POLICY ISSUE
(Information)

November 30, 2015 SECY-15-0148

FOR: The Commissioners

FROM: Victor M. McCree
Executive Director for Operations

SUBJECT: 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)

PURPOSE:

The purpose of this SECY paper is to respond to direction in Staff Requirements Memorandum (SRM)-SECY-12-0034, "Proposed Rulemaking—10 CFR 50.46c: Emergency Core Cooling System (ECCS) Performance during Loss-of-Coolant Accidents (LOCA)," dated January 7, 2013. Specifically, this SECY paper provides the staff's evaluation of fuel fragmentation, relocation, and dispersal (FFRD) under LOCA conditions as it relates to the draft final rule on ECCS performance during a LOCA (i.e., the § 50.46c rulemaking). The staff has concluded that the § 50.46c final rule may proceed without incorporation of regulatory requirements to address FFRD.

SUMMARY:

The staff has completed additional research on fuel fragmentation, relocation, and dispersal and has determined that the draft final rule should not include a new requirement related to these phenomena. This decision was made based on the staff's understanding of FFRD phenomena, considerations of current operating practices and modern fuel design. In addition, the staff's perspective on the relationship of the FFRD phenomena with ECCS requirements influenced the decision. The staff will continue efforts to quantitatively evaluate these phenomena and will remain engaged in international cooperative research programs that are providing additional insights.

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BACKGROUND:

On March 1, 2012, the staff issued SECY-12-0034 to obtain Commission approval to publish for public comment a proposed rule that would amend the U.S. Nuclear Regulatory Commission's (NRC) current requirements governing ECCS, which are set forth in Title 10 of the Code of Federal Regulations (10 CFR), Section 50.46. The proposed rule included new requirements to address a research finding that zirconium-based fuel cladding materials could embrittle at a lower combination of temperature and level of oxygen absorption than allowed under the current regulations. The proposed rule was determined to be necessary to ensure adequate protection of public health and safety by restoring that level of protection which the NRC thought would be achieved by the current regulations. The staff recognized that finalization and implementation of the new ECCS requirements would take several years and therefore the staff completed a detailed safety assessment to confirm safe operation relative to the new embrittlement research findings (Agencywide Documents Access and Management System (ADAMS) Accession No. ML12041A078). The staff was able to confirm current safe operation for every operating power reactor and the staff will verify continued safe operation on an annual basis until each licensee has implemented the new ECCS requirements[1].

In SECY-12-0034, the staff also provided information related to an emerging research finding that high burnup fuel pellets could fragment, relocate axially and possibly disperse outside of the fuel rod during postulated design-basis accidents including, but not limited to, LOCA. In March 2012, the staff did not have a sufficient technical basis for concluding whether and in what manner these phenomena should be addressed. The staff recommended that the proposed rule not be delayed to await resolution of the emerging FFRD issue because the revised requirements outlined in the proposed rule were necessary to ensure adequate protection of public health and safety.

The Commission provided a response to SECY-12-0034 in SRM-SECY-12-0034, which included direction to the NRC staff to complete its research on FFRD and incorporate any necessary changes before requesting Commission approval of the draft final rule. If the staff determined that this action was not practicable or had unintended consequences, the SRM instructed the staff to provide an information paper to the Commission containing additional details of the anticipated research on fuel fragmentation, the staff's best judgment of the impact the results of that research could have on the proposed rule, and the staff's best estimate of when final conclusions may be drawn from this work. In addition, this paper should clearly and specifically indicate which elements of the proposed rule, if any, should be deferred pending completion of fragmentation research and which elements, if any, could proceed to implementation without concern that they will be revised based on the anticipated research.

The staff's understanding of FFRD phenomena has advanced significantly since March 2012. The staff's efforts and conclusions are summarized in this paper. In response to SRM-SECY-12-0034, the staff has determined that inclusion of requirements related to FFRD in the draft final § 50.46c rule is not practicable, nor is it appropriate. The staff has determined that the draft final § 50.46c rule, in its entirety, can proceed to implementation without concern that any

[1] The final rule is due to the Commission in February 2016. The draft final rule language would require licensees to submit a plan for implementation within 6 months of the effective date of the rule.

element will be revised based on the anticipated research. The bases of the staff's conclusions are described below.

DISCUSSION:

Research Efforts Completed Since 2012

Throughout 2013, NRC staff collaborated with staff at the Halden Reactor Project, Kjeller Hot-Cell Laboratory, and Studsvik Hot Cell Laboratory to perform a comprehensive reassessment of examinations and observations from previous LOCA experiments. In addition, the NRC sponsored a small set of targeted new examinations to investigate emerging questions. The Halden Reactor Project and the Studsvik Cladding Integrity Project also continued to produce new data under the direction of their respective program review groups.

As a result of the reassessment of the previously available experimental results, combined with the new experimental observations available since 2012, the staff has developed a set of empirical thresholds for each phenomenon. Experimental results indicate that fine fuel fragmentation will be limited to high burnup rods and that fuel relocation will be limited to the region near the fuel rod rupture. Experimental results suggest that fine fragments from high burnup rods can easily disperse from ruptured rods during a LOCA, while larger fragments from lower burnup rods will not easily disperse from ruptured rods. The experimental results have continued to support the hypothesis that FFRD phenomena are primarily a high burnup fuel issue and that the current licensing limits in the U.S. are adequate to prevent dispersal of large quantities of fine fuel fragments.

The staff has also made large advances in analytical capabilities since 2012. The staff developed a methodology that coupled the NRC's fuel performance codes, FRAPCON and FRAPTRAN, with the NRC's reactor systems thermal-hydraulic code, TRACE, to provide quantitative insight into the amount of fuel dispersal that could occur under postulated LOCA conditions. The methodology made it possible to calculate the number of rods predicted to rupture in a postulated LOCA, and most importantly, to discern the number of first, second and third cycle rods predicted to rupture. The calculations showed that when fuel rod ruptures were predicted, they were predominantly in the high-power, low-burnup first and second cycle fuel rods. This information, combined with the empirical thresholds on fragmentation size as a function of burnup and fuel relocation propensity, allowed the staff to estimate dispersed fuel mass for several postulated LOCA scenarios and for three different plant types. The estimates of dispersed fuel mass were relatively small for the scenarios investigated. However, the calculations revealed that the estimates of dispersed fuel mass are closely related to assumptions on how high-burnup fuel is operated; namely, the assumption that high burnup fuel is operated at significantly lower power than lower burnup fuel. The calculations also indicate that during a postulated large break LOCA fuel cladding rupture of low burnup, high power rods, which are not vulnerable to FFRD, may occur early in the transient. Therefore, preventing or minimizing the degree of fuel cladding rupture as a means to prevent or minimize fuel dispersal could require highly conservative limits during normal operation for rods that are not susceptible to fine fuel fragmentation and dispersal.

The staff presented the experimental and analytical research efforts described above to the Advisory Committee on Reactor Safeguards (ACRS) Materials, Metallurgy, and Reactor Fuels

Subcommittee's meeting on fuel dispersal, on December 4, 2013 (ADAMS Accession No. ML13356A004). The ACRS expressed interest in being updated on the staff's progress on FFRD, but did not issue a letter or make any specific recommendations to the staff.

Current State-of-Knowledge

On March 13 and 14, 2014, the NRC held a public meeting to discuss and exchange information on experimental and analytical research on FFRD. The purpose of the public meeting was to discuss fuel research programs and findings. During the meeting, presentations were made by NRC staff, international research organizations and fuel vendors. The presentations fell generally into three categories: (1) presentations covering details of experimental results from research programs related to FFRD, (2) presentations covering details of analytical studies to estimate fuel dispersal, and (3) presentations on various perspectives of these research findings. There were multiple opportunities for the public to ask questions, provide comments, and give feedback on the topics been discussed. After each category of presentation, an open discussion session provided an opportunity for the NRC staff, panelists, and meeting participants to engage in discussion. The perspectives communicated by representatives of the U.S. industry, international regulatory bodies, international research organizations, public citizens, and NRC staff were relatively consistent: FFRD under LOCA conditions need to be better understood, and research should continue, but the results to date do not indicate there is a need for immediate regulatory action because current fuel design and operating practices result in estimates of fuel dispersal under LOCA conditions that are minimal. The public meeting summary can be found in ADAMS at ML14100A131.

On May 20 and 21, 2015, NRC staff participated in an international workshop on FFRD under LOCA conditions that was jointly organized by the Halden Reactor Project and the Working Group on Fuel Safety of the Nuclear Energy Agency, Organisation for Economic Co-operation and Development (NEA/OECD). Roughly 90 participants from around the world attended the workshop. The workshop was divided into four sessions, each hosted by a subject matter expert, on the topics of experimental evidence, modeling, implications of FFRD, and future experiments. Again, the perspectives communicated by representatives of the U.S. industry, international regulatory bodies, international research organizations, and NRC staff were relatively consistent: fragmentation, relocation, and dispersal of fuel under LOCA conditions need to be better understood and research should continue, but the results to date do not indicate there is a need for immediate regulatory action. The NEA/OECD is expected to issue a technical report that consolidates the abstracts and papers presented at the workshop in the next few months.

The experimental programs in which FFRD phenomenon are being studied are focused on fuel behavior under LOCA conditions. However, the current state-of-knowledge indicates that FFRD is not necessarily limited to LOCA and could occur during non-LOCA design-basis events in which fuel rod ruptures are predicted to occur. Any future regulatory action, if needed, should be developed to ensure safety in these non-LOCA scenarios as well. Because the reactor coolant pressure boundary remains intact during postulated non-LOCA design-basis accidents, the population of fuel rods susceptible to rupture, and therefore susceptible to fuel dispersal, is significantly smaller.

Prompted by the staff's understanding that FFRD may not necessarily be limited to LOCA, the staff completed a safety assessment on the potential impact of FFRD on accident progression, safety-related system performance, and radiological consequences during the following postulated design basis accidents (DBAs): main steam line break accident, reactor coolant pump locked rotor accident, control rod ejection accident, and control rod drop accident. The staff reviewed the Updated Final Safety Analysis Report for each operating power plant to collect information on the predicted core damage, core damage assumed in dose calculations, predicted onsite and offsite dose consequences and allowable onsite and offsite dose consequences for each of these DBAs. For each DBA, the safety assessment documented the number of fuel rods susceptible to fragmentation and dispersal and used this information to assess the safety margin to relevant criteria (e.g., dose, reactor coolant system integrity). The safety assessment provides reasonable assurance that the amount of fuel dispersal during these postulated accidents would be insignificant and radiological consequences would remain below applicable limits.

The research and assessments completed to date indicate that near-term regulatory action is not needed to address FFRD phenomena at this time. However, this conclusion is closely linked with current fuel design limits and assumptions on how high-burnup fuel is operated. Fuel assembly designs, materials, and manufacturing processing continue to change to meet the needs of the industry. For example, the industry has submitted multiple fuel vendor topical reports requesting review and approval of fuel designs with fuel additives designed to mitigate the impact of pellet-cladding interaction and fission gas release during normal operation. It is not clear if fuel additives would change the empirical threshold on fragmentation size as a function of burnup. In addition, licensees are operating fuel under more demanding conditions (e.g., longer cycles, higher fuel burnup). For example, the industry has submitted fuel vendor topical reports requesting review and approval of extended fuel burnups beyond 62 gigawatt-days per metric ton of uranium (GWd/MTU) rod average. Research has shown that as burnup exceeds 62 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.

The research findings available to date indicate that certain changes in fuel design and plant operations can increase the number of ruptured rods or impact fuel fragmentation behavior, and thus could have an adverse impact with respect to FFRD phenomena. Ongoing international research is largely focused on identifying which fuel design and fuel utilization variables control FFRD behavior. In particular, two ongoing research programs, the Halden Reactor Project and the Studsvik Cladding Integrity Project, are expected to produce insights on the controlling fuel design variables for FFRD over the next few years. The NRC staff is actively influencing these programs and will evaluate the information as it becomes available.

Potential Safety Concerns

Qualified core physics, fuel performance, thermal-hydraulic, and reactor systems' analytical models are used to simulate postulated DBAs and demonstrate that mitigating actions from safety-related Reactor Protection System and Engineered Safety Feature Actuation System functions limit fuel damage (e.g., ballooning of cladding), preserve a coolable geometry, and ensure acceptable consequences. These performance demonstrations are based on a known core configuration (i.e., fuel stack within cladding, rods within bundle array). FFRD may introduce uncertainty and analytical complexity into the performance demonstration, may alter the accident progression, and may impact the performance of these safety-related systems, structures, and components (SSCs).

High enthalpy fuel particles dispersed into the reactor coolant will rapidly release their stored energy. The rate of release depends on many factors including particle size distribution and coolant quality. This fuel-coolant interaction generates steam resulting in a pressure pulse which may challenge the integrity of the fuel bundle, reactor internals, and reactor coolant system (RCS) pressure boundary. In addition, any rapid infusion of thermal energy into the reactor coolant will alter local thermal-hydraulic conditions (e.g., impacting “departure from nucleate boiling ratio” calculations) and may affect the overall accident progression.

Non-LOCA DBA radiological consequences employ explicit source terms based on accident progression, mitigating actions of safety-related SSCs, and estimated fuel damage. Fragmentation-induced fission gas release introduces a new component to the accident source term (beyond the pre-existing gap inventory). This additional component potentially increases the source term which may promote higher on-site and off-site dose. In addition, dispersed and deposited fuel particles may create local radiological “hot spots” within the RCS, containment, and shutdown cooling system which may impact operability of instrumentation and cables important to accident mitigation and post-accident monitoring.

Finally, the performance demonstration would need to address the long-term decay heat removal of both the intact portion of the core and the dispersed fuel particles. Fuel transport and deposition depend on many variables including fuel particle size distribution, coolant mass flow, and geometry. Due to uncertainties related to predicting quantity, location, and geometry of dispersed and deposited fuel particles, demonstrating long-term decay heat removal becomes significantly more complex.

Bases for Not Including New Requirements on Fuel Dispersal within 50.46c Rulemaking

The staff has determined that inclusion of requirements related to FFRD in the draft final § 50.46c rule is not practicable, nor is it appropriate. The staff believes that no elements of the draft final rule should be deferred pending completion of FFRD research and that all elements should proceed to implementation without concern that they will be revised based on the anticipated research. The bases for the staff’s conclusion are provided below.

- Research and analyses provide reasonable assurance that no imminent safety concern exists with operating reactors.

- The current state-of-knowledge indicates that FFRD is not necessarily limited to LOCA and could occur during non-LOCA design-basis events in which fuel rod ruptures are predicted to occur. Any future regulatory action, if needed, should be developed in a holistic manner to address both LOCA and non-LOCA scenarios. Therefore, it would not be appropriate to address FFRD in a fragmented way by adding requirements to prevent FFRD in LOCA scenarios in § 50.46c and adding requirements to prevent FFRD in non-LOCA events elsewhere.

- Regulations proposed in the draft final 10 CFR 50.46c rulemaking define ECCS performance requirements. During a postulated large break LOCA, fuel cladding rupture may occur early in the transient. Requirements for ECCS performance to prevent or minimize the degree of fuel cladding rupture as a means to prevent or minimize fuel dispersal would likely not be practical. However, fuel performance requirements could be developed as part of a separate regulatory effort to focus on preventing rupture in rods susceptible to fine fuel fragmentation, and therefore susceptible to fuel dispersal, while avoiding unnecessary restrictions on rods that are not susceptible to fine fuel fragmentation. Establishing this boundary condition (i.e. no rupture of fuel rods susceptible to fine fuel fragmentation) addresses one of the Commission's concerns in SRM-SECY-12-0034 by minimizing the likelihood of repetitive costs relative to § 50.46c implementation.

- The susceptibility of fuel rods to FFRD depends on (1) accident progression, (2) fuel design parameters, and (3) fuel rod operating history. In many aspects, the accident progression (e.g., RCS pressure, coolant flow, reactor power) is fixed. Controlling fuel design parameters and rod power histories (in particular, the power level of high burnup fuel) appear to be the most effective ways to minimize fuel fragmentation and dispersal. Ongoing international research is mostly focused on identifying which, if any, fuel design performance metrics are appropriate to ensure FFRD will not impact safety.

- Inclusion of any new analytical requirements associated with FFRD into the draft final 10 CFR 50.46c rule would delay implementation of revised requirements that are necessary to ensure adequate protection to the public health and safety.

In SECY-12-0034, the staff noted that the results of the ongoing FFRD research may require additional changes to the provisions of the draft final (then proposed) 10 CFR 50.46c rule to establish appropriate requirements related to FFRD. The staff also noted that such changes could mean that many of the steps required for implementing the draft final 10 CFR 50.46c rule would need to be redone to account for the new FFRD requirements. Now that the staff's understanding of FFRD has advanced, this concern has lessened. The staff now believes that any necessary regulatory requirements governing FFRD would be more effectively and appropriately addressed through requirements on fuel design parameters, rather than through new ECCS performance or analytical requirements.

Future Activities

Given the burnup and utilization limitations on existing fuel designs, the staff does not foresee the ongoing research would identify a need to withdraw approval of existing fuel designs.

However, the industry continues to develop advanced fuel designs and more economical fuel loading patterns. The research findings described above indicate that changes in fuel design and plant operations may have an adverse impact with respect to FFRD phenomena. Yet, without established guidance to define the boundary of safe operation for key fuel design and operating parameters, the staff is challenged to evaluate the acceptability of future fuel design advancements and fuel utilization changes.

The SRM directed the staff to provide a best estimate of when final conclusions may be drawn from FFRD research. Additional research into FFRD is ongoing and sufficient results to support a decision regarding whether additional regulatory actions are necessary are anticipated in the next few years. The staff will continue to follow the international experimental programs, perform analytical assessments, interact with stakeholders, and coordinate with international counterparts in order to support the development of a sound technical basis upon which to evaluate whether a new regulatory framework is necessary. The staff anticipates that any new regulatory framework (e.g., fuel management guidance, fuel performance requirements) would be applied to the review of future applications involving fuel design advancements and fuel utilization changes.

Conclusions

In SRM-SECY-12-0034, the Commission directed the staff to complete its research on FFRD. Additional research and analyses have been completed since 2012, and the NRC continues to participate in several multilateral research activities on FFRD. With respect to the Commission's second direction to incorporate any necessary changes into the draft final § 50.46c rule, the staff has determined that the inclusion of new requirements associated with FFRD within § 50.46c is not practicable or appropriate, and, therefore, can proceed without its inclusion. Future regulatory action can be initiated, if needed, if information is developed that would support the need for the adoption of additional requirements to address FFRD in all relevant scenarios.

The staff will continue multilateral research activities and interactions with stakeholders with the goal of developing a regulatory framework to address FFRD, if needed, in the next few years.

<u>COORDINATION</u>:

The Office of the General Counsel has reviewed this Commission paper and has no legal objection.

Interactions with the Advisory Committee on Reactor Safeguards

The NRC staff briefed the ACRS Materials, Metallurgy, and Reactor Fuels Subcommittee on fuel dispersal on December 4, 2013. The staff has provided updates on the subject during Materials, Metallurgy, and Reactor Fuels Subcommittee meetings on December 2, 2014 and November 2, 2015.

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