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 of 2023 (Public Law 117-328). The explanatory statement directed the NRC to report on its preparedness for accident tolerant fuel (ATF) licensing, focusing on the steps being taken to ensure that licensing activities (including for higher burnup and enrichment) support projected deployment schedules.

Potential applicants are moving forward with plans to seek approval to batch load[1] fuel assemblies with one of two ATF concepts (coated cladding and doped pellets) or with higher burnup limits and increased enrichment by the mid-to-late 2020s. The enrichment, fabrication, transportation, and use of ATF fuel assemblies in some cases requires NRC approval. The NRC has already received licensing action requests for the use of ATF, including for 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 U.S. Department of Energy's (DOE's) and the industry's research and development activities. In performing these activities, the NRC verifies that licensee use of ATF technologies will provide reasonable assurance of adequate protection of public health and safety, promote the common defense and security, and protect the environment.

The NRC Is Ready to License Accident Tolerant Fuel Concepts, 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. As noted below, efforts are underway to implement these enhancements.

The NRC developed the ATF Project Plan (Ref. 3) to prepare for reviews of ATF concepts, higher burnup, and increased enrichment fuel designs. The ATF Project Plan, revised in September 2021, addresses the complete nuclear fuel cycle, including fuel enrichment, 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 NRC keeps information contained in the ATF Project Plan current through continued stakeholder interactions.

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

The ATF Project Plan outlines an enhanced approach to fuel licensing in which the NRC engages with applicants earlier in their research and development phases to help identify and promptly resolve potential safety issues and close information gaps. The NRC continues to pursue opportunities for increased communication and engagement on many fronts. These include routine participation in vendor status meetings, attendance at industry conferences, and actively supporting pre-submittal meetings. These engagements allow the NRC and its stakeholders to exchange information effectively and increase the efficiency of the review process.

Additionally, the NRC continues to hold meetings and issue communications to further support dialogue with stakeholders about specific technical or administrative issues. In January 2022, the NRC sent a letter (Ref. 4) to the Nuclear Energy Institute (NEI) and other industry stakeholders to provide a generic, nominal schedule for the review of topical reports and licensing actions for the deployment of ATF concepts, higher burnup, and increased enrichment fuels. The letter encouraged further engagement on any intended specific topical report or site-specific licensing action targeted for deployment by the mid-2020s and provided generic licensing timelines. In January 2023, the NRC staff and external stakeholders presented an overview of ATF activities to the NRC Commissioners (Ref. 5). The NRC also continues to meet routinely with the 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 concepts, 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," to implement 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 (Ref. 6) and section 4.14.1.1 of Draft NUREG-1437, Revision 2 (Ref. 7)). Specifically, these NEPA analyses support 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 potential burnup levels as high as 75 GWd/MTU along with various forms of ATF, the use of such new reactor fuels is outside of the conditions for the use of Tables S-3 and S-4. Thus, a new environmental review will be needed to support future licensing actions involving these new fuel types. Although these reviews could be performed on a site-specific basis as a part of the licensing review, the NRC is generically evaluating the environmental impacts related to the uranium fuel cycle, transportation of unirradiated ATF, waste, and decommissioning to improve the efficiency of the licensing process. To this end, the NRC is applying information from past studies to ATF concepts, higher burnup, and increased enrichment designs and assessing the available fuel performance analyses, data, and studies to develop a generic study of environmental impacts of ATF concepts, increased enrichment and higher burnup fuels. Even if this environmental evaluation cannot be applied in a specific future licensing action, the generic study should provide an analytical template for completing such analyses for different enrichment and burnup conditions.

The NRC continuously takes steps to ensure its readiness to review license applications for these new fuel types. For instance, the NRC issued reports containing phenomena identification ranking tables (PIRTs)[2], which rank the relative importance of selected topics associated with ATF to assist the staff in making risk-informed decisions, as well as fuel performance literature reviews. These reports included spent fuel transportation and storage as well as reactor operating and accident conditions. These reports help the agency broaden its understanding of phenomena associated with the various technologies being considered and identify any changes to the regulatory infrastructure that may be needed before receiving submittals. The NRC staff maintains a Web page of ATF-related documents on its public website (Ref. 8).

The NRC continues to develop and revise existing computer codes to be used for independent confirmatory calculations. These confirmatory calculations provide insight into fuel and reactor systems behavior, potential consequences of transient and accident scenarios, and the identification of risk-significant factors. For example, the NRC modified some of its codes to add material properties for new ATF materials more easily. This will allow the NRC to quickly update its codes as data and information are received and reduce unnecessary conservatisms in technical evaluations.

Other General Preparatory Activities

The NRC participates as an observer in two Electric Power Research Institute (EPRI) groups that are coordinating research on ATF concepts, 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.[3] Participation in both research groups allows the NRC to be better prepared to review future licensing submittals by providing 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 NRC participated in the Organisation for Economic Co-operation and Development (OECD)/NEA and supported the Studsvik Cladding Integrity Project led by Studsvik in Sweden. This effort provided data on higher burnup fuel and cladding performance during a simulated loss-of-coolant accident (LOCA).

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

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[2] The phenomena identification and ranking table (PIRT) process is a systemic way of gathering information from experts on a specific concept and ranking the importance of the information to help guide research or develop regulatory requirements.

[3] The NRC's role as an observer in the Extended Storage Collaboration Program involves, among other things, presenting updates on NRC activities and technical topics, providing input, and being represented on the Extended Storage Collaboration Program Steering Committee.

- 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 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 the FIDES Joint Experimental Programmes includes tests on ATF concepts and higher burnup fuel under normal operating conditions, anticipated transients, and design-basis accidents.

Active participation in these international research programs enhances the NRC's understanding of safety-significant fuel and thermal-hydraulic system behavior. It also provides valuable data to develop and validate independent models for the NRC's confirmatory analysis codes. Confirmatory calculations performed during safety reviews with analysis codes provide insight on the fuel and reactor systems behavior, during transient and accident scenarios.

Near-Term Accident Tolerant Fuel Concepts

The NRC anticipates that coated cladding, doped pellets, higher burnup limits, and increased enrichments levels will 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, as well as additional operational flexibility for power reactors. The NRC has not yet received any in-reactor topical reports or license amendment requests for batch loads of fuel with coated cladding. However, the NRC has actively engaged with stakeholders to understand vendor approaches and to obtain information that will facilitate NRC licensing reviews.

The NRC is prepared to review future licensing submittals for coated fuel rod cladding. For example, the NRC contracted with nuclear fuels experts from the DOE's Pacific Northwest National Laboratory to perform a literature review (Ref. 9) and a PIRT exercise on degradation and failure phenomena related to chromium-coated fuel rod cladding. The NRC published interim staff guidance (ISG) on the subject (Ref. 10). This ISG informs NRC staff reviews of topical reports on coated cladding fuels, which should help reduce the potential for schedule uncertainty and delays. As stated above, although the NRC has not yet received any vendor topical reports for batch loads of coated cladding, the NRC has received multiple license amendment requests related to lead test assemblies (LTAs) with coated cladding features, including two with coated cladding and doped pellet features (Refs. 11, 12). LTAs are fuel assemblies that contain design features or materials for which additional data may be needed to support approval for unrestricted use.[4]

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 additional operational flexibility during normal operation and promoting fission product gas retention during accident conditions.

The NRC reviewed and approved three doped pellet topical reports[5] for boiling-water reactor fuels (Refs. 13, 14, 15) and four license amendment requests (Refs. 16, 17, 18, 19). The NRC is in the process of reviewing one doped pellet topical report for pressurized-water reactor (PWR) fuels (Ref. 20).

Higher Burnup

The current fuel burnup limits differ slightly among fuel vendors and fuel products, but fuel assemblies are limited to a maximum rod-average burnup of 62 GWd/MTU. Some potential applicants are interested in raising this limit to a rod-average burnup of approximately 75 GWd/MTU. Burnup limits are not specified in NRC regulations but instead are incorporated into power reactor licenses after they are approved in topical reports.

The NRC has reviewed and approved one higher-burnup-related topical report (Ref. 21), which covered increased burnup limits for fuel cladding material. The NRC is also reviewing an additional higher burnup topical report, which would support extending burnup to 68 GWd/MTU in PWRs (Ref. 22). The NRC is currently reviewing an additional request to re-insert previously irradiated LTAs with coated cladding and doped pellet technology into a reactor, to gather data about performance at higher burnups (Ref. 23).

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," (Ref. 24), to expand its 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 technologies 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 content 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. NRC staff is continuing to engage with stakeholders on both

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[4] The term "unrestricted use" means that, unlike LTAs, the fuel has been approved for use at a plant without limits on quantity or placement within the core (except for those limits that are part of the approval). License amendments for approval of unrestricted use are commonly called "fuel transitions." Similar terms sometimes used include "batch quantities" and "reload quantities" of fuel assemblies.

[5] A topical report is a report containing generic technical or regulatory information on a topic relevant to nuclear power plant safety or licensing. The NRC process is utilized to increase efficiency by providing for a streamlined review of a subject with generic applicability and potential for subsequent referencing in multiple licensing actions.

revisions, through public meetings (Ref. 25), comment periods, and routine engagements. 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 the 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 regulations require that the fuel be maintained in a coolable geometry following a design-basis LOCA. In practice, this has meant demonstrating that the fuel stack remains intact and resides within the fuel rod cladding, and that the fuel bundle array is maintained. Research on higher burnup fuel has shown that fuel pellets can break apart into fine (less than 1 millimeter) fragments when subjected to accident conditions. Experimental data has shown that the extent of fragmentation increases 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 product gas may be released under LOCA conditions, which may impact fuel rod ballooning and burst behavior. Dispersal of copious 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. Such dispersal could also present other potential safety concerns (e.g., re-criticality 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 their applications 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 at High Burnup," dated December 17, 2021 (Ref. 26). 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 product gas release and FFRD under LOCA conditions. RIL 2021-13 provides the 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. The NRC will be sponsoring a PIRT exercise related to fuel dispersal and its consequences, based, in part, on information in RIL 2021-13. This exercise is expected to provide more information on the important aspects of FFRD to better focus the agency's evaluations.

To remain 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; three vendors have done so to date. The NRC staff anticipates additional preapplication meetings once vendors have further refined their approaches. Additionally, the NRC's participation as an observer in CRAFT will allow the agency to understand potential applicants' approaches to filling data gaps and the novel approaches to licensing requests that are being developed for FFRD.

Members of the industry have stated that they intend to pursue a risk-informed approach to addressing FFRD for PWRs. The NRC has historically considered risk when licensing the use of nuclear fuel and can use its existing risk-informed framework to inform the licensing reviews of these new fuel types. In June 2021 and August 2022 (Ref. 27, 28), the NRC met with representatives from the nuclear industry for a high-level discussion about an EPRI-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 it further develops this approach so that the agency can identify any potential technical or policy issues that may arise early and the industry can take steps to address them.

In addition to the ATF Project Plan, the NRC has proactively reached out to potential applicants on higher burnup limits through three NRC-led public workshops. The first, which took place on July 30, 2020 (Ref. 29), included an overview of higher burnup limits and increased enrichment levels, as well as an exchange of information focusing on the components of a quality submittal. During the followup workshop on June 10, 2021 (Ref. 30), the NRC discussed RIL 2021-13, the environmental aspects of higher burnup limits, and higher burnup spent fuel storage and transportation issues. The third workshop, which took place on August 24, 2022 (Ref. 31), included an update on the increased enrichment rulemaking, discussed below; industry FFRD risk-informed approaches, discussed in the previous paragraph; and the NRC regulatory framework assessment, discussed above; as well as a discussion on the outlook for ATF technologies. These three 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 using 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 specified in the regulations could seek 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. 32), 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 weight-percent uranium-235 for increased regulatory efficiency and consistency. 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. 33). This rulemaking will produce a generic approach informed by public comment and reduce the need for individual exemption requests. The staff plans to complete this effort by 2026.

The NRC is in the process of reviewing five topical reports that support increasing enrichment for PWR fuels beyond the current limit of 5 weight-percent uranium-235 (Refs. 34, 35, 36). The NRC is also reviewing a license amendment request to load LTAs with coated cladding, doped pellets, and increased enrichment into a PWR (Ref. 37).

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 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 longer-term ATF concepts. 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

Regarding licensing the front-end (i.e., enrichment, fuel fabrication, and fresh fuel transportation) and the back-end (i.e., spent fuel transportation and storage) of the fuel cycle for coated cladding, the NRC staff has reviewed the applicable existing regulations and guidance. The staff has also performed literature reviews of the relevant proposed ATF concepts and has determined that no additions or modifications to the front-end or back-end regulatory framework are needed. These literature reviews 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 product gas release, nuclear fuel rod internal pressure, cladding oxide thickness, and hydrogen content (Ref. 38), in addition to evaluating the impact of increased enrichment and higher burnup fuels on decay heat and radionuclide inventory. These activities will prepare the NRC 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. For example, with respect to increased enrichment, the NRC has reviewed and approved several licensing actions that serve as preparatory steps to allow fuel cycle facilities to achieve enrichments above 5 weight-percent uranium-235 (Refs. 39, 40). The NRC has issued a variety of approvals related to the transportation of ATF concepts, increased enrichment, and higher burnup fuel designs. For example, the NRC has issued one approval (Ref. 41) 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 approved two additional changes to this same transportation package in April 2022 to allow new cladding coating types, doped pellets, and additional increased enrichment contents (Ref. 42); and in January 2023, to allow international shipments of ATF LTAs with coated cladding, doped pellets, and increased enrichments (Ref 43). The NRC also approved a revised certificate of compliance for a transportation package for fresh fuel with coated cladding (Ref. 44). In March 2023, the NRC issued a transportation package approval (Ref. 45) for shipments of uranium hexafluoride with an enrichment up to 20 weight-percent uranium-235.

The NRC is also undertaking actions to ensure efficiency and effectiveness in its independent safety reviews for the front-end and back-end of the fuel cycle. As mentioned above, the NRC has begun a rulemaking to evaluate the regulations that limit enrichments to 5 weight-percent uranium-235, as discussed in the staff requirements memorandum for SECY-21-0109 (Ref. 33). Separately, the NRC has also issued letters to potential applicants identifying critical path items for reviewing front-end licensing actions.

Conclusion

The NRC is ready to review license amendment requests to support the batch-loading of fuel with near-term ATF concepts (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 potential applicants, licensees, and other stakeholders to ensure that ATF concepts, higher burnup, and increased enrichment licensing reviews are both timely and thorough and that they provide reasonable assurance of adequate protection of public health and safety, promote the common defense and security, and protect the environment.

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