UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
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May 23, 2016

Mr. John Kotek
Acting Assistant Secretary for Nuclear Energy
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Dear Mr. Kotek:

The Nuclear Waste Technical Review Board (Board) held its 2016 Winter Meeting in Knoxville, Tennessee, on February 17, 2016, to review U.S. Department of Energy (DOE) research and development activities related to the performance of high-burnup[1] commercial spent nuclear fuel (HBF) during storage and transportation. The public meeting included speakers from DOE, the U.S. Nuclear Regulatory Commission, and national laboratories. Based on presentations given at the meeting, the Board offers several observations and recommendations noted below. Because of the large scope of HBF research activities and the time limitations of a one-day public meeting, not all research topics were discussed. Therefore, the Board plans to conduct follow-up discussions with DOE and laboratory technical experts to obtain additional information. The Board's staff are in contact with your staff to make the needed arrangements.

The Board recognizes the level of effort and coordination required to prepare for a public meeting of this type and thanks your staff and the technical experts from the national laboratories for their work preparing for the meeting and providing informative presentations. The meeting agenda, presentation slides, transcript, and an archived version of the meeting webcast are all available on the Board's website at www.nwtrb.gov/meetings.

In conjunction with the public meeting, several Board members and staff members toured some of the facilities at the Oak Ridge National Laboratory (ORNL) on February 16, 2016. The tour was planned and coordinated by Mr. Rob Howard of ORNL and was extremely informative. The ORNL staff involved in the tour described HBF testing equipment and research, which was very helpful to the Board members in understanding the unique issues involved with testing irradiated material. The laboratory tour was also particularly useful in providing a perspective for the research activities discussed during the Board's public meeting.

Background

History. Dry storage of commercial spent nuclear fuel (SNF) began in the 1980s when utilities needed to remove relatively low-burnup fuel[2] from the spent fuel storage pools at reactor sites to allow space for additional SNF to be stored from reactor operations. Extensive analysis, testing,

[1]Burnup is a measure of the amount of thermal energy produced per unit mass of nuclear fuel. In the U.S., "high-burnup" fuel is defined as fuel with a burnup greater than 45 gigawatt-days per metric ton uranium (GWd/MTU).
[2]In the early 1980s, SNF burnup was typically limited to 35 GWd/MTU.

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and modeling were conducted to determine the potential degradation mechanisms and changes in SNF cladding mechanical properties during both normal and accident conditions of storage and transportation. Based on the early studies of fuel with burnups of less than 35 GWd/MTU, researchers concluded that no change in the condition of the low-burnup fuel was expected during dry storage and transportation. Subsequently, two complicating issues arose in extending the earlier conclusion to HBF.

The first issue is the evolving condition of the SNF in dry storage systems. For example, at a Board meeting held in Las Vegas in 2009, a panel composed of representatives of nuclear utilities, a firm that makes dry storage systems for SNF, and the Electric Power Research Institute concluded that understanding the evolving condition of the SNF in dry storage systems is important because it must be shipped, possibly repackaged, and eventually disposed of after a potentially long period in dry storage. The technical implications of long-term dry storage had not been previously investigated. The Board continued its review of extended storage activities and documented its findings and recommendations in a 2010 report, *Evaluation of the Technical Basis for Extended Dry Storage and Transportation of Used Nuclear Fuel.*

A second issue also arose when fuel manufacturers introduced fuel assembly designs that allowed the fuel to reach higher burnups. As fuel burnups increased, changes in the fuel occurred more rapidly than had been observed previously, such as increased mass concentration of metal hydrides in the cladding and higher internal fission gas pressure, As a result, the cladding may be subjected to increased stress. These changes appear in fuel with burnups above 45 GWd/MTU and usually increase with burnup.

The increased mass concentration of metal hydrides in the cladding and their orientation will, to varying degrees, reduce the ductility of the cladding (the ability of the cladding to stretch while retaining its integrity, as opposed to fracturing). Initially, the metal hydrides in the cladding are in the form of platelets aligned as along the direction of the rim of a wheel (circumferential hydrides) when the SNF cools during pool storage. However, when SNF is loaded into dry-storage canisters and vacuum-dried, the fuel temperature temporarily increases significantly, causing greater internal rod pressure and greater stress on the cladding. When the cladding cools following canister loading, drying, and sealing in a storage cask, the hydrogen will precipitate again as hydrides, but may be in the form of platelets aligned as in the direction of the spokes of a wheel (radial hydrides). This phenomenon is called hydride reorientation. The cladding may become more brittle (embrittlement) than with only circumferential hydrides. When the applied stress due to internal pressure and external loads during transportation is perpendicular to the radial hydrides, the cladding is more susceptible to fracturing during handling and transportation to an extent depending on many factors.[3]

Well-established models of hydride reorientation and internal pressure effects can predict the embrittlement behavior of low-burnup fuel. However, these models have not been adapted to and verified for HBF. As a result, DOE undertook more work to determine the applicability of the existing embrittlement models to HBF during extended dry storage and to determine the implications of model results for the probability and consequences of degradation of HBF during subsequent normal transportation operations or transportation accident conditions.

[3] See Dr. Louthan's presentation at the Board's February 17, 2016, meeting.

Current Research Activities In response to growing uncertainties about the performance of HBF during extended storage and subsequent operations, DOE initiated new research efforts. Three of the more significant DOE efforts are the High Burnup Dry Storage Cask Research and Development Project (HDRP),[4] the study of vibrational loads on SNF expected during rail or road transportation, and research to better understand the effects of hydride reorientation on cladding embrittlement. These three efforts were discussed at the Board's public meeting in Knoxville and are summarized in the following subsections.

High Burnup Dry Storage Cask Research and Development Project — Dr. Brady Hanson of the Pacific Northwest National Laboratory (PNNL) presented an update on the HDRP during the Knoxville meeting. In this project, Dominion Virginia Power will load a dry storage cask, modified to include instrumentation, with a variety of HBF assembly types, take initial cask gas samples, seal the cask, and store it for ten years while monitoring fuel temperatures. After ten years in storage, DOE plans to open the cask and withdraw selected fuel rods to undergo characterization in hot cells.

DOE removed 25 "sister rods" from the SNF assemblies that will be placed in the HDRP dry storage cask or from assemblies of the same design and with the same operational power history as the assemblies to be placed in the HDRP dry storage cask. The sister rods will be characterized in hot cells at ORNL and PNNL. The characterization effort will determine the initial characteristics of the sister fuel rods for comparison with the final characteristics of the fuel rods to be withdrawn from the HDRP cask after ten years of dry storage.

In early 2014, the Board provided comments on the HDRP in a letter to DOE Assistant Secretary Peter Lyons during the initial planning stage of the HDRP.[5] Three Board observations from the letter were the need to: 1) use passive instrumentation that can be attached to or installed in the cask to monitor the condition of the HBF, 2) conduct more than one dry storage cask demonstration or examine the condition of the fuel and storage system materials in several casks that contain SNF and have a range of burnups and storage histories, and 3) place a high priority on establishing the capability and infrastructure to receive and open dry storage casks to examine HBF in a dry environment. *Time constraints during the Knoxville meeting prevented full discussion of all these topics. Therefore, the Board plans to include these topics in the follow-up discussions with DOE and laboratory technical experts.*

Vibrational Effects — Results from the second DOE effort, vibrational effects research, were presented by three speakers[6] at the Knoxville meeting. This research is designed to obtain data concerning the effects of the stresses that HBF will experience during transportation. This effort includes tests to determine the number of vibrational cycles that will lead to cladding failure for fuel rods under a variety of vibrational stresses. In addition, measurements of actual road vibrational loads to which the fuel rods will be subjected were made using simulated casks and

[4] See the *High Burnup Dry Storage Cask Research and Development Project, Final Test Plan*, Rev. 0, February 27, 2014, Electric Power Research Institute.

[5] Letter to Dr. Peter Lyons, *Comments on the DOE Research and Development Program Related to Long-Term Dry Storage of High Burnup Spent Nuclear Fuel*. June 5, 2014.

[6] Drs. Bevard, McConnell, and Tang.

payloads. DOE plans call for measurement of vibrational loads to which SNF will be subjected during transportation to be made in the near future using a full-size rail cask.

Hydride Reorientation — Dr. Mike Billone of the Argonne National Laboratory, and Dr. Mac Louthan, a consultant to the Savannah River National Laboratory, discussed research on hydride reorientation. This effort includes research to better understand changes in cladding properties and degradation mechanisms during storage and transportation due to hydride reorientation, and the resulting implications for cladding embrittlement.

Board Observations and Recommendations

Although the presentations at the meeting in Knoxville provided the Board with insight into a number of the important scientific issues, these issues need to be framed in the context of risk by addressing components of risk:[7]

- **What can go wrong?** For example, what degradation of HBF cladding might occur, leading to an unsafe condition (*e.g.*, HBF cladding rupture and release of radioactive material)?

- **How likely is it?** For example, what is the probability that HBF cladding will degrade due to embrittlement and fracture from the loads imposed on the HBF during normal and accident conditions of storage and transportation?

- **What are the consequences?** For example, what would be the result of HBF cladding failure in terms of release of radioactive material and radiation exposure to workers and the public?

Recommendation 1 - The Board recommends that the research program be structured such that the focus is on the likelihood and consequences of cladding failure during interim storage, transportation, possible repackaging, and eventual disposal of HBF in a repository.

Relating Behavior of Unirradiated Cladding to Irradiated Cladding. The Board recognizes that testing irradiated fuel and cladding is extremely difficult and expensive. It is very costly to maintain the facilities and equipment required to conduct tests on irradiated material and, as a result, the test data are scant. Moreover, the data available from testing irradiated cladding have a built-in uncertainty due to the variability of the type of cladding and its characteristics after irradiation. For example, in irradiated fuel rods, there is variability in cladding hydride mass concentration in the radial, axial, and circumferential directions. The applicability of the resulting data-dependent models may be limited to only the cladding types and burnups from which a significant amount of experimental data were obtained.

Testing unirradiated materials[8] is significantly easier and less expensive than testing irradiated materials, as testing can be conducted in unshielded facilities where equipment is much easier to

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[7] S. Kaplan and B. J. Garrick, "On the Quantitative Definition of Risk", *Risk Analysis*, Vol. I, No. I, 1981.

[8] In this letter, the term "unirradiated materials" also includes ion-beam-irradiated materials, which are not as radioactive as reactor-irradiated materials and can be characterized more easily than reactor-irradiated materials.

maintain. Consequently, more material types, specimens, and conditions can be tested, and there is the added benefit that testing can also be done in university facilities where costs are lower and the next generation of nuclear materials scientists is being trained.

However, the data obtained from research conducted on unirradiated fuel and cladding need to be defensibly related to the actual behavior of irradiated SNF during storage and transportation. This was one of the major conclusions Dr. Mac Louthan presented in his talk[9] analyzing the outcome of the DOE-sponsored American Society for Testing and Materials meeting[10] on hydride reorientation in Jackson Hole, Wyoming, in June 2014. In its follow up discussions with DOE, the Board plans to include discussion of the applicability of current and future models to other zirconium cladding compositions such as Ziron (Zr-1%Fe) irradiated under different conditions.

Recommendation 2 - The Board recommends that DOE develop a physical-chemical model that relates the behavior of unirradiated cladding to the behavior of irradiated cladding. This work should also include experimental work to test the model's predictions and evaluate the associated uncertainties.

High Burnup Dry Storage Cask Research and Development Project. The presentations by Mr. Ned Larson of DOE and Dr. Brady Hanson of PNNL mentioned that the goal of the HDRP was to "collect data to validate and confirm the technical basis for extended storage of high-burnup spent fuel." The Board interprets this statement to mean that the ongoing DOE work is aimed at confirming the view of DOE and others that the existing understanding of low-burnup fuel forms a reliable basis for predicting the behavior of HBF during extended storage and transportation.

The Board notes that focusing on confirming the current understanding and assumptions can narrow the focus of research and development, which may mean that other potentially important degradation mechanisms and processes are not identified. Additionally, time did not allow full discussion of the HDRP's plans to potentially obtain gas samples from the dry storage cask during the ten-year storage period or to examine the fuel rods to be extracted from the dry storage cask after ten years of storage. These are aspects of the HDRP the Board intends to discuss with DOE and national laboratory technical experts during the follow-up discussions.

A number of studies on HBF characterization and performance are being conducted in other parts of DOE or other national laboratory programs and by other countries. Mr. Larson noted that the DOE Office of Nuclear Energy is funding university research through its Nuclear Energy University Programs. It was not clear how the results of these studies were used, or will be used, in the overall technical evaluation of HBF performance. The Board believes all sources of relevant information should be considered when drawing technical conclusions and will discuss this issue in the follow-up discussions with DOE and the national laboratory technical experts.

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[9] Dr. Louthan stated that the conclusions were his and did not necessarily reflect the DOE position.

[10] 2nd ASTM International Workshop on Hydrides in Zirconium Alloy Cladding, June 10, 2014, Jackson Hole, WY

Recommendation 3 - The Board recommends that DOE make transparent how it integrates the results from Nuclear Energy University Programs, and other relevant U.S. and foreign research activities into its overall research program on HBF degradation.

Focus of the Board Follow-up Discussions with DOE

As noted above, time constraints during the meeting on February 17, 2016, meant that not all of the issues associated with HBF performance during storage and transportation could be discussed fully, and some were not discussed at all. Consequently, the Board is planning additional discussions with representatives of the DOE Office of Nuclear Energy and their technical experts from the laboratories. The follow-up issues include, for example, the effect of vibrational loads measured in road and rail transportation tests on the probability of degradation of cladding during normal transportation conditions, the consequences of cladding degradation, the applicability of cladding embrittlement data obtained from testing unirradiated cladding to embrittlement of irradiated cladding, details of the characterization of the "sister rods" planned at ORNL and PNNL and how the resulting data will be used, and details of plans for gas sampling in the HDRP cask

These additional discussions will provide insights necessary for the Board to review the DOE program that addresses research and development related to HBF extended storage and transportation. In addition, the Board will want to discuss the thermal and structural modeling efforts related to HBF cladding degradation during dry storage and transportation.

On behalf of the Board, thank you again for the participation of the DOE Office of Nuclear Energy staff and technical experts from the national laboratories at the February meeting. We look forward to your response to the Board's recommendations.

Sincerely,

Rodney C. Ewing
Chairman