UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
2300 Clarendon Boulevard, Suite 1300
Arlington, VA 22201-3367

August 12, 2021

Dr. Kathryn D. Huff
Acting Assistant Secretary for Nuclear Energy
U.S. Department of Energy
1000 Independence Ave., SW
Washington, D.C. 20585

Dear Dr. Huff:

On behalf of the U.S. Nuclear Waste Technical Review Board (Board), I want to thank you and your staff, as well as the staff from the national laboratories, for supporting the Board's Spring 2021 Meeting, which was held virtually on May 12–13, 2021. The purpose of the meeting was to review information on U.S. Department of Energy, Office of Nuclear Energy (DOE-NE) research and development (R&D) activities related to advanced nuclear fuels for light water reactors (LWRs), including accident tolerant fuels (ANF/ATF), and the impact of these fuels on spent nuclear fuel (SNF) management and disposal. This letter presents the Board's observations, findings, and recommendations to DOE resulting from the meeting. The agenda and presentation materials for the meeting are posted on the Board's website at https://www.nwtrb.gov/meetings/past-meetings/spring-2021-board-virtual-meeting---may-12-13-2021. The meeting transcript and an archived recording of the webcast also are posted on the same web page.

The Board also thanks the staff from DOE and the national laboratories for supporting a technical fact-finding meeting that was held virtually on April 26, 2021. This fact-finding meeting enabled the Board to prepare for the Spring 2021 public meeting.

Background

Since the 2011 Fukushima Daiichi nuclear accident in Japan, there has been significant R&D in several countries to enhance the accident tolerance of reactor fuels. In 2012, Congress directed DOE to give priority to developing ATFs.[1] Pursuant to the Congressional mandate, DOE-NE has been supporting R&D with nuclear fuel vendors to give priority to developing "enhanced fuels and cladding for light water reactors to improve safety in the event of accidents in the reactor or spent fuel pools." Concurrently, the U.S. Nuclear Regulatory Commission (NRC) has been working to ensure that the existing regulatory framework will support the licensing of ATFs in current commercial LWRs. The state-of-the-art in ATFs has progressed from research reactor irradiation campaigns for characterizing new fuels and new cladding materials, to demonstrations

[1] See Consolidated Appropriations Act, 2012, Conference Report 112-75.

of full-scale lead test assemblies in commercial nuclear reactors, and post irradiation examinations of the first batch of discharged ATFs at DOE national laboratory hot cell facilities.

Near-term ATFs are envisioned to be licensed for use in the current commercial fleet of LWRs in the U.S. in the next 5 to 10 years. The ANF/ATF comprise a diverse class of fuel materials and claddings, including ceramic claddings, metallic fuels, and some innovative fuels that are designed to operate to higher burnups and to utilize higher enrichments of uranium-235. Background information on the fuel designs is provided in the Appendix to this letter and are included in the public meeting presentation materials.

Although DOE has made significant progress in the development of ANF/ATF, there has been less effort focused on planning for the management and disposal of the resulting SNF. To address these issues, the Board planned its Spring 2021 public meeting to hear from DOE, national laboratories, and the nuclear industry in the U.S. and to gain insights from experts from some other countries (Switzerland, Sweden, and United Kingdom) about some of their development activities for ANF/ATF but ultimately focusing on the plans for management and disposal of the resulting SNF in those countries.

Public Meeting

DOE-NE Office of Nuclear Fuel Cycle and Supply Chain and Idaho National Laboratory
Mr. Bill McCaughey (DOE-NE) and Dr. Dan Wachs (Idaho National Laboratory [INL]) provided an overview of the DOE-supported, industry-led ATF R&D activities from 2012 to present. Mr. McCaughey recognized the ATF program as one of DOE-NE's highest priorities with strong government support of the program and hundreds of participants. Mr. McCaughey stated that the two guiding principles of the Congressional mandate to develop ATFs were that the technology supports the existing LWR fleet and that the technology be developed as quickly as possible.

The technical presentation was given by Dr. Wachs and covered design specifications and safety attributes of the fuel and cladding materials for candidate ATF designs. The R&D is led by commercial fuel vendors Westinghouse, General Electric/Global Nuclear Fuel (GE/GNF), and Framatome. The near-term ATFs include chromium-based coatings on zirconium alloy claddings and chromium-doped uranium dioxide (UO_2) fuel and, in the longer-term, iron-based claddings like iron-chromium-aluminum (FeCrAl), ceramic composite claddings like silicon carbide (SiC) and other high density fuels like uranium nitride (UN). More background information on ATFs is provided in the Appendix.

Dr. Wachs described the on-going irradiation testing of ATF specimens in the INL Advanced Test Reactor for NRC fuel qualification and licensing, and testing the response of specimens when subjected to accident conditions in the Transient Reactor Test Facility. Dr. Wachs also described the irradiation of full-scale lead test assemblies in eight commercial LWRs and the plan for subsequent post irradiation examination work (see Appendix, Figure A1). Dr. Wachs stated that international collaborations also support the U.S. ATF R&D through partnerships with other countries that enable DOE to access their facilities. The three main fuel vendors also have their networks around the world.

Lightbridge Corporation

Dr. Aaron Totemeier (Lightbridge) described Lightbridge's metallic fuel technology and helical fuel rod design. Lightbridge Fuel is a type of ANF being developed for existing and future LWRs. Unlike traditional LWR UO_2 fuel rods, comprised of stacked UO_2 pellets in cylindrical zirconium alloy cladding, Lightbridge Fuel is an innovative fuel design with a helical (twisted) rod geometry formed from a metallic alloy of uranium and zirconium, with a metallurgically bonded zirconium-niobium cladding. Dr. Totemeier stated that Lightbridge Fuel offers several increased safety benefits over traditional zirconium alloy-clad UO_2 fuel (e.g., higher thermal conductivities, lower fuel operating temperatures, etc.) and is envisioned to be developed with enrichments of uranium-235 higher than that in current LWR fuels, such as high assay low-enriched uranium (HALEU).[2] Currently, Lightbridge Fuel is considered a longer-term ANF technology and is supported in part by DOE to partner with INL for Advanced Test Reactor irradiation testing and with Pacific Northwest National Laboratory (PNNL) on fuel casting techniques for fabricating metallic fuel. According to Dr. Totemeier, the SNF management implications of Lightbridge Fuel are not currently expected to present any "showstoppers," and Lightbridge has plans to explore SNF management topics in the future.

U.S. Nuclear Regulatory Commission

Ms. Marilyn Diaz and Dr. John Wise described the NRC ATF Project Plan,[3] the purpose of which is to guide the NRC staff to ensure that the necessary regulatory processes and knowledge will be in place to consider applications for the use of ATFs in commercial reactors. ATF designs that have been given higher priority in the Project Plan are chromium-coated zirconium alloy claddings, FeCrAl cladding, and doped fuel pellets. The Project Plan considers mainly ATF qualification and reactor operational issues but also considers storage and transportation of the resulting SNF. Ms. Diaz provided a high-level overview of the activities in the Project Plan, which includes identification of critical paths for required regulatory actions and for conducting research on ATFs through technical assessments, confirmatory code development, and expert elicitations.[4]

One of the new paradigms of the Project Plan is to conduct NRC activities in parallel with nuclear industry development efforts in order to build NRC staff expertise early. Ms. Diaz also stated that the NRC has proactively communicated early and often with stakeholders on regulatory activities through public meetings, reports, and regular, formal interactions relating to licensing considerations for ATFs. Ms. Diaz noted that the NRC will update the Project Plan in Fall 2021.

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[2] High assay low-enriched uranium (HALEU) based fuel has a uranium-235 assay greater than 5% but less than 20%. The current commercial fleet of LWRs relies on low-enriched uranium which is enriched to less than 5% uranium-235.

[3] *Project Plan to Prepare the U.S. Nuclear Regulatory Commission for Efficient and Effective Licensing of Accident Tolerant Fuels*. ML19301B166, Version 1.1. U.S. Nuclear Regulatory Commission. October 2019.

[4] The NRC uses an expert elicitation process called the Phenomena Identification and Ranking Table (PIRT) process.

Dr. John Wise highlighted technical aspects of new ATF designs that will be important to consider when licensing them for fabrication, fresh fuel transportation, reactor operations, and management of the resulting SNF. Dr. Wise noted that key characteristics of ATF designs to be considered when evaluating SNF transportation and storage are criticality safety and cladding performance. An initial study conducted by PNNL for NRC on the impact of ATF cladding designs[5] (chromium-coated zirconium alloy cladding and FeCrAl cladding) on storage and transportation revealed no significant issues. However, Dr. Wise stated that there are limited data available on the mechanical and thermal properties and fatigue lifetimes of new cladding designs. The missing relevant data will need to be obtained by the fuel vendors to support computer model development and NRC evaluation of the ATF designs. Regarding evaluation of SNF disposal, the NRC staff has no current plans on that topic, but Dr. Wise stated that the NRC will consider potential disposal implications as ATF technologies advance.

DOE-NE Office of Spent Fuel and Waste Disposition and Sandia National Laboratories
Dr. William Boyle (DOE-NE) and Dr. Sylvia Saltzstein (Sandia National Laboratories [SNL]) discussed preliminary considerations for the potential impacts of ANF/ATF on SNF management and disposal. In the opening remarks for DOE, Dr. Boyle stated that DOE will follow the terms of the Standard Contracts that are in place between DOE and the nuclear utilities, and that DOE will do any testing and modeling of the SNF that is needed to support disposal of the SNF.

Dr. Sylvia Saltzstein summarized the results of a high-level "gap analysis" report[6] prepared by SNL with input from Oak Ridge National Laboratory (ORNL), Argonne National Laboratory, and PNNL. The report identifies information needs (gaps) that, when met, will support a thorough evaluation of the impacts of ATFs on SNF storage and transportation. Dr. Saltzstein pointed out that, since no post irradiation examination of ATFs has yet been completed, there are many gaps. The technical gaps for ATFs were grouped into the same priority groupings (called tiers) that SNL had identified in previous gap analyses for high burnup SNF (which involves information on standard UO_2 fuel with zirconium alloy cladding utilized to high burnup). The top three tiers are:

Tier 1	Thermal profiles in SNF dry cask storage systems, stress profiles in SNF assemblies and cladding, and welded canister-atmospheric corrosion.
Tier 2	Measuring the efficiency of drying SNF in dry cask storage systems.
Tier 3	External monitoring of SNF dry cask storage systems, hydrogen effects in SNF cladding, consequences of SNF canister failure, and fuel transfer options.

For the purposes of the gap analysis, the proposed fuels investigated are categorized as:

- doped fuel pellets (chromia and chromia/alumina dopants)
- modified current (coated zirconium alloy) and new claddings (FeCrAl, SiC, etc.)
- fuels with higher density than uranium dioxide to facilitate higher burnup and higher power while reducing fuel temperature:

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[5] *Spent Fuel Storage and Transportation of Accident Tolerant Fuel Concepts; Cr-Coated Zirconium Alloy and FeCrAl Cladding*, PNNL-30451, September 2020.

[6] *High Level Gap Analysis for Accident Tolerant and Advanced Fuels for Storage and Transportation.* SAND2021-4732, Revision 6. Albuquerque, New Mexico: Sandia National Laboratories. April 2021.

    - uranium metals (including Mo or Pu/Zr alloys, etc.)
    - uranium nitrides
    - uranium silicides
- fuel (UO_2-based or other) with enrichment of 5 to 20% to increase burnup, cycle length, and power
    - HALEU

The general conclusion of the ATF gap analysis, according to Dr. Saltzstein, is that for LWR fuel in a traditional pellet-in-rod design, the information needs can be met by examining the new ATF SNF in the existing facilities and test equipment used to examine the zirconium alloy-clad "sibling pins" in DOE's High Burnup Dry Storage Cask Research and Development Project (HDRP).[7] Non-traditional fuels (e.g., TRISO fuels) will require alternate testing plans to be developed. Dr. Saltzstein stated that updates to the ATF gap analysis report are expected to become integrated into the gap analysis process that covers the broad range of SNF DOE expects to accept eventually from the nuclear utilities.

ANF/ATF Development and Approval Process and Plans for SNF Management in Other Countries

Switzerland

Dr. Stefano Caruso (Kernkraftwerk Gösgen, [KKG]) highlighted some of the Swiss ATF R&D activities and collaborations, the license application process and various assessments for approving new fuels in Switzerland, and outlined the Swiss strategy for management of SNF. Switzerland is considering ATF candidates that are similar to those in the U.S. and in some cases working with the same fuel vendors. The Swiss ATF candidates[8] include chromium-coated zirconium alloy claddings and chromium- and aluminum-doped UO_2 fuel in the near-term. Alternative claddings will be developed in the long-term like SiC composites and iron-based alloys to replace conventional zirconium alloy claddings (see Appendix for more information on U.S. ATF candidates). KKG has several collaborations with Framatome involving chromium-coated zirconium alloy cladding development including manufacturing, irradiation, and post irradiation examination activities. Dr. Caruso described the IMAGO (Irradiation of Materials for Accident-tolerant fuels in the Gösgen reactor) R&D program to verify the behavior of ATF concepts in representative pressurized water reactor conditions. In the GOCHROM R&D program, which is a follow-up program to the IMAGO R&D program, test assemblies have completed two irradiation cycles with full-length fuel rods of chromium-coated M5 (lead test rods with Framatome's zirconium alloy based cladding) inserted in the Gösgen reactor; these included traditional and doped UO_2 fuel.

Prior to use in a commercial nuclear reactor, new nuclear fuel designs in Switzerland must be approved by ENSI (Swiss Federal Nuclear Safety Inspectorate; like the U.S. NRC) after consideration of all aspects of the safety of the new fuel design and the related in-core

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[7] The High Burnup Dry Storage Cask Research and Development Project (HDRP) is a project, cosponsored by DOE and the Electric Power Research Institute, to study the effects of long-term dry storage and transportation on high burnup SNF. The project includes the testing of mechanical properties of 25 high burnup SNF rods ("sister rods" or "sibling pins") to establish a baseline prior to storage and transportation. The sister rods include fuel with Zircaloy-4, low-tin Zircaloy-4, ZIRLO®, or M5® cladding.

[8] Dr. Caruso noted that these were some examples and not intended to be a comprehensive list of all of the Swiss ATF R&D.

performance. The approval process includes irradiation of lead test assemblies that include the new fuel design, in-pool inspections of the fuel, and detailed post irradiation examination of the fuel. The Gösgen nuclear power plant supports many of these activities.

The ENSI approval process for a new fuel design includes an evaluation of the safety of the fuel during all phases of the fuel life cycle, including fuel performance in the reactor, during storage and transportation, during pre-disposal operations (e.g., encapsulation), and during the post-closure period. As the implementor of the radioactive waste disposal program in Switzerland, Nagra [the National Cooperative for the Disposal of Radioactive Waste] is involved in the process to evaluate the performance of new fuel designs in pre-disposal and disposal scenarios.

Dr. Caruso discussed the characteristics of new fuel designs that are important during transportation, storage, and disposal. Fuel assembly and cladding integrity (as affected by cladding oxidation, burnup levels, hydride reorientation, etc.) and radiation shielding are key features considered when evaluating the fuel for transportation, storage, and pre-disposal operations (e.g., encapsulation). For post-closure safety, no credit is taken for cladding integrity, but other fuel characteristics, such as burnup credit (for criticality safety), the potential rate of radionuclide release, and the decay heat of the fuel are important factors that are taken into account.

To evaluate SNF performance, KKG is also participating in several international activities. KKG, Nagra, and Framatome have a joint program that is evaluating the long-term aging of fuel assembly structural components by simulation of the aging process during dry storage; Dr. Caruso noted that this is an important pre-disposal activity for Nagra.

Sweden
Dr. Anders Sjöland (SKB [Svensk Kärnbränslehantering AB]) described the Swedish nuclear industry, the types of ATFs being developed in Sweden, and the Swedish approach for management of SNF resulting from ANF/ATF. SKB is owned by the Swedish utilities and its mission is to manage and dispose of nuclear waste in Sweden. Like many other nations, Sweden's leading ATF candidates include coated zirconium alloys and chromium-doped UO_2 fuels in the near-term. Longer-term candidates include higher enriched (fuel enrichments of 5 to 6% uranium-235) UO_2 fuels and FeCrAl and SiC composite claddings.

In contrast to the United States, all fuels proposed for Swedish nuclear power plants have to be approved in advance by SKB and the Swedish regulator to ensure that the resulting SNF is compatible with the waste management program, including transportation, intermediate wet storage, encapsulation, and disposal. Approval of new nuclear fuel is typically a nine-month process, and involves formal decision making meetings. New nuclear fuel designs are reviewed to ensure that the resulting SNF will meet certain acceptance criteria, including dimension and weight limits, criticality safety requirements, radiation levels, and mechanical integrity.

According to Dr. Sjöland, SKB and the regulator can refuse to allow utilities to load a new fuel type if it has not been demonstrated to meet the transportation, storage and disposal requirements, or if the resulting SNF will result in significant increases in the cost of the waste management program or require changes to the current waste management infrastructure. The fuel also has to have a low dissolution rate in water over a long period, which is considered a major test for acceptability for disposal. Accordingly, the doped UO_2 fuels have already been approved for use in Swedish reactors. Regarding the possibility of using more advanced ATF designs, Dr. Sjöland noted that there is a limitation in Sweden that nuclear fuel must have a UO_2 fuel matrix, and no other fuel matrix is accepted.

United Kingdom (U.K.)

Mr. Dave Goddard and Mr. David Hambley (both from National Nuclear Laboratory [NNL]) summarized ATF R&D in the U.K., described the U.K. approach to licensing new fuels, and explained the decision making required prior to the loading of new fuel designs in existing reactors. Mr. Dave Goddard provided technical details on some of the current ATF R&D at NNL, including claddings and high density fuels that are similar to the U.S. ATF candidate designs. The ATF designs include chromium-coated zirconium alloy cladding and other coatings on zirconium alloy claddings, SiC composite claddings, and iron-based claddings. New fuel matrix materials include doped UO_2, composite fuel, fuels with higher thermal conductivity, fuels with higher enrichments, and high density fuels. NNL engages in several international collaborations to develop ATFs including irradiation and non-destructive post irradiation examination at the Massachusetts Institute of Technology reactor facilities, burst tests at ORNL, quench tests at Karlsruhe Institute of Technology in Germany, and participation in the Nuclear Energy Agency-Framework for Irradiation Experiments international fuel and materials testing program. Mr. Goddard described the Advanced Fuel Cycle Program in UK in which two of the areas of focus (one in future fuels and one in recycling of fuels from future reactors) are being led by NNL, and he noted how bringing the two focus areas together helped ensure the right decision-making. Mr. Goddard stated that, for the near-term ATF concepts such as coated zirconium alloy claddings, commercial deployment is not expected to be limited by waste management considerations. However, longer-term advanced claddings or high density fuels will require substantially more R&D, including research on the implications for SNF storage, transport, and disposal. He further indicated that testing of irradiated fuels will be necessary, under conditions to simulate storage and disposal.

Mr. David Hambley discussed the U.K. national policy to transition from a closed fuel cycle to an open fuel cycle and the U.K. process for managing SNF. He described the roles of the utilities and the developer of the waste management program, Radioactive Waste Management (RWM), in preparing for the introduction of new fuel designs. Mr. Hambley stated that the U.K. regulatory process requires demonstration of fuel lifecycle management prior to new reactor builds and before a new fuel design can be used in U.K. nuclear power plants. Disposability of new fuels is a consideration by regulators and environmental agencies, but it is not a part of the formal licensing process. According to Mr. Hambley, the disposability assessment process is a "confidence-building measure" by the applicant to show that materials can be packaged in a manner that is compliant with the geologic disposal facility design assumptions and provides a route to adapt the geologic disposal facility concept or design, if required. Another consideration that is not a part of the formal licensing process is the generic design assessment process. This process is a way of providing fuel vendors and reactor designers the confidence that a design can be licensed before production or construction, respectively, are started. Mr. Hambley noted that this helps RWM to avoid future potential liabilities.

A panel session discussion followed the technical information sessions. The purpose of the panel discussion was to identify the main implications of ANF/ATF on SNF management and disposal based on the materials presented during the two days of the public meeting. The panelists were also asked about R&D activities that would help countries interested in ANF/ATF designs for their LWRs understand the implications of such a change. The panelists then also shared their views on opportunities for international collaboration in planning for SNF management of ANF/ATF. Finally, the panelists discussed the kinds of regulatory changes related to SNF management that needed to be implemented to support the use of ANF/ATF. The panel discussion helped to highlight the importance of early stakeholder engagement and creating a discussion with a broader community (that includes implementors, regulators, and utilities) to support the introduction of the use of new fuel types. Discussions also ensued on the kinds of early R&D activities that would help prepare countries that are interested in ATF (which oftentimes involves interest in developing the same types of fuels and claddings) and preparing to manage and dispose of the resulting SNF.

Board Findings, Conclusions, and Recommendations

After discussing and examining the information presented at the fact finding meeting and the public meeting, the Board has derived several findings, conclusions, and recommendations as noted below.

Findings and Conclusions:

- Certain other countries developing ATFs have taken waste management issues (disposability, cost, fuel matrix composition, etc.) into account when approving new fuel designs for use in nuclear reactors. In contrast, in the United States there appears to be little, if any, consideration of waste management issues during the development of new ANF/ATF.

- Pursuant to the Congressional direction to improve the safety of LWR fuel technology for existing reactors in the event of accidents, development of ANF/ATF is one of DOE-NE's highest priority R&D programs. The R&D is conducted at various national laboratories and is led by commercial fuel vendors. However, the Board notes that the current coordination and level of integration on R&D activities among the two involved DOE-NE offices responsible for ANF/ATF development (the Office of Nuclear Fuel Cycle and Supply Chain) and spent ANF/ATF disposition (the Office of Spent Fuel and Waste Disposition) appear to be limited, and only preliminary considerations have been made regarding plans for storage and transportation of the SNF that will result from the use of ANF/ATF.

- DOE is working with organizations in other countries (e.g., the Nuclear Energy Agency, the Institut de Radioprotection et de Sûreté Nucléaire, and the Japan Atomic Energy Agency) on a variety of topics related to ATFs. The Board commends DOE for funding this work and helping to facilitate collaborative research with international partners, but the Board notes that collaborative international research on SNF management including disposal of ANF/ATF is also warranted.

- Since the 2011 Fukushima Daiichi accident, early stakeholder and general public engagement on advancements in nuclear technology have had an impact on public trust in nuclear energy. The Board observes that, in some other countries, the same considerations for early stakeholder and public engagement in ATF development occur in all parts of the fuel cycle. This early engagement provides additional confidence in the acceptability of a new fuel design for current waste management infrastructure and is considered a part of successful implementation of the new fuels. Within the DOE-funded ATF program, there is currently only limited information available to the public regarding the impacts of the new fuels on the various stages of the fuel cycle.

- The scope of the high-level "gap analysis" report (SNL 2021) on managing SNF resulting from the use of ANF/ATF is limited to storage and transportation. The Board notes that relevant fuel vendor data and results, international lessons learned, and preliminary disposal considerations for ATF and other advanced fuels would enhance the next update of the gap analysis report.
  - Sweden, for instance, considers fuel matrix dissolution rate in a repository environment an important consideration for waste management planning when it is reviewing new, proposed ANF/ATF.

- DOE's current SNF post-irradiation examination plans are limited to testing specimens that are like the zirconium alloy-clad "sibling pins" in DOE's HDRP and will be tested in the same facilities. Some of the other proposed ATF claddings include very different materials compared to zirconium alloy or coated zirconium alloy ATF claddings, paired with different fuel forms, and could include fuel designs with higher enrichments of uranium. Thus, ANF/ATF may require different approaches and facilities.

- DOE's investment in ATF and its commitment to support fuel vendors is substantial; thus, DOE may be able to leverage that support to obtain some of the fuel performance data it needs from the vendors to prioritize R&D programs and to optimize the entire fuel cycle, including disposal.
  - Characterization data obtained from irradiated ATF specimens and the specimens themselves could be shared among DOE offices, including the Office of Spent Fuel and Waste Disposition.
  - The high-level gap analysis report on ATF storage and transportation (SNL 2021) was prepared without access to or the opportunity to consider relevant and important fuel vendor data, including the potential impacts of using higher enrichments nuclear fuels that can achieve higher burnups. Higher enrichments and higher burnups, among other SNF characteristics, can significantly affect how SNF performs during storage, transportation, and disposal.

Board Recommendations:

1. *The Board recommends that the DOE Office of Spent Fuel and Waste Disposition coordinate and integrate in an ongoing fashion with the DOE Office of Nuclear Fuel Cycle and Supply Chain on preparing for the storage, transportation, and disposal of SNF resulting from deploying ANF/ATF in existing LWRs. Steps that can be taken include, but are not limited to, forming collaborative working groups, sharing laboratory*

facilities and equipment, and sharing irradiated fuel specimens and fuel characterization data.

2. *The Board recommends that the next update to DOE's gap analysis report for SNF management be expanded in scope beyond storage and transportation to include disposal of SNF resulting from the use of ANF/ATF.*

3. *The Board recommends that DOE-NE work to improve its access to fuel characterization data obtained during DOE-sponsored ANF/ATF development programs. Some of these data are important for assessing and closing the knowledge gaps related to ANF/ATF storage, transportation, and disposal.*

4. *The Board recommends that DOE evaluate the approaches used and experiences gained in other countries regarding early consideration of the potential impacts of new ANF/ATF designs on SNF storage, transportation, and disposal. Based on the lessons learned in other countries, DOE should implement mechanisms to provide feedback to ANF/ATF development work that accounts for the impact of these new fuels on SNF management and disposal. The feedback process can also be used to prioritize SNF management research and development.*

5. *The Board recommends that DOE increase the accessibility of ATF information to the general public in the interest of clearly demonstrating openness, facilitating public engagement, factoring in public concerns in planned R&D, and avoiding the perception that there may be unexplored or unresolved issues (including issues affecting SNF management and disposal) related to the introduction of the new fuel designs.*

The Board thanks DOE for the efforts of its staff and those of the national laboratories to prepare detailed technical presentations, and we thank all for their participation in the meeting. We look forward to continuing our ongoing review of DOE's technical activities related to managing and disposing of SNF and high-level radioactive waste.

Sincerely,

{Signed by}

Jean M. Bahr
Chair

Appendix

This Appendix provides further information about the types of advanced nuclear fuels (ANF) including accident tolerant fuels (ATF) within the scope of the public meeting. The ANF/ATF included in the discussions can be divided into two groups: “near-term” fuels and “longer-term” ATFs, which include claddings and fuel designs. Near-term ANF/ATF generally include chromium-coated and ARMOR-coated zirconium alloy claddings and doped UO_2 fuels (i.e., the UO_2 fuel matrix includes additives to improve the performance of fuel during irradiation). A doped UO_2 fuel has a higher density than traditional UO_2 fuel. In these fuels, sintering additives of chromium and aluminum (as in the doped UO_2 pellets) are typically incorporated to help form a denser fuel matrix that improves fuel performance and helps extend core cycle length (OECD 2018).

In contrast, longer-term ATF designs will require more R&D and potential, additional regulatory changes to support commercial operation. Longer-term ATF cladding materials include iron-chromium-aluminum (FeCrAl) and silicon carbide (SiC) composite claddings, that will replace zirconium alloy claddings and are envisioned to be paired with doped or other high density fuels. Longer-term fuel matrix designs aim to achieve higher fuel density, make use of higher enrichments of uranium-235, and achieve higher burnups. Although ATFs with FeCrAl cladding were among the first to be tested in commercial nuclear reactors (see Figure A1), licensing of the FeCrAl cladding concept has fallen behind that of the other near-term ATF concepts.

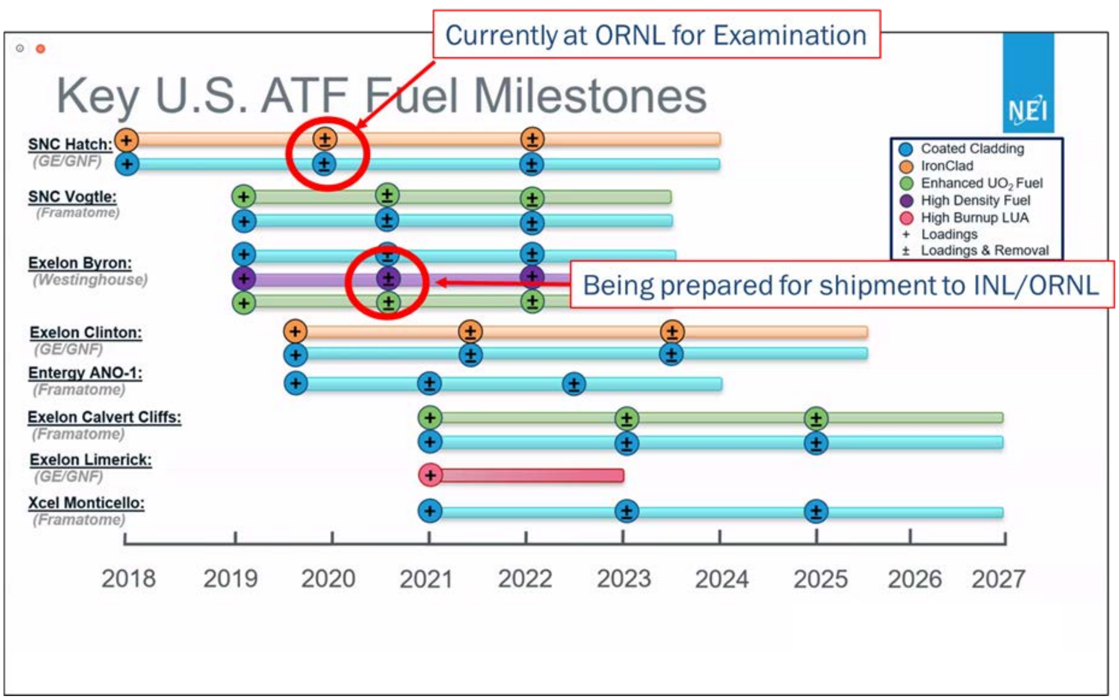

Figure A1. Industry-led lead test assemblies and lead test rods at eight commercial reactors for full-scale irradiation testing of ATFs. (Original image source: Nuclear Energy Institute, 2021, modified and adopted from Dan Wach’s presentation, May 12, 2021, NWTRB Spring 2021 Meeting, https://www.nwtrb.gov/docs/default-source/meetings/2021/may/wachs.pdf?sfvrsn=4; Acronyms: SNC is Southern Nuclear Company; ANO is Arkansas Nuclear One; LUA is lead use assembly).

Therefore, the Board considers the FeCrAl cladding concept to be grouped among the longer-term ANF/ATF designs. Other longer-term fuel matrix compositions like uranium nitride (UN) are being actively considered by the fuel vendors; uranium silicides were once considered a part of the DOE ATF program but are no longer considered an ATF candidate due to compatibility issues with LWR water chemistry.

Figure A1 was presented by Idaho National Laboratories (modified from original source: NEI 2021) in its presentations. The candidate ATF fuels (see Figure A1, legend) and the status of loadings and removals of lead test assemblies (commercial irradiation testing) are shown. The ATF design concepts being tested include chromium and other coatings on zirconium alloy cladding, FeCrAl cladding, chromium and aluminum doped UO_2, and other fuel loadings that are intended to be utilized to higher burnups. The left side of Figure A1 indicates the eight commercial reactors that are involved in the full-scale testing demonstrations; the fuel vendor name appears in parentheses. The ATF fuel loadings (+) and removals (-) are indicated in the figure. The graphic further indicates that two sets of lead test assemblies have completed their irradiation cycles and have been discharged for shipment and post irradiation examinations at national laboratories.

Another longer-term fuel design is the Lightbridge Fuel design which is a private venture with some on-going DOE national laboratory support, such as GAIN [Gateway for Accelerated Innovation in Nuclear] vouchers that give recipients access to DOE's national laboratory facilities for research. Lightbridge has been award GAIN vouchers to support initial irradiation testing and fuel fabrication for their fuel. Lightbridge Fuel is a uranium-zirconium alloy helical rod with a metallurgically bonded zirconium-niobium cladding. Many of these new fuel designs, including Lightbridge Fuel, use uranium enrichments[9] of between 5% and 20% uranium-235 and will achieve higher burnups than conventional fuel designs. This can improve fuel efficiency and cost savings during reactor operations.

References:

OECD. 2018. *State-of-the-Art Report on Light Water Reactor Accident-Tolerant Fuels*. NEA No. 7317. Paris, France: Nuclear Energy Agency. Organization for Economic Co-Operation and Development. October.

SNL. 2021. *High Level Gap Analysis for Accident Tolerant and Advanced Fuels for Storage and Transportation*. SAND2021-4732, Revision 6. Albuquerque, New Mexico: Sandia National Laboratories. April 2021.

[9] Note the current U.S. LWR fleet uses low enriched uranium, i.e. uranium with an assay below 5% uranium-235. DOE is funding the development of a commercial domestic HALEU capability. See "What is High-Assay Low-Enriched Uranium (HALEU)," https://www.energy.gov/ne/articles/what-high-assay-low-enriched-uranium-haleu, April 7, 2020 (last visited 6/9/2021).