PREPAREDNESS FOR ACCIDENT TOLERANT FUEL LICENSING, INCLUDING HIGHER BURNUP AND ENRICHMENT

A Report for the
Senate Committee on Appropriations and the
House Committee on Appropriations

By the U.S. Nuclear Regulatory Commission

Enclosure

Introduction

The U.S. Nuclear Regulatory Commission (NRC) developed this report as directed by the explanatory statement accompanying the Consolidated Appropriations Act, 2022 (Public Law 117-103). The explanatory statement directed the NRC to report on the preparedness for accident tolerant fuel (ATF) licensing with a focus on what are steps being taken to ensure that licensing activities (including higher burnup and enrichment) support projected deployment schedules.

Applicants are moving forward with plans to seek approval to batch load[1] fuel assemblies with two ATF technologies (coated cladding and doped pellets) or with higher burnup limits and increased enrichment by the mid-2020s. The enrichment, fabrication, transportation, and use of the ATF fuel assemblies requires NRC licensing review and approval. The NRC has already received some licensing action requests for the use of ATF, including higher burnup limits with or without increased enrichment levels. The current list of these submittals and their approvals, if applicable, can be found on the NRC's ATF public web page (Ref. 1).

The NRC completed or is performing the activities detailed in this report to support agency efforts to complete the licensing of ATF, including higher burnup limits and increased enrichment, in parallel with the Department of Energy's (DOE's) and the industry's research and development activities while maintaining reasonable assurance of adequate protection of public health and safety, promoting the common defense and security, and protecting the environment.

The NRC Is Ready to License Accident Tolerant Fuel-Concept, Higher Burnup, and Increased Enrichment Fuels

The NRC staff assessed its regulatory framework (Ref. 2) and found that the existing regulations and guidance will support the licensing of near-term ATF concepts (i.e., coated cladding and doped pellets). Similarly, the NRC found that no changes to the regulatory framework are necessary to support the licensing of fuel with increased enrichment (from 5 to approximately 10 weight-percent uranium-235) and higher fuel burnup limits (from 62 to 75 gigawatt-days per metric ton of uranium (GWd/MTU), rod average). Although the existing regulatory framework and licensing processes will support the licensing of these new fuel types, the NRC has identified certain areas, discussed further in the remaining sections of this report, in which the framework can be enhanced to improve the effectiveness and efficiency of the process.

The NRC has developed the ATF Project Plan (Ref. 3) to prepare for reviews of ATF-concept, higher burnup, and increased enrichment fuel designs. The ATF Project Plan, revised in September 2021, addresses the complete nuclear fuel cycle, including fuel fabrication, fresh fuel transport, in-reactor requirements, and spent fuel storage and transportation. In developing the plan, the NRC staff engaged extensively with its stakeholders, including licensees, nuclear fuel vendors, industry groups, nongovernmental organizations, and international counterparts, consistent with the NRC's Principles of Good Regulation and statutory requirements.

The ATF Project Plan outlines an enhanced approach to fuel licensing in which the NRC engages with applicants earlier in their research and development phase to help identify and resolve potential safety issues and information gaps promptly. The NRC continues to pursue

[1] A batch load is the replacement of approximately one-third of the fuel assembles in the reactor core after each operating cycle.

opportunities for increased communication and engagement on many fronts, including routine vendor status meetings, attendance at industry conferences, and a significant increase in the number and frequency of presubmittal meetings. These meetings allow the NRC and stakeholders to exchange information and increase the efficiency of the review process. Additionally, the NRC continues to hold meetings and issue communications to further support dialogue with stakeholders over specific technical or administrative issues. In January 2022, the NRC sent a letter (Ref. 4) to the Nuclear Energy Institute and other industry stakeholders to provide a generic, nominal schedule for the review for topical reports and licensing actions for deployment of ATF-concept, higher burnup, and increased enrichment fuels. The letter encouraged further engagement on any intended specific topical report or site-specific licensing action targeted for approval or deployment by the mid-2020s and provided generic licensing timelines. Further, the NRC continues to meet routinely with DOE to share information on ATF status and research, which helps the NRC staff anticipate what reviews may be needed.

As part of the licensing process for ATF-concept, higher burnup, and increased enrichment designs, the NRC must also evaluate the potential environmental effects of its licensing actions under the regulations in Title 10 of the *Code of Federal Regulations* (10 CFR) Part 51, "Environmental Protection Regulations for Domestic Licensing and Related Regulatory Functions," for implementation of Section 102(2) of the National Environmental Policy Act of 1969, as amended (NEPA). NEPA analyses previously performed by the NRC staff addressed the environmental effects for enrichment levels of 5 weight-percent uranium-235 or less and spent fuel burnup levels up to 62 GWd/MTU (see Section 4.12.1.1 of NUREG-1437, Revision 1, "Generic Environmental Impact Statement for License Renewal of Nuclear Plants," issued June 2013 (Ref. 5)). Specifically, these NEPA analyses supported the continued use of 10 CFR 51.51(b), table S-3, "Table of Uranium Fuel Cycle Environmental Data," and 10 CFR 51.52(c), table S-4, "Environmental Impact of Transportation of Fuel and Waste To and From One Light-Water-Cooled Nuclear Power Reactor," as still bounding for light-water reactor licensing actions. With the nuclear industry considering enrichment levels up to 10 weight-percent uranium-235 and burnup levels as high as 80 GWd/MTU along with various forms of ATF, the use of such new reactor fuels is outside of the conditions for use of Tables S-3 and S-4. Thus, a new NEPA analysis needs to be performed to support future licensing actions involving these new fuel types. Although these evaluations could be performed on a site-specific basis as a part of the licensing review, the NRC is considering generically evaluating the environmental impacts related to the uranium fuel cycle, transportation of fuel and waste, and decommissioning to improve the efficiency of the licensing process. To this end, the NRC is evaluating past studies and assessing the available fuel performance analyses, data, and studies in pursuit of a generic study of environmental impacts of ATF technologies and increased enrichment and higher burnup fuels.

In addition to the above, the NRC is continuing to take steps to ensure readiness to license these new fuel types. For example, the NRC issued reports concerning phenomena identification and ranking tables and fuel performance literature reviews concerning near-term ATF concepts, higher burnup, and increased enrichment, which included spent fuel transportation and storage and reactor operating and accident conditions. These reports help the agency broaden its understanding of phenomena associated with the various technologies being considered, as well as help the agency to identify any changes to the regulatory infrastructure that may be needed prior to receiving submittals. The NRC staff maintains a web page of ATF-related documents on its public website (Ref. 6).

The NRC continued to develop or revise existing computer codes to be used for independent confirmatory calculations. These confirmatory calculations provide insight into fuel and reactor

systems behavior as well as potential consequences of transient and accident scenarios and the identification of risk-significant factors. For example, the NRC modified some of its codes to more easily add material properties for new ATF materials. This will allow the NRC to quickly update its codes as data and information are received.

Other General Preparatory Activities

The NRC is actively involved in two Electric Power Research Institute industry research frameworks/groups that are coordinating research on ATF, higher burnup, and increased enrichment limits. The first is the Collaborative Research on Advanced Fuel Technologies for Light-Water Reactors (CRAFT). The second is the Extended Storage Collaboration Program. Participation in both research frameworks/groups allows the NRC to be better prepared to review future licensing submittals due to its heightened awareness of vendor plans and research activities. It also provides the NRC with the opportunity to offer feedback to stakeholders as appropriate.

The NRC frequently interacts with international counterparts and subject matter experts through Nuclear Energy Agency (NEA) working groups—most notably the Working Group on Fuel Safety—and through international cooperative research programs to expand its technical database and maintain awareness of relevant policy and technical issues with ATF. Some notable international activities include the following.

- The Organisation for Economic Co-operation and Development (OECD)/NEA-supported Studsvik Cladding Integrity Project led by Studsvik in Sweden has provided data on high burnup fuel and cladding performance during a simulated loss-of-coolant accident (LOCA).

- The Japan Atomic Energy Agency has provided data on chromia doped fuel performance during a reactivity-initiated accident conducted in its Nuclear Safety Research Reactor.

- The NRC staff participates in the Cabri International Project, led by the Institute for Radiological Protection and Nuclear Safety in France, which studies the behavior of nuclear fuel and cladding during reactivity-initiated accidents.

- The NRC staff is participating in the OECD/NEA's QUENCH-ATF project, through which it obtains data on coated cladding behavior in design-basis and beyond-design-basis LOCA conditions.

- The NRC staff is participating in the OECD/NEA Framework for Irradiation Experiments (FIDES), which was launched to continue the spirit of international cooperation and highly leveraged access to nuclear safety, fuels, and materials research that was lost with the 2018 closure of the Halden reactor in Norway. The first round of FIDES Joint Experimental Programmes includes tests on ATF and high burnup fuel under normal operating conditions, anticipated transients, and design-basis accidents.

These international research programs enhance the NRC's understanding of safety-significant fuel and thermal-hydraulic system behavior and provide valuable data to develop and validate independent models for the NRC's confirmatory analysis codes.

Coated cladding, doped pellets, higher burnup limits, and increased enrichments levels are expected to be the first set of technologies submitted to the NRC for licensing review. The next sections describe the NRC's preparations for each of these technologies.

Coated Cladding

Nuclear fuel vendors are currently researching and testing fuel that uses a zirconium alloy cladding with a thin outer coating of either chromium or a proprietary material. This thin coating is intended to provide resistance to corrosion and wear and additional operational flexibility for power reactors. The NRC has not yet received any in-reactor topical reports or license amendment applications for batch loads of coated cladding but has actively engaged with stakeholders; however, the NRC expects that to change soon as vendors finalize their approaches.

The NRC is prepared to review licensing submittals for coated fuel rod cladding. To get ready, the NRC contracted with nuclear fuels experts from the DOE's Pacific Northwest National Laboratory to perform a literature review (Ref. 7) on degradation and failure phenomena related to the ATF concept of chromium-coated fuel rod cladding and to conduct a phenomena identification and ranking tables exercise on the topic. The NRC then published interim staff guidance (ISG) on the subject (Ref. 8). This ISG is available for vendors to consult in preparing their topical report submittals, which should help reduce the potential for schedule uncertainty and delays caused by submitting incomplete documents for review. Although the NRC has not yet received any vendor topical reports for coated cladding technologies, the NRC has reviewed and approved two requests to install lead test assemblies with coated cladding and doped pellet features (Refs. 9 and 10).

Doped Pellets

Fuel vendors are researching and testing fuel pellets that mix other materials, known as dopants, into the pellet during the manufacturing process. These dopants change the physical properties of the resulting fuel pellet with the goal of providing benefits during normal operation and accident conditions.

The NRC reviewed and approved two doped pellet topical reports for boiling-water reactor fuels (Refs. 11 and 12) and a license amendment (Ref. 13). The NRC is in the process of reviewing two doped pellet topical reports for pressurized-water reactor fuels (Refs. 14 and 15).

Higher Burnup

The current fuel burnup limits differ slightly among fuel vendors and fuel products, but fuel assemblies are generally limited to a maximum rod-average burnup of 62 GWd/MTU. Some potential applicants are interested in raising this limit to around 75 GWd/MTU rod-average. Burnup limits are not specified in any regulations but instead are incorporated into power reactor licenses once approved in topical reports. Therefore, rulemaking is not needed in this area, although the staff will need to review topical reports and license amendment requests in order to approve increased burnup limits. The NRC is in the process of reviewing two higher burnup topical reports. One topical report covers increased burnup limits for a fuel cladding material (Ref. 16) and the other would support extending burnup to 68 GWd/MTU in pressurized-water reactors (Ref. 17).

To enhance the efficiency of the licensing process, the NRC is revising Regulatory Guide (RG) 1.183, Revision 0, “Alternative Radiological Source Terms for Evaluating Design Basis Accidents at Nuclear Power Reactors,” issued July 2000 (Ref. 18), to expand applicability to encompass fuel burnup extensions up to 68 GWd/MTU (rod average) and enrichments up to 8 weight-percent uranium-235 for near-term ATF designs and modern fuel management. The approach to this update is to leverage readily available data and analyses to support these near-term licensing activities. This guidance is intended for large light-water reactor designs and specifies the necessary content and information that should be included in submittals. This includes the scope, nature, and documentation of associated analyses and evaluations with consideration of impacts on analyzed risk. The guidance describes methods that the NRC staff considers acceptable in complying with regulations for design-basis accident dose consequence analysis using an alternative source term. Ongoing research efforts are underway to further expand the applicability of the proposed Revision 1 to RG 1.183 to accommodate the industry’s longer-term burnup and enrichment targets. The staff will incorporate the results of this research into the anticipated Revision 2 of RG 1.183. The NRC is working to complete both revisions to RG 1.183 in a timeframe that will support the industry’s stated timeline for deployment of batch loads of higher burnup fuel.

A phenomenon called fuel fragmentation, relocation, and dispersal (FFRD) remains an area of significant interest to the NRC. The NRC’s existing regulatory philosophy revolves around maintaining the fuel in a coolable geometry. In practice, this has meant demonstrating that the fuel stack remains intact, resides within the fuel rod cladding, and that the fuel bundle array is maintained. Research on high burnup fuel has shown that fuel can break apart into fine (less than 1 millimeter) fragments when subjected to LOCA conditions. The extent of fragmentation has been observed to increase with burnup. Highly fragmented fuel has been observed to relocate axially with gravity, into the regions of the fuel rod that balloon under LOCA conditions. If rod rupture occurs, experiments have shown that the fragmented and relocated fuel can disperse out of the rod into the coolant. Research has also shown that additional fission gas may be released under LOCA conditions, which may impact fuel rod ballooning and burst behavior. Dispersal of large quantities of fuel particles creates an unknown geometry making it difficult to demonstrate long-term residual heat removal for both the intact portion of the core and the dispersed fuel particles, as well as addressing other potential safety concerns (e.g., recriticality of dispersed fuel and energetic fuel-coolant interactions). The extent to which FFRD could constitute a safety concern is dependent on the design and operational characteristics chosen for the fuel because these characteristics will impact if or how many fuel rods are projected to burst during a postulated LOCA. Therefore, fuel vendors and licensees will need to address FFRD as part of the approval process for higher burnup fuels.

The NRC has published multiple documents on FFRD-related research over the past 15 years, culminating in the issuance of Research Information Letter (RIL) 2021-13, “Interpretation of Research on Fuel Fragmentation, Relocation, and Dispersal (FFRD) at High Burnup,” dated December 17, 2021 (Ref. 19). RIL 2021-13 presents research from several domestic and international research programs, including the Studsvik Cladding Integrity Project and the Halden Reactor Project, related to transient fission gas release and FFRD under LOCA conditions. The RIL provides NRC technical reviewers with timely interpretations of a complex technical issue in a way that is easy to use and presented in the context of fuel safety.

To be aware of the progress in addressing both the technical and licensing issues associated with FFRD, the NRC staff is encouraging fuel vendors to have preapplication meetings on their licensing approaches to FFRD, which three vendors have done to date. The NRC staff expects additional preapplication meetings once vendors have further refined their approaches.

Additionally, the NRC's participation in CRAFT will allow the agency to understand potential applicants' approaches to filling data gaps and the new approaches to licensing requests that are being developed for FFRD.

Recently, the industry has stated that it intends to pursue a risk-informed approach to addressing FFRD for pressurized-water reactors. The NRC has historically considered risk when licensing the use of nuclear fuel and can use its existing risk-informed framework to support the licensing of these new fuel types. In June 2021 (Ref. 20), the NRC met with representatives from the nuclear industry for a high-level discussion about an Electric Power Research Institute-led effort to develop an alternative licensing strategy for higher burnup fuel, which includes a risk-informed analysis of LOCA-induced FFRD. The NRC has encouraged the industry to continue to engage with the agency as this approach gets finalized so that any potential technical or policy issues that may arise can be identified early and steps can be taken to address them.

In addition to the ATF Project Plan, the NRC has proactively reached out to potential applicants on higher burnup limits through two NRC-led public workshops. The first, which took place on July 30, 2020, included an overview of higher burnup limits and increased enrichment levels and an exchange of information focusing on the components of a quality submittal. During the follow-up workshop on June 10, 2021, the NRC discussed the research information letter, the environmental aspects of higher burnup limits, and higher burnup spent fuel storage and transportation issues. These two workshops provided a valuable exchange of information with a variety of stakeholders.

Increased Enrichment

The existing regulatory framework supports the licensing of fuel with increased enrichment levels (from 5 to approximately 10 weight-percent uranium-235) in the near term through the use of license amendments and exemptions. License amendments would be needed to change the enrichment limits in individual licenses, and each licensee that wishes to exceed the enrichment limits in the regulations would need an exemption.

In December 2021, the staff provided the Commission SECY-21-0109, "Rulemaking Plan on Use of Increased Enrichment of Conventional and Accident Tolerant Fuel Designs for Light-Water Reactors" (Ref. 21), which requested approval to initiate a rulemaking to amend requirements for the use of light-water reactor fuel containing uranium enriched to greater than 5.0 weight-percent uranium-235. On March 16, 2022, the Commission approved the staff's proposal to initiate a rulemaking, as discussed in the staff requirements memorandum for SECY-21-0109 (Ref. 22). This rulemaking will produce a generic approach informed by public input and reduce the need for individual exemption requests. The NRC plans to complete this effort in 2026.

The NRC is in the process of reviewing a topical report that would support increasing enrichment for pressurized-water reactor fuels beyond the current limit of 5 weight-percent uranium-235 (Ref. 23).

Iron-Chromium-Aluminum Cladding and Longer-Term Accident Tolerant Fuel Concepts

The NRC monitors progress on the development of iron-chromium-aluminum (FeCrAl) cladding and longer-term ATF concepts, such as silicon carbide cladding. The NRC staff frequently

engages with the DOE and fuel vendors to understand the current status and future direction of these concepts.

The NRC has not yet received the relevant detailed schedules, specific physical characteristics, or technical data from vendors for FeCrAl or other longer term ATF concepts. The NRC staff has, however, begun preliminary research to prepare for these reviews and to determine whether, and to what extent, changes to the existing regulatory framework may be needed to safely license these ATF technologies. With uncertain submittal timelines for these technologies, it would be premature for the NRC to undertake more intensive preparatory activities at this time.

Front End and Back End of the Fuel Cycle

With regard to licensing the front end (i.e., enrichment, fuel fabrication, and fresh fuel transportation) and the back end of the fuel cycle (i.e., spent fuel transportation and storage) for coated cladding, the NRC staff has reviewed the applicable regulations and guidance. The staff has performed literature reviews of the relevant proposed ATF concepts and has determined that no additions or modifications to the front-end and back-end regulatory framework are needed. This activity included consideration of doped pellets, coated cladding, and increased enrichment up to 10 weight-percent uranium-235 for both the front end and back end of the fuel cycle, as well as increased burnup for the back end of the fuel cycle. The NRC is identifying areas where more data would improve confidence in the predictive capabilities of computer codes and reduce uncertainties. This includes key end-of-life characteristics of spent fuel, such as fission gas release, nuclear fuel rod internal pressure, cladding oxide thickness, and hydrogen content (Ref. 24), in addition to evaluating the impact of increased enrichment and higher burnup fuels on decay heat and radionuclide inventory. These activities will ensure that the NRC is prepared to efficiently review front-end and back-end licensing actions consistent with the agency's safety and security mission and in parallel with the industry's efforts.

The NRC has approved multiple licensing actions for fuel enrichment and fresh fuel transportation. With respect to increased enrichment, the NRC has reviewed and approved several licensing actions that serve as preparatory steps to allow a fuel facility to achieve enrichments above 5 weight-percent uranium-235 (Refs. 25 and 26). In addition, the NRC has issued one approval (Ref. 27) that allows a fuel vendor to transport fresh fuel rods with doped fuel pellets, coated cladding, and enrichments above 5 weight-percent uranium-235. The NRC further approved changes to this same transportation package for a separate certificate holder in March 2022 that allow for new cladding coating types, doped pellets, and additional increased enrichment contents (Ref. 28). Finally, the NRC issued another transportation package approval (Ref. 29) for fresh fuel with coated cladding.

The NRC is also undertaking actions to ensure efficiency and effectiveness in its safety reviews for the front end and back end of the fuel cycle. As mentioned above, the NRC is undertaking a rulemaking activity to evaluate the regulations limiting enrichments to 5 weight-percent uranium-235. Any changes that may result from the Commission's rulemaking would likely increase the efficiency of the licensing process. The NRC has also issued letters to potential applicants identifying critical path items for reviewing front-end licensing actions. These included a public letter to the Nuclear Energy Institute (Ref. 30) describing enrichment facility critical path items for approving batch fuel loadings in 2023.

Conclusion

The NRC is ready to review licensing requests to support the batch-loading of fuel with near-term ATF technologies (i.e., coated cladding and doped pellets), higher burnup limits, and increased enrichment levels. In addition, the NRC continues to take steps to maximize its preparedness and to improve the efficiency of the licensing process to safely license new fuel designs. The NRC will continue to engage with potential applicants, licensees, and other external stakeholders to ensure that the appropriate steps are taken so that ATF, higher burnup, and increased enrichment licensing reviews are both timely and complete, consistent with maintaining reasonable assurance of adequate protection of public health and safety, promoting the common defense and security, and protecting the environment.

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