Mr. Daniel H. Dorman  
Executive Director for Operations  
U.S. Nuclear Regulatory Commission  
Washington, DC  20555-0001  

SUBJECT: RESEARCH INFORMATION LETTER (RIL) 2021-13 ON INTERPRETATION OF RESEARCH ON FUEL FRAGMENTATION, RELOCATION, AND DISPERsal AT HIGH BURNUP  

Dear Mr. Dorman:  

During the 691st meeting of the Advisory Committee on Reactor Safeguards (ACRS), November 30 - December 2, 2021, we completed our review of the Research Information Letter (RIL) for fuel fragmentation, relocation, and dispersal (FFRD) during a loss-of-coolant accident (LOCA). Our Metallurgy and Reactor Fuels Subcommittee reviewed this topic on November 17, 2021. During these meetings, we had the benefit of discussions with the U.S. Nuclear Regulatory Commission (NRC) Research staff. We also had the benefit of the referenced documents.  

CONCLUSIONS AND RECOMMENDATIONS  

1. The current data set on FFRD has been expanded. However, there remains a significant degree of uncertainty in large part because the problem is multivariate and the experiments from which the data were developed did not always represent actual light water reactor (LWR) conditions. Our letter suggests a number of cautions that should be considered when applying this RIL. They are described in detail in our final thoughts section.  

2. The staff recognized, and we agree, that this document would benefit from additional context by identifying the entire scope necessary to resolve the safety issues related to FFRD and describing the role of the RIL as a specific piece of that overall scope.  

3. A risk informed approach should be undertaken that examines both the likelihood of expected event conditions combined with a more complete modeling evaluation of FFRD consequences. This activity could add substantial value to future research program development and to the regulatory decision-making process.
BACKGROUND

The RIL evaluates the publicly available experimental data related to fuel fragmentation, relocation, and dispersal at high burnup during a loss-of-coolant accident (LOCA) and is an update to LOCA research that has been ongoing for over 40 years. It began with study of cladding embrittlement and performance during a LOCA and has evolved to include fuel fragmentation and dispersal at high burnup. Several documents related to this topic have been published. These include:

2. RIL-0801, “Technical Basis for Revision of Embrittlement Criteria in 10 CFR 50.46,” May 2008,
3. NUREG-2121, “Fuel Fragmentation, Relocation, and Dispersal during the Loss-of-Coolant Accident,” March 2012,

The NRC’s current research studies on FFRD seek to gain a better understanding of fuel performance, under LOCA conditions, in particular for fuel with burnup greater than the current license limit of approximately 62 GWh/MTU. The RIL’s purpose is to provide a current assessment of the results of the latest experimental programs on FFRD and to suggest conservative, empirical thresholds for FFRD-related phenomena.

It is intended that the RIL will serve as a foundation for the next steps in evaluating the effects of FFRD on LOCA performance at high burnup, which may include developing regulatory guidance.

DISCUSSION

The goal of the analysis performed by the Office of Nuclear Regulatory Research staff was to provide important and timely interpretations of a complex technical issue regarding high burnup fuel behavior during a LOCA. To this end the staff sponsored or participated in experimental programs to determine the potential impacts of FFRD on fuel performance at and beyond the current approved limits. These include the Studsvik Cladding Integrity Program (SCIP)-III research conducted at U.S. National Laboratories and the Halden reactor. Experimental results from the literature as well as other international laboratories were also included. The results of the analysis:

1. Suggest an empirical threshold at which fuel pellets become susceptible to fine fragmentation.
2. Identify a local cladding strain threshold above which fuel relocation becomes a concern as a result of a LOCA.

3. Provide a conservative estimate for the mass fraction of “dispersible” fuel as a function of burnup.

4. Provide an estimate for a range of packing fractions of relocated but nondispersed fuel in the balloon region that may affect heat transfer.

5. Evaluate the potential for significant transient Fission Gas Release (tFGR) that may impact ballooning and burst behavior of high-burnup fuel under LOCA conditions.

**Studsvik LOCA Accident Testing**

From 2009 through 2011, NRC sponsored LOCA accident testing experiments at Studsvik Nuclear Laboratory in Sweden. The experimental program included:

1. Six single-rodlet integral LOCA tests,

2. Four rodlets with segment burnup ranging from 72 to 78 GWd/MTU, and

3. Two rodlets with segment burnup around 60 GWd/MTU.

The pressurized, high-burnup, fueled rod segments were subjected to a temperature transient in a steam environment to induce ballooning, burst, and high-temperature steam oxidation. However, the rodlets were not subject to nuclear heating. The tests were conducted in a hot-cell facility. A 30-cm rodlet was externally heated using an infrared furnace in a flowing steam environment from 300 degrees Centigrade (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 bounded a typical end-of-life rod to induce ballooning and burst, with burst hoop strains in the range of 25 to 55 percent (%).

After the LOCA simulation, the rods were subjected to four-point bend tests to measure the residual mechanical behavior of the ballooned and burst region. Subsequently, a “shake test” determined the mobility of fuel fragments that remained within the fuel rod.

**Studsvik Cladding Integrity Programs (SCIP)**

The NRC also participated in the SCIP-III program. Some of the SCIP-III tests used the same equipment built for the earlier NRC-sponsored work, while other tests used a newly designed test device with similar features. The SCIP-III project generated 18 test results similar to the six NRC-sponsored tests, to further evaluate how various parameters including fuel burnup and microstructure, cladding strain, temperature, internal gas pressure and gas flow at the time of burst, and magnitude of tFGR effect FFRD. The experimental methods developed in the third phase of the SCIP-III are continuing to be used in the SCIP-IV international research project. NRC remains a participant in the project.

**Oak Ridge National Laboratory (ORNL)**

In 2019, three hot-cell integral LOCA tests were conducted in the Severe Accident Test Station at ORNL. 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. Experimental methods were comparable to those used at Studsvik. Following the LOCA simulation, fuel fragments were shaken out of the rods and examined to determine the particle size distribution.

Halden Reactor Project

Thirteen LOCA tests were conducted with segments of fuel rods irradiated in commercial power reactors. Seven tests were on pressurized water reactor (PWR) fuel rodlets (IFA-650.3/4/5/9/10/15/16), four tests were on boiling water reactor (BWR) fuel rodlets (IFA-650.7/12/13/14), and two tests were on Russian VVER reactor fuel rodlets (IFA-650.6/11). Rodlet burnup values ranged from 44 to 92 GWd/MTU. Heatup rates varied from 2 to 6 degrees C per second. For some cases, heater power was slightly adjusted during the transient to obtain the desired target peak cladding temperature (PCT). The overall range of PCT for the test series was from 800 to 1,200 degrees C. A key difference between the Halden and other tests is that, in the Halden tests, nuclear heating was used.

The results of the Halden tests exhibited considerable variability. For example, Halden LOCA test IFA-650.14 was subjected to more prototypical LOCA conditions but did not burst. However, significant tFGR (18.6%) was observed during the test.

Axial fuel relocation and packing were observed during test IFA-650.9 in a high-burnup PWR rod when subjected to LOCA conditions. Post-test gamma scans showed that 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.

The results of the Halden tests suggest that it is not clear whether tests using rodlets and a furnace are truly conservative or comparable relative to in-pile LOCA conditions.

General Results-Discussion

The results of the staff's analysis for the experimental conditions of the data base suggested that FFRD manifests itself in regions of the core with the following specific characteristics:

1. It appears that fine fragmentation is limited to regions with burnups above 55 GWd/MTU pellet average burnup.

2. Axial fuel relocation was observed in regions of the fuel rod with a local cladding strain greater than 3%. Relocated fuel fragments could occupy between 60% and 85% of the fuel rod cross-sectional area in the balloon region. The propensity for fuel dispersal was correlated with fuel fragment size and burst opening size. However, cladding burst and fuel relocation were prerequisites.

3. The data suggest 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.

The above observations provided the bases for the staff to suggest that FFRD should be evaluated at rod average burnup limits below the current limit of 62 GWd/MTU. Moreover, the RIL provided suggestions for models that should be considered in such an evaluation. The staff proposed a conservative approach to FFRD. Fuel fragmentation should be assumed for rods that exceed burnups of 55 GWd/MTU. The subsequent potential for relocation and dispersal
should be assessed once a calculated cladding strain of 3% is reached during the LOCA. The staff acknowledges that the model uncertainty is high given limited data but may be considered reasonably conservative for this data set.

The staff also questioned whether the publicly available experiments adequately represent the conditions affecting FFRD in the design basis LOCA event and whether these experimental results are truly conservative. External peer review group members suggested that this concern was not warranted. However, the staff concludes that much uncertainty in performance data and modeling remains.

**Final Thoughts on Future Work**

A number of cautions should be considered going forward:

1. The conditions of the experiments often differed significantly from conditions that would exist at PWR operating conditions. Depending on the specific test, key variables that were not always prototypic include: linear heat generation rate (low), terminal temperature (high) and heatup rate (low).

2. The fuel/thermal variables influencing fragmentation and relocation phenomena are many. While fuel burnup is easily calculated, and verified by measurement, the cladding strain must be calculated - a calculation fraught with uncertainty. Fuel pellet cracking occurs almost immediately on initial startup. The evolution of fuel microstructure during burnup, including the rim, also introduces uncertainty.

3. Operational variables, including flow-induced vibration (normal and accident) can strongly influence the fragmentation and relocation process as well as dispersal after cladding breach.

4. It is one thing to determine an observed burnup at which fuel fragmentation begins to occur. In this case, it is essential to determine the difference between conditions of a test/examination and the conditions that would exist under actual operating conditions. A careful evaluation of uncertainty will be key. It is quite another thing to determine the point at which FFRD actually influences LOCA performance. The RIL made no claims in this area, one that is critical to determination of practical consequences. There are a number of experimental programs that will produce data that more closely approach PWR conditions including the TREAT tests. These results will likely provide more prototypic data and hence reduce uncertainty.

5. Lastly, the larger picture should be considered. The document would benefit from additional context by identifying the entire scope necessary to resolve the safety issues related to FFRD and describing the role of the RIL as a specific piece of that overall scope. Because this RIL suggests a numerical threshold burnup for the onset of fragmentation that is different than that used presently for licensing actions, the document should identify the purpose for transmitting this different burnup limit to the Office of Nuclear Reactor Regulation and identify plans to provide additional information relative to its potential impact on any future regulatory activity.

Additional experimental programs and data sets that examine a broader range of transient conditions and fuel types are important to resolve these remaining uncertainties and address these cautions. In addition, we recommend a risk-informed approach be undertaken that examines both the likelihood of expected event conditions
combined with a more complete modeling evaluation of FFRD consequences. This activity could add substantial value to future research program development and to the regulatory decision-making process.

We look forward to the results of additional tests (SCIP-IV, TREAT) that will shed further light on the FFRD phenomena and its likely effect on fuel performance under LOCA conditions at high burnup.

Member Rempe recused herself from the deliberation of RIL 2021-13.

Sincerely,

Matthew W. Sunseri, Chairman

REFERENCES


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