU \leq 55 \\ .05(BU - 55), 55 < BU < 75 \\ 1, BU > 75 \end{cases}$$

Defining a fragment size threshold of either 1 mm or 2 mm as “dispersible” is arbitrary. A surrogate fine fragmentation size has been used elsewhere as a means to use the observed fragmentation changes with burnup to predict dispersal changes with burnup (Capps, et al., 2021; Yueh, 2014); however, this may be problematic. Fragments larger than 2 mm have dispersed during tests, and fragments smaller than 1 mm were often retained in the test segments during tests. Therefore, these size thresholds do not relate directly to the size of fragments dispersed versus those retained during LOCA tests. Looking at one test in particular in Figure A-8 and considering a 1-mm threshold for “dispersible fuel,” a model based only on this surrogate would predict that the fuel mass in the dark blue box will disperse, and none of the mobile mass in the orange box will disperse. Comparing the mass of fuel smaller than 1 mm that did not disperse (in the green boxes) to the mass of fuel larger than 1 mm that did disperse (in the red boxes) can indicate whether this is a conservative or nonconservative prediction.

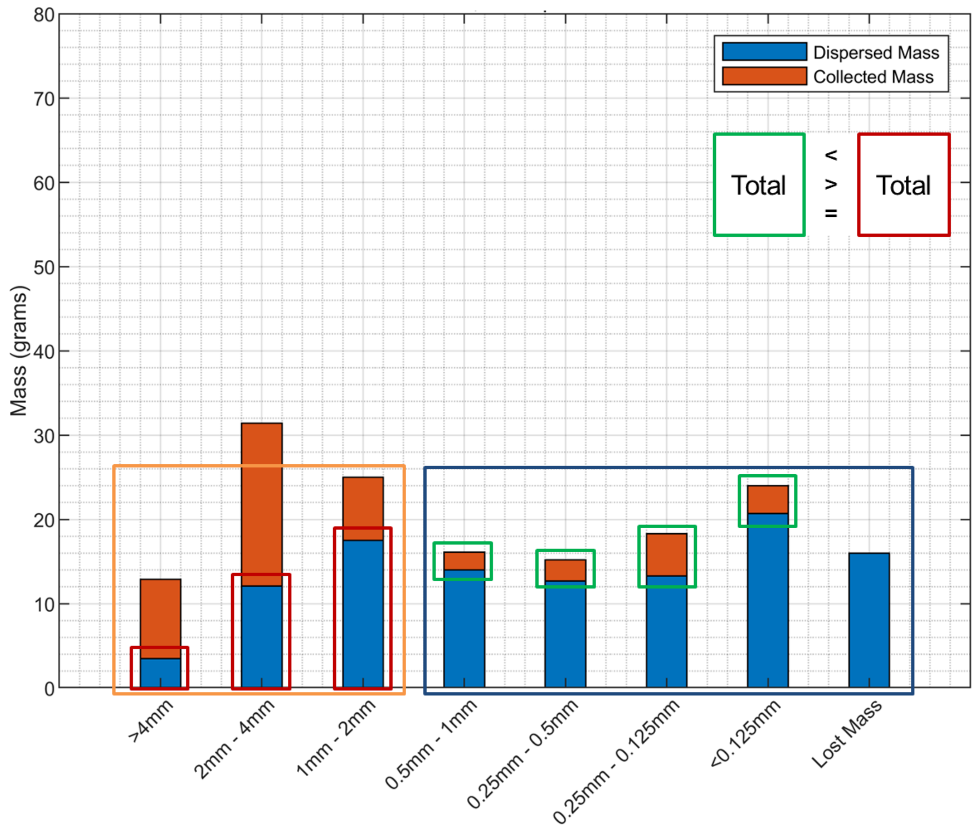

Figure A-8. Illustration of a means to evaluate the conservatism of a fragment size threshold as a surrogate for “dispersible” fuel.

The comparison of “dispersed mass” to the surrogate boundary depicted in Figure A-8 is not complete, because it captures only part of the relevant phenomena. The model for mass fraction of fuel of either size must then be combined with a parameter accounting for the influence of local cladding strain in order to calculate a prediction of mass dispersed. Observations of the strain threshold suggest that fuel in regions with lower than 2-percent strain is very rarely mobile and fuel in regions with lower than 3-percent strain is often not mobile.

Taking these features together, in the first class of models, the mass fraction of fragments smaller than a defined “dispersible” size surrogate is multiplied by the total mass of fuel in the length of the fuel rod above a defined strain threshold for mobile fuel. Figure A-9 illustrates this model, as well as the proposed relationship between the mass fraction of fuel below 1 mm and 2 mm and burnup.

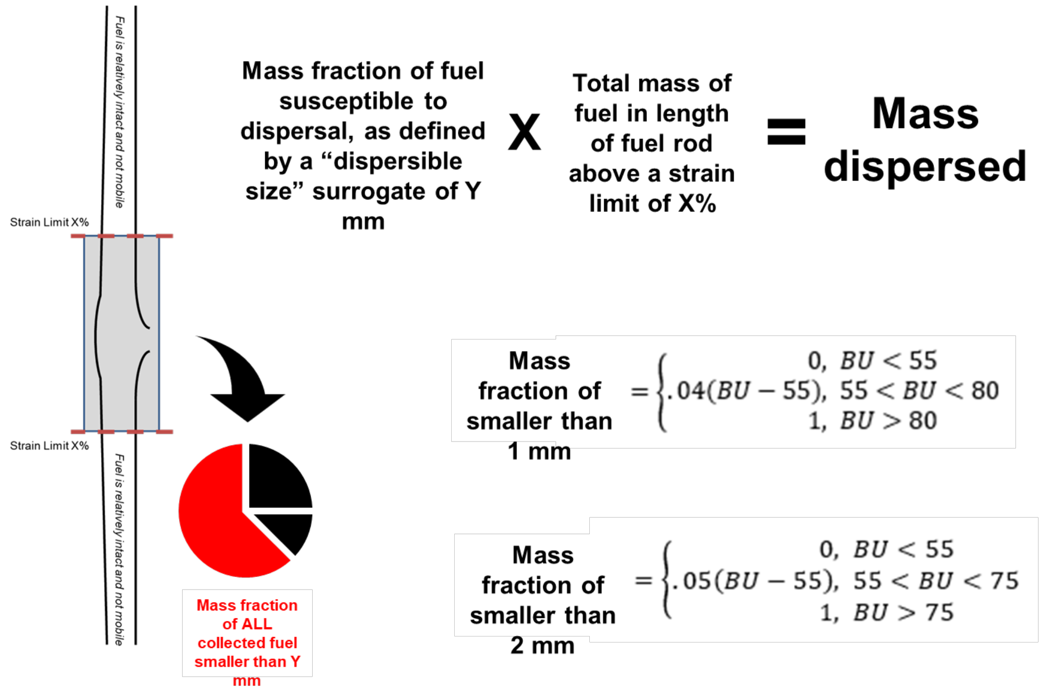

Figure A-9. Illustration of elements of a model to predict fuel dispersal mass.

With respect to the second class of proposed models, the RES staff also considered two models in which fuel fragments of any size are dispersible. These two models depend only on a strain threshold and have no implicit reliance on aspects of the scaled testing described in the RIL that may not fully represent design-basis LOCA conditions at operating reactors. For instance, burst strain and opening sizes may be affected by a broader set of parameters such as heating rate and means of heating the cladding, rod length, and deformation of surrounding fuel rods. In addition, the powerful, oscillatory external forces acting on the fuel in a design-basis LOCA could result in greater dispersal than observed during these experiments. Finally, the degree to which fuel could be swept from the region of the rod with high strain may not be prototypic in each of the cited experiments.

The “shaking” of fuel from the test segments is not intended to be representative of any specific force anticipated during a LOCA. However, the quantity of mobile fuel collected after shaking is more than the quantity of fuel collected during the LOCA simulation, indicating some of the fuel fragments retained in the rod during the experiments could disperse if applied forces were more extreme. If the LOCA simulation in the experiments cited does not replicate all forces in a design-basis LOCA, then the quantity of fuel collected after shaking may be closer to the quantity dispersed during a design-basis accident. To compensate for the uncertainty associated with these test limitations, one could conservatively propose that all fuel in the length of the fuel rod above a defined strain threshold (e.g., 2–3 percent) will disperse. In this case, the model for the dispersible mass fraction would be as follows:

$$Mass\ fraction = \begin{cases} 0, BU \leq 55 \\ 1, BU > 55 \end{cases}$$

The predicted mass of dispersal would only be a function of the predicted cladding strain for fuel above the 55 GWd/MTU pellet average burnup threshold.

In summary, six possible models are proposed for the prediction of dispersed fuel mass:

A. All fuel **smaller than 1 mm** in the length of the rod with **greater than 3% strain**
B. All fuel **smaller than 2 mm** in the length of the rod with **greater than 3% strain**
C. All fuel in the length of the rod with **greater than 3% strain**
D. All fuel **smaller than 1 mm** in the length of the rod with **greater than 2% strain**
E. All fuel **smaller than 2 mm** in the length of the rod with **greater than 2% strain**
F. All fuel in the length of the rod with **greater than 2% strain**

Note that the above models are applied only above the 55 GWd/MTU pellet average burnup threshold at which rods are susceptible to FFRD.

Model Predictions

To examine the ability of the various models to predict dispersed mass, the models were used to predict fuel dispersal in seven tests from SCIP III. These seven tests were examined because the fragment size distribution was measured twice, first for the fuel dispersed during the LOCA tests and again for the fuel collected following shaking, allowing for a comparison of the fuel fragment size distribution. In addition, the strain profile was measured to a relatively fine resolution such that the length of the fuel rod with less than 2-percent and 3-percent strain could be differentiated. Table A-2 presents key characteristics of each of the seven tests.

Table A-2. Relevant characteristics of seven SCIP III tests used to examine the proposed models (Mileshina and Magnusson, 2019a, b, c, d, e; Magnusson and Sheng, 2018).

	Burnup (GWd/ MTU)	Fill Pressure (bar)	Reported strain thresholds above and below balloon.[12] (%)	Minimum burst opening dimension (mm)	Fuel weight (g)	Fuel column length (mm)	Length of cladding >3% (mm)	Mass of fuel column with strain >3% (g)	Length of clad-ding >2% (mm)	Mass of fuel column with strain >2% (g)
OL1L04-LOCA-2	60	80	4.9, 4.5	4.1	209	338	338	209	338	209
N05-LOCA	64	80	1.6, 1.9	9.8	161	296	118	64	132	72
VUR1-LOCA-1	66	80	2.5, 2.1	11.9	219	397	345	191	368	203
WZR0067-LOCA	73	80	1.5. <8	16.1	173	319	144	78	154	84
VUL2-LOCA1	74	80	2.0, 4.6	9.7	163	293	200	111	221	123
VUL2-LOCA3	76	21	1.8, 3.9	6.3	221	401	345	190	368	203
VUL2-LOCA4	76	40	4.6, <4	8.8	199	360	346	191	350	193

In these seven tests, a strain threshold for mobile fuel was identified by examining gamma scan measurements and posttest profilometry. As Table A-2 shows, there were instances where the reported strain for mobility was different than 2 percent or 3 percent. Figure A-10 indicates the mass of fuel in the region below 2 percent and 3 percent strain, together with the mass dispersed and mobile, for each test.

12 Gamma scan measurements were examined, in combination with cladding profilometry, to identify the local strain that marked the boundary where fuel remained in the rod and appeared intact. See, for example, Figure 5 of the RIL.

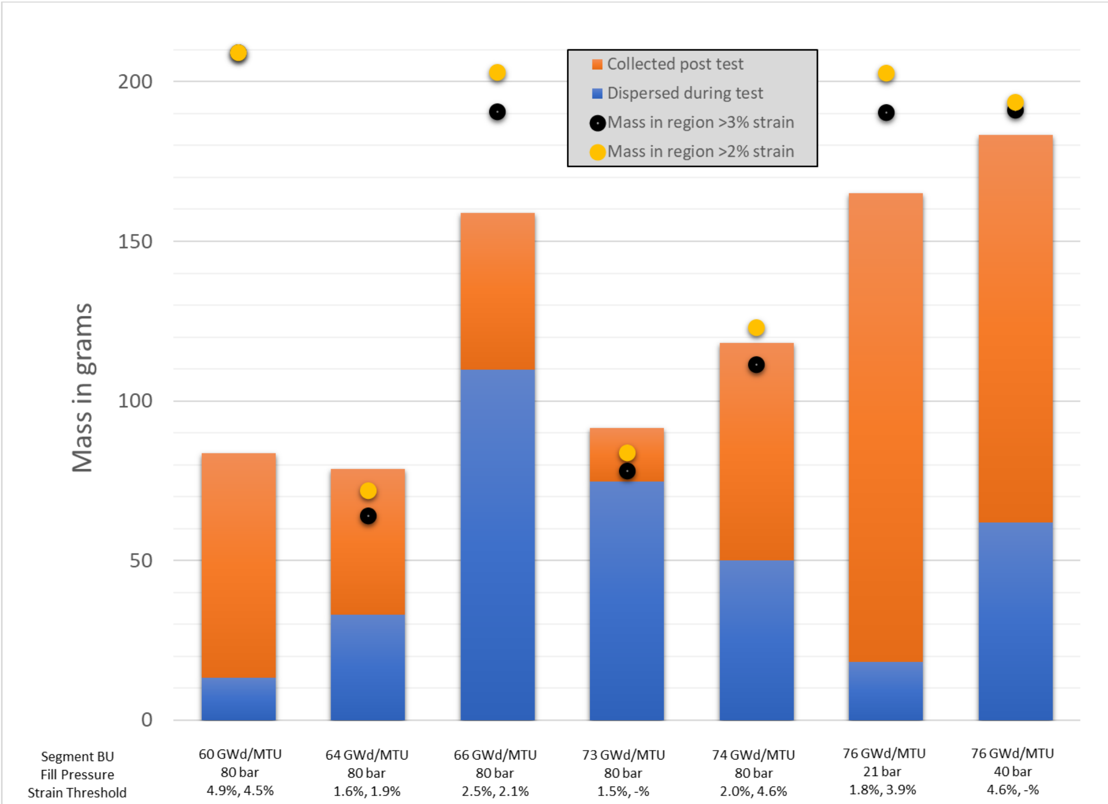

Figure A-10. Comparison of mass below 2-percent and 3-percent strain compared to mass dispersed and mobile.

Table A-3 shows the comparison of predictions from Models A, B, and C to the actual dispersed mass observed in each experiment. Table A-4 shows the comparison of Models D, E, and F to the actual dispersed mass observed in each experiment. In both tables, positive values of the comparison indicate the model is conservative, while negative values (in red) mean the model is nonconservative; values greater than 100 percent indicate the model is conservative, while values less than 100 percent indicate the model is nonconservative.

Table A-3. Comparison of measured and predicted dispersed mass using Models A, B, and C in seven SCIP III tests.

	Difference between dispersal predicted by the model and ***dispersal observed*** in the experiment					
	A (mass, g)	A (%)	B (mass, g)	B (%)	C (mass, g)	C (%)
OL1L04-LOCA-2	29	314%	39	393%	196	1,571%
N05-LOCA	-10	70%	-4	88%	31	182%
VUR1-LOCA-1	-26	76%	-5	95%	81	158%
WZR0067-LOCA	-18	75%	-4	94%	3	102%
VUL2-LOCA1	34	169%	56	211%	61	221%
VUL2-LOCA3	142	874%	172	1,040%	172	949%
VUL2-LOCA4	99	259%	129	308%	129	303%

Table A-4. Comparison of measured and predicted dispersed mass using Models D, E, and F in seven SCIP III tests.

	Difference between dispersal predicted by the model and ***dispersal observed*** in the experiment					
	D (mass, g)	D (%)	E (mass, g)	E (%)	F (mass, g)	F (%)
OL1L04-LOCA-2	29	314%	39	393%	196	1571%
N05-LOCA	-7	65%	-1	98%	39	218%
VUR1-LOCA-1	-21	70%	2	102%	93	185%
WZR0067-LOCA	-14	73%	1	101%	9	112%
VUL2-LOCA1	43	168%	67	233%	73	246%
VUL2-LOCA3	152	797%	184	1108%	184	1108%
VUL2-LOCA4	101	255%	131	312%	131	312%

Again, returning to the uncertainties associated with modeling burst opening size and the possibility that the experiments cited do not replicate all forces expected in a design-basis LOCA, a more meaningful comparison of the model prediction could be against the total mass dispersed combined with the total mass shaken out of the rod following the test. Table A-5 shows the comparison of predictions from Models A, B, and C to the mass of all mobile fuel observed in each experiment. Table A-6 shows the comparison of Models D, E, and F to the mass of all mobile fuel observed in each experiment.

Table A-5 Comparison of predicted dispersed mass to all mobile fuel using Models A, B, and C in seven SCIP III tests.

	Difference between dispersal predicted by the model and ***all mobile fuel observed*** in the experiment					
	A (mass, g)	A (%)	B (mass, g)	B (%)	C (mass, g)	C (%)
OL1L04-LOCA-2	-42	50%	-31	62%	125	250%
N05-LOCA	-56	29%	-50	37%	-19	76%
VUR1-LOCA-1	-75	53%	-54	66%	15	109%
WZR0067-LOCA	-35	61%	-21	77%	-16	83%
VUL2-LOCA1	-34	72%	-12	89%	-7	94%
VUL2-LOCA3	-5	97%	25	115%	8	105%
VUL2-LOCA4	-23	88%	8	104%	5	102%

Table A-6. Comparison of predicted dispersed mass to all mobile fuel using Models D, E, and F in seven SCIP III tests.

	Difference between dispersal predicted by the model and ***all mobile fuel observed*** in the experiment					
	D (mass, g)	D (%)	E (mass, g)	E (%)	F (mass, g)	F (%)
OL1L04-LOCA-2	-42	50%	-31	62%	125	250%
N05-LOCA	-53	33%	-46	41%	-7	91%
VUR1-LOCA-1	-70	56%	-47	70%	44	128%
WZR0067-LOCA	-31	66%	-16	82%	-8	91%
VUL2-LOCA1	-25	79%	-1	99%	5	104%
VUL2-LOCA3	5	103%	38	123%	38	123%
VUL2-LOCA4	-21	89%	10	105%	10	105%

Considerations for Selecting a Model

All six models are highly empirical and, based on engineering judgment, define a dispersible fragment size or a strain threshold for relocation. A model can be selected based on the desired conservatism and can be considered in terms of individual rod predictions or corewide dispersal predictions.

The RES staff has taken the position that the most meaningful comparison of the model to observed behavior is made when considering the total mass of mobile fuel. This observation is based on the staff's perception that a model derived directly from the mass of fuel dispersed during the experiments described in the RIL may underpredict the dispersal experienced during an actual LOCA at an operating reactor. In addition to fuel burnup, dispersal is expected to be influenced by parameters such as the size of a cladding burst opening, the volume and pressure of gas internal to a fuel rod, and the external forces acting on fuel rods in a real LOCA event, among other things. While the scaled, single-rodlet tests considered in the RIL have attempted to account for physical phenomena of greatest significance to dispersal, practical scaling requirements limit the degree to which all relevant phenomena occurring in a reactor core may be representatively modeled in individual tests. While the net effect of these test scaling limitations cannot be estimated with quantitative accuracy, in the RES staff's judgment, a model derived directly from the fuel dispersed during the tests would likely tend to underestimate fuel dispersal during an actual LOCA.

The comparisons shown in Table A-5 and Table A-6 help to illustrate this point. Looking at the comparison of the model predictions to all mobile fuel, using either a 1-mm or 2-mm surrogate for "dispersible" fuel consistently results in significant nonconservatism. Only the models that predict all fuel in the region of the rod with greater than either 2-percent or 3-percent strain provide some conservative and some nonconservative predictions. Because the application of any model could result in corewide predictions of fuel dispersal, it is acceptable for a model to sometimes offer nonconservative predictions if it offers conservative predictions at other times. Considering only the seven tests examined here, Model C (all fuel in the length of the rod with greater than 3-percent strain will disperse) offers predictions that are reasonably conservative. 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.

Application of the Model

An important consideration for all of the models proposed here is their reliance on fuel performance models that accurately predict the cladding strain along the axial length of a fuel rod. Most LOCA ballooning models are calibrated to accurately predict the maximum cladding strain in the balloon but are not necessarily calibrated to accurately predict the axial length of the balloon region. Without a validated model for the prediction of axial strain values, conservative assumptions may be needed in combination with the proposed model for predicting fuel dispersal.

References

Capps, N., et al., 2020. “Integral LOCA fragmentation test on high-burnup fuel,” *Nuclear Engineering and Design,* p. 110811.

Capps, N., et al., 2021. “A Critical Review of High Burnup Fuel Fragmentation, Relocation, and Dispersal under Loss-of-Coolant Accident Conditions,” *Journal of Nuclear Materials,* Vol. 546, p. 152750.

Geelhood, K., et al., 2021. PNNL-31160, “FAST-1.0.1: A Computer Code for Thermal-Mechanical Nuclear Fuel Analysis under Steady-state and Transients,” Pacific Northwest National Laboratory, Richland, WA.

König, M., 2021a. “STUDSVIK-SCIP III-236 Rev. 2, Integral LOCA test to study the resistance to axial loads during quench or post transient: WZtR165 LOCA1,” Studsvik Nuclear AB, Sweden.

König, M., 2021b. “STUDSVIK-SCIP III-237 Rev. 2, Integral LOCA test to study the resistance to axial loads during quench or post transient: WZtR165 LOCA 2a and 2b,” Studsvik Nuclear AB, Sweden.

König, M., 2019c. “STUDSVIK-SCIP III-238 Rev. 2, Integral LOCA test to study the resistance to axial loads during quench or post transient: 01E7 LOCA3,” Studsvik Nuclear AB, Sweden.

Magnusson, P., Sheng, C., 2018. “STUDSVIK-SCIP III-227, Integral LOCA test to study fuel fragmentation of the high burnup and low last cycle local power fuel rod VUR1,” Studsvik Nuclear AB, Sweden.

Magnusson, P., 2017. “STUDSVIK-SCIP III-209, Integral LOCA test to study fuel fragmentation of the high burnup fuel rod 3V5-Q13,”Studsvik Nuclear AB, Nykoping, Sweden.

Magnusson, P., et al., 2020. “STUDSVIK-SCIP III-253—Subtask 1.1: Fuel fragmentation, relocation and dispersal, Final Summary Report,”Studsvik Nuclear AB, Nykoping, Sweden.

Magnusson, P., Sheng, C., 2017. “STUDSVIK-SCIP III-214, Integral LOCA test to study fuel fragmentation of the high burnup fuel rod R2D5-LOCA1,” Studsvik Nuclear AB, Sweden.

Mileshina, L. and P. Magnusson, 2019a. “STUDSVIK-SCIP III-230, Integral LOCA test to study effect of pressure on fuel fragmentation: VUL2 LOCA3,” Studsvik Nuclear AB, Sweden.

Mileshina, L. and P. Magnusson, 2019b. “STUDSVIK-SCIP III-235, Integral LOCA test to study burnup threshold on fuel fragmentation: 09-OL1L04 LOCA2,” Studsvik Nuclear AB, Sweden.

Mileshina, L. and P. Magnusson, 2019c. “STUDSVIK-SCIP III-240, Integral LOCA test to study burnup threshold on fuel fragmentation: WZR0067 LOCA1,” Studsvik Nuclear AB, Sweden.

Mileshina, L. ,and P. Magnusson, 2019d. “STUDSVIK-SCIP III-232, Integral LOCA test to study effect of pressure on fuel fragmentation: VUL2 LOCA4,” Studsvik Nuclear AB, Sweden.

Mileshina, L. and P. Magnusson, 2019e. “STUDSVIK-SCIP III-241, Integral LOCA counterpart test on rodlets from fuel rod 36U-N05,” Studsvik Nuclear AB, Sweden.

Mileshina, L. and P. Magnusson, 2018. “STUDSVIK-SCIP III-216, Integral LOCA test to study cladding strain and non-depressurization effects on fuel fragmentation: R2D5 LOCA3,” Studsvik Nuclear AB.

Mileshina, L., Tejland, P., Magnusson, P., 2019. “STUDSVIK-SCIP III-254, Integral LOCA test to study effect of plenum gas volume on fuel fragmentation: 09-VUR1 LOCA2,” Studsvik Nuclear AB, Sweden.

U.S. Nuclear Regulatory Commission, 2013. NUREG-2160, “Post-Test Examination Results from Integral, High-Burnup, Fueled LOCA Tests at Studsvik Nuclear Laboratory,” Washington, DC, August 2013. (ADAMS Accession No. ML13240A256)

Wiesenack, W., 2013. “HRP-380, Summary of the Halden Reactor Project LOCA Test Series IFA-650,” Halden Reactor Project, Halden, Norway.

Wiesenack, W., 2015. “HPR-383, Summary and Comparison of LOCA Tests with BWR Fuel in the Halden Reator Project Test Series IFA-650,” Halden Reactor Project, Halden, Norway.

Yueh, K., N. Snis, D. Mitchell, C. Munoz-Reja, 2014. “Fuel fragmentation data review and separate effects testing,” *Proceedings of the 2014 Water Reactor Fuel Performance Meeting*, Sendai, Japan.

Appendix B
Summary of Peer Review Comments and Resolution

An external peer review group participated in the development of this research information letter (RIL). The peer reviewers were selected based on their expertise related to fuel fragmentation, relocation, and dispersal (FFRD) phenomena and familiarity with the research captured in the RIL. The reviewers included the following experts:

- Nathan Capps, Oak Ridge National Laboratory
- Tatiana Taurines, Institut de radioprotection et de sûreté nucléaire, France
- Fabiola Cappia, Idaho National Laboratory
- Ken Yueh, Electric Power Research Institute
- Daniel Jädernäs, Studsvik Nuclear AB

The following summarizes the comments received from the peer review group, as well as how they were resolved.

Abstract

- Reviewers offered edits for clarity.
- Edits were made to reflect changes resulting from reviewer comments made in other sections of the RIL.

Introduction

- Reviewers offered edits for clarity.
- Edits were made to reflect changes resulting from reviewer comments made in other sections of the RIL.

Motivation for This Research Information Letter

- Reviewers requested specificity of the burnup values referenced (i.e., rod average, pellet average) in multiple statements within the section. Edits were made.
- Reviewers requested clarification of the five elements addressed by the RIL. Edits were made here, consistent with changes resulting from reviewer comments made in other sections of the RIL.
- *Specific comment:* "Is the packing fraction described in the RIL applicable to fuel that may accumulate outside of the balloon region, for example, on the grid spacers?" *Reply:* The basis for the limit discussed in the RIL has considered only the packing fraction in the balloon region. It should not be interpreted to be applicable for any other situation.

Experimental Programs Considered in This Research Information Letter

- Reviewers noted statements that deserved more specificity or clarification. Edits were made.
- Reviewers pointed to analysis of fuel temperatures during Halden and Studsvik LOCA testing that suggest the experimental setups in the two programs result in similar fuel

temperatures during the LOCA heatup stage. The RIL now references a recent report where supporting analysis was documented.

Definitions and Terms

- This is a new section that defines many terms of art used throughout the RIL. Many of these terms are unique to this RIL (i.e., not yet defined elsewhere or commonly used within the nuclear fuel community). Adding this section addressed a number of comments from reviewers throughout the RIL.
- Reviewers commented that the RIL effectively equates pellet average and segment average burnups in that the empirical limits (stated as pellet average) are based on segment average data and that this should be stated clearly. Discussion of various burnup characteristics was added by defining rod average, segment average, and pellet average burnup.

Element 1 - Establish an empirical threshold at which fuel pellets become susceptible to fine fragmentation.

- Reviewers noted statements that deserved more specificity or clarification. Edits were made.
- Reviewers commented that the definition of this element as a “burnup threshold” is too prescriptive and narrow in scope. The RIL already acknowledged that burnup is not likely to be the only parameter influencing fine fragmentation, even while the empirical threshold offered in the RIL is a function only of burnup based on today’s state of knowledge. This comment was accepted. Reviewers also commented that the possibility that there is also a temperature threshold should be acknowledged. This comment was not accepted in the discussion of Element 1; however, the authors addressed it in the “Limitations of the Empirical Database” section later in the RIL.
- Reviewers suggested that the RIL specify the basis for examining the mass of fuel fragments smaller than 1 and 2 millimeters. Text was added to explain that these size categories were considered for their indication of trends with burnup.

Element 2 - Establish a local cladding strain threshold below which fuel relocation is limited.

- Reviewers noted that the impact of local cladding strain might be different when considering fuel fragmentation and fuel relocation, specifically that the threshold for fragmentation is probably lower than that of relocation. Further, the comments throughout the section suggest that information may not be precise enough to say how extensive fragmentation is at low strain—researchers can know something about fragmentation only for fuel that also relocated. Edits were made to reflect these comments, limiting the discussion in this section to define only a strain threshold for relocation but not fragmentation. A large amount of text was removed from this section.

Element 3 - Examine experimental results of the mass of “dispersible” fuel as a function of burnup

- Reviewers suggested stating, “Cladding restraint and burst size impact fuel dispersal as indicated in Appendix A. Applicants may offer approaches and additional experimental [evidence] to reduce or minimize mobile fuel through their licensing application." This comment was not accepted. Related guidance not yet developed could include this type of discussion; however, it is not within the scope of this RIL.

- Reviewers questioned the position in the RIL that a fuel dispersal model assume all "mobile" fuel can disperse, commenting that the mechanisms for dispersal of *all* mobile fuel should be further explored (and in doing so, likely conclude that the position is overly conservative). The reviewers offered valid reasons why this limit may be overly conservative. Nevertheless, the authors continue to take a conservative position on this element, while discussing the conservatism in Appendix A.
- *Specific comment:* "The amount of fuel dispersal should be limited to within the burst spans." *Reply:* This is a reasonable conclusion that could be reached through the application of the strain threshold offered in the RIL; however, this connection cannot be made based on the research results discussed in the letter.
- Reviewers commented that the U.S. Nuclear Regulatory Commission's (NRC's) loss-of-coolant accident (LOCA) testing at the Studsvik Nuclear Laboratory represents conservative behavior. While the NRC's LOCA test results do have higher values with respect to burst opening, balloon strain, and fragmented fuel than those from most other test programs, no specific hypothesis has been formulated that would point to these tests being more conservative than other test programs or overly conservative generally. No changes were made.

<u>Element 4 - Provide evidence of significant tFGR that may impact ballooning and burst behavior of high burnup fuel under LOCA conditions.</u>

- Reviewers noted statements that deserved more specificity or clarification. Edits were made.
- Reviewers pointed to experimental evidence that transient fission gas release (tFGR) may not be directly related to fuel fragmentation. Edits were made to reflect these comments.
- Reviewers noted that there is little evidence to support burnup or cladding strain thresholds for tFGR. This comment was accepted, and edits were made to remove references to these thresholds. The title of this element was also modified to better reflect changes made to the section based on reviewer comments.
- Reviewers commented that the mechanism behind tFGR is unclear. This comment was accepted. Edits were made to remove discussion of the mechanism of tFGR and to focus more on observed trends (without explaining the mechanism behind the trends).

<u>Element 5 - Establish the basis for a range of packing fractions of relocated but nondispersed fuel in the balloon region.</u>

- Reviewers noted statements that deserved more specificity or clarification. Edits were made.
- Reviewers suggested that the RIL should discuss the packing fraction of fuel dispersed from the rod (e.g., on spacer grids). This comment was not accepted because transport of fragments within the reactor coolant system is outside of the scope of the RIL.

- Reviewers commented that packing fraction would impact only peak cladding temperature (PCT), which should already be covered by existing LOCA evaluation models required by Title 10 of the *Code of Federal Regulations* 50.46, “Acceptance criteria for emergency core cooling systems for light-water nuclear power reactors.” It is true that existing evaluation models should account for packing fraction because this phenomenon has been known for some time. However, this discussion is outside the scope of the RIL. Furthermore, the staff disagrees that packing fraction would impact only PCT. Results from a relocation model implemented in the Fuel Rod Analysis Program Transient (FRAPTRAN) code by Quantum Technologies (Sweden) show differences in cladding temperature and ballooning behavior before burst compared to results without the relocation model active, thus demonstrating that the relocation and fuel packing fraction influence more than just PCT.
- Reviewers suggested removing references to low and high gap conductivity for cases without and with fuel relocation in Figure 9. This comment was not accepted.
- Reviewers pointed out that packing fraction was estimated for some Halden Reactor Program tests. A sentence was added to present Halden estimations for packing fraction.
- Reviewers commented on whether self-shielding would significantly impact gamma scan—and thus packing fraction—results. Studsvik Cladding Integrity Program (SCIP) reports do not discuss whether ignoring self-shielding is an appropriate assumption. A sentence was added to state that more work is needed to evaluate the assumptions used to calculation packing fraction.
- Reviewers asked for clarification of how the axial distribution of packing fraction in Figure 12 relates to single values of the packing fraction cited for the various tests. This comment was accepted, and discussion was added about the particular test shown in Figure 12.
- Reviewers pointed to recently published discrete element modeling work on packing fraction. The RIL now references this work. In general, the discrete element model results are in good agreement with the SCIP data and help explain the trend in packing fraction increasing with burnup.
- Reviewers asked for clarification of the appropriate range of packing fractions and pointed out that many tests showed results as low as 60 percent (compared to the lower bound of 70 percent mentioned in the RIL). Edits were made to note that 60-percent packing fractions were observed for lower burnup fuel, consistent with discrete element modeling results for cases with larger fuel fragments.
- Reviewers asked how one would trigger relocation in a computer code and whether the impact of packing fraction on various phenomena (e.g., gap conductivity) can be adequately captured by existing models. This is outside the scope of the RIL. However, the staff notes that at least one model for relocation has been proposed and implemented in FRAPTRAN that accounts for many of the relevant phenomena. This model seems to produce good results compared to a single Halden test, but much more validation work is needed.

Prototypicality and Representativeness of Empirical Database

- Reviewers offered edits for clarity.

Discussion of Consequences and Consequence Modeling

- No comments

Limitations of the Empirical Database

- The RIL states that while evidence suggests that there is a temperature threshold for fragmentation (in addition to a burnup threshold), at this time, the authors do not consider the available information sufficient to offer such a threshold in the RIL. Reviewers expressed reservations about this conclusion. The comments were considered, but no change was made.
- Reviewers commented that the discussion of the state of knowledge on ballooning models, including models to predict burst opening size, was incomplete. Edits were made to incorporate specific comments. In addition, the RIL now references a recent effort to develop a burst opening model.

Summary and Conclusions

- Reviewers reiterated comments made in Element 5. Conforming changes were made in the summary and conclusions.

Appendix A—A Model for Predicting Dispersal

- Reviewers noted that the basis for concluding that fuel dispersal during the experiments may not be conservative because, in a design-basis LOCA, external forces not simulated in the tests may be acting on the fuel (resulting in greater dispersal than observed during these experiments). The authors acknowledge that the staff's observations related to this may be overly conservative. Nevertheless, considering the unknowns in modeling a LOCA, the authors continue to maintain its validity given the information that is currently available.