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Package Performance Study: A Historical Perspective and Planning for a Path Forward

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Abstract — *The topic of spent nuclear fuel (SNF) transportation often draws public attention and concerns regarding safety, and with large-scale shipping campaigns expected in the future, public interest is anticipated to substantially increase.*

In 1999, the U.S. Nuclear Regulatory Commission (NRC) began an initiative called the Package Performance Study (PPS) that initially focused on SNF transportation cask responses to severe transportation accidents. A public participation approach was to be used to help guide the scope and parameters of the study, which was also to consider using full-scale physical testing of a SNF transportation cask, where appropriate. In 2010, the NRC decided not to go forward with physical testing as proposed.

In 2006, the National Academy of Sciences (NAS) conducted a study on SNF and high-level radioactive waste transportation in the United States. The NAS study recommended that full-scale cask testing, as well as other accepted methodologies, continue to be used as part of the package performance evaluation. In 2012, the Blue Ribbon Commission on America's Nuclear Future (BRC) recommended conducting the PPS with a full-scale rail transportation cask for the purpose of building public trust and confidence in the safety of SNF transport.

In 2021, the U.S. Department of Energy (DOE) restarted a consent-based siting process, focusing on how to site federal facilities for the interim consolidated storage of SNF using a consent-based approach. Large-scale SNF transportation would be necessary for any such interim storage facility. As the planning activities begin for future large-scale shipping campaigns, the DOE is considering options for conducting a DOE-led PPS to help build public trust and confidence in the transportation of SNF. Therefore, the DOE is gathering information related to the previous NRC-led PPS efforts, as well as applicable international experience with the testing of SNF packages. This paper discusses previous NRC efforts, as well as the current status of a DOE-led PPS, which is in the early planning stages.

Keywords — *Package performance study, PPS, spent nuclear fuel, transportation, public participation approach.*

Note — *Some figures may be in color only in the electronic version.*

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I. U.S. NUCLEAR REGULATORY COMMISSION–LED PACKAGE PERFORMANCE STUDY HISTORY

In 1999, the U.S. Nuclear Regulatory Commission (NRC) began an initiative called the Package Performance Study (PPS) that was to focus on spent nuclear fuel (SNF) cask responses to severe transportation accidents. The PPS was going to be unlike the three previous transportation risk studies (NUREG-0170,[1] NUREG/CR-4829,[2] and NUREG/CR-6672)[3] that were conducted by the NRC, in that it was going to use a public participation approach where the public and stakeholders would help guide the scope and parameters of the study. Additionally, one of the main differences between the PPS and the previous transportation risk studies was that PPS was to consider using full-scale testing of SNF transportation casks, where appropriate.

As discussed in this paper, the evolution of the PPS test programs proposed by the NRC at various times included extra-regulatory, regulatory (i.e., consistent with requirements in 10 CFR Part 71),[4] and/or demonstration tests. Figure 1 shows the progression or timeline of the NRC-led PPS using selected documents that are discussed in this paper.

I.A. PPS Activities in 2002

In 2002, NUREG/CR-6768[5] (also known as the "Issues Report") was published to present the results of the scoping phase of the PPS. One of the objectives of the scoping phase was to solicit public and stakeholder comments as a means to identify the type of research that could be conducted to increase public confidence in the safety of SNF transportation. NUREG/CR-6768 considered issues and concerns that were brought up at the associated public meetings, as well as questions and comments that were submitted to the NRC as a result of those meetings.

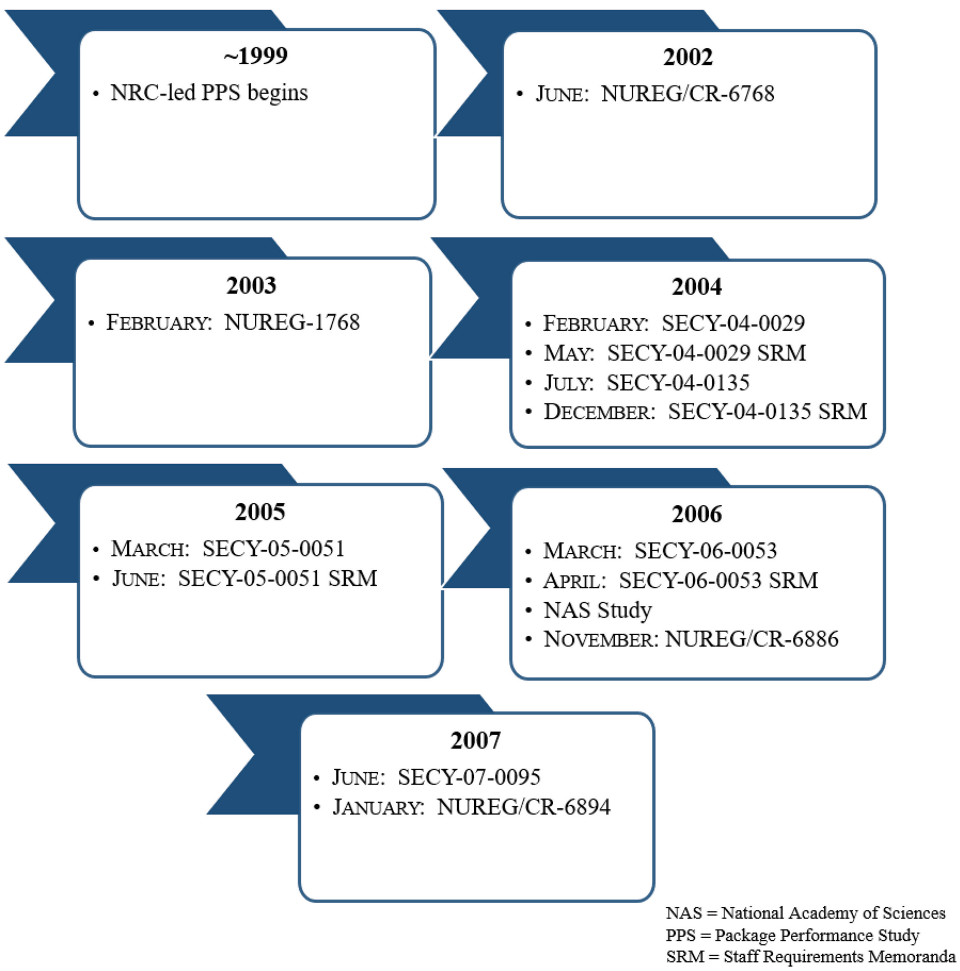

Fig. 1. Timeline of selected documents discussed from the NRC-led PPS: 1999 to 2007.

I.B. PPS Activities in 2003

In 2003, NUREG-1768[6] (also known as the "Test Protocols Report") was published to present the preliminary plans for the PPS, but also asked for comments on those preliminary plans (i.e., the test protocols) from the public and stakeholders. The NRC anticipated that public comments could result in changes to the underlying test approaches and plans.[6] The proposed test plan presented in NUREG-1768 was extreme impact and fire tests on a NRC-certified rail transportation cask and a truck transportation cask [e.g., high-speed impact with an unyielding surface and a fire test longer than the 10 CFR 71.73(c)(4)-specified 30 min]. There were four dominant public comment themes that came from the various interactions between the NRC and the public (e.g., public meetings, comment letters) with two of those themes, full-scale testing to regulatory limits and realistic testing scenarios, shaping the PPS going forward.[7]

I.C. PPS Activities in 2004

In February 2004, the NRC staff presented four testing options to the Commission[a] in SECY-04-0029,[7,b] with Option 1 being the testing proposed from NUREG-1768 and the other three options being different variations of regulatory rail or truck, or demonstration rail or truck tests. Note that Attachment 1 to SECY-04-0029 also identified four additional impact and fire tests using Commission guidance and public comments that could be conducted in various combinations as part of the PPS.

In May 2004, the Commission approved testing of a full-scale NRC-certified rail transportation cask, one that was currently being used or was expected to be used in the foreseeable future for the transport of SNF, in the SECY-04-0029 Staff Requirements Memoranda (SRM).[10,c] The Commission stated that the test of the cask shall consist of a realistically conservative demonstration test (e.g., a train traveling 75 mph) and fully engulfing fire. One of the criterion for the tests stated in the SECY-04-0029 SRM was that there should not be a need to conduct additional tests on other certified casks after this testing was completed (i.e., the tested cask should be representative of those being used or expected to be used in the foreseeable future).

In July 2004, the NRC staff proposed a demonstration test in SECY-04-0135[12] involving the collision of a locomotive and rail transportation cask attached to a railcar. This scenario was based on a 1995 accident that involved three trains, one of which was stopped and impacted at a low speed by a second train, that resulted in a derailment of a railcar that overturned onto an adjacent track and was subsequently struck by a third train at a relatively high speed. Note that as directed by the Commission in the SECY-04-0029 SRM, the NRC staff also added a fully engulfing fire; however, they provided two options.

For the first option, the NRC staff considered a fully engulfing fire consistent with the fire scenario in 10 CFR 71.73, which was consistent with the Commission's direction. The cask would be removed from the railcar and placed on a test stand in a fire test pit and the test would be consistent with the regulatory fire [i.e., 10 CFR 71.73(c)(4)]. For the second option, the NRC staff considered a more realistic scenario that would include constructing a "pit" around and under the railcar carrying the cask at its post-impact location. It is noted that the NRC staff had not fully developed this scenario, as the test conditions and boundary conditions would be difficult to define and conduct, and would result in a fire test that could not be predicted or controlled and only measured and assessed after the test. As outlined in SECY-04-0135, the NRC staff recommended the fully engulfing fire since this option was consistent with the Commission's direction in the SECY-04-0029 SRM and would also be a "conservative" post-impact fire test with well-controlled conditions.

As discussed in SECY-04-0135, in order for the NRC staff to develop and propose a demonstration test, they researched items such as accident statistics and accident reports, and considered four hypothetical cask and railcar accident derailment scenarios: (1) cask and railcar impact with a rock outcrop, (2) cask and railcar impact with a tunnel entrance, (3) cask and railcar impact with a bridge abutment, and (4) collision of a locomotive and a cask (attached to a railcar), with the fourth scenario being chosen as described previously (i.e., the 1995 accident scenario). The NRC staff determined that the fourth scenario could represent a "realistically conservative" challenge by potentially imparting enough energy into

[a] The NRC is headed by five Commissioners, with one of the Commissioners designated to be the Chairman and official spokesperson of the Commission. The Commission performs functions such as formulating policies and developing regulations governing nuclear reactor and nuclear material safety.[8]

[b] Note that a SECY is a NRC written issues paper that the NRC staff submits to the Commission to inform them about policy, rulemaking, and adjudicatory matters.[9]

[c] Note that a SRM is NRC documentation of the Commission's decisions on a NRC staff–written issue paper and any related tasks assigned to the NRC staff with the date due.[11]

Fig. 2. GNS CONSTOR® V/TC.[15]

the cask to challenge its integrity.[12] Additionally, the United Kingdom used this accident scenario for a demonstration test that was conducted by the Central Electricity Generating Board (CEGB) in 1984 named "Operation Smash Hit," which is a well-known demonstration test that is discussed further in Sec. IV.

In the December 2004 SECY-04-0135 SRM,[13] the Commission noted that drop testing of two different transportation rail cask designs had been completed in Germany and that these tests "… could provide appropriate data to reaffirm aspects of our existing regulatory approach without the NRC replicating these tests."[13] The Commission was referring to the German Federal Institute for Materials Research and Testing (BAM; Bundesanstalt für Materialforschung und -prüfung) which had performed 9-m regulatory drop tests on two full-scale spent fuel casks: the Gesellschaft für Nuklear-Service mbH (GNS) CONSTOR® V/TC (181 tonnes; see Fig. 2) and the Mitsubishi Heavy Industries, Ltd. (MHI) MSF-69BG (127 tonnes).[14] These tests took place at BAM during the 14th International Symposium on the Packaging and Transportation of Radioactive Materials (PATRAM 2004) technical tours.

While the Commission did approve proceeding with the PPS in the SECY-04-0135 SRM, they provided some modifications from what the NRC staff proposed in SECY-04-0135. They stated that the NRC should conduct "an integral demonstration test (a test that involves the system as a whole and not a test of individual components) as one means of increasing public confidence on the viability of existing spent fuel transportation casks."[13] They stated that the NRC should conduct a demonstration test of a single spent fuel rail transportation cask that represented a viable transportation accident, not necessarily the worst case scenario or a hypothetical accident requiring multiple events to occur simultaneously. The Commission said the test should consist of a simulated rail crossing with the train colliding at a 90-deg angle with a transportation cask on its rail carrier car in a normal transportation configuration.

Note the speed of the train should be "appropriate" and the test would only be the collision and the natural results of the collision. This test would be conducted to demonstrate the robustness of the cask design as well as the overall transportation system. There would be no immersion testing and no fire testing, and the testing should be done at an existing facility, such as the U.S. Department of Transportation's Transportation Technology Center (TTC) testing facility in Pueblo, Colorado.

I.D. PPS Activities in 2005

In March 2005, the NRC staff proposed a test scenario of a fully assembled SNF transportation cask with surrogate fuel assemblies on a carrier railcar that is impacted by another train at a 90-deg angle at 60 mph at a simulated rail crossing (SECY-05-0051).[16] As directed by the Commission in the December 2004 SECY-04-0135 SRM, there would not be any fire testing or immersion testing. The train would be a locomotive with several freight railcars (note that a structural analysis would be performed prior in order to determine the number of freight railcars as well as the load in each of the railcars that would be required to simulate the relevant momentum and energy of an average-length train). The transportation cask would be one that the U.S. Department of Energy (DOE) was likely to use for transport to a repository and would have a current NRC Certificate of Compliance (CoC).

As discussed in SECY-05-0051, the 60-mph[d] speed was determined by the NRC staff after discussions with staff of the Federal Railroad Administration (FRA) and the Association of American Railroads (AAR), who specified that the speed at rail-to-rail crossings is limited to 45 to 50 mph for maintenance reasons. According to the FRA, the track layout at the TTC facility could be modified for testing to be performed at 60 to 70 mph; therefore, the NRC staff determined that a speed of 60 mph would represent a viable, realistic, and conservative scenario, although it would not be a "worst case" accident. Another item that was discussed in SECY-05-0051 was the use of railcars that are manufactured and certified to AAR Standard S-2043.[17] At that time, there were no railcar suppliers that had submitted an application for certification to AAR Standard S-2043, so it was assumed that the railcar used

[d] As stated in SECY-04-0135, the NRC staff had to research defining an appropriate "realistically conservative" impact speed for this scenario. The 1995 accident that the NRC staff was using as a basis involved an impact speed of approximately 50 mph; however, in the SECY-04-0029 SRM, the Commission direction had suggested a speed of 75 mph.

for the SNF transportation cask would be equivalent to one that complies with the standard.

The NRC staff also discussed that they were negotiating a cooperative agreement with BAM to be able to have access to the testing results of the two transportation casks that were tested at the BAM facility. Note the cooperative agreement would also allow the NRC staff to have access to additional future drop tests performed at the BAM facility as well.

The Commission approved the proposed test plan in June 2005, and also requested that the NRC staff add the fire testing scenario involving the fully engulfing, optically dense, hydrocarbon fire for a half-hour duration post collision (SECY-05-0051 SRM).[18] The Commission also stated that the NRC staff should continue to review and analyze full-scale and quarter-scale testing and recommend any enhancements to the PPS that may result from this continued review and analysis. The Commission noted that the proposed test plan from the NRC staff "… is not the final word on this issue, as the project is subject to additional modifications and Commission direction once additional information becomes available."[18] They further stated the NRC staff should continue to negotiate a cooperative agreement with BAM and, if there was a need in the future, the NRC staff should submit a plan to the Commission for full-scale testing to regulatory limits.

I.E. PPS Activities in 2006

In March 2006, the NRC staff provided a PPS status update to the Commission in SECY-06-0053,[19] which included adding the fire test scenario as requested in the SECY-05-0051 SRM. The NRC staff provided the Commission with two transportation cask options for performing the demonstration test. The first option, which was recommended by the NRC staff, was using a transportation cask that DOE was likely to use to transport SNF to a central repository. The transportation cask design would also have a CoC to transport commercial SNF. The NRC staff learned that the schedule for DOE procuring transportation casks had been delayed; therefore, for this option, the demonstration test would be delayed until transportation casks to support the central repository were ordered or the NRC issued a CoC for the transportation cask design, whichever came later. In the second option, the PPS activities would not be tied to the cask procurement or the CoC issuance. While this option could expedite the start of a demonstration test, the transportation cask used for testing may not be the one for transporting SNF to the central repository.

The first option, which was tied to when an order was placed for the procurement of a transportation cask or the NRC issued a CoC for the cask design (whichever was later), was selected by the Commission (SECY-06-0053 SRM).[20] In 2006, the NRC staff signed a cooperative agreement with BAM and obtained full-scale and scale-model transportation cask test data for the two casks.[21] As discussed in SECY-06-0053,[19] the drop test data for the CONSTOR® V/TC and MHI MSF-69BG would be reviewed and analyzed to determine (1) the extent to which the drop test data supported the PPS objectives and (2) any enhancements that could be recommended for the PPS as a result of the review and analysis of the data.

II. 2006 NAS STUDY

The NAS published a study in 2006 entitled "Going the Distance? The Safe Transport of Spent Nuclear Fuel and High-Level Radioactive Waste in the United States."[22] The NAS undertook the study to provide what it saw as a national need for an independent, objective, and authoritative analysis of SNF and high-level radioactive waste transportation in the United States.[22] The study found that the International Atomic Energy Agency (IAEA) performance standards and the NRC regulations were "… adequate to ensure package containment effectiveness over a wide range of transport conditions, including most credible accident conditions."[22]

The study recommended that

> … full-scale testing should continue to be used as part of integrated analytical, computer simulation, scale-model, and testing programs to validate package performance. Deliberate full-scale testing of packages to destruction should not be required as part of this integrated analysis or for compliance demonstrations.[22]

As discussed in SECY-07-0095,[21] the NRC staff believed that the NAS study recommendation (1) supported the NRC's current practice of using a combination of analytical techniques for package approvals (e.g., computer simulation, full- or partial-scale model testing, component testing), (2) was consistent with the NRC's plans to perform a demonstration test for the PPS that entailed a realistic rail impact and fire, and (3) supported the decision by the NRC not to test a full-scale package to destruction for the PPS.

The study did, however, recommend that additional analyses be completed to demonstrate an understanding of package performance for very long duration, fully engulfing fires for a representative set of package designs that would possibly be used in a large-scale shipping campaign. In response to this NAS study recommendation, the NRC completed two studies that looked at the performance of representative transportation casks in severe rail and highway tunnel fires.

The first study involved the Baltimore Tunnel Fire (NUREG/CR-6886),[23] which was based on an accident that occurred in the Howard Street railroad tunnel in Baltimore, Maryland in July 2001. NUREG/CR-6886[e] analyzed the potential response of three NRC-certified transportation casks, the HI-STAR 100 and TN-68, which are rail transportation casks, and the NAC-Legal Weight Truck (LWT), which is a truck cask that has been shipped by rail, in a severe rail tunnel environment based on the Howard Street tunnel fire. The second study involved the Caldecott Tunnel Fire (NUREG/CR-6894),[24] which was based on an accident that occurred in the Caldecott Tunnel near Oakland, California in April 1982. The Caldecott Tunnel is a highway tunnel; therefore, the NAC-LWT transportation package, which is an over-the-road truck cask, was chosen for the analysis to determine the potential response in this scenario. The results of both studies indicated that fission products from SNF would not be expected to be released from the transportation casks.

It should be noted that the NRC undertook several other studies in addition to NUREG/CR-6886 and NUREG/CR-6894 to further look at real-world accidents involving very long duration, fully engulfing fires. The third study (NUREG/CR-7206)[25] involved the MacArthur Maze accident that occurred in April 2007 in Oakland, California. Although this accident involved a gasoline tanker truck and not SNF, it was studied due to the severity of the fire which caused the overhead roadway segments to collapse onto the roadway where the fire was burning. The General Atomics (GA)-4 Legal Weight Truck Spent Fuel Shipping Cask was selected for this study.

The fourth study (NUREG/CR-7207)[26] considered the Newhall Pass highway tunnel accident that occurred in October 2007 near Santa Clarita, California. Although this accident also did not involve SNF, it was evaluated due to the length of the fire as well as the wide range of potential fire exposure scenarios due to the large number of vehicles (24 commercial tractor trailer rigs were involved in the fire) that were involved in the accident and in the fire. The GA-4 Legal Weight Truck Spent Fuel Shipping Cask was selected for this study. A compendium (NUREG/CR-7209)[27] was also completed that summarized the truck and rail transport accident studies that involved fires relative to the regulatory requirements for commercial SNF shipments.

Several studies were also undertaken by the NRC to examine samples recovered from these incidents. Railcar components that were recovered from the train involved in the Howard Street railroad tunnel fire were studied to estimate the fire duration and temperatures that were achieved by the components (NUREG/CR-6799),[28] samples were collected and examined from the MacArthur Maze accident and estimates of temperatures reached during the fire were estimated (NUREG/CR-6987),[29] and the potential performance of the structural materials that were exposed to the high-temperature fire environment of the Newhall Pass highway tunnel were evaluated (NUREG/CR-7101).[30] Two other studies were also completed to assist in determining the different types and frequencies of railway accidents (NUREG/CR-7034)[31] and roadway accidents (NUREG/CR-7035)[32] that involved severe, long duration fires that could possibly impact SNF rail transport and roadway transport, respectively.

The NAS study also recommended that the Commission implement operational controls for the transportation of SNF and high-level waste as necessary to reduce the chances of having the conditions for such a long duration fire to take place. One such operational control that was implemented by NRC request was the revision of AAR Circular No. OT-55[33] to prohibit trains carrying flammable gases or liquid from being in a tunnel at the same time as a train carrying SNF.

III. BLUE RIBBON COMMISION ON AMERICA'S NUCLEAR FUTURE 2012 FINAL REPORT

The Blue Ribbon Commission on America's Nuclear Future (BRC) was formed in 2010 by the Secretary of Energy at the request of the President of the United States. The purpose of the BRC was "… to conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle and recommend a new strategy."[34] The 2012 BRC final report stated that the NAS study endorsed the NRC's approach and recommended that "… full scale cask testing, as well as other accepted methodologies, should continue to be used … ."[34] The NRC staff proposed full-scale testing of a transportation rail cask involving a collision with a locomotive traveling at a high speed followed by a hydrocarbon fire in 2005 was supported by DOE. The BRC recommended conducting the PPS with a full-scale rail cask for the purpose of building public trust and confidence.

IV. INTERNATIONAL TESTING

A successful example of international testing includes a program conducted in the United Kingdom in 1981 by the CEGB. Although the CEGB was considered to be the world's

[e] Note that Revision 1 of NUREG/CR-6886 was published in November 2006. Revision 2 was published in February 2009.

longest established and largest transporter of SNF at that time and had no accidents involving the release of radioactivity, there was still public anxiety about SNF transport in the United Kingdom.[35] The CEGB conducted the program with specific objectives, which included investigating the validity of scale model use to represent full-size transportation cask behavior [see Fig. 3 which shows the full-sized Magnox flask (i.e., transportation cask) along with the associated 1/2-, 1/4-, and 1/8-scale models] and to study the relevance of the IAEA regulatory tests[f] in relation to unlikely but real transport accidents.[35]

The program, which was conducted with the Magnox Mk2c design because it was the most widely used in the United Kingdom at that time,[35] spanned 4 years.[36] There were over 100 tests on the transportation cask components, models of the transportation cask, other test pieces, and drop testing of a full-sized Magnox spent fuel flask.[35] The testing concluded with a public demonstration test of a locomotive hitting a Magnox spent fuel flask (see Figs. 4 and 5) at 100 mph with minimal damage to the transportation cask, named "Operation Smash Hit." Even today, over 35 years later, it is possible to read articles or view the testing on the internet, which attests to the success of the program and its positive impression on the public.

V. PATH FORWARD AND CURRENT STATUS

The NRC eventually decided not to go forward with physical testing as proposed; however, the DOE would like to build on the prior information and knowledge that has been collected regarding the NRC-led PPS.

Fig. 3. Magnox fuel flasks: full-scale (background), and 1/2-, 1/4-, and 1/8-scale models (foreground).[22] © Nuclear Decommissioning Authority.

Fig. 4. Configuration of the full-scale crash test of the Magnox spent fuel flask.[22] © Nuclear Decommissioning Authority.

Fig. 5. CEGB public demonstration test with the Magnox spent fuel flask.[22] © Nuclear Decommissioning Authority.

A DOE-led PPS is in the early planning stages and is a multinational laboratory effort. The planning effort includes subject matter experts with a diverse mix of transportation and packaging experience and backgrounds from Sandia National Laboratories, Oak Ridge National Laboratory, Savannah River National Laboratory, and Pacific Northwest National Laboratory. Currently, a functions and requirements document is being developed to start discussing possible options for the PPS, including items such as the potential tests that could be performed, as well as potential test sites, transportation casks, and analytical tools.

Preliminary plans for a DOE-led PPS include conducting regulatory tests with an NRC-certified rail transportation cask with a nominal weight of between 150 000 and 420 000 lb. It is noted that there are few test facilities that have an unyielding surface for drop testing that can accommodate the assumed weight of the cask [i.e., IAEA Specific Safety Guide (SSG)-26[37] states "The combined

[f] Note the current IAEA regulations at the time were the IAEA "Regulations for the Safe Transport of Radioactive Material" (1973 revised edition, as amended).

mass of the steel and concrete should be at least 10 times that of the specimen for the tests … .”][g]. Tests are also being considered, such as a train collision with the transportation package in a “realistic” type of scenario and performing an immersion test in a body of water.

The overall goals for a DOE-led PPS include (1) building public trust and confidence in the safety of SNF transportation casks and SNF transportation by rail by demonstrating the robustness of a SNF transportation cask, (2) gathering technical data to further validate computer models, and (3) recording high-resolution video to use in DOE communication products and public outreach. DOE is considering public engagement and stakeholder outreach strategies in support of the PPS to explore additional opportunities to strengthen relationships between DOE and the public, and to further enhance DOE’s efforts to build trust.

External engagement activities in 2022 included participating in the National Transportation Stakeholder’s Forum (NTSF) Annual Meeting in June and the International High Level Radioactive Waste Management (IHLRWM) Conference in November. DOE plans to explore additional opportunities for external engagement and trust building through a recent Consent-Based Siting Funding Opportunity Announcement (FOA).

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One of the main objectives of this paper is to encourage discussion on a PPS and to begin to consolidate historical information from numerous reports, papers, and other works that have provided valuable insight and knowledge as a DOE-led PPS is evaluated for a possible path forward. In summarizing the information presented herein, full credit is acknowledged to the original authors of those works.

This is a technical paper that does not take into account contractual limitations or obligations under the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (Standard Contract) (10 CFR Part 961). To the extent discussions or recommendations in this paper conflict with the provisions of the Standard Contract, the Standard Contract governs the obligations of the parties, and this paper in no manner supersedes, overrides, or amends the Standard Contract.

This paper reflects technical work which could support future decision making by the U.S. Department of Energy (Department or DOE). No inferences should be drawn from this paper regarding future actions by DOE, which are limited both by the terms of the Standard Contract and Congressional appropriations for the Department to fulfill its obligations under the Nuclear Waste Policy Act including licensing and construction of a spent nuclear fuel repository.

[g] The definition provided by the IAEA regulations in SSG-26, paragraphs 717.1 and 717.2, is used as guidance in the United States for an unyielding surface.

Disclosure Statement

No potential conflict of interest was reported by the author(s).

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