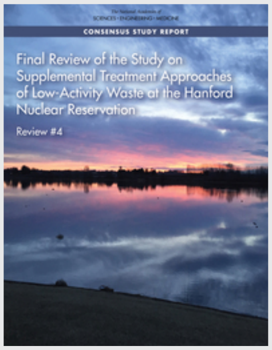

Final Review of the Study on Supplemental Treatment Approaches of Low-Activity Waste at the Hanford Nuclear Reservation: Review #4 (2020)

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Final Review of the Study on Supplemental Treatment Approaches of Low-Activity Waste at the Hanford Nuclear Reservation

Review #4

Committee on Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation

Nuclear and Radiation Studies Board

Division on Earth and Life Studies

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Preface

The scale and complexity of the radioactive and hazardous waste disposal problem at the Hanford Nuclear Reservation are well known. The U.S. Department of Energy's Office of Environmental Management (DOE-EM) has called the Hanford site the most challenging clean-up task in DOE's nuclear complex.

DOE's current plan for treating the nearly 56 million gallons of radioactive and hazardous chemical waste contained in 177 large tanks is to separate it into two waste streams: a high-level waste (HLW) stream that will have less than 10 percent of the volume but more than 90 percent of the radioactivity, and a low-activity waste (LAW) stream that will have more than 90 percent of the volume but less than 10 percent of the radioactivity. (DOE's intention is to send the HLW to a deep, mined geologic repository, while the LAW can be disposed of in near-surface disposal facilities.) Notably, DOE's determination as to whether a given volume of waste can be considered LAW depends on the removal of "key radionuclides to the maximum extent that is technically and economically practical," as stated in DOE's *Radioactive Waste Manual*. However, this processing could still leave more than 90 percent of long-lived radionuclides such as iodine-129 (half-life of 15.7 million years) and technetium-99 (half-life of 210,000 years) in the LAW stream, and these radionuclides are problematic because of their high mobility in an oxidizing environment as compared to most other radionuclides. According to DOE's plan, once the under-construction Waste Treatment and Immobilization Plant becomes operational, it will vitrify (treat by binding the waste into a glass-like product) the HLW stream, as well as one-third to perhaps one-half of the LAW stream. The excess LAW that still needs to be treated is called supplemental LAW (SLAW). DOE, the Washington State Department of Ecology, and the U.S. Environmental Protection Agency—the three parties under the legally binding 1989 Tri-Party Agreement—have yet to agree on the SLAW treatment method. The use of technologies other than vitrification for *any* LAW is controversial at Hanford—though they have been adopted at other DOE-EM sites such as the use of grout at the Savannah River Site and the development of a fluidized bed steam reforming treatment facility at Idaho National Laboratory—and the use of non-glass technologies is currently opposed by the State of Washington, key tribal nations, and many Hanford stakeholders.

In Section 3134 of the fiscal year 2017 National Defense Authorization Act, Congress directed DOE to contract with a Federally Funded Research and Development Center (FFRDC) to analyze at least three potential technologies for treating the SLAW—vitrification, grouting (binding the waste in a cementitious form), and fluidized bed steam reforming (binding the waste in a calcined powder or a monolithic crystalline ceramic waste form)—and to report on its findings. It further directed DOE to contract with the National Academies of Sciences, Engineering, and Medicine (the National Academies) to undertake an independent peer review of the FFRDC report, not only after the final draft report is completed, but also at certain points during the FFRDC's effort in previous draft reports. Congress also expressly required the FFRDC and the National Academies review committee to solicit and consider stakeholder input at every step of the process.

DOE appointed Savannah River National Laboratory (SRNL) as the FFRDC to lead this study, and then SRNL assembled a team of experts from SRNL and other DOE national laboratories to perform the analysis. The National Academies appointed its committee to conduct the overlapping review. The first committee report, published on June 8, 2018, began an iterative exchange between the FFRDC team and the National Academies committee that—together with stakeholder comments—is intended ultimately to lead to a final report on which key decision-makers can rely in reaching a decision regarding the treatment and disposal of the SLAW. On November 2, 2018, the second committee report was published and that interim report provided the committee's review of the FFRDC team's draft report, dated July 15, 2018. On

August 15, 2019, the third review report was published, and it provided the committee's overall assessment of the FFRDC team's final draft report, dated April 5, 2019.

The FFRDC team has presented its work to the committee seven times: first in an introductory meeting in Washington, DC, on December 12-13, 2017; second in a meeting describing the status of the FFRDC's draft analysis, held in Richland, Washington, on February 28 and March 1, 2018; third in a meeting describing the FFRDC's draft report, held in Richland, Washington, on July 23-24, 2018; fourth in a meeting describing the FFRDC's progress toward a final draft report, held in Richland, Washington, on November 29-30, 2018; fifth in a meeting discussing the next steps required for the FFRDC to produce a final draft report, held in Atlanta, Georgia, on January 8, 2019; sixth in a meeting discussing the final and complete draft report, held in Kennewick, Washington, on May 16, 2019; and most recently in a meeting focusing on receiving final stakeholders' and interested members of the public's comments on the previously published review report, as well as on presentations from the FFRDC team on their final report, held in Richland, Washington, on October 31, 2019. The FFRDC's final report is dated October 18, 2019, and is marked "Predecisional." In keeping with the iterative nature of the congressionally mandated review process, the committee is not expected to review the final FFRDC report. Rather, the committee's fourth and final review focuses on comments on the *committee's* third review report.

Throughout this study, the committee has been grateful for the time and effort that went into the team's draft reports, final report, and presentations, as well as the presentations and comments by other interested government agencies, stakeholders, and members of the public. The Washington State Department of Ecology, in particular, presented in detail and responded to the committee's questions at every public meeting in Richland and Kennewick.

The committee's third review report provides an overall assessment of the FFRDC's final draft report and makes findings and recommendations according to the terms of the Statement of Task, with a particular focus on how the FFRDC's report can be used by decision-makers. In this final review report, the committee stands by the third review's findings and recommendations, but it provides commentary on selected findings and recommendations in light of events since the publication of the third review and comments received from stakeholders and members of the public. This final review also summarizes those comments and shows the executive summary and conclusions of the FFRDC final report.

We hope that this final review will provide a useful guide to this study for decision-makers, other stakeholders, and interested members of the public.

John S. Applegate, *Chair*
Allen G. Croff, *Vice-Chair*
Committee on Supplemental Treatment of Low-Activity Waste
at the Hanford Nuclear Reservation

Acknowledgments

A number of people and organizations contributed to the successful completion of this report. The committee wishes to thank the study sponsor, the U.S. Department of Energy's Office of Environmental Management (DOE-EM), for supporting this project, and especially the following DOE staff:

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The committee appreciates the work of Jennifer Colburn of Mission Support Alliance, LLC, in helping with public and external communications to Hanford area stakeholders about the study's public comment period and the committee's seventh public meeting on October 31, 2019.

The committee also thanks the presenters and speakers who gave high-quality presentations during the public meetings as listed in Appendix E. In particular, for the most recent public meeting on October 31, 2019, the committee is pleased to note the very informative presentations given by Federally Funded Research and Development Center team leader, Bill Bates, and team members Thomas Brouns and Michael Stone. In addition, the committee is grateful for stakeholder presentations during that public meeting, notably the continued public engagement during this meeting and other meetings by the Washington State Department of Ecology, Oregon Department of Energy, Tri-City Development Council, Hanford Communities, and Hanford Advisory Board. Moreover, the committee thanks representatives of the major tribes in the region for their presentations during the course of the study. Furthermore, the committee is grateful for additional submitted stakeholders' and public comments, which were essential in helping the committee better understand concerns and views during this final phase of the study.

The committee deeply appreciates the outstanding assistance provided by the National Academies of Sciences, Engineering, and Medicine staff in supporting the committee's work, organizing the committee's meetings, and preparing this final review report. The chair and vice-chair are especially thankful for the time and energy devoted by the committee members.

Reviewer Acknowledgments

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

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Sue E. Ion (NAE), independent consultant, Leyland, United Kingdom
Kevin Smith, independent consultant, Richland, Washington
Gabrielle Wong-Parodi, Stanford Woods Institute for the Environment, Stanford, California

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Michael L. Corradini, University of Wisconsin–Madison, and Robert J. Budnitz, Lawrence Berkeley National Laboratory (retired). They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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Summary

Section 3134 of the National Defense Authorization Act for Fiscal Year 2017 (P.L. 114-328) (Sec. 3134) calls for a Federally Funded Research and Development Center (FFRDC) "to conduct an analysis of approaches for treating the portion of low-activity waste (LAW) at the Hanford Nuclear Reservation" intended for supplemental treatment.[1] The U.S. Department of Energy (DOE) has contracted with Savannah River National Laboratory (SRNL), an FFRDC, to provide the called-for analysis. SRNL assembled a team of experts from SRNL and other national laboratories to perform the analysis. Sec. 3134 also calls for the National Academies of Sciences, Engineering, and Medicine (the National Academies) "to conduct a review of the analysis" performed by the FFRDC that is independent of and concurrent with the FFRDC's analysis "to improve [its] quality…." The complete text of the congressional mandate in Sec. 3134 is provided in Appendix C, and the Statement of Task for the National Academies review is provided in Appendix D.

This review report, the final of four to be issued by the National Academies to address the congressional mandate, focuses on the Statement of Task's study charge for the committee to provide a summary of public comments on the third committee review report, which was published on August 15, 2019, and the committee's views, if any, on these comments and whether they change any of the findings or recommendations in the third review report. The comment period began on August 15, 2019, and concluded on November 20, 2019. According to Sec. 3134, the comment period was to last for a minimum of 60 days. The period was extended to allow stakeholders and members of the public to submit comments in light of additional information that was received at the final public meeting on October 31, 2019, and the FFRDC final report, which is dated October 18, 2019. Notably, during this final phase of the study, the committee is neither required nor expected to perform a peer review of that final report.

As "ground rules" for this final review, first, the committee has considered all comments received during the comment period from August 15, 2019, to November 20, 2019; for the list of commenters and summaries of the comments, see Appendix E. Second, for potential revisions to the committee's Review #3, the committee decided to revise where a correction is needed or where there is either an objective error or omission. (For completeness and as an aid to readers, Appendix A reproduces the essential parts of Review #3, including findings and recommendations as well as the committee's review of the FFRDC final draft report and the committee's advice for decision-makers.) Third, this final review acknowledges significant new information, which became available only after the committee's Review #3 was published and which the committee considered in deciding whether to change or modify any of its findings and recommendations in Review #3. The new information involves (a) the performance assessment for the Integrated Disposal Facility (IDF) at Hanford was made available leading to an additional recommendation (Recommendation 5-1) on the drinking water standard; and (b) the final FFRDC report was published, and the committee received comments from the FFRDC on Review #3. Fourth, the committee does not respond in a one-to-one manner to each comment received. Instead, the committee has identified concepts and themes among these comments and has responded with observations on selected comment themes.

[1]According to DOE's *Radioactive Waste Manual*, low-activity waste means the waste that remains after as much of the radionuclides as technically and economically practicable have been removed from the tank waste, and that when immobilized in waste forms, may be disposed as low-level waste in a near-surface facility, as long as the waste meets criteria in the Waste Incidental to Reprocessing determination. Supplemental treatment refers to processing of the low-activity waste that is excess to that portion to be treated by vitrification in the Waste Treatment and Immobilization Plant.

As a reminder, throughout this process the committee was neither charged to evaluate the supplemental treatment approaches nor to recommend any particular approach. Equally important, the committee notes that several important questions for the Hanford site were not in the scope of the FFRDC's analysis (and thus not in the scope of the committee's review), in particular, tank waste management, high-level waste (HLW) processing and treatment, treatment and disposal of LAW not considered SLAW, the proper definition or interpretation of high-level waste or other legal agreements or requirements, and the Waste Treatment and Immobilization Plant's (WTP's) design, construction, and operations.

Indeed, the FFRDC, quite properly, does not identify a preferred option for supplemental treatment in its report, but instead it separately evaluates the treatment alternatives against the baseline, as well as against one another, for a number of factors important to selecting a preferred alternative. The de facto baseline is vitrification of the LAW in the supplemental LAW (SLAW) treatment facility because it is the current expectation of many stakeholders and a similar facility (the WTP) is currently under construction to be followed by disposal of the resulting wastes in the IDF at Hanford. The FFRDC's task is to provide data and analysis to enable DOE, with congressional oversight, to decide whether to use vitrification, grouting, fluidized bed steam reforming (FBSR), or other treatment approaches to treat the SLAW by converting it into a waste form for disposal.

Importantly, the committee notes that the evaluations of treatment options for the SLAW include more than just the solidification of the liquid LAW. The objective of the SLAW treatment is to ensure that the solidified wastes can be permanently disposed of in a near-surface land disposal site. Because these sites have "waste acceptance criteria," additional pre-treatment processing is sometimes required so that the final SLAW form or forms can be accepted for disposal. Additionally, the primary treatment and pre-treatment processes produce "secondary wastes" that also need to be disposed of in a near-surface disposal site. It is this entire SLAW process, from pre-treatment through treatment to disposal, which the FFRDC evaluates and compares.

In addition to the three primary treatment options, the FFRDC also identified two near-surface land disposal options to analyze and compare. The existing IDF located at Hanford is considered as the "baseline" LAW disposal facility, again, because it is the current expectation (and has, in fact, been constructed). In this baseline option, the liquid LAW (including SLAW) would be solidified using vitrification, and the secondary waste would be grouted. While both types of waste are slated to be disposed at the IDF, the Washington State Department of Ecology has yet to approve waste acceptance criteria that would allow for the disposal of grouted secondary waste or even the primary vitrified LAW in the IDF. The second disposal site analyzed is operated by Waste Control Specialists (WCS), and located near Andrews, Texas. WCS is situated in a semi-arid and sparsely populated region of western Texas, and it has become an active commercial low-level waste disposal facility in recent years. It is also designated as a Federal Waste Disposal Facility. The FFRDC report describes the differing, and less restrictive, waste acceptance criteria for WCS as compared with what is anticipated for the IDF, and the effect that using the WCS site would have on the SLAW treatment. The FFRDC also mentions the possibility of disposal at the EnergySolutions site near Clive, Utah, and estimates that this site would require removal of almost all of the strontium-90 from the waste stream to meet its Class A low-level waste acceptance criteria.

Using the criteria specified in Sec. 3134, including risks, benefits, costs, schedules, regulatory compliance, and obstacles to implementation, the FFRDC in its report analyzed five alternatives for treating the primary SLAW: (1) vitrification for disposal at the IDF, (2) grouting for disposal at the IDF, (3) grouting for disposal at WCS, (4) FBSR for disposal at the IDF, and (5) FBSR for disposal at the WCS site. (Because vitrification is already the expectation for the on-site IDF, there is no reason to consider WCS for vitrified waste.) The vitrification option would result in significant amounts of secondary waste, which, as mentioned above, would be grouted and is proposed to be disposed at the IDF, although the FFRDC also considers the possibility of disposal of this waste at WCS.

The FFRDC in its report estimated that:

- The vitrification technology would take 10 to 15 years to implement and would cost $20 billion to $36 billion.

- The grouting technology would take 8 to 13 years to implement and would cost $2 billion to $8 billion.
- The fluidized bed steam reforming technology would take 10 to 15 years to implement and would cost $6 billion to $17 billion.

The cost estimates are based on technologies that, for the most part, have not yet been fully developed or deployed with Hanford's uniquely voluminous and heterogeneous tank wastes, and are based on costs from similar technologies, as well as assuming ideal funding conditions (i.e., sustained funding without caps) and no redirection during a multi-year effort. Thus, there are large attendant uncertainties, suggesting that costs could be much higher than estimated, and are unlikely to be much lower. The FFRDC team also concluded that a SLAW treatment and disposal option that meets formal regulatory requirements for disposal can be developed using any of the three treatment technologies evaluated. In addition, the FFRDC report notes that "the required time for construction and startup require an immediate start to allow completion by the required startup date" for some treatment alternatives, because DOE's current plan is a target date of 2034 for the SLAW treatment to begin (which is essentially the same time as the pre-treatment and HLW vitrification facilities in the WTP are scheduled to begin operations). Recent news reports suggest that this target date may slip by at least a few years (Cary, 2019).

The FFRDC and the committee have gone through multiple iterations of draft FFRDC analysis reports and committee review reports, with both formal and informal comments and responses. The committee finds that the FFRDC has been responsive to most comments, and the most recent FFRDC report, published on October 18, 2019, and stated as being the last while labelled as "predecisional," has improved very considerably over its predecessors in focus, responsiveness to the congressional mandate, and technical analysis. As detailed in the following Findings and Recommendations, the committee believes that the FFRDC advances the overall understanding of the waste treatment options for SLAW by providing the basis for the kinds of detailed technical studies that would be required for reaching a final decision on the treatment and disposal of SLAW. Based on the committee's review of comments received during the comment period and the new information received (specifically the IDF's Performance Assessment [PA]) during this period, the committee has, for the most part, not changed its findings and recommendations from Review #3, which are reproduced here, but the committee notes that it has made additions to Recommendations 1-1 and 2-1. In addition, the committee has a new recommendation in this review report as the committee discusses in Chapter 2 and states in the final section of the Summary.

USING THE FFRDC REPORT

Overall Assessment

Finding 1-1

The purpose of the committee's review is to advise whether DOE, Congress, regulators, and other stakeholders can rely on the FFRDC report to evaluate and decide on a treatment approach for the SLAW. The committee finds that, in its current iteration, the FFRDC's analysis:

a. When taken alone, does not yet provide a complete technical basis needed to support a final decision on a treatment approach;
b. Does not yet clearly lay out a framework of decisions to be made among treatment technologies, waste forms, and disposal locations; but
c. Can form the basis for further work as described below in the committee's findings and recommendations.

Analysis of Costs, Benefits, and Risks

Finding 2-1

The cost estimates in the FFRDC report are based on technologies that, for the most part, have not yet been fully developed, tested, or deployed for Hanford's particular, and particularly complex, tank wastes, and instead use costs from similar technologies. As a result, there are large attendant uncertainties, suggesting that costs could be much higher than estimated, but are unlikely to be much lower.

Finding 2-2

The cost estimates in the FFRDC report are based on continuing funding at and beyond current levels to optimize the waste treatment technologies and speed of progress. These involve very large annual appropriations, which are inevitably uncertain over the planned decades of activity, especially because current planning assumptions anticipate a two- or three-fold increase in expenditures at certain points in the SLAW treatment process. This, too, introduces the possibility that funding shortfalls will lead to longer schedules, increased total costs, and higher chances of additional tank leaks or structural failures, which will themselves increase costs as well as health and environmental risks.

Finding 2-3

The report's analysis of costs does not enable the reader to analyze key trade-offs among specific alternatives or variations of major alternatives.

Disposal Risk Assessment

Finding 3-1

Assessment of waste form performance would have to include consideration of the characteristics of the disposal sites and the transport pathways to receptors over relevant periods of time, as well as be based on the inherent characteristics of the waste form.

Finding 3-2[2]

The committee did not have access to the 2017 IDF PA that has been prepared by DOE or to the Performance Evaluation (PE) data and analysis prepared by the FFRDC. Therefore, it was impossible for the committee to critically review the differences in the performance of the three waste forms and their associated disposal systems over time. Additionally, the technical bases for waste degradation models and mechanisms used in the PE analyses for the IDF by the FFRDC team are not well documented and justified.

Finding 3-3[3]

Without the proper supporting documentation for the FFRDC's PE, or the IDF PA on which it was based, the committee is unable to assess the potential significance of mobile, long-lived fission products such as iodine-129, technetium-99, and other long-lived radionuclides (possibly selenium-79 and others). It would have been useful for the FFRDC to include the human health risk estimates (dose) over time for

[2]The committee notes that subsequent to publication of Review #3, it received access to the PA. See the discussion in Chapter 2 of this review report for the committee's observations about relevant aspects of the PA and about what was available in the FFRDC final report on the PE.

[3]See the previous footnote about the committee's views on the PA and the PE as discussed in Chapter 2.

all of the long-lived radionuclides that are listed in Table F-2 of their report, not just iodine-129 and technetium-99.

Finding 3-4

The FFRDC report gives little consideration in its analysis to the environmental, health, and safety consequences of hastening or further delaying remediation of the Hanford waste storage tanks, which is related to the probability that additional tank leaks or structural failures will occur over the long period of time expected for the removal and treatment of the waste in the tanks.

Pre-Treatment to Remove Iodine-129 and Technetium-99

Finding 4-1

The FFRDC performed an analysis of whether removal of iodine-129 and technetium-99 was needed to comply with the disposal waste acceptance criteria, and examined the status of technologies for removing these radionuclides from the SLAW feed stream, but the FFRDC report does not respond fully to the congressional direction (in Sec. 3134) because the report does not address immobilization of the iodine-129 and technetium-99 recovered from the LAW as part of the separate high-level glass waste form to be produced in the WTP.

Other Observations

Finding 5-1

The report makes little use of the experience with grouting and other technologies at other DOE sites and commercial operations. While there are unquestionably meaningful differences among the waste forms, technologies, and disposal environments as compared to Hanford, the extensive experience gained at Savannah River Site, in particular, is an invaluable source of insight.

Finding 5-2

The committee was repeatedly told that the selection and implementation of an approach to treat tank waste would be hampered by the insistence by the State of Washington and some other stakeholders that any approach other than vitrification must be "as good as glass." The term "as good as glass" is not defined in law, regulation, or agreement, and it is only tentatively defined by its advocates. The analysis in, and the public presentations of, the draft FFRDC reports offer a follow-on opportunity for DOE to engage with its regulators and stakeholders to identify performance standards based on existing regulatory requirements for waste form disposal and to pursue a holistic approach to selecting a treatment technology.

Comparisons

Finding 6-1

Over multiple iterations, the FFRDC report has increasingly enabled side-by-side comparisons among the SLAW treatment approaches, exemplified by the table of alternatives and criteria. It remains difficult, however, for the reader to see comparisons and trade-offs in the supporting narrative.

The FFRDC Report's Steps Forward

Finding 7-1

The report represents useful steps forward by:

a. Confirming that versions of vitrification, grouting, and steam reforming are treatment technologies that merit further consideration for the SLAW;
b. Establishing the likelihood that vitrification, grouting, or steam reforming are capable of meeting existing or expected regulatory standards for near-surface disposal albeit with varying amounts of pre-treatment being required;
c. Highlighting the important contribution of the iodine-129 in the secondary waste streams disposed at the IDF to the total estimated radiation dose rate to the receptors;
d. Underscoring the regulatory and acceptance uncertainties regarding approaches other than vitrification technology for processing the SLAW; and
e. Opening the door to serious consideration of other disposal locations, specifically the WCS facility near Andrews, Texas, and possibly the EnergySolutions facility near Clive, Utah.

Use the FFRDC Report as a Pilot or Scoping Study

Recommendation 1-1

The committee recommends that the "Preliminary Draft" FFRDC report reviewed by the committee (that is, the document dated April 5, 2019) be accepted as a pilot or scoping study for a full comparative analysis of the SLAW treatment alternatives, including:

- Vitrification, grouting, and steam reforming as treatments for the SLAW;
- Pre-treatment to remove iodine-129, technetium-99, and other long-lived radionuclides (e.g., selenium-79) to ensure that regulations are met or reduce cost, and pre-treatment to assure that the waste product meets land disposal requirements;
- Pre-treatment of strontium-90, if it is not removed during the cesium-137 pre-treatment process; and
- Disposal at the IDF, WCS, and (possibly) the EnergySolutions facility.

The draft report should either be substantially revised and supplemented (though the committee understands that the FFRDC team's funding may not permit this), or be followed by a more comprehensive analysis effort and associated decisional document, which needs to involve the decision-makers or their representatives. This comprehensive analysis should adopt a total systems approach (one that includes addressing relevant externalities to SLAW that were outside the FFRDC's scope) to provide a substantially complete basis for decision-making.

Organize the Report or Decisional Document Around Four Interrelated Areas

Recommendation 2-1

The final FFRDC report or follow-on decisional document should include technical data and analyses to provide the basis for addressing four interrelated areas, as follows:

a. Selection of a technology that will produce an effective waste form. This has two parts:
- The treatment (immobilization) technology:
    - How well will it work? Is the technology well understood, tested or used under real-world conditions, dependent on other technologies, or relatively simple?

  - What types and volumes of secondary waste are created by each technology?
  - What is the lifetime cost and duration, and uncertainties therein?
  - What are the risks (e.g., programmatic and safety) and uncertainties therein?
- The waste forms and associated disposal sites:
  - How effective is each waste form in immobilizing the waste (e.g., the materials science of the incorporation, corrosion, and release processes) and over what time periods?
  - What is their performance under the expected disposal conditions (e.g., release from the disposal facility and transport through the geosphere to a receptor)?
  - How do the waste form performances actually differ? This goes further than simply demonstrating compliance, but rather demonstrates an understanding of how the waste forms and disposal environments actually interact.

The committee notes the limited amount of information and pervasiveness of uncertainty in many aspects of the decisions to be made. Although it may seem counter-intuitive, the committee suggests that probabilistic approaches be used in future analyses because, when information is limited, the result is in the form of uncertainties, which are very useful to decision-makers.

b. Selection among available disposal sites. The report describes the IDF and WCS, and it briefly mentions the EnergySolutions facility near Clive, Utah. Selection requires an understanding of how each site will "work" over time in providing a barrier to the release and migration rate of key radionuclides, especially and specifically technetium-99 and iodine-129.

- What is the role of the hydrogeology at each site (the IDF and WCS) in preventing/slowing radionuclide release and migration?
- How might the disposal facility design be modified to enhance the performance of each waste form?

Important site-related issues include regulatory compliance, public acceptance, cost, safety, expected radiation dose to the maximally exposed individual over time, and differences among the disposal environments.

c. Determining how much and what type of pre-treatment is needed to meet regulatory requirements regarding mobile, long-lived radionuclides and hazardous chemicals, and possibly to reduce disposal costs. The congressional charge specifically mentions technetium-99 and iodine-129, but other long-lived radionuclides, such as selenium-79, may be relevant. The analysis should consider both:

- Leaving the technetium (Tc), iodine (I), and other long-lived radionuclides in the waste form for the SLAW, with possible use of enhanced engineered barriers such as getters, which are added materials that can better retain the contaminants of concern; and
- Removing the Tc and I (and possibly other radionuclides) to create a new waste stream with its own (and possibly different) form of immobilization and final disposition, including incorporating it into the separate vitrified HLW stream.

d. Other relevant factors. Other factors that would affect the selection of a SLAW treatment alternative include:

- The costs and risks of delays in making decisions or funding shortfalls in terms of additional resource requirements and the increased chance of tank leaks or structural failures over time, and the need to address the consequences (notably, all 149 single-shell tanks have exceeded their design life and the 28 double-shell tanks will have exceeded their design life before the waste is slated to be removed);

- DOE's proposed reinterpretation of the definition of HLW waste could change the SLAW size and performance requirements by altering the feed volume and composition depending on how the reinterpretation is implemented;
- Thorough consideration of the experience at other DOE sites (e.g., Savannah River Site) and relevant commercial facilities; and
- Outcomes of DOE's proposed Test Bed Initiative, the second phase of which would have involved (and perhaps still could involve) grout treatment of 2,000 gallons of LAW and shipment to WCS (the first phase involved a proof of concept treatment of 3 gallons of LAW that was sent to WCS and was completed in December 2017). The future of the second phase of the Initiative is now in doubt due to DOE's withdrawal in late May 2019 of the state permit application.

Need Direct Comparisons of Alternatives to Aid Decision-Making

Recommendation 3-1

The analysis in the final FFRDC report and/or a comprehensive follow-on decisional document needs to adopt a structure throughout that enables the decision-maker to make direct comparisons of alternatives concerning the criteria that are relevant to the decision and which most clearly differentiate the alternatives.

Consideration of Parallel Approaches

Recommendation 4-1

The FFRDC report could also provide the springboard for serious consideration of adopting an approach of multiple, parallel, and smaller scale technologies, which would have the potential for:

a. Faster startup to reduce risks from tank leaks or structural failures if adequate funding is available to support parallel approaches;
b. Resilience through redundancy (like the parallel uranium enrichment and plutonium separation methods during the Manhattan Project);
c. Taking positive advantage of the unavoidably long remediation duration to improve existing technologies and adopt new ones; and
d. Potentially lower overall cost and program risk by creating the ability to move more quickly from less successful to more successful technologies, with less stranded cost in the form of large capital facilities that are inefficient or shuttered before the end of their planned lifetime.

CONCLUDING OBSERVATIONS

Based on its review of relevant aspects of the performance assessment of the IDF, the committee notes that the U.S. Environmental Protection Agency (EPA) drinking water standard (DWS) for iodine-129 and perhaps technetium-99 appears to be a key consideration in future decisions concerning the need for pretreatment to lower the concentrations of these two long-lived radionuclides and preferences for a particular waste form. This standard is based on radiation protection approaches dating from the 1950s and is no longer currently recommended by radiation protection authorities.

Recommendation 5-1

It would behoove DOE to consult with its regulators (particularly EPA and Washington State Department of Ecology) to determine whether risk-informing the current drinking water standard in terms of its underlying dosimetry and the assumed point-of-compliance is appropriate for application to SLAW disposal, or whether a more up-to-date standard for drinking water should be adopted. In view of the extent to which disposal decisions are driven by this standard, such a re-assessment would be well worth the effort.

The committee concludes the Summary with noting key points from the stakeholder's and members of the public's comments. Many commenters expressed concern about placing long-lived radionuclides such as iodine-129 and technetium-99 in non-vitrified waste forms for near-surface disposal in the IDF at Hanford. A major driver of this concern is the potential hazard to drinking water and the river system, especially the Columbia River. Related to the concern about durability and waste retention of non-vitrified forms is the strongly held view among many commenters that vitrified waste forms would provide more protection for waste disposed at Hanford and is encapsulated in the saying "as good as glass." On the other hand, there is widespread interest in the potential for out-of-state disposal of non-vitrified waste forms. Finally, representatives of tribal nations and many members of the concerned and engaged public have clearly stated that decision-makers need to consider the entire ecosystem at Hanford and the potential for major climatic changes, massive flooding, and seismic activity, which might adversely affect waste disposal at Hanford.

1

Introduction

As the committee has mentioned in its three previous review reports, the nation's biggest and most complex nuclear clean-up challenge is at the Hanford Nuclear Reservation. While the Hanford site has several clean-up challenges, the focus of this congressionally mandated study is approaches for treatment and disposal of the supplemental portion of the low-activity waste (LAW) from the tanks, as defined in the following section. At the site, 177 underground tanks collectively contain about 211 million liters (about 56 million gallons) of waste (WRPS, 2018) that includes high-activity and low-activity materials. This diverse waste is incompletely documented and characterized, chemically complex, and difficult to manage and dispose of safely due to many factors. These include the use of three different methods for plutonium extraction from irradiated nuclear fuel, the mixing of wastes among tanks from transfers over decades to optimize tank usage, the prior efforts to neutralize or otherwise alter the waste, the (incomplete) recovery of cesium-137 and strontium-90, which were placed in separately stored capsules, and the addition of materials to the tanks from auxiliary processes (Peterson et al., 2018). The U.S. Department of Energy's Office of Environmental Management (DOE-EM) is responsible for managing and cleaning up the waste and contamination at the Hanford site under a legally binding Tri-Party Agreement (TPA) with the Washington State Department of Ecology (the Department of Ecology) and the U.S. Environmental Protection Agency (EPA).

This review report, the final of four to be issued by the National Academies to address the congressional mandate, focuses on the Statement of Task's study charge for the committee to provide a summary of public comments on the third committee review report, which was published on August 15, 2019, and the committee's views, if any, on these comments and whether they change any of the findings or recommendations in the third review report (see Appendix D).

As in the previous review reports, the committee in this introductory chapter describes the context and tasks of the congressional mandate in Section 3134 (Sec. 3134) of the National Defense Authorization Act of Fiscal Year 2017 (see Appendix C). This chapter also introduces the study process for this final review.

PROPOSED TREATMENT PLAN AND CONGRESSIONAL MANDATE TO ANALYZE AND REVIEW THE ANALYSIS OF SUPPLEMENTAL TREATMENT APPROACHES

DOE-EM has proposed to retrieve the waste from the tanks to produce two waste streams, by removing several specific radionuclides that contain most of the radioactivity from the liquids and dissolved salt cake in the tanks, yielding liquid LAW, and then combining the removed radionuclides with the remaining solids to yield high-level waste (HLW). DOE-EM estimates that the HLW will contain more than 90 percent of the radioactivity and less than 10 percent of the total volume, while the LAW will consist of less than 10 percent of the radioactivity and more than 90 percent of the volume. This is accomplished by removing "key radionuclides to the maximum extent practical" (DOE, 2011a) during the initial processing of the waste streams in the Waste Treatment and Immobilization Plant (WTP), which is already under construction at Hanford. Of particular concern are the long-lived radionuclides iodine-129 (half-life of 15.7 million years) and technetium-99 (half-life of 210,000), and these radionuclides are problematic because of their high mobility in an oxidizing environment as compared to most other radionuclides and more than 90 percent of iodine-129 and technetium-99 could end up in the LAW stream.

To treat these two waste streams, the baseline plan is to use vitrification, that is, immobilization in glass waste forms, for all of the HLW stream and for about one-third of the direct (primary) LAW stream. Secondary LAW waste comprised of liquid wastes, off-gas filters, and other internally generated wastes is expected to be grouted, that is, immobilized in a cementitious waste form. Due to capacity limits in the LAW vitrification facility portion of the WTP, DOE-EM anticipates that there will be substantial amounts of the LAW that the WTP cannot process. To increase the LAW treatment capacity, DOE-EM intends to decide on a supplemental treatment approach and build another treatment facility to implement it. The supplemental LAW (SLAW) to be treated would be similar in composition to the LAW to be treated in the WTP. The immobilized LAW—whether from the WTP or the SLAW facility—is intended to be disposed of in the existing near-surface Integrated Disposal Facility (IDF) at Hanford, though more recently consideration has been given to an off-site location such as the Waste Control Specialists (WCS) facility near Andrews, Texas.

DOE-EM has yet to formally select a supplemental treatment approach, though the Department of Ecology and some stakeholders believe that DOE has previously promised to use vitrification. To help with the final selection, Congress directed DOE-EM in Sec. 3134 to contract with a Federally Funded Research and Development Center (FFRDC) to perform analysis on treatment approaches. According to Sec. 3134, the treatment approaches considered should at a minimum include:

1. Vitrification, to produce glass waste forms either using Joule-heated melters, which are to be used in the WTP, or bulk vitrification;
2. Grouting, to produce cementitious waste forms; or
3. Fluidized bed steam reforming (FBSR), to produce a calcined powder or a monolithic crystalline ceramic waste form.

Sec. 3134 also asks for identification by DOE of additional alternative treatment approaches, if appropriate. At this final stage of the study, neither DOE nor the FFRDC has identified additional alternative primary approaches, though the FFRDC has identified some variants of the primary approaches. As discussed in the FFRDC's final draft report, dated April 5, 2019, as well as the final report, dated October 18, 2019, the FFRDC team narrowed its consideration of alternatives to five SLAW treatment cases: (1) vitrification for disposal at the IDF, (2) grouting for disposal at the IDF, (3) grouting for disposal at WCS, (4) FBSR for disposal at the IDF, or (5) FBSR for disposal at WCS. (If the waste is vitrified, there would be little purpose to shipping it off-site, so only the IDF is considered for vitrified waste.) The vitrification method being considered is use of Joule-heated melters. In addition, secondary wastes, which were assumed to be grouted in all cases, are produced in amounts that depend on the treatment alternative, and these can contribute significantly to the dose rate to a public receptor. Also, to implement the five currently identified alternatives, additional waste conditioning (pre-treatment) might be needed, for example, to remove certain radionuclides, or to adjust the composition of the waste to make it more suitable or less costly for treatment and disposal. Notably, Sec. 3134 requires an analysis of "further processing of the low-activity waste to remove long-lived radioactive constituents, particularly technetium-99 and iodine-129, for immobilization with high level waste."

In parallel to selecting an FFRDC, DOE was directed in Sec. 3134 to contract with the National Academies of Sciences, Engineering, and Medicine (the National Academies) to conduct a concurrent, iterative review of the FFRDC report as it develops to inform and improve the FFRDC's work.[1] DOE contracted with Savannah River National Laboratory (SRNL), an FFRDC, and then SRNL formed a team of experts from SRNL and other DOE national laboratories. The charge to the FFRDC team from Sec. 3134 is in Appendix C. The Statement of Task for the National Academies committee is in Appendix D. For both the FFRDC team and the National Academies' committee, the charge is limited to analysis of methods for the

[1]For clarity, to the extent possible, this review report uses the nomenclature of *team* for the FFRDC's investigators, *committee* for the National Academies committee, *final draft report* or *final report* for the FFRDC team's work, and *review* or *review report* for the committee's work.

treatment of SLAW, considering disposal location and possible pre-treatment as needed for that analysis. Neither the FFRDC nor the committee is to make a recommendation regarding the treatment or disposal of SLAW, and certainly neither is a decision-maker.

The FFRDC team's task is to provide DOE and Congress with facts and analyses regarding treatment approaches, but not a recommendation concerning a preferred alternative. Likewise, the committee, as peer reviewer, does not offer or imply a recommendation among alternative approaches in its reviews. The committee's role as peer reviewer, though, did involve two iterations before the committee's comprehensive report (its third), as envisioned by Sec. 3134.

This congressionally mandated study has come about in part due to a 2017 U.S. Government Accountability Office (GAO) report that indicated significant cost savings if a grout treatment approach were to be used as compared to vitrification, based on the experience of the Savannah River Site's (SRS's) use of grout for about 4 million gallons (as of the date of that report) of LAW (GAO, 2017). Because the LAW at the SRS is not as chemically complex as the LAW at Hanford, however, the cost and performance of using grout treatment at Hanford could differ significantly from the cost at the SRS. The GAO report, therefore, recommended:

> Congress should consider specifically authorizing DOE to classify Hanford's supplemental LAW based on risk, consistent with existing regulatory authorities … [and] that DOE develop updated information on the performance of treating LAW with alternate methods, such as grout, before it selects an approach for treating supplemental LAW. (GAO, 2017)

In its report, GAO noted that "DOE agreed with both recommendations."

Additionally, the committee notes another very recent GAO report on risk-informed decision making (GAO, 2019). In that report, the GAO writes:

> Independent reviews conducted since the mid-1990s have found that DOE and other agencies would benefit from adopting a risk-informed approach to making clean-up decisions—that is, a decision-making approach that helps agencies consider trade-offs among risks to human health and the environment, cost, and other factors in the face of uncertainty and diverse stakeholder perspectives. In the context of this report, we define "risk" in terms of the probability and adverse consequences to human health or to the environment of exposure to an environmental hazard. These reviews have found that agencies could benefit from prioritizing federal funding in a way that better manages risks while considering limited resources. (GAO, 2019)

Performing such trade-offs and prioritization of federal funding is particularly relevant to the Hanford situation, as will be discussed in Chapter 5. The GAO report outlines the essential elements of a framework for making risk-based clean-up decisions.

The congressional charge, reflected in the Statement of Task, is very specific to treatment options for SLAW; moreover, neither the FFRDC nor the committee was charged to select, reject, or recommend any particular supplemental treatment approaches. Thus, the scope of this review report is very limited by comparison to the many, much larger, elements of the overall Hanford clean-up. SLAW, indeed, is the "tail" element of the treatment sequence. In particular, several important questions for the Hanford site were not within the scope of the FFRDC's analysis (and thus not in the scope of the committee's review). Those not within the scope include, tank waste management, HLW processing and treatment, treatment and disposal of LAW not considered SLAW, the proper definition or interpretation of high-level waste or other legal agreements or requirements, and the WTP's design, construction, and operations. In addition, while the committee specifically references the overall funding (Finding 2-2) and length of the Hanford clean-up (Finding 3-4, Recommendation 4-1), the Statement of Task clearly does not permit a comprehensive analysis of the clean-up process.

Clearly, there is solid logic to limiting the FFRDC and committee's scope: the SLAW infrastructure has yet to be built; it makes for a manageable task for the FFRDC in the time allotted; and it avoids further delays in progress toward completing the infrastructure that would result from having to perform a comprehensive analysis. Nevertheless, as the committee has previously observed (Reviews #2 and #3), decisions about the SLAW "tail" are unavoidably part of a larger, interdependent system: upstream decisions frame the options for SLAW; decisions about the SLAW "tail," even if made independently, have upstream implications; and SLAW decisions themselves have downstream implications for disposal, and disposal options have implications for SLAW. As ecologists say, everything is connected to everything; at Hanford this is literally true, and the interactions and total system will ultimately need to be addressed. Consequently, the limited scope means that very consequential upstream elements (such as tank management, HLW-LAW separation, and pre-treatment) and downstream elements (such as expected future use of the site) of the treatment process are clearly beyond the scope of the FFRDC study. DOE and Congress may ultimately decide, therefore, that a broader view of the treatment and disposal system is desirable to achieve their goals of an effective, thorough, safe, and efficient clean-up of the Hanford site.

STUDY PROCESS

In this fourth review report, according to the Statement of Task, the committee is required to "provide a summary of public comments on the third committee report and the committee's views, if any, on these comments and whether they change any of the findings or recommendations in that report." In other words, the committee is to summarize, and consider as appropriate, comments on the *committee's* review, not the FFRDC's report. Importantly, the committee is not expected to perform a further peer review of the FFRDC's final report.[2] Rather, the committee's peer review of the FFRDC analysis formally concluded with its assessment of the FFRDC's final draft report, dated April 5, 2019.[3] At the public meeting preceding the present (fourth) review, on October 31, 2019, in Richland, Washington, members of the FFRDC team presented the main results in their final report and also discussed how they addressed several of the committee's findings and recommendations in Review #3. Table 1-1 lists the FFRDC's presentations from this meeting.[4] The webcast videos of the public meetings are archived and available for viewing.[5] During the most recent public meeting in Richland, Washington, several stakeholders presented their views to the committee (see Appendix E for a list of those presentations).

Throughout the study, in addition to comments received during the public meetings, the National Academies has received comments submitted via e-mail and mail as well as most recently during the congressionally mandated comment period, via a Web survey form. All comments are available in the study's Public Access File.[6] Sec. 3134 specifies that "the National Academies of Sciences, Engineering, and Medicine shall provide an opportunity for public comment, with sufficient notice, to inform and improve the quality of the review." Also, Sec. 3134 highlights the necessity of consultation with the State of Washington

[2]To access the FFRDC's final report, see http://dels.nas.edu/resources/static-assets/nrsb/miscellaneous/SRNL-RP-2018-00687-Final-Report-Hanford-SLAW.pdf.

[3]To access the FFRDC's final *draft* report, see http://dels.nas.edu/resources/static-assets/nrsb/miscellaneous/ffrdc-2019-4.pdf.

[4]For the FFRDC's presentations and other presentations from the October 31, 2019, public meeting, see http://dels.nas.edu/Past-Events/Meeting-Supplemental-Treatment/DELS-NRSB-17-02/11480.

[5]For the first public meeting's video recording, see https://livestream.com/NASEM/DELS-NRSB; for the second public meeting's video recording, see http://www.tvworldwide.com/events/nas/180228; for the third public meeting's video recording, see http://www.tvworldwide.com/events/nas/180723; for the fourth public meeting's video recording, see http://www.tvworldwide.com/events/nas/181129; for the fifth public meeting's audio recording (no video was recorded), see http://www.tvworldwide.com/events/nas/190108; for the sixth public meeting's video recording, see http://www.tvworldwide.com/events/nas/190516; and for the seventh public meeting's video recording, see http://www.tvworldwide.com/events/nas/191031.

[6]To request information in the Public Access File for this project, see https://www8.nationalacademies.org/pa/ManageRequest.aspx?key=49905.

and an opportunity for it to comment on the FFRDC's draft report and the committee's review of that report. The committee received invited presentations during the second, third, fourth, sixth, and most recent seventh public meetings from the Department of Ecology and has considered these presentations in its reviews.

Table 1-2 shows the study's schedule, including the FFRDC's work, the committee's reviews, the public meetings, and the briefings to stakeholders. While the last activity in this schedule is subject to change, it was designed to allow adequate time for the FFRDC and the committee to do their work in the iterative fashion described in the Statement of Task, and for regulators, stakeholders, and the public to provide comments.

TABLE 1-1 List of the FFRDC's Presentations, Given on October 31, 2019, in Richland, Washington

Presentation No.	Title—Presenter
1	FFRDC Overview—Final Report on Analysis of Supplemental Treatment Approaches for Low-Activity Waste at the Hanford Nuclear Reservation—Bill Bates
2	Evaluation of Supplemental Low-Activity Waste Treatment Options: Performance Evaluation and Other Options—Thomas Brouns
3	Key Updates, Conclusions, & Areas for Further Study—Michael Stone

TABLE 1-2 Study Schedule

Timing	Activity
December 12-13, 2017	The committee's first information-gathering meeting convened in Washington, DC.
February 14, 2018	The FFRDC sent *draft working papers* as a document for the committee's first review.
February 28-March 1, 2018	The committee's second information-gathering meeting convened in Richland, Washington.
March-May 2018	The committee's **first review report** was prepared and reviewed.
June 8, 2018	The committee's **first review report** was published; the FFRDC received this review report to take into account during its continued work on its analysis.
July 15, 2018	The committee received the FFRDC's *second draft report* to review.
July 23-24, 2018	The third public meeting was held in Richland, Washington during which the FFRDC presented its work to the committee.
August-October 2018	The committee's **second review report** was prepared and reviewed.
November 2, 2018	The committee's **second review report** was published. The FFRDC received the committee's review to take into account during its work on the final draft report.
November 29-30, 2018	Public meeting #4 was held in Richland, Washington, during which the second review report and the FFRDC's progress toward its final draft report were discussed, as well as hearing from stakeholders.
December 21, 2018	FFRDC sent a *draft report* but the committee determined that it was not sufficiently complete and thus not ready for review.
January 8, 2019	Public meeting #5 in Atlanta, Georgia, that discussed the *incomplete FFRDC draft report*.
April 5, 2019	The FFRDC completed a *final draft report* that was sent to the committee for review.
May 16, 2019	Public meeting #6 convened in Kennewick, Washington, during which the *complete final draft report* and the views of the Washington State Department of Ecology on that report were presented.
May-August 2019	The committee's **third review report** was prepared and reviewed.
August 15, 2019	Publication of **third review report** and the minimum 60-day public review period began.

October 18, 2019	Publication of the FFRDC's *final report*.
October 31, 2019	Final public meeting of the committee in Richland, Washington, and the cutoff date for receipt of comments from stakeholders and the public.
November 20, 2019	End date of the extended comment period for the receipt of final comments from stakeholders and the public.
February 2020	Publication of the committee's fourth and **final review report**.
February-March 2020	Final briefings to Congress, DOE, Washington State, and other stakeholders.

To perform the peer review task, the National Academies formed a committee composed of 13 experts and one technical adviser whose expertise spans the issues relevant for reviewing the FFRDC's analysis, including risk assessments, cost estimation, cost-benefit analysis, waste processing, supplemental treatment approaches, legal and regulatory requirements, and large scale nuclear construction projects. A majority of the committee members have prior experience in studying clean-up activities at the Hanford Nuclear Reservation and at other DOE-EM sites. Appendix F contains biographical information about the committee members' qualifications and experiences. The committee also has found it necessary to perform additional fact finding, for example, by receiving briefings from experts outside the FFRDC team about aspects of the supplemental pre-treatment, treatment, or analysis approaches. Any information learned by the committee during additional fact-finding is available in the study's Public Access File.

The FFRDC team was assigned a very large task to be accomplished in a short period of time, that is, to review a long history and large technical literature on three or more very different treatment technologies and, as the analysis developed, the permanent disposition of waste material in two (or potentially three) very different disposal sites. (As the committee has noted in previous reports, the choice among treatment approaches cannot meaningfully be made without consideration of the disposal environment and transporting the waste to the disposal site.) The FFRDC team has, as the committee has also noted, worked very hard to grapple with the task it was assigned. It has gathered a large amount of information, performed analysis on it, and improved its approach and presentation of results in response to comments. Importantly, the FFRDC is not in the role of a decision-maker in selecting one treatment approach over another.

REVIEW REPORT ORGANIZATION

The remainder of this review report proceeds in four parts. In Chapter 2, the committee discusses developments since publication of Review #3, in particular, the availability of the performance assessment (PA) for the IDF, and the publication of the FFRDC's final, revised report and FFRDC comments on Review #3. In Chapter 3, the committee provides a summary of comments received during the comment period and categorizes the comments by themes or groupings. In Chapter 4, the committee responds to comments according to the ground rules described at the start of Chapter 3. Finally, Chapter 5 provides the committee's conclusions about this study.

2

Developments Since Publication of Review #3

AVAILABILITY OF THE PERFORMANCE ASSESSMENT FOR THE INTEGRATED DISPOSAL FACILITY

Since publication of Review #3 on August 15, 2019, the committee has received access to the Performance Assessment (PA) for the Integrated Disposal Facility (IDF) at Hanford.[1] In Review #3 (see Appendix A), the committee mentioned in Finding 3-2 that it did not have access to the PA or to the Performance Evaluation (PE) data and analysis prepared by the Federally Funded Research and Development Center (FFRDC), and thus, "it was impossible for the committee to critically review the differences in the performance of the three waste forms and their disposal systems over time." In addition, Finding 3-3 specified,

> Without the proper supporting documentation for the FFRDC's PE, or the IDF PA on which it was based, the committee is unable to assess the potential significance of mobile, long-lived fission products such as iodine-129 and technetium-99, and other long-lived radionuclides (possibly selenium-79 and others).

While the committee had limited time to review the PA, which runs to more than 1,800 pages, during this final review, it has focused on searching the PA for information and data relevant for the concerns expressed in above findings from Review #3. In its October 31, 2019, meeting, the committee was told by Pat Lee, a co-author of the PA, that the final PA results do not differ from those provided to the committee at the February 28, 2018, public meeting.

First, the committee reminds readers that in Review #3 and in the FFRDC's final draft report, it was emphasized that the PA applies only to a vitrified primary low-activity waste (LAW) form as well as grouted secondary waste forms. However, the grout assumed for the PA for secondary wastes is not the same grout as would be used for primary waste forms, according to the analysis in the FFRDC's final draft report. In addition, the PA does not address steam reformed or grout waste forms for the primary supplemental LAW (SLAW). It is these considerations that led the FFRDC to develop a performance evaluation for primary SLAW that consistently addressed all three treatment alternatives.

Second, the committee assesses that the information that it was able to review in the PA does not change the findings or recommendations in Review #3 as they relate to the vitrified waste alternative. But as noted below, the committee has added a new recommendation.

Third, the committee underscores that the U.S. Department of Energy's Office of River Protection (DOE-ORP) has to meet multiple regulatory requirements as described in the PA (although not concisely) and addressed for the baseline (primary vitrification and secondary grouted waste) alternative. As far as the committee can ascertain from its time-limited review of the PA, there are three important requirements: meeting (a) DOE dose limits to the public, (b) land disposal restriction (LDR) requirements, and (c) the drinking water standard (DWS) limits.

[1]While the PA was released by DOE on July 31, 2019, the study director was notified on August 14, 2019, and then received a copy of the PA on August 24, 2019. Even if the PA had been received on July 31, 2019, it would have been too late for the committee's consideration for Review #3.

(a) DOE dose limits are risk-based, and the disposed material must meet the prescribed dose limit. The analysis was done, and the calculated doses were well below requirements. The committee notes two interesting points within the analysis. First, a number of radionuclides other than iodine-129 and technetium-99 were the most important determinants of compliance in many instances, which makes the primacy of the DWS and these particular radionuclides suspect. Second, the most important dose scenario to a public receptor was inadvertent intrusion by a farmer and not the infiltration-leaching-radionuclide transport scenario that underlies the DWS. In both ways, the PA's analysis may be inapposite to the analysis undertaken in the FFRDC report.

(b) LDR requirements are definitely not risk-based in the sense of the risk of their presence in a particular disposal site; rather, they are based on specified leachate concentrations of statutory and regulatory lists of chemicals. Hanford tank waste may contain a number of these chemicals, but their concentrations are very uncertain because of the difficulty and cost of sampling tanks containing heterogeneous wastes. All of this is acknowledged in the FFRDC's final draft and final reports. The committee observes that this uncertainty may pose an opportunity for a hybrid approach (along the lines of Recommendation 4-1 in Review #3) in which the retrieved waste is analyzed a batch at a time and then routed to an appropriate treatment process that includes treatment for LDR constituents or not, as needed.

(c) The DWS is ostensibly risk-based in that the limits on the amount of the two key radionuclides in drinking water (iodine-129 and technetium-99) are expressed in terms of dose. The committee notes that the National Drinking Water Standards, as promulgated by the U.S. Environmental Protection Agency's (EPA's) 40 CFR 141, limits beta and gamma emitting radionuclides as a class in terms of dose in 40 CFR 141.66(d). The maximum contamination levels or MCLs (EPA, 2002) are based on Handbook 69 (NBS, 1959); however, Handbook 69 is based on dosimetry guidance found in International Commission on Radiological Protection's (ICRP's) Publication 2, published in 1959. Thus, the committee observes that this guidance would benefit from updating to the current international radiological dosimetry practices. Additionally, the committee notes that DOE assumes the point-of-compliance for the DWS is 100 meters from the edge of the IDF by rule.These observations lead to the following recommendation:

Recommendation 5-1

The committee believes it would behoove DOE to consult with its regulators (particularly EPA and Washington State Department of Ecology) to determine whether risk-informing the current drinking water standard in terms of its underlying dosimetry and the assumed point-of-compliance is appropriate for application to SLAW disposal, or whether a more up-to-date standard for drinking water should be adopted. In view of the extent to which disposal decisions are driven by this standard, such a re-assessment would be well worth the effort.

See Chapter 1 for a brief discussion of risk-informed decision-making with reference (GAO, 2019).

PUBLICATION OF THE FFRDC'S FINAL REPORT AND COMMENTS RECEIVED FROM THE FFRDC

FFRDC Final Report

On October 18, 2019, the FFRDC published its final report, and it is available on the National Academies website.[2] In addition, Appendix B of this review reproduces the executive summary and conclusions of that report. The final report contains numerous significant changes, and the committee appreciates the substantial effort that the FFRDC team made to respond to the committee's Review #3. As explained in Chapter 1 of this review, the committee is not required to conduct a further peer review. Nevertheless, out

[2]See http://dels.nas.edu/resources/static-assets/nrsb/miscellaneous/SRNL-RP-2018-00687-Final-Report-Hanford-SLAW.pdf.

of respect for the FFRDC's efforts and to assure the completeness of this Review #4, the committee highlights in this section notable changes in the final report.

The committee observes, first, that the final report has a substantially revised executive summary, and that is now written in a manner more accessible to a non-technical readership. Likewise, the executive summary and the introductory chapter provide a set of clearly stated conclusions. The committee also notes that the final report has additional useful information about cost comparisons and provides updated summary tables that help show the comparisons of the relevant factors useful for decision-makers who need to decide among the treatment and disposal options. In these and other ways, the FFRDC final report contributes valuably to the understanding of the leading alternatives for SLAW treatment and disposal, which should "be accepted as a pilot or scoping study for a full comparative analysis of the SLAW treatment alternatives," as stated in Recommendation 1-1 of Review #3.

FFRDC Comments on the Committee's Review #3

During the public comment period, the FFRDC submitted to the National Academies its comments on Review #3. Here the committee summarizes those comments and provides its views.

The team notes that the committee's Finding 1-1 implies that the FFRDC team has failed to provide a decision framework, but the team believes that such a framework is not in the scope of the team's task. The committee stands by Finding 1-1 that the FFRDC's analysis "does not yet provide a complete technical basis needed to support a final decision on a treatment approach." This should not be construed as a failure on the part of the FFRDC because it was not within their scope, and if it were, it would have been infeasible, given the team's limited time for completion, to do more than an overview or scoping study. As suggested by a comparison with the scope and detail of the PA for just one alternative, full analysis of each alternative will be a very significant undertaking. Rather, the FFRDC was tasked with providing a foundation for comparison of possibilities, and the committee stands by its assessment of the valuable contributions of the team's analysis, as noted in Finding 7-1.

The team suggests that in Finding 2-1, "it would be more correct to say: The cost estimates are based on technologies that, for the most part, have not yet been fully developed or **deployed for treating Hanford SLAW,** and are based on costs from similar **applications of these** technologies" [emphasis was present in the submitted comments]. The committee appreciates this clarification from the team. The committee stands by its larger point about the uncertainties about the technical maturity and capacity of each treatment approach.

The team states that in Finding 2-2 it "is not clear how this finding is different from the descriptions and conclusions in the FFRDC [final draft] report." Also, the team notes that in Finding 2-3, "the cost delta between the different variants of each technology was too small to be accurately assessed. It is not clear how the committee intends the FFRDC team to address this finding." The committee observes that the FFRDC final report has come closer to Finding 2-2 and that it has shown responsiveness to Finding 2-3.

In commenting on Finding 3-2, the team acknowledges that it has provided additional details in its final report about how the performance evaluation (PE) was conducted. The committee recognizes this additional information, but it stands by Finding 3-2 that it did not have access to the PA and did not receive much of the data on the PE during the time of its review. Moreover, as described above, the PA only details one of the alternative approaches. The committee observes that the team in the final report is responsive to Finding 3-3.

The team comments that Finding 3-4 points to an evaluation concerning how delays in waste treatment could lead to tank failures, but the team believes this analysis is outside of its scope. The team, however, notes that its report "does state that delays will result in extension of tank duration and risk." This is a fair point, and the committee (in Review #3) has previously praised the FFRDC report for specifically acknowledging the consequences in time, cost, and risk of an unaffordable path forward for SLAW, as that it is absolutely fundamental to the decisions that DOE must make.

The team notes that Recommendation 1-1 implies that "additional studies would significantly change the conclusions reached by the FFRDC study" and that the committee did not state which of the main conclusions are "inadequately supported." In Recommendation 2-1, the team comments that it "is not clear from the recommendation what additional information is needed versus when the committee is simply requesting the existing information be reorganized." While, as mentioned above, the committee recognizes the laudable effort in the revised report, it stands by these recommendations that lay out the detailed questions and factors that need to be fully addressed and placed in a format to support a decision framework. The committee underscores that the FFRDC final draft report and its latest revision provide a useful scoping study that identifies many practical findings, as noted in Recommendation 1-1, and gives a basis for a follow-on study and decisional document. This is not a case of damning with faint praise; the FFRDC team has provided valuable analysis, even if not the final technical analysis that will ultimately be required for decision-makers. The committee has added to Recommendation 1-1 the text: This comprehensive analysis should adopt a total systems approach (one that includes addressing relevant externalities to SLAW that were outside the FFRDC's scope) to provide a substantially complete basis for decision-making.

Notably, as discussed below and shown in Appendix B of this review, the team itself recommends several items for further study. The committee also observes that the team provides in the final report new and better organized information that is responsive to Recommendation 2-1; however, it still does not clearly show the trade-offs, as outlined in the committee's recommendation. The committee has added to Recommendation 2-1 the text: The committee notes the limited amount of information and pervasiveness of uncertainty in many aspects of the decisions to be made. Although it may seem counter-intuitive, the committee suggests that probabilistic approaches be used in future analyses because, when information is limited, the result is in the form of uncertainties, which are very useful to decision-makers.

The team points to several places in Chapter 2 of Review #3 where the committee highlights several items that are outside the scope of the FFRDC's analysis. The team requests that these items not be considered "deficiencies in the report." The committee's intent is to underscore that the scope is limited and that the system for SLAW treatment is just one part of a much bigger, complex system for treating Hanford tank waste that would have to be considered in an integrated manner in future studies.

The team itself makes clear in its revised executive summary (see Appendix B) and updated final report that:

> Several key aspects of this study may benefit from further verification and technical analysis to increase confidence in several cases. These include the following:
>
> - Treatment of organics restricted from land disposal (on-site and off-site grout cases)
> - Treatment of technetium and iodine (on-site grout case)
> - Treatment of liquid secondary wastes (vitrification case)
> - Performance of grouted waste forms (on-site grout case)
> - Performance of steam reformed waste forms (on-site SR case)

The committee in Review #3 pointed out:

> The [final draft] report notes on p. 13 and Sec. 1.4, subsection 7, that
>
> numerous alternative concepts for tank waste processing at Hanford have been proposed in various levels of detail, which, if adopted, could impact the SLAW assumptions used to perform this analysis. Examples include:
>
> - Direct Feed HLW,
> - At-Tank Treatment Alternatives,

- HLW Definition Clarifications, [and]
- Improved LAW glass or process models.

> Any of these examples would result in direct or indirect impacts on the assumptions in this analysis. It is not possible in this study to evaluate each potential future scenario as many of the scenarios have not been defined sufficiently well to allow a definitive impact evaluation. If these scenarios progress, the impact on the SLAW mission needs to be considered.

Also, as the committee stated in Review #3:

> *The committee observes that if any of these developments were to occur, the scope and scale of the SLAW treatment could be profoundly affected, and the need for treating the SLAW could be eliminated albeit at a cost of unknown magnitude and duration. The committee suggests that decision-makers view these possible developments as uncertainties to be considered when deciding how to proceed with the SLAW treatment.* [Italicized for emphasis.]

3

Themes of the Comments Received During the Comment Period

For this final phase of the study, the committee discusses here the ground rules for this report. First, the committee has considered all comments received during the comment period from August 15, 2019, to November 20, 2019. The methods used to receive comments are noted in Chapter 1; Appendix E summarizes the comments. Second, the committee decided to revise Review #3 only where a correction is needed or where there is an objective error or an omission. (For completeness and as an aid to readers, Appendix A reproduces the summary and main body of Review #3, including all findings and recommendations, as well as the committee's review of the final draft report and the committee's advice for decision-makers. As mentioned in Chapter 2, the committee made two revisions to Recommendations 1-1 and 2-1; otherwise the findings and recommendations are unchanged.) Third, this final review acknowledges significant new information, which became available only after the committee's Review #3 and which the committee considered in deciding whether to change or modify any of its findings and recommendations from Review #3. Fourth, the committee did not respond in a one-to-one manner to each comment received. Instead, the committee has identified several concepts and themes among these comments and has responded with views on selected groupings or themes of comments. In this chapter, the committee selects themes that are within the scope of the Statement of Task (see Appendix D) and the issues addressed by Review #3 (see Appendix A) and the Federally Funded Research and Development Center's (FFRDC's) report (see Appendix B). Fifth, when the committee responds in Chapter 4 to themes, it focuses on themes specific to Review #3. The committee acknowledges there are comments clearly outside the scope of study, that is, beyond supplemental treatment of low-activity waste LAW.

Appendix E lists and summarizes the comments received during the comment period. More than 60 comments were received. Of these, at least 45 were clearly from individual members of the public; there were also 7 anonymous commenters, so the committee is not able to determine whether they are individuals or represent specific entities such as nongovernmental organizations or even governmental agencies. Four nongovernmental organizations, the Consortium for Risk Evaluation with Stakeholder Participation (CRESP), Hanford Challenge, Hanford Communities, and Tri-City Development Council, were identified in their submitted comments. Two tribal nations, the Wanapum and the Yakama, provided comments. Two state regulatory agencies, Washington State Department of Ecology (Department of Ecology) and Oregon Department of Energy, submitted comments. Two advisory boards, Hanford Advisory Board and Oregon Hanford Cleanup Board, provided comments. This chapter provides the themes of those comments that are relevant for the scope of this study and the committee's task for this review. In the next chapter, the committee discusses whether and how it responds to these themes under the ground rules described above.

OPPOSITION TO GROUT FOR TREATMENT OF SUPPLEMENTAL LOW-ACTIVITY WASTE AND DISPOSAL AT HANFORD AND CONCERNS ABOUT RETENTION OF LONG-LIVED RADIONUCLIDES IN THE GROUT WASTE FORM

Many individuals (about 25 commenters) express opposition to use of grout for treatment of primary supplemental low-activity waste (SLAW) for disposal at the Integrated Disposal Facility (IDF) at Hanford. (One individual noted that he is sending suggested form letter text provided by Hanford Challenge, which according to its website is "a nonprofit watchdog and advocacy organization based in Seattle.") Hanford

Challenge also clearly expresses opposition to grout in its organization's submitted comments. These commenters also want to have the long-lived radionuclides, in particular, iodine-129 and technetium-99, removed from the SLAW waste form, whether grouted or not. Many commenters express concern that grout would not adequately contain long-lived radionuclides due to their understanding that grout, as a concrete waste form, would degrade relatively quickly. Several commenters raise concern about the relative proximity of the IDF to groundwater and the Columbia River. Protection of the Columbia River is a major theme in many comments.

CONCERNS ABOUT CLIMATIC CHANGE, MAJOR FLOODING, AND SEISMIC ACTIVITY IN THE HANFORD REGION

Considering climatic changes and geological changes, some commenters (a couple of individuals, Hanford Challenge, and the Yakama Nation) caution that the Hanford region is prone to major flooding and that they believe that the scenarios considered for disposal at the IDF do not adequately consider this potential devastating event. Major flooding could occur due to increased rainfall from climate changes and glacial lakes' melting. Related concerns are dam failures and overflows of the Columbia River. Some have also mentioned that long-term seismic activity needs to be considered. (The committee notes that the recently released performance assessment [PA] does consider this suite of catastrophic scenarios for vitrified waste at the IDF.)

TRIBAL MEMBERS CALL FOR CARE OF THE LAND FOR ALL FUTURE GENERATIONS

During the October 31, 2019, public meeting, representatives from the Yakama Nation and the Wanapum tribe spoke of the responsibility to take care of this land for their children and grandchildren, pointing out that cultural uses of this land have "existed from time immemorial." To meet this responsibility, they are opposed to leaving any waste on the Hanford site. In particular, the written comments from the Yakama Nation specifically cite the adverse impact on their rights under the Treaty of 1855, under which they ceded more than 15 million acres to the United States but reserved their rights to access "accustomed places," (see Appendix E, p. 104) especially for gathering foods and medicines and for fishing along the Columbia River. Keeping waste on Hanford land in perpetuity would restrict their ability to exercise these rights for the foreseeable future. Thus, they point to the social cost to the Yakama Nation and members of other regional tribes of leaving any waste on the land, even if treated and immobilized.

INTEREST IN USE OF WASTE CONTROL SPECIALISTS FOR DISPOSAL OF NON-VITRIFIED WASTE FORMS

Some commenters (a few individual commenters, Hanford Communities, and the Department of Ecology) are interested in the option to send SLAW waste forms to the Waste Control Specialists (WCS) near Andrews, Texas. Several people are open and willing to have grout used for treating the SLAW as long as it is disposed in WCS. No one expressed opposition to use of WCS although one resident of Texas asks that the decision take into consideration what is acceptable to those living outside of Washington State. In its submitted comments, the Department of Ecology expresses cautious optimism about the potential for use of WCS.

In addition to the WCS alternative disposal site, the FFRDC mentioned the possibility of disposal in the EnergySolutions facility near Clive, Utah, as a possible waste disposal site, in particular, for Class A waste. The committee has previously endorsed the value of considering disposal sites other than Hanford because they may create upstream opportunities for a speedier, less costly clean-up. Any such consideration would have to include any other plausible sites, for example, the U.S. Department of Energy (DOE)-owned Nevada National Security Site, which might be appropriate for disposal of SLAW. As mentioned later in this chapter, CRESP in its submitted comments also mentions the potential use of the Nevada National Security Site.

STRUCTURAL INTEGRITY AND MONITORING IN PERPETUITY OF THE INTEGRATED DISPOSAL FACILITY

Paul Flaherty of CHC Consulting, LLC, cautions that “the predicted degradation on the structural integrity of the landfill [IDF] will ultimately lead to adverse groundwater impacts” and “modeling variables should also consider daily operational activities during the active life of” the IDF “prior to capping of the landfill.” He recommends considering the impacts of weather events on the structural integrity. Moreover, he believes that the federal government should “provide post-closure integrity assurance into perpetuity” (see Appendix E, p. 101).

Hanford Challenge in its written comments casts doubt on the ability to put in place such indefinite monitoring and links this concern to its opposition to disposing of long-lived radionuclides, in particular, iodine-129 and technetium-99, in the IDF. Hanford Challenge notes, “Future use scenarios assume continuous institutional controls over the entire life of the project, including unrealistic restrictions on land uses” (see Appendix E, p. 101).

CONCEPT OF “AS GOOD AS GLASS”

Concerning the concept of “as good as glass,” the Department of Ecology in its submitted comments agrees “that the term [‘as good as glass’] needs to be objectively defined” (see Appendix E, p. 103). The Department of Ecology stated that a detailed approach to this definition was developed in the 2003 timeframe (see Appendix E, p. 103)

> when the “as good as glass” term was first coined and agreed to between Ecology and the United States Department of Energy (DOE). The State would welcome an opportunity to rekindle the discussion around a comprehensive working definition with DOE and DOE’s selected technical community representatives.

In its submitted comments, members of CRESP, which is a multi-university consortium funded by DOE through a cooperative agreement, highlight that Review #3 “begins with the premise that there is a ‘perceived agreement’ that the final waste form for tank SLAW will be vitrification or another final waste form that is ‘as good as glass’” (see Appendix E, p. 107). They then point out that “DOE has not entered into any such agreement, and urge that this error in [Review #3] be corrected” and “should make clear that the Hanford Federal Facility Agreement (FFA), which is the legally binding agreement … [and] contains no such agreement.” The CRESP members also suggest “that the focus should not be on any specific waste form (e.g., glass versus others) but instead on defining the necessary technical performance requirements of any waste form that would be used for low-level waste burial in the IDF” (see Appendix E, p. 107). They underscore their view that there is noncompliance with the Federal Facility Compliance Act (FFCA) at the IDF such that the FFCA provides that requirements to federal facilities apply “in the same manner, and to the same extent” as requirements applicable to private parties and to “impose on Hanford a requirement that LAW be vitrified or the equivalent, when no such requirement is imposed on private LAW disposal sites, could constitute a violation of the parity requirement of FFCA” (see Appendix E, p. 107). In addition to the IDF and WCS, they recommend consideration of the Nevada National Security Site as a potential disposal site for Hanford SLAW.

ADVANCED GLASS WASTE FORMS TO REDUCE OR ELIMINATE SLAW TREATMENT

During the public meeting of October 31, 2019, and in written comments, research and development of advanced glass waste forms were discussed. In particular, Albert Kruger, a glass scientist at DOE, described his research on advanced glass waste forms and indicated that such glass formulations might result in avoiding the necessity for a SLAW treatment facility or lessening such necessity if the waste loading in the LAW vitrification system could be increased sufficiently.[1] In a submitted comment after his presentation, an anonymous commenter stated that the presentation "provided the perspective that better glass formulations have the 'potential to realize nearly the entire soda inventory in the WTP LAW Facility and within an acceptable mission duration.'" This commenter then stated that

> this perspective requires the flow sheet and mass balance to be closed around all of the WTP equipment, not just the melters. If the process duration is compressed that means the tank waste feed is being treated at a rate much faster than was used as the basis for design of the WTP LAW Off-Gas treatment system, or the tank waste effluents management system. The promise of an easy fix with good glass must be evaluated in terms of the concentrations in the off-gas effluents, and whether the increased off-gas burden creates equipment capacity problems, including at ETF, or equipment corrosion problems, due to higher concentrations of halides, for example. It may be premature to suggest relying on better glass as a basis for deleting secondary LAW treatment. This will be especially true if the DFLAW off-gas and effluents systems do not perform as advertised. (see Appendix E, pp. 107-108)

CONSIDERATION OF ADDITIONAL TREATMENT TECHNOLOGIES

Several commenters (eight individuals, two anonymous submissions, and the Yakama Nation) raise concern that the FFRDC was too limited in its analysis of the treatment approaches it considered for its final draft report. As mentioned previously, these three approaches are vitrification using Joule-heated melters, grout, and fluidized bed steam reforming. One commenter provides extensive comments about the capability of GeoMelt's bulk vitrification technology and asks that this method be re-considered for treating SLAW at Hanford. Another commenter believes that the FFRDC may not have fully addressed the congressional mandate in Sec. 3134 (see Appendix C) because of the requirement to consider "other alternative approaches identified by the U.S. Department of Energy for immobilizing the low-activity waste" (see Appendix E, p. 101). (The committee notes that the FFRDC in its final draft report clearly stated that earlier in the study it had considered 22 variants but then narrowed down to the main three approaches with two disposal sites.) Additionally, a commenter suggests that the Department of Ecology should convene a meeting that would solicit new ideas and expresses his view that DOE needs to "think outside the box" and consider technologies such as the syn-rock technology that was applied at Oak Ridge National Laboratory (see Appendix E, p. 100).

COSTS AND BUDGETARY CONSIDERATIONS

Several commenters (four individual commenters, an anonymous submission, Hanford Challenge, and the Yakama Nation) express their concern that cost savings has become the dominant consideration in selecting treatment approaches. Some of them mention that there is a long history of driving toward "faster, cheaper" approaches that then result in spiraling upward costs and billions of dollars spent with little or no treatment performed. In addition, they state that the main consideration needs to be on long-term protection of human health and the environment and not on "short-sighted" cost considerations. Three other individual commenters have presented a different view that Hanford is unlikely to receive more than the approximately $2 billion per year that it is currently allocated. While the total budget for DOE's Office of Environmental Management (DOE-EM) has been upward of about $7 billion per year, DOE-EM has to balance among several sites across its clean-up complex. Some commenters are concerned that complex technical processes would continue to result in cost escalation. For example, an anonymous commenter asks for consideration of the "exponential savings that are possible by not having a technically complex process and by not having a high temperature off-gas process" (see Appendix E, p. 100).

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[1]See http://dels.nas.edu/resources/static-assets/nrsb/miscellaneous/hanford7/kruger.pdf.

SPECIFIC COMMENTS DIRECTED TO THE COMMITTEE'S REVIEW #3

The Yakama Nation requests that the committee "should include a recommendation for evaluation of impacts to Tribal people and resources in Recommendations 2-1 and 3-1" of Review #3 and suggests that "the committee add Tribal, State, and Other Entities opposition as a bullet point to Recommendation 2-1 (d)" (see Appendix E, p. 104).

The CRESP members support the committee's point in Review #3 "that having start/stop capability may be particularly important because … the receipt rate [of the SLAW] is projected to be highly variable." They believe that it would be incomplete for the committee "*not* to include analysis of options for SLAW disposition using the *current HLW definition adopted by the Department*" (see Appendix E, p. 107) [in the *Federal Register* notice in June 2019] [emphasis in the submitted comment], but they note that this definition has yet to be implemented at Hanford.

In addition, the CRESP members believe that Review #3

> does not address the important issue of regulatory authority over mixed waste, and its implications for regulation of SLAW. RCRA [Resource Conservation and Recovery Act] regulators have the authority to regulate the chemically hazardous aspects of mixed waste, whereas regulators with nuclear regulatory authority—here DOE—have authority over the radioactive components. Under this allocation, RCRA regulators do not have authority to impose different regulatory requirements depending on the radioactivity of mixed wastes unless those differences affect the chemically hazardous character of the wastes (see Appendix E, p. 107).

Moreover, the CRESP members state,

> Developing an adequately protective and cost-effective treatment plan for non-HLW SLAW wastes requires that DOE, Washington state, and EPA [U.S. Environmental Protection Agency] fully and carefully consider the potential applicability of all available LDR [land disposal restrictions] flexibility mechanisms…. The analysis should evaluate the prospects for each major category of non-HLW SLAW waste stream to meet the criteria required for regulatory approval for use of each of the RCRA LDR flexibility mechanisms.… If the analysis is not possible for this [study], we strongly recommend that it be considered for a follow-on NAS [National Academy of Sciences] study. (see Appendix E, p. 107)

Furthermore, they point out the need for a more accurate inventory of RCRA tank wastes and that the current operating assumption is that all of the tanks contain all of the hazardous materials under RCRA, thus substantially increasing the costs for clean-up and the need to understand the impact of RCRA tank closure requirements on SLAW volume.

4

The Committee's Observations and Responses to Comments

In this chapter, the committee provides its views on selected themes of the comments relevant to its Review #3 and does not provide a one-to-one response to every specific comment or theme. Also, the committee follows the ground rules as described in Chapter 3.

CONCEPT OF "AS GOOD AS GLASS"

As to the comments on "as good as glass," the committee appreciates that the Washington State Department of Ecology (Department of Ecology) acknowledges in its written comments that objective criteria still need to be developed. The committee also recognizes the Consortium for Risk Evaluation with Stakeholder Participation (CRESP) members' comment that there is no legally binding agreement that supplemental low-activity waste (SLAW) be treated with vitrification (see Appendix E, p. 106). The committee does not state in Review #3 that there is a "perceived agreement" that has some legal or regulatory basis; rather, Finding 5-2 states in part, "The term 'as good as glass' is not defined in law, regulation, or agreement, and it is only tentatively defined by its advocates." Review #3 also points out that some stakeholders strongly hold the view that there is an agreement on "good as glass," an observation that is demonstrated by the comments described in Chapter 3. In addition, the committee appreciates CRESP members' comment that "the focus should not be on any specific waste form (e.g., glass versus others) but instead on defining the necessary technical performance requirements of any waste form that would be used for low-level waste burial in the IDF" (see Appendix E, p. 106). The committee notes that Review #3 adequately addresses the committee's comments about the need for a stepwise comparison.

In Review #3, the committee also discusses the (lack of) maturity of vitrification as a waste form by focusing primarily on the unique and uniquely challenging nature of the Hanford waste. It is worth repeating that vitrification has an inconsistent history of success, and that even where successful it has high operating and maintenance costs, as well as significant periods of planned and unplanned unavailability.

GROUT WASTE FORMS, RETENTION OF LONG-LIVED RADIONUCLIDES, AND CONCERNS ABOUT RELEASES OF IODINE-129 AND TECHNETIUM-99 INTO THE ENVIRONMENT

Concerning releases of long-lived radionuclides, in particular, iodine-129 and technetium-99, into the environment, stakeholders such as the Oregon Department of Energy, the Oregon Advisory Board (citing the letter prepared by the Oregon Department of Energy), the Department of Ecology, Hanford Challenge, tribal nations, and other individual members of the public raise concerns about grout's capability to sufficiently retain these radionuclides for possible disposal at the Integrated Disposal Facility (IDF) at Hanford. The committee notes that the Oregon Department of Energy's letter contains a detailed review of the literature on this topical area, and here, the committee provides its response on the main themes of that letter.

The letter from the Oregon Department of Energy raises two main points related to the disposal of grout at Hanford: (1) the lack of rigorous public review of the Performance Assessment (PA) for the IDF, and (2) the use of short-term laboratory performance data on reducing grout and grout with getters, and extrapolation of these data to predict long-term waste form performance in a dynamic storage environment.

The committee has addressed aspects of both items during public meetings and interim review reports. Finding 3-2 of Review #3 specifically highlights the committee's inability to review the draft PA for waste form comparisons (see Chapter 2 of this review for the committee's comments on aspects of the PA). In Review #3, the committee also notes that the Federally Funded Research and Development Center's (FFRDC's) evaluation did not include a scenario where the PA was rejected by the Washington State regulator. In interim and the final FFRDC reports, the FFRDC team mentioned that it used information from the draft PA and included it in the team's analysis. Complete review of the PA will likely occur as the disposal options mature and as the U.S. Department of Energy's Office of Environmental Management (DOE-EM) and DOE's Office of River Protection take the next steps toward reaching a decision on SLAW treatment and disposal.

The reliance on short-term, condition-specific studies on waste forms is also a subject of interest to the committee, and one that is coupled with the PA. Obviously, extrapolation from short-term studies is unavoidable in predictions of the long-term behavior of any waste form. Nevertheless, the committee recognizes that the inclusion of degradation models, chemical reaction mechanisms, and radionuclide speciation to describe waste form behavior would improve data usage and applicability for analysis of disposal options and anticipated long-term behavior. In Review #3, the committee calls for the waste forms to be compared with respect to waste loading, density, composition, radionuclide speciation, and radionuclide release mechanisms. Within a waste form composition, the addition of getters to the grout is noted as a topic requiring further assessment. The need for detailed understanding of radionuclide speciation highlights the oxidation state behavior, and how this property is influenced, stabilized, or altered by other waste form components. As noted in the Oregon Department of Energy's letter, the oxidation state of the radionuclides strongly influences solubility and mobility. Radionuclide speciation is also coupled to radionuclide release and retention mechanisms in the waste form. In Review #3, the committee highlights these waste form material properties as a means to promote further research that will provide the scientific foundations for understanding long-term behavior of radionuclides in a disposal environment.

The committee also notes that Hanford Challenge in its submitted comments asserts that "the grout form proposed by the FFRDC report is itself toxic and a potential threat to the environment" because of the use of fly ash from coal combustion. In response, the committee observes that in April 2015, the U.S. Environmental Protection Agency published in the *Federal Register* its final ruling on "Hazardous and Solid Waste Management System; Disposal of Coal Combustion Residuals From Electric Utilities." This ruling, in part, discusses that an "encapsulated beneficial use is one that binds the CCR [coal combustion residual] into a solid matrix that minimizes mobilization into the surrounding environment." A major example of an encapsulated beneficial use is: "Fly ash used as a direct substitute for Portland cement during the production of concrete" or grout (EPA, 2015).

ADVANTAGES OF WASTE CONTROL SPECIALISTS VERSUS THE INTEGRATED DISPOSAL FACILITY

The Waste Control Specialists (WCS) facility near Andrews, Texas, has a number of advantages over the IDF at Hanford for any waste form, but it is mainly relevant for non-vitrified waste forms. As mentioned in Chapter 2, the PA for the IDF is for a primary low-activity waste (LAW) that is vitrified. But the secondary waste from that treatment process would be grouted. The Department of Ecology has yet to issue a permit based on the PA, and in the Department of Ecology's submitted written comments, it states that since the 2012 Tank Closure and Waste Management Environmental Impact Statement, it has been known that "some of the secondary waste would have to be treated with improved grout formulations. Vitrification alternatives analysis should not be unfairly penalized by treating the secondary waste with lesser performing grout." In contrast, the WCS facility has an approved PA and waste acceptance criteria as part of a license to operate. The committee notes that the FFRDC final draft report and final report mention the possibility of shipping the grouted secondary waste to WCS. Many commenters support that option. In particular, Pam Larsen, executive director of the Hanford Communities, emphasized in her presentation on October 31, 2019, and her written comments, that the Test Bed Initiative has provided a demonstration of treating LAW as grout and successfully sending it to WCS. WCS has the main advantage of having no drinking water aquifer underneath its disposal facility; moreover, there is no nearby river and no potential for flooding.[1] That site also appears to have a stable geology, although the committee notes that it never received a detailed presentation on the geological and hydrological characteristics of WCS. All of these physical features of WCS could mitigate the concerns of many commenters about releases of iodine-129 and technetium-99 from non-vitrified waste forms. This is why the committee emphasizes in Review #3 that one of the principal contributions of the FFRDC study is to "[open] the door to serious consideration of other disposal locations, specifically the WCS facility near Andrews, Texas, and possibly the EnergySolutions facility near Clive, Utah."

Concerning additional engineered changes to the IDF, the committee acknowledges the Department of Ecology's comment that Review #3 "appeared to advocate consideration of enhancing the disposal facility design to enhance the performance of each waste form…. If there is a proven basis for considering these kinds of disposal facility enhancements in relation to long term performance, (e.g., substantially greater than 1,000 years)," (see Appendix E, p. 103) the Department of Ecology asks for the committee to refer to that basis and that if there is none, it requests that the committee rescind those comments. In Review #3, the committee simply states the obvious point that, in principle, performance of the entire waste disposal system could be extended either by improvements to the waste form *or* by improvements to the disposal facility *or* both. The committee was not tasked with, and did not, perform an engineering analysis of the IDF, but it stands to reason that realistic improvements to the disposal facility, if they exist, should be explored. As an example and as a reference, the committee notes that DOE submitted a request to the U.S. Environmental Protection Agency (EPA) in 2006 for emplacing magnesium oxide in the Waste Isolation Pilot Plant (WIPP) repository for transuranic waste. EPA notes that magnesium oxide "is an engineered barrier that DOE included as part of the original WIPP Certification Decision that ensures repository releases will be well within the EPA's regulatory limits" (EPA, 2006). As in Review #3, the committee would not support ruling out a priori a category of potential improvements to the disposal system.

BULK VITRIFICATION

Early in the FFRDC's analysis, the team considered about 22 variants. Bulk vitrification in a metal container was one of them. This treatment method was tested at Hanford between 2003 and 2008, and subsequent plans called for construction and operation of a demonstration facility. However, DOE cancelled the project and related development work in 2008 after an independent technical review (Independent and External Team of Experts, 2006) that identified 19 technical issues that could result in the failure of the demonstration to meet performance requirements and 26 areas of concern that might have resulted in a change to design or require additional testing, followed by a U.S. Government Accountability Office (GAO) report (GAO, 2007) that was critical of the proposed demonstration because of concerns about technical and project management.

During its work, the FFRDC developed flowsheets for bulk vitrification and conducted analyses to assess bulk vitrification (e.g., Sect. B.2 and p. 169 of the final FFRDC report). However, in an effort to make its results more transparent and comprehensible, the FFRDC reduced the number of variants from 22 to the five now considered in its final report. Those five did not include bulk vitrification, noting the need for "additional development and testing to resolve key process issues" for bulk vitrification (p. 169). The committee agrees with this approach because (a) it did contribute to making the FFRDC's report more transparent and comprehensive, (b) the issues that need to be resolved indicate that substantial time would be required to advance the technology so that it could be confidently deployed, and (c) the vitrification

[1]The WCS website notes: "The WCS site in Andrews County, Texas was selected due to its location atop a ridge of 600-ft. thick red-bed clay in a relatively remote, semi-arid, sparsely inhabited area of far west Texas, with the nearest residence approximately 3.5 miles to the west in New Mexico and annual rainfall of less than 16 inches." That website also notes that the nearest aquifer is 6 miles north of the site. In addition, water would have to travel up a gradient to reach the site. See http://www.wcstexas.com/about-wcs/environment.

alternatives that are addressed in the FFRDC report and the committee's reviews are applicable to the essential features of bulk vitrification with the exception being that bulk vitrification was to be deployed as a set of connected modules in the field and not in a large concrete and steel structure.

EXAMINE THE ENTIRE SYSTEM

As the committee has mentioned in previous reviews, the scope of this study is limited to analyzing treatment approaches for SLAW, but the committee has also drawn attention in earlier reviews to the fact that SLAW is one part of a much bigger, complex waste treatment system. Moreover, this system is interconnected to the even larger system of the surrounding environment, including the Columbia River and the regional ecosystem. Furthermore, the timescales are immense—consider the half-life of 15.7 million years for iodine-129—that have to be taken into account when examining the impacts on human health and the other parts of the living environment.

In light of these interrelated systems across the landscape, network of rivers and wetlands, and the long temporal period for some radionuclides, the committee recognizes the serious concerns of many stakeholders and members of the public. In particular, the committee calls attention to concerns about climatic impacts, risks of major flooding, and seismic events that have not yet been taken into account for all waste forms.

The committee acknowledges the Department of Ecology's comments that one cannot look at the IDF in isolation, and specifically,

> while it may be possible to control future releases of chromium, nitrate, Tc-99, and I-129 from IDF (by controlling the waste forms, limiting [what] is disposed of in IDF, or both), there is little to no possibility of controlling the future release of [these contaminants] from waste already disposed of to the soils across the Hanford Site. These additional contributions are why the State is looking for results that are significantly lower than the EPA drinking water MCLs [maximum contaminant levels]. (see Appendix E, p. 103)

As noted above, the current MCLs may warrant reconsideration, as they are based on outdated methodologies. In any event, the FFRDC's and the committee's scope is limited to the contribution of SLAW treatment and disposal, and the committee has insufficient information (and it may be that no one does) to translate the legitimate overall concern into practical guidance for performance levels for SLAW disposal. Indeed, this kind of overarching assessment is precisely why clean-up decisions are committed to DOE, which has the widest overview of the Hanford situation.

When considering the entire system, experience has confirmed that a rigorous assessment of the uncertainties fills the gap of the lack of information. In particular, it is possible to do a probabilistic analysis of risks and cost regardless of the state of the design or the process. In situations where little is known, the result of the analysis is in the form of uncertainty, which can always be quantified with evidence-based probabilities. Thus, this would be a calibration of the areas of uncertainty that are exposed and can be ranked by importance. Information on uncertainties and their distribution can be very useful to decision-makers. Such results might be applied to SLAW using the risk-informed decision-making framework suggested by the GAO (2019) as described in Chapter 1.

SPRINGBOARD CONCEPT

Some commenters (five) express support for the concept in Recommendation 4-1 that the FFRDC's analysis could be used as a "springboard" to considering the possibility of hybrid approaches, or approaches that permit consideration of new or improved technologies. It seems inevitable that the management of Hanford's tank waste will take decades to complete, and rather than fighting the timeline, it may be possible to take advantage of it. Technologies of waste treatment and disposal systems are constantly evolving.

Novel techniques are gaining maturity with additional use. Also, our understanding of pathways of contaminants, their effects, and means of protection are constantly improving. An approach to SLAW treatment and disposal should be open to, and if possible encourage, such opportunities. This would be a novel approach at Hanford and elsewhere within DOE, but the sheer size and complexity of the Hanford site may be the strongest argument for considering the possibilities.

Areas for Additional Study

As the committee noted in Chapter 2, the FFRDC team has already identified some areas for additional study:

- Treatment of organics restricted from land disposal (for the grout waste form cases of disposal at the IDF and WCS)
- Treatment of technetium and iodine (for the case of grout waste form disposal at the IDF)
- Treatment of liquid secondary wastes (for vitrification case of disposal at the IDF)
- Performance of grouted waste forms (for the case of disposal at the IDF)
- Performance of steam reformed waste forms (for the case of disposal at the IDF)

When assessing the readiness of various technologies, the committee suggests that assessors use a rigorous structured assessment process such as that described in DOE's *Technology Readiness Assessment Guide* (DOE, 2011b).

The committee also points out the need for researching improvements in secondary waste forms, enhancements for engineered barriers at the IDF to be tailored for the particular waste forms instead of treating as one size fits all, and methods to place the technetium and iodine into high-level waste forms. In addition, the committee notes the need for more research and development on the best performing grout and the getters, which are added materials that can better retain the contaminants of concern. Finally, the committee underscores Recommendation 4-1 from Review #3 on development of hybrid options.

5

Conclusion

The U.S. Department of Energy (DOE) faces many difficult choices in the management of the tank waste at Hanford, one essential part of which is the management of the supplemental low-activity waste (SLAW). While SLAW represents a significant fraction (at least one-third) of the waste volume and a small fraction (less than 10 percent) of the overall radioactivity, the costs and consequences of its treatment are by any standard extremely significant. The congressionally mandated report of the Federally Funded Research and Development Center (FFRDC) team advances the understanding of the options available to DOE, in part by limiting the universe of possibilities to a suite that can likely meet regulatory standards and can be directly compared on other grounds, and in part by expanding the realistic disposal options beyond a controversial on-site facility. While the committee offers numerous comments and cautions regarding the final FFRDC report, it is clear that the FFRDC took on a very difficult task and were responsive to both the congressional mandate and to the committee's iterative peer reviews.

Moreover, the FFRDC report shines a light on several fundamental issues that are beyond the scope of the congressional mandate but that will have to be part of the ultimate decision-making process for SLAW and other key clean-up decisions at Hanford. For instance, the report reveals a fundamental disconnect between the current clean-up baseline and long-term funding streams. Unless this is explicitly resolved in decision-making about SLAW and other decision-making at the Hanford site, there are risks of slippage in time to completion, increase in cost, and increased risk of failure of the current waste configuration. Likewise, the report's appropriate focus on iodine-129 and technetium-99, which may be disposed in LAW and SLAW, highlights potential inconsistencies in the treatment of long-lived radionuclides, which DOE will have to resolve. Finally, the report also suggests the potential value of a mixed or hybrid approach that gains resilience with parallelism and is capable of adapting to new and improved technologies that are virtually certain to appear over the coming decades.

The committee has observed in previous review reports (see, in particular, Review #3) through the course of this study that the most effective opportunities for making meaningful improvements in Hanford's overall environmental outcomes would require consideration of a broader scope of issues than that defined by Sec. 3134 and the Statement of Task. The treatment and disposal of SLAW will be in many ways the literal end of a long chain of decisions and actions that will not only constrain the options for SLAW, but will also sharply limit the degree to which any SLAW decision—however carefully considered in and of itself—can affect the overall environmental outcomes or costs of the Hanford clean-up. In addition to constraining technical options to be compared, it has become apparent that costs for the Hanford site will be far above $2 billion per year (a level that is much higher than what DOE's Office of River Protection has received in preceding years). And the overall consequence of insufficient funding is like an indefinite extension of the project length—which, as the committee has previously observed in Review #3, puts the Hanford site environment at increased risk. This is because the projected costs of upgrading the tanks, conducting tank operations, and constructing the Waste Treatment and Immobilization Plant exceed that level (see Figure 2-1 in Appendix A). Thus, the comparisons and trade-offs among SLAW options, while important in themselves, tend to mask the fundamental problem that even the least costly SLAW alternative is likely beyond the available funding.

In his oral comments during the October 31, 2019, public meeting, Chief Rex Buck, Jr., of the Wanapum tribe expressed his view that the FFRDC and committee, while so intensely focused on cost and benefit computations, had lost sight of the true problem, which is to clean up the land called Hanford, and that there is a "responsibility to take care of the land" so that it can be passed down to future generations for their use.[1] The committee will not pretend that it can fairly represent all that he wished to convey, but his statement did strike a vein of truth for the committee about the dilemma posed by this project's scope. Cost-benefit analysis (which is one objective of Sec. 3134's SLAW comparison) can be incomplete in identifying meaningful system-wide improvements when the options it will evaluate are defined too narrowly, such as by excluding significant interdependencies with other decisions affecting the system of which they are inextricably a part. Such is the case for the present analysis scope.

The combination of these two factors—large funding increases that appear to be needed into the future for Hanford clean-up and the technical dependency of the definable SLAW options on a set of fixed upstream decisions and actions—has created a situation in which analysis of one component is incomplete and outcomes cannot truly be optimized independently. This realization does not render the work of the FFRDC unimportant or inconsequential; however, it has promoted a clearer recognition—one that the committee wishes to highlight—that the challenge facing Hanford cannot be solved by incremental improvements in the SLAW portion of the clean-up alone.

[1] See http://www.tvworldwide.com/events/nas/191031.

References

Cary, A. 2019. Hanford's $17 billion vit plant is at serious risk of not being finished on time. *Tri-City Herald*. September 4, 2019.

DOE (U.S. Department of Energy). 2011a. *Radioactive Waste Management Manual*, DOE M 435.1-1, Change 2.

DOE. 2011b. *Technology Readiness Assessment Guide*. DOE G 413.3-4A.

EPA (U.S. Environmental Protection Agency). 2002. *Radionuclides in Drinking Water: A Small Entity Compliance Guide*. February 2002.

EPA. 2006. WIPP Magnesium Oxide (MgO)—Planned Change Request. https://www.epa.gov/radiation/wipp-magnesium-oxide-mgo-planned-change-request (accessed December 6, 2019).

EPA. 2015. Hazardous and Solid Waste Management System; Disposal of Coal Combustion Residuals From Electric Utilities. *Federal Register* Notice Vol. 80, No. 74, April 17, 2015.

GAO (U.S. Government Accountability Office). 2007. *Nuclear Waste: DOE Should Reassess Whether the Bulk Vitrification Demonstration Project at Its Hanford Site is Still Needed to Treat Radioactive Waste*. GAO-07-762, June 2007.

GAO. 2017. *Nuclear Waste: Opportunities Exist to Reduce Risks and Costs by Evaluating Different Waste Treatment Approaches at Hanford*. Report to Congressional Addressees, GAO-17-306, May 2017.

GAO. 2019, *Environmental Liabilities: DOE Would Benefit from Incorporating Risk-Informed Decision-Making into Its Cleanup Policy*. Report to Congressional Requesters, GAO-19-339, September 2019.

Independent and External Team of Experts. 2006. *A Comprehensive Technical Review of the Demonstration Bulk Vitrification System*. Technical Assessment Conducted by an Independent and External Team of Experts. Volume 1. RPP-31314, September 28, 2006.

NBS (National Bureau of Standards). 1959. *Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure*, Handbook 69 (June 5, 1959).

Peterson, R.A., E.C. Buck, J. Chun, R.C. Daniel, D.L. Herting, E.S. Ilton, G.J. Lumetta, and S.B. Clark. 2018. Review of the scientific understanding of radioactive waste at the U.S. DOE Hanford Site. *Environmental Science & Technology* 52(2):381-396.

WRPS (Washington River Protection Solutions). 2018. The Tanks. https://wrpstoc.com/tank-operations/the-tanks (accessed December 5, 2019).

Appendix A

Major Parts of *Review of the Final Draft Analysis of Supplemental Treatment Approaches of Low-Activity Waste at the Hanford Nuclear Reservation: Review #3*

CONTENTS

Appendix A

Summary

Section 3134 of the National Defense Authorization Act for Fiscal Year 2017 (P.L. 114-328) (Sec. 3134) calls for a Federally Funded Research and Development Center (FFRDC) "to conduct an analysis of approaches for treating the portion of low-activity waste (LAW) at the Hanford Nuclear Reservation" intended for supplemental treatment.[1] The U.S. Department of Energy (DOE) has contracted with Savannah River National Laboratory (SRNL), an FFRDC, to provide the called-for analysis. SRNL assembled a team of experts from SRNL and other national laboratories to perform the analysis. Sec. 3134 also calls for the National Academies of Sciences, Engineering, and Medicine (the National Academies) "to conduct a review of the analysis" performed by the FFRDC that is independent of and concurrent with the FFRDC's analysis "to improve [its] quality." The complete text of the congressional mandate in Sec. 3134 is provided in Appendix C, and the Statement of Task for the National Academies review is provided in Appendix D.

This review report, the third of four to be issued by the National Academies to address the congressional mandate, focuses on the Statement of Task's study charge for the committee to provide an "overall assessment." The committee's overall assessment is divided into two parts: a technical review (based on the elements in the committee's Statement of Task) of the FFRDC final draft analysis and a "guide" of the report to aid decision-makers. The committee's comments in this review report are based on the FFRDC's final draft report of 278 pages, dated April 5, 2019, and a set of 43 slides produced by the FFRDC and presented at the public meeting on May 16, 2019, in Kennewick, Washington, as well as FFRDC team members' and others' public presentations (see Appendix E) at that meeting.

This review report is the final opportunity for the committee to review the FFRDC's work. It is anticipated that the FFRDC will produce a final report for publication in fall 2019 and that the FFRDC will make use of the committee's review report in doing so. After publication of the committee's review report, stakeholders and the interested public will have an opportunity to offer comments on that report and the FFRDC's final draft report for a period of at least 60 days. The committee's final task will be to produce a fourth review report that will provide a summary of public comments on the third committee review report and the committee's views, if any, on these comments and whether they change any of the findings or recommendations in this, the third, review report.

The committee's overarching task has been to provide a concurrent, independent peer review of the ongoing FFRDC analysis. The committee is neither charged to evaluate the supplemental treatment approaches nor recommend any particular approach. Equally important, the committee notes what is not in the scope of the FFRDC's analysis and the committee's review, namely, tank waste management, high-level waste (HLW) processing and treatment, and the Waste Treatment and Immobilization Plant's (WTP's) design, construction, and operations. Indeed, the FFRDC does not identify a preferred option for supplemental treatment, but instead in its report, it separately evaluates the treatment alternatives against the baseline, as well as against one another, for a number of factors important to selecting a preferred alternative. The de facto baseline is vitrification of the LAW in the supplemental LAW (SLAW) treatment facility because it is the current expectation of many stakeholders and a similar facility (the WTP) is currently under

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[1]According to DOE's *Radioactive Waste Manual*, low-activity waste means the waste that remains after as much of the radionuclides as technically and economically practicable have been removed from the tank waste, and that when immobilized in waste forms, may be disposed as low-level waste in a near-surface facility, as long as the waste meets criteria in the Waste Incidental to Reprocessing determination. Supplemental treatment refers to processing of the low-activity waste that is excess to that portion to be treated by vitrification in the Waste Treatment and Immobilization Plant.

construction to be followed by disposal of the resulting wastes in the Integrated Disposal Facility (IDF) at Hanford. The FFRDC's task is to provide data and analysis to enable DOE, with congressional oversight, to decide whether to use vitrification, grouting, fluidized bed steam reforming (FBSR), or another treatment approach to treat the SLAW by converting it into a waste form for disposal.

Importantly, the committee notes that the evaluations of treatment options for the SLAW include more than just the solidification of the liquid LAW. The objective of the SLAW treatment is to ensure that the solidified wastes can be permanently disposed of in a near-surface land disposal site. Because these sites have "waste acceptance criteria," additional pre-treatment processing is sometimes required so that the final waste forms can be accepted for disposal. Additionally, the primary treatment and pre-treatment processes produce "secondary wastes" that also need to be disposed of in a near-surface disposal site. It is this entire process from pre-treatment through treatment to disposal that the FFRDC evaluates and compares.

In addition to the three primary treatment options, the FFRDC also identified two near-surface land disposal options to analyze and compare. The existing IDF located at Hanford is considered as the "baseline" LAW disposal facility, again because it is the current expectation. In this baseline option, the liquid LAW (including SLAW) would be solidified using vitrification, and the secondary waste would be grouted. While both types of waste are slated to be disposed of at the IDF, the Washington State Department of Ecology has yet to approve waste acceptance criteria that would allow for the disposal of grouted secondary waste or even the primary vitrified LAW in the IDF. The second disposal site analyzed is operated by Waste Control Specialists (WCS), and located near Andrews, Texas. WCS is located in an arid and isolated region of western Texas, and it has become an active commercial low-level waste disposal facility in recent years, as well as being designated as a Federal Waste Disposal Facility. The FFRDC report describes the differing, and less restrictive, waste acceptance criteria for WCS as compared with what is anticipated for the IDF and the effect that using the WCS site would have on the SLAW treatment. The FFRDC also mentions the possibility of disposal at the EnergySolutions site near Clive, Utah, and estimates that this site would require removal of almost all of the strontium-90 from the waste stream to meet its Class A low-level waste acceptance criteria.

Using the criteria specified in Sec. 3134, including risks, benefits, costs, schedules, regulatory compliance, and obstacles to implementation, the FFRDC in its report analyzed five alternatives for treating the primary SLAW: (1) vitrification for disposal at the IDF, (2) grouting for disposal at the IDF, (3) grouting for disposal at WCS, (4) FBSR for disposal at the IDF, and (5) FBSR for disposal at the WCS site. The vitrification option would result in significant amounts of secondary waste, which, as mentioned above, would be grouted and proposed to be disposed of at the IDF, although the FFRDC also considers the possibility of disposal of this waste at WCS.

The FFRDC in its report concluded that:

- The vitrification technology would take 10 to 15 years to implement and would cost \$20 billion to \$36 billion.
- The grouting technology would take 8 to 13 years to implement and would cost \$2 billion to \$8 billion.
- The fluidized bed steam reforming technology would take 10 to 15 years to implement and would cost \$6 billion to \$17 billion.

The cost estimates are based on technologies that, for the most part, have not yet been fully developed or deployed, and are based on costs from similar technologies, as well as assuming ideal funding conditions (i.e., no funding caps) and no redirection during a multi-year effort. Thus, there are large attendant uncertainties, suggesting that costs could be much higher than estimated, but are unlikely to be much lower. The FFRDC team also concluded that a SLAW treatment and disposal option that meets regulatory requirements for disposal can be developed using any of the three treatment technologies evaluated. In addition, the FFRDC report (on p. 22) notes that for some treatment alternatives, "the required time for construction and startup require an immediate start to allow completion by the required startup date" because DOE's current plan is a target date of 2034 for the SLAW treatment to begin in combination with the WTP.

The FFRDC and the committee have gone through multiple iterations of draft FFRDC analysis reports and committee review reports, with both formal and informal comments and responses. The committee finds that the FFRDC has generally been responsive to comments, and the most recent FFRDC report has improved considerably over its predecessors in focus, responsiveness to the congressional mandate, and technical analysis. Furthermore, in offering the suggestions in this review report, the committee recognizes that the FFRDC's work is planned to end in fall 2019. Thus, the suggested improvements are included to aid the reader in interpreting the contents of the FFRDC report and for potential use in follow-on studies.

Based on the committee's technical review (see Chapter 2 for details) of the FFRDC's final draft report and the presentation materials from the May 16, 2019, public meeting, and based on the committee's consideration of the usefulness of the final draft analysis for decision-makers (see Chapter 3 for details), the committee has reached consensus on the following findings and recommendations.

USING THE FFRDC REPORT

Overall Assessment

Finding 1-1

The purpose of the committee's review is to advise whether DOE, Congress, regulators, and other stakeholders can rely on the FFRDC report to evaluate and decide on a treatment approach for the SLAW. The committee finds that, in its current iteration, the FFRDC's analysis:

a. When taken alone, does not yet provide a complete technical basis needed to support a final decision on a treatment approach;
b. Does not yet clearly lay out a framework of decisions to be made among treatment technologies, waste forms, and disposal locations; but
c. Can form the basis for further work as described below in the committee's findings and recommendations.

Analysis of Costs, Benefits, and Risks

Finding 2-1

The cost estimates in the FFRDC report are based on technologies that, for the most part, have not yet been fully developed, tested, or deployed for Hanford's particular, and particularly complex, tank wastes, and instead use costs from similar technologies. As a result, there are large attendant uncertainties, suggesting that costs could be much higher than estimated, but are unlikely to be much lower.

Finding 2-2

The cost estimates in the FFRDC report are based on continuing funding at and beyond current levels to optimize the waste treatment technologies and speed of progress. These involve very large annual appropriations, which are inevitably uncertain over the planned decades of activity, especially because current planning assumptions anticipate a two- or three-fold increase in expenditures at certain points in the SLAW treatment process. This, too, introduces the possibility that funding shortfalls will lead to longer schedules, increased total costs, and higher chances of additional tank leaks or structural failures, which will themselves increase costs as well as health and environmental risks.

Finding 2-3

The report's analysis of costs does not enable the reader to analyze key trade-offs among specific alternatives or variations of major alternatives.

Disposal Risk Assessment

Finding 3-1

Assessment of waste form performance would have to include consideration of the characteristics of the disposal sites and the transport pathways to receptors over relevant periods of time, as well as be based on the inherent characteristics of the waste form.

Finding 3-2

The committee did not have access to the 2017 IDF Performance Assessment (PA) that has been prepared by DOE or to the Performance Evaluation (PE) data and analysis prepared by the FFRDC. Therefore, it was impossible for the committee to critically review the differences in the performance of the three waste forms and their associated disposal systems over time. Additionally, the technical bases for waste degradation models and mechanisms used in the PE analyses for the IDF by the FFRDC team are not well documented and justified.

Finding 3-3

Without the proper supporting documentation for the FFRDC's PE, or the IDF PA on which it was based, the committee is unable to assess the potential significance of mobile, long-lived fission products such as iodine-129, technetium-99, and other long-lived radionuclides (possibly selenium-79 and others). It would have been useful for the FFRDC to include the human health risk estimates (dose) over time for all of the long-lived radionuclides that are listed in Table F-2 of their report, not just iodine-129 and technetium-99.

Finding 3-4

The FFRDC report gives little consideration in its analysis to the environmental, health, and safety consequences of hastening or further delaying remediation of the Hanford waste storage tanks, which is related to the probability that additional tank leaks or structural failures will occur over the long period of time expected for the removal and treatment of the waste in the tanks.

Pre-Treatment to Remove Iodine-129 and Technetium-99

Finding 4-1

The FFRDC performed an analysis of whether removal of iodine-129 and technetium-99 was needed to comply with the disposal waste acceptance criteria, and examined the status of technologies for removing these radionuclides from the SLAW feed stream, but the FFRDC report does not respond fully to the congressional direction (in Sec. 3134) because the report does not address immobilization of the iodine-129 and technetium-99 recovered from the LAW as part of the separate high-level glass waste form to be produced in the WTP.

Other Observations

Finding 5-1

The report makes little use of the experience with grouting and other technologies at other DOE sites and commercial operations. While there are unquestionably meaningful differences among the waste forms, technologies, and disposal environments as compared to Hanford, the extensive experience gained at Savannah River Site, in particular, is an invaluable source of insight.

Finding 5-2

The committee was repeatedly told that the selection and implementation of an approach to treat tank waste would be hampered by the insistence by the State of Washington and some other stakeholders that any approach other than vitrification must be "as good as glass." The term "as good as glass" is not defined in law, regulation, or agreement, and it is only tentatively defined by its advocates. The analysis in, and the public presentations of, the draft FFRDC reports offer a follow-on opportunity for DOE to engage with its regulators and stakeholders to identify performance standards based on existing regulatory requirements for waste form disposal and to pursue a holistic approach to selecting a treatment technology.

Comparisons

Finding 6-1

Over multiple iterations, the FFRDC report has increasingly enabled side-by-side comparisons among the SLAW treatment approaches, exemplified by the table of alternatives and criteria. It remains difficult, however, for the reader to see comparisons and trade-offs in the supporting narrative.

The FFRDC Report's Steps Forward

Finding 7-1

The report represents useful steps forward by:

a. Confirming that versions of vitrification, grouting, and steam reforming are treatment technologies that merit further consideration for the SLAW;
b. Establishing the likelihood that vitrification, grouting, or steam reforming are capable of meeting existing or expected regulatory standards for near-surface disposal albeit with varying amounts of pre-treatment being required;
c. Highlighting the important contribution of the iodine-129 in the secondary waste streams disposed at the IDF to the total estimated radiation dose rate to the receptors;
d. Underscoring the regulatory and acceptance uncertainties regarding approaches other than vitrification technology for processing the SLAW; and
e. Opening the door to serious consideration of other disposal locations, specifically the WCS facility near Andrews, Texas, and possibly the EnergySolutions facility near Clive, Utah.

Use the FFRDC Report as a Pilot or Scoping Study

Recommendation 1-1

The committee recommends that the "Preliminary Draft" FFRDC report reviewed by the committee (that is, the document dated April 5, 2019) be accepted as a pilot or scoping study for a full comparative analysis of the SLAW treatment alternatives, including:

- Vitrification, grouting, and steam reforming as treatments for the SLAW;
- Pre-treatment to remove iodine-129, technetium-99, and other long-lived radionuclides (e.g., selenium-79) to ensure that regulations are met or reduce cost, and pre-treatment to assure that the waste product meets land disposal requirements;
- Pre-treatment of strontium-90, if it is not removed during the cesium-137 pre-treatment process; and
- Disposal at the IDF, WCS, and (possibly) the EnergySolutions facility.

The draft report should either be substantially revised and supplemented (though the committee understands that the FFRDC team's funding may not permit this), or be followed by a more comprehensive analysis effort and associated decisional document, which needs to involve the decision-makers or their representatives.

Organize the Report or Decisional Document Around Four Interrelated Areas

Recommendation 2-1

The final FFRDC report or follow-on decisional document should include technical data and analyses to provide the basis for addressing four interrelated areas, as follows:

(a) Selection of a technology that will produce an effective waste form. This has two parts:

- The treatment (immobilization) technology:
  - How well will it work? Is the technology well understood, tested or used under real-world conditions, dependent on other technologies, or relatively simple?
  - What types and volumes of secondary waste are created by each technology?
  - What is the lifetime cost and duration, and uncertainties therein?
  - What are the risks (e.g., programmatic and safety) and uncertainties therein?
- The waste forms and associated disposal sites:
  - How effective is each waste form in immobilizing the waste (e.g., the materials science of the incorporation, corrosion, and release processes) and over what time periods?
  - What is their performance under the expected disposal conditions (e.g., release from the disposal facility and transport through the geosphere to a receptor)?
  - How do the waste form performances actually differ? This goes further than simply demonstrating compliance, but rather demonstrates an understanding of how the waste forms and disposal environments actually interact.

(b) Selection among available disposal sites. The report describes the IDF and WCS, and it briefly mentions the EnergySolutions facility near Clive, Utah. Selection requires an understanding of how each site will "work" over time in providing a barrier to the release and migration rate of key radionuclides, especially and specifically technetium-99 and iodine-129.

- What is the role of the hydrogeology at each site (the IDF and WCS) in preventing/slowing radionuclide release and migration?
- How might the disposal facility design be modified to enhance the performance of each waste form?

Important site-related issues include regulatory compliance, public acceptance, cost, safety, expected radiation dose to the maximally exposed individual over time, and differences among the disposal environments.

(c) Determining how much and what type of pre-treatment is needed to meet regulatory requirements regarding mobile, long-lived radionuclides and hazardous chemicals, and possibly to reduce disposal costs. The congressional charge specifically mentions technetium-99 and iodine-129, but other long-lived radionuclides, such as selenium-79, may be relevant. The analysis should consider both:

- Leaving the technetium (Tc), iodine (I), and other long-lived radionuclides in the waste form for the SLAW, with possible use of enhanced engineered barriers such as getters, which are added materials that can better retain the contaminants of concern; and
- Removing the Tc and I (and possibly other radionuclides) to create a new waste stream with its own (and possibly different) form of immobilization and final disposition, including incorporating it into the separate vitrified HLW stream.

(d) Other relevant factors. Other factors that would affect the selection of a SLAW treatment alternative include:

- The costs and risks of delays in making decisions or funding shortfalls in terms of additional resource requirements and the increased chance of tank leaks or structural failures over time, and the need to address the consequences (notably, all 149 single-shell tanks have exceeded their design life and the 28 double-shell tanks will have exceeded their design life before the waste is slated to be removed);
- DOE's proposed reinterpretation of the definition of HLW waste could change the SLAW size and performance requirements by altering the feed volume and composition depending on how the reinterpretation is implemented;
- Thorough consideration of the experience at other DOE sites (e.g., Savannah River Site) and relevant commercial facilities; and
- Outcomes of DOE's proposed Test Bed Initiative, the second phase of which would have involved (and perhaps still could involve) grout treatment of 2,000 gallons of LAW and shipment to WCS (the first phase involved a proof of concept treatment of 3 gallons of LAW that was sent to WCS and was completed in December 2017). The future of the second phase of the Initiative is now in doubt due to DOE's withdrawal in late May 2019 of the state permit application.

Final Review of the Study on Supplemental Treatment Approaches of LAW at Hanford: Review #4

Need Direct Comparisons of Alternatives to Aid Decision-Making

Recommendation 3-1

The analysis in the final FFRDC report and/or a comprehensive follow-on decisional document needs to adopt a structure throughout that enables the decision-maker to make direct comparisons of alternatives concerning the criteria that are relevant to the decision and which most clearly differentiate the alternatives.

Consideration of Parallel Approaches

Recommendation 4-1

The FFRDC report could also provide the springboard for serious consideration of adopting an approach of multiple, parallel, and smaller scale technologies, which would have the potential for:

a. Faster startup to reduce risks from tank leaks or structural failures if adequate funding is available to support parallel approaches;
b. Resilience through redundancy (like the parallel uranium enrichment and plutonium separation methods during the Manhattan Project);
c. Taking positive advantage of the unavoidably long remediation duration to improve existing technologies and adopt new ones; and
d. Potentially lower overall cost and program risk by creating the ability to move more quickly from less successful to more successful technologies, with less stranded cost in the form of large capital facilities that are inefficient or shuttered before the end of their planned lifetime.

Appendix A

1

Context and Setting

The nation's biggest and most complex nuclear cleanup challenge is at the Hanford Nuclear Reservation. From 1944, when plutonium production began in the B Reactor during the Manhattan Project, to 1987, when the ninth and last plutonium production reactor was shut down, the Hanford Nuclear Reservation had produced about two-thirds—approximately 67 metric tons—of the nation's plutonium stockpile for nuclear weapons. The massive scale of the production processes resulted in substantial amounts of radioactive and other hazardous wastes. Presently, 177 underground tanks collectively contain about 211 million liters (about 56 million gallons) of waste (WRPS, 2018). The chemically complex and diverse waste is difficult to manage and dispose of safely because of several factors. These include the use of three different methods for plutonium extraction from irradiated nuclear fuel, the mixing of wastes among tanks from transfers to optimize tank usage, the prior efforts to neutralize or otherwise alter the waste, the (incomplete) recovery of cesium-137 and strontium-90, which were placed in separately stored capsules, and the addition of materials to the tanks from auxiliary processes (Peterson et al., 2018). The U.S. Department of Energy's Office of Environmental Management (DOE-EM) is responsible for managing and cleaning up the waste and contamination under a legally binding Tri-Party Agreement (TPA) with the Washington State Department of Ecology (the Department of Ecology) and the U.S. Environmental Protection Agency (EPA).

In its first and second review reports, the committee underscored in the introductory chapters the fundamental importance to the tasks of the congressional mandate in Section 3134 (Sec. 3134) of the National Defense Authorization Act of Fiscal Year 2017 (see Appendix C). As in the previous reviews by the committee, this chapter of the review report also provides a brief introduction to the congressional mandate to set the stage for this review and about the study process. In addition, it gives brief historical context about the waste treatment approaches considered or developed since 1989, when the TPA began. This context is important to highlight that past developments continue to influence the present treatment plan for the tank waste.

PROPOSED TREATMENT PLAN AND CONGRESSIONAL MANDATE TO ANALYZE AND REVIEW THE ANALYSIS OF SUPPLEMENTAL TREATMENT APPROACHES

DOE-EM has proposed to retrieve the waste from the tanks to produce two waste streams, high-level waste (HLW) and low-activity waste (LAW), by removing several specific radionuclides that contain most of the radioactivity from the liquids and dissolved salt cake in the tanks, yielding liquid LAW, and then combining the removed radionuclides with the HLW solids. DOE-EM estimates that the HLW will contain more than 90 percent of the radioactivity and less than 10 percent of the total volume, while the LAW will consist of less than 10 percent of the radioactivity and more than 90 percent of the volume. This is primarily accomplished by removing "key radionuclides to the maximum extent practical" (DOE, 2011b) during the processing of the waste streams in the Waste Treatment and Immobilization Plant (WTP), which is already under construction at Hanford.

To treat these two waste streams, the current plan is to use vitrification, that is, immobilization in glass waste forms, for all of the HLW stream and for at least one-third and perhaps all of the direct (primary) LAW stream, depending on decisions yet to be made. Secondary LAW waste comprised of liquid wastes, off-gas filters, and other internally generated wastes is expected to be grouted, that is, immobilized in a cementitious waste form. Due to capacity limits in the LAW vitrification facility portion of the WTP, which is also under construction, DOE-EM anticipates that there will be substantial amounts of the LAW that the WTP cannot process To increase the LAW treatment capacity, DOE-EM intends to decide on a supplemental treatment approach and build another treatment facility to implement it. The supplemental LAW (SLAW) to be treated would be similar in composition to the LAW to be treated in the WTP. The immobilized LAW—whether from the WTP or the SLAW facility—is intended to be disposed of in the existing near-surface Integrated Disposal Facility (IDF) at Hanford, though more recently consideration has been given to an off-site location such as the Waste Control Specialists (WCS) facility near Andrews, Texas.

DOE-EM has yet to formally select a supplemental treatment approach, though the Department of Ecology and some stakeholders believe that DOE has previously promised to use vitrification. To help with the final selection, Congress directed DOE-EM in Sec. 3134 to contract with a Federally Funded Research and Development Center (FFRDC) to perform analysis on treatment approaches. According to Sec. 3134, the treatment approaches considered should at a minimum include:

1. Vitrification, to produce glass waste forms either using Joule-heated melters, which are to be used in the WTP, or bulk vitrification;
2. Grouting, to produce cementitious waste forms; or
3. Fluidized bed steam reforming (FBSR), to produce a calcined powder or a monolithic crystalline ceramic waste form.

Sec. 3134 also asks for identification by DOE of additional alternative treatment approaches, if appropriate. At this stage of the study, neither DOE nor the FFRDC has identified additional alternative primary approaches, though the FFRDC has identified some variants of the primary approaches. As discussed in the FFRDC's final draft report, dated April 5, 2019, the FFRDC team is considering five cases: (1) vitrification for disposal at the IDF, (2) grouting for disposal at the IDF, (3) grouting for disposal at WCS, (4) FBSR for disposal at the IDF, or (5) FBSR for disposal at WCS. In addition, secondary wastes, which were assumed to be grouted in all cases, are produced in amounts that depend on the treatment alternative, and these can contribute significantly to the dose rate to a public receptor. In a previous draft analytic report, the FFRDC had considered nine variants of the three primary treatment alternatives. Also, to implement the five currently identified alternatives, additional waste conditioning (pre-treatment) might be needed, for example, to remove certain radionuclides, or adjust the composition of the waste to make it more suitable or less costly for treatment and disposal. Notably, Sec. 3134 requires an analysis of "further processing of the low-activity waste to remove long-lived radioactive constituents, particularly technetium-99 and iodine-129, for immobilization with high level waste."

In parallel to selecting an FFRDC, DOE was directed in Sec. 3134 to contract with the National Academies of Sciences, Engineering, and Medicine (the National Academies) to conduct a concurrent, iterative review of the FFRDC report as it develops to inform and improve the FFRDC's work.[1] DOE contracted with Savannah River National Laboratory (SRNL), an FFRDC, and then SRNL formed a team of experts from SRNL and other DOE national laboratories. The charge to the FFRDC team from Sec. 3134 is in Appendix C. The Statement of Task for the National Academies of Sciences, Engineering, and Medicine's (the National Academies') committee is in Appendix D.

The FFRDC team's task is to provide DOE and Congress with facts and analyses regarding treatment approaches, but not a recommendation concerning a preferred alternative. Likewise, the committee, as peer reviewer, does not offer or imply a recommendation among alternative approaches.

This congressionally mandated study has come about in part due to a 2017 U.S. Government Accountability Office (GAO) report that indicated significant cost savings for the grout treatment approach as compared to vitrification, based on the experience of the Savannah River Site's (SRS's) use of grout for about

[1]For clarity, to the extent possible, this review report uses the nomenclature of *team* for the FFRDC's investigators, *committee* for the National Academies committee, *draft report* for the FFRDC team's work, and *review* or *review report* for the committee's work.

4 million gallons (as of the date of that report) of LAW (GAO, 2017). Because the chemical composition of the LAW at the SRS is not as complex as the LAW at Hanford, however, the cost and performance of using grout treatment at Hanford could differ significantly from the cost at the SRS. The GAO report, therefore, recommended:

> Congress should consider specifically authorizing DOE to classify Hanford's supplemental LAW based on risk, consistent with existing regulatory authorities … [and] that DOE develop updated information on the performance of treating LAW with alternate methods, such as grout, before it selects an approach for treating supplemental LAW. (GAO, 2017)

In its report, GAO noted that "DOE agreed with both recommendations."

STUDY PROCESS

In this third review report, the committee provides its peer review and discusses its observations of the FFRDC's final draft report, dated April 5, 2019,[2] and the FFRDC's presentations at the public meeting in Kennewick, Washington, on May 16, 2019.[3] Table 1-1 lists the FFRDC's presentations from this meeting. The webcast videos of the public meetings are archived and available for viewing.[4]

During the most recent public meeting in Kennewick, Washington, the committee received briefings from some presenters who were not from the team, as listed in Appendix E. In addition, throughout the study, the National Academies has received comments submitted via e-mail and mail, which are available in the Public Access File. Sec. 3134 specifies that "the National Academies of Sciences, Engineering, and Medicine shall provide an opportunity for public comment, with sufficient notice, to inform and improve the quality of the review." Also, Sec. 3134 highlights the necessity of consultation with the State of Washington and an opportunity for it to comment on the FFRDC's draft report and the committee's review of that report. The committee received invited presentations during the second, third, fourth, and most recent sixth public meetings from the Department of Ecology and has considered these presentations in its review.

Table 1-2 shows the current schedule for the FFRDC's work, the committee's review, the public meetings, and the briefings to stakeholders. While this schedule is subject to change, it is designed to allow adequate time for the FFRDC and the committee to do their work in the iterative fashion described in the Statement of Task, and for regulators, stakeholders, and the public to provide comments. The next public meeting, in Richland, Washington, is planned for October 31, 2019.

To perform the peer review task, the National Academies formed a committee composed of 13 experts and one technical adviser whose expertise spans the issues relevant for reviewing the FFRDC's analysis, including risk assessments, cost estimation, cost-benefit analysis, waste processing, supplemental treatment approaches, legal and regulatory requirements, and large scale nuclear construction projects. A majority of the committee members have prior experience in studying cleanup activities at the Hanford Nuclear Reservation, as well as at other DOE-EM sites. Appendix F contains biographical information about the committee members' qualifications and experiences. The committee also has found it necessary to perform additional fact finding, for example, by receiving briefings from experts outside the FFRDC team about aspects

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[2]To access the FFRDC's final draft report, see http://dels.nas.edu/resources/static-assets/nrsb/miscellaneous/ffrdc-2019-4.pdf.

[3]For this public meeting's presentations, see http://dels.nas.edu/Past-Events/Meeting-Supplemental-Treatment/DELS-NRSB-17-02/10052.

[4]For the first public meeting's video recording, see https://livestream.com/NASEM/DELS-NRSB; for the second public meeting's video recording, see http://www.tvworldwide.com/events/nas/180228; for the third public meeting's video recording, see http://www.tvworldwide.com/events/nas/180723; for the fourth public meeting's video recording, see http://www.tvworldwide.com/events/nas/181129; for the fifth public meeting's audio recording (no video was recorded), see http://www.tvworldwide.com/events/nas/190108; and for the sixth public meeting's video recording, see http://www.tvworldwide.com/events/nas/190516.

of the supplemental pre-treatment, treatment, or analysis approaches. Any information learned by the committee during additional fact-finding will be made available in the study's Public Access File.[5]

TABLE 1-1 List of the FFRDC's Presentations, Given on May 16, 2019, in Kennewick, Washington

Presentation No.	Title
1	Introduction of FFRDC Team Study and Final Draft Report—Bill Bates
2	Performance Evaluation (PE) Inputs and Overview—Tom Brouns
3	Performance Evaluation Results—Tom Brouns
4	FFRDC Team Conclusions—Michael Stone
5	Next Steps—Bill Bates

TABLE 1-2 Study Schedule

Timing	Activity
December 12-13, 2017	The committee's first information-gathering meeting convened in Washington, DC.
February 14, 2018	The FFRDC sent draft working papers as a document for the committee's first review.
February 28-March 1, 2018	The committee's second information-gathering meeting convened in Richland, Washington.
March-May 2018	The committee's first review report was prepared and reviewed.
June 8, 2018	The committee's first review report was published; the FFRDC received this review report to take into account during its continued work on the analysis.
July 15, 2018	The committee received the FFRDC's second draft report to review.
July 23-24, 2018	Convened third public meeting in Richland, Washington; the FFRDC presented its work to the committee.
August-October 2018	The committee's second review report was prepared and reviewed.
November 2, 2018	The committee's second review report was published. The FFRDC received the committee's review to take into account during its work on its final draft report.
November 29-30, 2018	Public meeting #4 in Richland, Washington, that presented the second review report and the FFRDC's progress toward its final draft report, as well as heard from stakeholders.
December 21, 2018	FFRDC sent a draft report but the committee determined that it was not sufficiently complete and thus not ready for review.
January 8, 2019	Public meeting #5 in Atlanta, Georgia, that presented the incomplete FFRDC draft report.
April 5, 2019	The FFRDC completed a final draft report that was sent to the National Academies for the committee's review.
May 16, 2019	Public meeting #6 convened in Kennewick, Washington, that presented the complete final draft report and the views of the Washington State Department of Ecology on that report.
May-August 2019	The committee's third review report was prepared and reviewed.

[5]To request information in the Public Access File for this project, see https://www8.nationalacademies.org/pa/ManageRequest.aspx?key=49905.

August 15, 2019	Publication of third review report and start of minimum 60-day public review period.
October 2019	Anticipated publication of the FFRDC's final report.
October 31, 2019	Final public meeting of the committee in Richland, Washington, and the cutoff date for receipt of stakeholders' and public comments.
January 2020	Anticipated publication of the committee's fourth and final review report that will consider stakeholders' and public comments on the third committee review report and the FFRDC final draft report.
January-February 2020	Anticipated final briefings to Congress, DOE, Washington State, and other stakeholders.

The FFRDC team was assigned a very large task in a short period of time, that is, to review a long history and large technical literature on three or more very different treatment technologies and, as the analysis developed, the permanent disposition of waste material in two (or potentially three) very different disposal sites. (As the committee has noted in previous reports, the choice among treatment approaches cannot meaningfully be made without consideration of the disposal environment.) The FFRDC team has, as the committee has also noted, worked very hard to grapple with the task it was assigned. It has gathered a large amount of information, performed analysis on it, and adjusted its approach and presentations in response to comments. Nevertheless, as Chapter 2 of this review demonstrates, there are significant technical limitations to the conclusions that can be drawn from the team's work, especially regarding the analysis of costs and risks, as well as the uncertainties surrounding the technologies themselves, costs, and several important programmatic risks.

The committee's review is constrained, it goes without saying, by the Statement of Task, which expressly calls for the committee to "evaluate the technical quality and completeness" of the FFRDC report on the treatment options for the SLAW. This is a double limitation: the committee's report is to be "technical," and the committee's scope (along with the FFRDC's) is to be on treatment approaches to the SLAW. Neither the FFRDC nor the committee was tasked to offer views on broader policy issues or on the overall system for managing tank waste at Hanford. While one may quite reasonably find such limitations frustrating and sometimes even question-begging, they represent Congress's laudable effort to obtain a well-informed and reliable technical answer to a particular and important question before it.

BRIEF HISTORICAL CONTEXT OF TANK WASTE TREATMENT APPROACHES

To help explain why the Hanford waste treatment approaches are being considered, this section provides brief historical context about tank waste treatment at Hanford. Under the TPA, since 1989, DOE-EM (which was formed in 1989) has tried and discontinued or substantially modified several different approaches to treat and dispose of Hanford's tank waste. In 1989, the initial approach was to treat only the waste in the double-shell tanks. The preferred alternative in the 1987 Defense Waste Environmental Impact Statement, the basis for the 1989 plan and for DOE's 1988 Record of Decision on "Disposal of Hanford Defense High-Level, Transuranic, and Tank Waste," was to pre-treat the existing and future double-shell tank waste into two fractions with the high-level fraction being processed in the High-Level Waste Vitrification Plant "and disposed of in a geologic repository, and the remaining low-activity fraction grouted and disposed of near-surface in preconstructed lined concrete vaults." Regarding the single-shell tanks, in the 1988 Record of Decision, DOE, in selecting the preferred alternative, "decided to conduct additional development and evaluation before making decisions on final disposal" (DOE, 1988). The near-surface vaults would have been on-site and would have been covered by a protective barrier; these vaults would also have had a marker system to warn people about the disposal site. The facility would have been called the Hanford Grout Disposal Facility.

The 1988 DOE Record of Decision announced that all grouting and vitrification of the waste in the double-shell tanks would be completed in 2016 (DOE, 1988). Under that plan, DOE-EM would defer decisions on the single-shell tanks until about 2015. In November 1989, DOE awarded a $550 million construction contract to start building the High-Level Waste Vitrification Plant, and the TPA called for construction to begin in July 1991 (GAO, 1991). Pre-treatment was to be done in the World War II–era B Plant (DOE, 1988). Here, pre-treatment refers to separation of the tank waste into high-activity and LAW portions prior to the treatment stage that would produce the waste forms for each portion. B Plant would have used a process then being developed called Transuranic Extraction (GAO, 1991). By 1994, 14 grout vaults for the LAW portion were to be constructed (Dunning, 2016). Eventually, dozens of vaults would have to have been constructed.

In 1990, DOE determined that it could not defer a decision on treatment of the single-shell tanks because of various hazards associated with those tanks. Notably, the Defense Nuclear Facilities Safety Board (DNFSB) issued recommendations in 1990 to DOE to take corrective action on these tanks. DNFSB's Recommendation 90-3 (issued in March 1990) called for DOE to develop a plan for responding to unexpected degradation of a tank or its contents and to an explosion in a tank (DNFSB, 1990a). Then in October 1990, because the DNFSB concluded that DOE's proposed implementation plan was not adequately responsive, it issued Recommendation 90-7 that specified: "Immediate steps should be taken to add instrumentation to the single shell tanks containing ferrocyanide that will establish whether hot spots exist or may develop in the future in the stored waste." In addition, that recommendation called for other sensors, instrumentation, and sampling to meet "the urgent need for a comprehensive and definitive assessment of the probability of a violent chemical reaction" (DNFSB, 1990b). The DNFSB's nuclear safety oversight and action-forcing recommendations have continued to the present day.

In addition, in January 1991, Senator Ron Wyden of Oregon issued a watch list covering 56 single-shell tanks and detailing several hazards, including criticality, hydrogen gas, flammability, and organic chemicals. While these watch list problems were resolved by 2001, concerns have continued about the status of the tanks, leaks from some tanks, and the potential for additional leaks or structural failure (e.g., collapse of a tank roof). (All of these scenarios are included in the term "failure," as used in this review report.) For example, Senator Wyden has underscored the urgency in dealing with the tanks, and in 2013, he called for an investigation by the GAO about the tank leaks and potential for further leaks (GAO, 2014). According to this GAO investigation, from 2012 to 2014, DOE assessed the physical condition of the tanks and "found them to be in worse condition than it assumed in 2011 when developing its schedule for emptying the tanks." In addition, as of November 2014, when the GAO finished its investigation, "DOE's current schedule for managing the tank waste does not consider the worsening conditions of the tanks or the delays in the construction of the Waste Treatment and Immobilization Plant" (GAO, 2014).

Because of the tank waste concerns of the early 1990s, DOE redesigned its cleanup plan to include treatment of all (single-shell and double-shell) tanks. This revised plan resulted in adjustment of the TPA milestones and changes in the earlier proposed pre-treatment and treatment approaches. In June 1991, for example, a GAO investigation pointed out that the B Plant for pre-treatment would not meet regulatory requirements. In particular, the GAO report stated that a 1989 DOE study found that

> B Plant's embedded pipes did not comply with DOE design criteria and concluded that the pipes would be almost impossible to replace. This study also pointed out that B Plant process tanks did not comply with federal double containment requirements and, recommended that DOE request a variance from the regulator to permit the use of these tanks for pre-treatment. A January 1990 study, directed by DOE Richland [Operations Office], concluded that the problem with the process tanks remained unresolved. (GAO, 1991)

Subsequently, in December 1991, DOE decided against using the B Plant for this purpose. By late 1992, the plan to grout the LAW was also dropped because of technical problems, including pipes that clogged and leaked and the poor retention of technetium in the grout formulation being considered at that time. Additionally, revised costs for the grout plant exceeded the projected costs for the vitrification plant for the LAW (Dunning, 2016).

In 1993, DOE's strategy called for completing the treatment facility prior to fully developing all other aspects of the waste treatment program. But after DOE had spent about $418 million, it recognized that the planned treatment facility would not have the capacity to treat all of the waste within the time frame acceptable to EPA and the Department of Ecology (GAO, 2015). As a result, DOE proposed changes to the TPA. In 1994, after renegotiation, the TPA was amended to extend the target date for mission completion to 2028. Vitrification was to proceed as a two-stage process: first a pilot plant would treat 18 percent of the waste, and then a second facility would vitrify the rest. Concerns soon arose that, after construction of the first plant, there would not be enough money available to build the second (Dunning, 2016).

To try to implement a proposed cost-effective approach, in September 1995, Secretary of Energy Hazel O'Leary announced a privatization arrangement under which the contractor would finance, design, build, and operate the facilities, and would receive payment via a fixed price contract from DOE. DOE initially estimated that the first phase of the project would have a contract price of $3.2 billion to treat about 10 percent of the waste in the pilot-scale facility. From 1996 to 2000, the price increased to more than $14 billion. In June 2000, DOE cancelled the contract. About $300 million had been spent, mostly on plant design (GAO, 2015).

In December 2000, DOE awarded a cost-reimbursable contract with incentive fees to Bechtel National, Inc., the current contractor in charge of the WTP construction, to complete the facility that the previous contractor had started to design. The initial estimate was that this pilot-scale facility would cost $4.3 billion and would be completed in 2011. In October 2002, the contractor recommended and DOE then authorized design changes that would eliminate the pilot-scale facility and instead scale up the WTP capacity to accelerate the cleanup and save an estimated $20 billion. In April 2003, DOE completed the renegotiated contract to include these design changes for the WTP project (GAO, 2015). Since then, there have been several WTP project schedule slips: in 2003, the projection was to start hot operations in 2007; in 2005, the projection was to start in 2017; in 2007, it was to start in 2019; in 2012, it was pushed to 2022; and in 2016, it was moved to 2036 (Dunning, 2016).

Notably, even after the cancellation of the grout plant in 1992, DOE has considered ways to reduce costs and schedules by using methods other than vitrification. For example, on November 14, 2001, Assistant Secretary for Environmental Management Jessie Roberson sent a memorandum to the Director of the Office of Management, Budget, and Evaluation at DOE that outlined a plan that would not vitrify about 75 percent of the LAW, and would develop two alternative technologies that could include grout and FBSR waste forms (Roberson, 2001). In addition, DOE examined an alternative vitrification technology known as bulk vitrification, which uses electrodes to melt waste, soil, and glass forming chemicals in a one-time-use container shaped like a dumpster. Bulk vitrification at that time looked to be a cheaper and faster form of vitrification for the low-activity waste. But in 2008, the bulk vitrification project was terminated due to technical and cost concerns (Dunning, 2016).

Presently, to keep the treatment of the HLW in the WTP on track over time to meet the amended TPA milestones, the plan is to have a supplemental treatment plant for the portion of the LAW that will exceed the capacity of the WTP (SLAW), because the SLAW must be treated concurrently to allow the HLW to be treated at the WTP's full potential capacity. In DOE's 2013 Record of Decision on Hanford tank waste management, DOE stated that it "does not have a preferred alternative regarding supplemental treatment for the LAW; DOE believes it is beneficial to study further the potential cost, safety, and environmental performance of supplemental treatment technologies" (DOE, 2013).

REVIEW REPORT ORGANIZATION

The remainder of this review report proceeds in two parts. In Chapter 2, the committee provides its technical review of the FFRDC's final draft report, dated April 5, 2019, and the set of slides that the FFRDC presented at the public meeting on May 16, 2019. This technical review is based on the factors identified in the committee's Statement of Task (see Appendix D). The committee's findings are at the end of that chapter and are intended to focus on potential improvements in any follow-on efforts. In Chapter 3, the committee poses questions that a decision-maker might ask when making a decision on the preferred alternative for the SLAW treatment and then addresses how the FFRDC's final draft report does or does not provide an adequate technical basis for the decision-maker to choose among the alternatives considered. The chapter concludes with the committee's recommendations.

Appendix A

2

The Committee's Technical Review of the FFRDC's Final Draft Analysis

For this review, the Statement of Task (see Appendix D) requires the committee to provide its overall assessment of the Federally Funded Research and Development Center's (FFRDC's) report in final draft form, as also required by Section 3134 (Sec. 3134) of the National Defense Authorization Act of Fiscal Year 2017 (see Appendix C). In this chapter, the committee gives its technical review of the FFRDC's report dated April 5, 2019. That report's chapters are listed in Table 2-1, and the report is available on the National Academies of Sciences, Engineering, and Medicine's (the National Academies') website.[1] The committee has also included in its review the set of slides presented by the FFRDC team at the May 16, 2019, public meeting in Kennewick, Washington. Those slides are available on the National Academies' website.[2] The committee's technical review follows the topical elements—specified in the major section headings—in study charges one through four in the Statement of Task.

TABLE 2-1 List of the Chapters and Appendixes in the FFRDC Final Draft Report, "Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation," Dated April 5, 2019

Chapter No.	Title
0	Executive Summary
1	Parameters of the Analysis
2	Criteria for Analysis of Treatment Approaches
3	Summaries of Analyses of Treatment Approaches
4	High-Level Comparison of the Five Cases for Hanford SLAW Immobilization
Appendix A	Pre-treatment
Appendix B	Vitrification
Appendix C	Grouting
Appendix D	Steam Reforming
Appendix E	Risk Assessment
Appendix F	Disposal
Appendix G	Transportation
Appendix H	Cost-Estimate Methodology and Results
Appendix I	Regulatory Compliance
Appendix J	Feed Vector
Appendix K	Bibliography

[1]See http://dels.nas.edu/resources/static-assets/nrsb/miscellaneous/ffrdc-2019-4.pdf.
[2]See http://dels.nas.edu/Past-Events/Meeting-Supplemental-Treatment/DELS-NRSB-17-02/10052.

Final Review of the Study on Supplemental Treatment Approaches of LAW at Hanford: Review #4

GENERAL OBSERVATIONS

This section examines the FFRDC report as a whole and from the perspective of its intended audience. The committee notes favorably that the FFRDC has done a considerable amount of useful analytic work and that the FFRDC's analysis has evolved and improved over the course of the team's work. However, as may be evident from the list of chapters and appendixes (see Table 2-1), the report is lengthy (278 pages) and parts of it are highly technical.

It is understandable, and unavoidable, that the FFRDC report is lengthy and highly technical, because treatment of supplemental low-activity waste (SLAW) is a complicated and technically challenging matter. Several consequences, however, arise from the technical content and length of the FFRDC report. First, the lengthy technical content does not explicitly address the concerns that people in the Hanford region have faced in the past, face today, and will face in decades to come. In fairness to the FFRDC, its task was to review existing waste disposal technologies for supplemental treatment of low-activity waste (LAW). Moreover, to the credit of the report's authors, they mention the urgency of the schedule for waste treatment and call this out in their Executive Summary. Even so, a reader easily could miss the pressing concerns about the waste tanks, the potential for future failures, and the hazards of the tank waste to current and future generations. Notably, extending tank cleanup schedules—whether it be the result of seeking better technologies, funding limitations, or technology or project management inadequacies—increases the chance that additional tanks will fail and release radionuclides and hazardous chemicals into the air or subsurface environment. Such an event is likely to cause even more delays and funding shortfalls as resources are diverted to address the consequences of the failure.

Second, as a consequence of the length and the technical nature of the report, the Executive Summary takes on increased importance as a means to guide the reader, especially a reader without extensive technical expertise in radioactive waste and disposal technologies. In all likelihood, the Executive Summary will be read by the largest number of people. Likewise, the report might also be improved by an introductory chapter or a "Reader's Guide" (similar to what long technical documents such as Environmental Impact Statements have included), using to the extent possible laypersons' terms.

In this chapter, the committee describes its primary findings concerning the FFRDC's final draft analysis report. The narrative text of the chapter is organized to reflect the committee's Statement of Task, but with formal findings collected at the end of the chapter because they often incorporate material from multiple parts of the Statement of Task and text. The analysis in this chapter's text and findings are informed by the following questions:

- Does the FFRDC analysis rise to a level that it is useful to the decision-maker, and if so how?
- Does the FFRDC analysis describe a framework of decisions that need to be made?
- Does the FFRDC report provide a strong technical basis in support of the major decisions to be made?

This chapter is informed by the committee's understanding of its fundamental task as a peer review of a report that describes alternative courses of action, and neither the FFRDC's report nor the committee's review is intended to select a preferred approach.

METHODS USED TO ASSESS RISKS, COSTS, BENEFITS, SCHEDULE, AND REGULATORY COMPLIANCE AND HOW THEY WERE IMPLEMENTED

Risk Analysis

Risk Assessment Methodology

The portion of the report on "Risks" (section 2.1, p. 23) includes the following statement on the FFRDC team's methodology for risk analysis:

The FFRDC team considered a range of risks[3] and candidate mitigation strategies. The FFRDC team used a semi-quantitative methodology to characterize the risks associated with each of the SLAW cases. A full quantitative risk assessment was not feasible because design and operational specifics currently available would not support that depth of analysis. The semi-quantitative approach adhered to a formal risk structure based on subject-matter expert analysis of the following triplet:

1. Scenario: The combinations of events that would result in deviations from design/operational/ programmatic intent.
2. Probability: The likelihood of occurrence of each combination of events.
3. Consequences: The impacts of each combination of events.

The consequence metrics on which the study primarily focused were the incremental cost and the required extension in duration of the tank waste treatment mission associated with each scenario. Following the analysis of the risks associated with the individual SLAW cases, the team performed a side-by-side comparison among the alternatives. [Note that the committee has inserted the footnote on the definition of "risk."]

Appendix E of the report goes on to explain that it used expert elicitation with team members as the subject-matter experts in a process that "involved team brainstorming to systematically identify and characterize risks associated with each technology option." The team's intent was "to establish a basis for preliminary risk-informed comparison between options as currently defined." Moreover, the team sought "to obtain approximate, comparative risk rankings of the technology options considered."

Appendix E identifies the scenarios that were considered in the exercise and reports their qualitative likelihoods. However, it does not provide any narrative explaining what the overall evaluation results mean for readers who are not familiar with risk analysis methods. Instead, it quickly follows the listing of the scenarios with a list of reasons to consider the exercise incomplete. In Appendix E, the FFRDC team describes two principal reasons why the scope of the scenarios it considered were incomplete (as paraphrased and quoted from p. 148 of the FFRDC report):

- Intended scope limitations, or known unknowns, mean that the convened experts did not have the ability to assess certain classes of risk. For example, a class of risks includes those beyond the control of the project. These classes of risk were mentioned in a list of programmatic risks, for example, the risk that there is inadequate funding appropriated for the project, but not analyzed further.
- Unintended scope limitations, or unknown unknowns, refer to possible scenarios that could adversely affect the tank waste cleanup mission but that the FFRDC did not identify. Such limitations are inherent in any risk assessment. However, "the strength of risk assessment as a specific approach resides in its ability to provide a systematic and transparent basis for decision-making in light of the information and knowledge available."

The committee notes that the list of known unknowns, or system risks (in Table E-3 on pp. 150-151 of the report) could cause the reader to question the usefulness of the analysis done under constraints, and that the reader's questions could unnecessarily undermine the insights from this part of the FFRDC's work. The committee also notes that, setting aside the unavoidable presence of intended and unintended scope limitations, the list of scenarios that would reasonably fall within the intended scope may not be as complete as it could have been. For example, while Appendix E does consider the scenario where the grout formulation does not meet the performance expectations and permitting requirements of the state regulator, it does not appear to consider the scenario that the regulator rejects the Performance Assessment (PA) performed by the U.S. Department of Energy (DOE) for the vitrified LAW per se and the grouted secondary waste for

[3]In this context, "risk" is used in its general sense: "A probability or threat of damage, injury, liability, loss, or any other negative occurrence that is caused by external or internal vulnerabilities, and that may be avoided through preemptive action" (www. businessdictionary.com). It is not used in the context of human health risk.

the Integrated Disposal Facility (IDF). This gap in the analysis is problematic, because such a rejection would affect the ability to dispose of vitrified LAW or SLAW, and the associated grouted secondary waste in the IDF. The committee does not discount the usefulness of the FFRDC's risk evaluation, but believes that the report would benefit from better integrating the risk assessment insights into a discussion of uncertainties in the main report.

Discussion of Uncertainties

The FFRDC has not properly presented the uncertainties elicited in the team's risk assessment. Uncertainties are large and fundamental to nearly every aspect of the risk analysis, yet the report is relatively terse in identifying the various sources of uncertainty and, especially, the probability distributions that characterize each source. Given the high degree of sensitivity to risk in Hanford decision-making, it is important to understand, even if only in qualitative terms, whether the uncertainty is clustered around a central value, or whether it ranges across a wide spectrum of values. Similarly, it is also important to understand whether the uncertainty is symmetrically distributed above and below a central value, or whether the range is wider to the high or low side of the central value.

In the FFRDC report, after listing the risk scenarios evaluated, and assigning them qualitative likelihoods and consequences, the only summary provided in Appendix E is in Figure E-4 (on p. 150). This figure is a bar chart of expected values for the cost and schedule risks of each of the five technology options.[4] The committee notes that the purpose of a risk assessment is to characterize the full range of uncertain values and the relative likelihood of outcomes over that full spectrum. Expected values are summary metrics that mask all of that subsumed information on uncertainty and risk, and so they are only useful when making decisions on a risk-neutral basis (i.e., when making a decision that is insensitive to the scale or tendency of the risks as compared to other factors). Risk neutrality has certainly not been a defining attribute of decision-making regarding the disposition of wastes at Hanford. Table E-2 and the cost-risk equation below this table on p. 146 of the report indicate how the FFRDC used the elicitation results quantitatively to develop the expected values presented in Figure E-4. It would, in addition, have been useful in Figure E-4 to indicate the full range of potential cost and schedule outcomes around those expected values, for example, in the form of a diagram that indicates the minimum, lower quartile, median, upper quartile, and maximum values (a box-and-whisker plot).

The committee also notes that the information in Appendix E mentions the potential that each technology option may cost more than one would estimate from the standard engineering-based evaluation that is presented in the cost section of the report (which is the source of the cost ranges in Table 2 of the report), and it is likely that these cost risks would have to be layered onto the cost ranges presented in the summary tables, Tables 2 and 10 of the report. The same is true of the schedule uncertainties.[5] However, the report provides no acknowledgment of the presence of greater uncertainty than is reported as apparent cost and schedule uncertainties in Tables 2 and 10. Thus, the FFRDC report does not represent the full range of uncertainties in costs and schedules that the FFRDC team has actually assessed.

Analysis of Costs and Benefits

Full Consideration of Benefits

In Section 2.2 of the report (p. 24), the FFRDC mentions the assessed benefits or advantages of each approach to treating Hanford SLAW, including waste form volume of both primary and secondary wastes,

[4]The chart in the FFRDC report uses the term "expectation values," which is a term more common to physics than to risk analysis, and itself lends to the overall opacity of the discussion. The committee prefers to use the more common term "expected value."

[5]During a question-and-answer session at the May 16, 2019, public meeting, the FFRDC confirmed that the cost ranges in Table 2 do not reflect the cost uncertainties explored in Appendix E.

pre-treatment requirements, ease of operation, and flexibility, and notes that the "benefits of the individual treatment options are summarized in Section 3.0 and detailed in Appendices A-D."

For the benefits of vitrification of the SLAW, Section 3.2.4 (p. 38 of the report) mentions (a) that design of the SLAW facility can be leveraged from the existing design for the primary LAW treatment facility in the WTP and thus is the "most technically mature technology;" (b) the waste form "has been studied extensively, so minimal further research is required;" (c) the high-temperature process destroys land disposal requirement (LDR) organics and most nitrates; and (d) the primary waste volume is comparatively low. The committee questions the claim that LAW vitrification is the most mature of the three treatment technologies. While it will undoubtedly be possible to capitalize on the research and design work underpinning the WTP LAW vitrification facility, this facility has itself neither been completed nor has it operated, and its scale is greater than any other experience with waste similar to Hanford LAW. In contrast, the Savannah River Site (SRS) has been grouting and disposing of similar LAW at an industrial scale for years with apparent success.

For the benefits of grouting of the SLAW, Section 3.3.4 on pp. 43-44 mentions that (a) it is the least complex process of the three options; (b) the process occurs at ambient temperatures and thus would not have the safety hazards to workers that high-temperature processes have; (c) it has the capability for relatively quick startup and shutdown that would more effectively accommodate variations in the SLAW feed rate; and (d) it has the lowest volume of secondary waste volume because the low operating temperature results in minimal off-gas. The committee notes that having start/stop capability may be particularly important because the SLAW is planned to receive the excess LAW that WTP cannot process and the receipt rate is projected to be highly variable (see Figure J-7 on p. 267 in the FFRDC report).

For the benefits of steam reforming of the SLAW, Section 3.4.4 on p. 50 mentions that (a) this process can tolerate variations in the SLAW feed rate and compositions and thus could give the flexibility to shut down temporarily or be operated with reduced feed rate; (b) it can efficiently destroy hazardous organics, nitrates and nitrous oxides, and ammonium compounds; (c) recent waste form durability tests indicate that this process can produce a durable waste form that would not increase waste volume during treatment and would not have liquid secondary wastes; and (d) because this process has a somewhat lower temperature as compared to vitrification, it reduces the amount of semi-volatiles that would be sent to off-gas and thus minimizes the recirculation in the treatment system of volatile and semi-volatile effluents. The committee notes that a high-temperature process such as steam reforming would entail an extensive off-gas processing system that would still produce some "secondary wastes" (e.g., see Figures D-2 and D-7 in the report). The report states that technetium and iodine will be completely removed by scrubbing and internally recycled (see Figure D-1); no separation process is complete. Also, the FFRDC analysis assumed that the carbon sorbents and high-efficiency particulate air (HEPA) filters do contain some technetium and iodine, even considering the effect of the recycle loop of the off-gas technology.

Section 4.1.2 on (pp. 57-58) provides the FFRDC's high-level summary and comparison of the benefits of these options, which addresses an observation in the committee's previous review (NASEM, 2018b) by "discuss[ing] or list[ing] the benefits for consideration of each treatment option," which the previous FFRDC draft report did not do.

Consideration of Costs

The FFRDC report on p. 25 states that cost estimates for each SLAW technology "are full life-cycle costs, which include technology development, construction, operations, transport, and deactivation and decommissioning." Sections 3.2.5, 3.3.5, and 3.4.5 provide summaries of the cost estimates for vitrification, grouting, and steam reforming. Appendix H provides a detailed discussion of cost estimation methodology. Section 4.1.3 on (pp. 58-59) has a brief discussion about cost comparison among the technology options. Cost and schedule estimation ranges are listed in Tables 2 and 10. The FFRDC's final draft analysis concluded that:

- The vitrification technology would take 10 to 15 years to implement and would cost $20 billion to $36 billion.
- The grouting technology would take 8 to 13 years to implement and would cost $2 billion to $8 billion.
- The fluidized bed steam reforming technology would take 10 to 15 years to implement and would cost $6 billion to $17 billion.

The cost estimates are based on technologies that, for the most part, have not yet been fully developed or deployed, and are based on costs from similar technologies, as well as assuming ideal funding conditions (i.e., no funding caps) and no redirection during a multi-year effort. Thus, there are large attendant uncertainties, suggesting that costs could be much higher than estimated, but are unlikely to be much lower. However, as discussed in this review's section on "Risk Analysis," these cost ranges provide the reader with a potentially incomplete view of the full range and nature of cost uncertainty.

Cost-Benefit Reasoning

Sec. 3134 (see Appendix C) calls for an "analysis" of the "benefits and costs of such [treatment] approaches," but not a cost-benefit analysis per se. As the committee has noted in prior reports (NASEM, 2018a,b), Sec. 3134 does not call for a comprehensive comparative analysis that would identify a preferred alternative. The distinction is important, as the preferred alternative analysis requires crucial judgments by decision-makers that are in no way factual, but rather involve values, legal and regulatory compliance, policies, and many other considerations. This is beyond the scope of Sec. 3134 and thus the task set out for the FFRDC and the committee. Moreover, a comprehensive preferred-alternative analysis would invade the province of the elected and administrative bodies (DOE, state regulators, and Congress) that are established to make such choices on behalf of the public.

The FFRDC team made some initial steps along the lines of performing a preferred-alternative analysis in an earlier report, but withdrew them from the current draft after the committee cautioned against it. Instead, the committee recommended (NASEM, 2018b) and the FFRDC team provided a qualitative comparison of relevant considerations. It is summarized in a large table (see Table 10, p. 61 of the FFRDC report), whose contents are drawn from the report and appendixes. What is currently missing, however, which would help to inform the ultimate selection of a preferred alternative by decision-makers using the FFRDC report is a summary of findings in a format that reflects the "marginal analysis" perspective that is fundamental to the logic of cost-benefit analysis. A cost-benefit optimum occurs when the marginal cost of "doing more" is equal to or greater than the marginal benefit gained by that increment in cost. Such an analysis is particularly appropriate when selecting among SLAW treatment alternatives that represent a discrete part of a larger system that is mostly well established (e.g., Hanford tank cleanup), and the differences in their costs are very large. This is a perfect setting for "cost-benefit thinking" of the type called for by Sec. 3134. For example, as one considers adopting a higher-cost option over a lower-cost option, one should ask how much the benefits of the higher-cost option are improved, and furthermore, to directly consider whether those incremental benefits are significant enough to be "worth" the incremental cost that would be absorbed. In addition, because the differences in benefits among the technology options at issue here are not along a single continuum, but have multiple attributes [as discussed in "Full Consideration of Benefits" above], an incremental approach to comparison of options could be extremely useful in bringing clear insight to a complex and uncertain situation.

Ultimately, a preferred-alternative analysis will be required by decision-makers, who are the ultimate audience of the FFRDC report. It will be for them to choose and explain the reasoning for a particular technology (or technologies), and an analysis of costs and benefits, as required by Sec. 3134, will be an essential component of that preferred alternative analysis. More could be done to summarize the information in the FFRDC report in a manner that would be consistent with that decision process, even if it is to be initiated by and completed in the future under the oversight of the decision-makers using the FFRDC report as input.

Schedule

Schedule Considerations

In Section 2.4 (p. 25), the report states: "Schedules were developed in conjunction with cost estimates for each case. The schedules reflect team experience in process development and recent DOE capital projects." In Section 3.0, the team provides its summaries of the schedule estimates for each technology option. For vitrification in Section 3.2.6 (p. 39), the estimated time is 10 to 15 years considering the time to complete additional research and development, design, construction, and cold and hot start up. For grouting in Section 3.3.6 (p. 44) the estimated time is 8 to 13 years considering the same factors. For steam reforming in Section 3.4.6 (p. 51), the estimated time is 10 to 15 years, and that section points out that the technology maturation plan and full-scale design are expected to benefit greatly from the experience at Idaho National Laboratory (INL) in developing the Integrated Waste Treatment Unit, "though that potential benefit is not assumed in the current cost and schedule estimates." Likewise, comparison with previous Hanford high-level waste (HLW) vitrification plant time estimates and actual results (see "Brief Historical Context" section in Chapter 1 of this review) could be informative of the potential gap between expectations and reality.

Impact of System Integration Failures

While the FFRDC has provided a rationale for its schedule estimates based on recent DOE capital projects, it has not considered the effects on the schedule of a technology functioning well as an individual component and not as a part of the larger integrated system. For example, an efficient and cost-effective method for removing iodine from the LAW being fed to the SLAW may exist or be found, but it could introduce chemicals into the product stream that are incompatible with the selected immobilization process. Given the complexity, interdependencies, and relative novelty of Hanford processes, system integration would have to be considered a significant technology risk.

Funding Risks

On pp. 24-25, the report provides information about annual funding requirements to complete the Hanford tank waste treatment mission beginning with current funding levels. This information shows the substantial increase in projected funding requirements to complete the WTP, to build tank farm infrastructure required to retrieve the tank waste and move it to the WTP via pipeline, and to build the SLAW facility using vitrification technology. In a nutshell, the estimated funding requirements increase from the current approximately $1.3 billion per year to a maximum of about $4.7 billion per year. Figure 2-1, reprinted from the FFRDC's report, shows the stacked estimated costs for the annual estimated budget. These costs are almost totally driven by the capital costs for the WTP, tank farm infrastructure, and the SLAW treatment plant. The FFRDC report states that meeting the funding requirements is one of the major challenges in successfully treating the SLAW, and the committee agrees. The committee also notes that these annual funding requirements do not include requirements to continue aspects of Hanford cleanup other than tank waste, such as facility decontamination and decommissioning, managing contaminated subsurface water plumes, and maintaining and operating common site infrastructure (e.g., water, roads, electricity, effluent treatment, waste evaporators), with costs that vary but are around $1 billion per year.

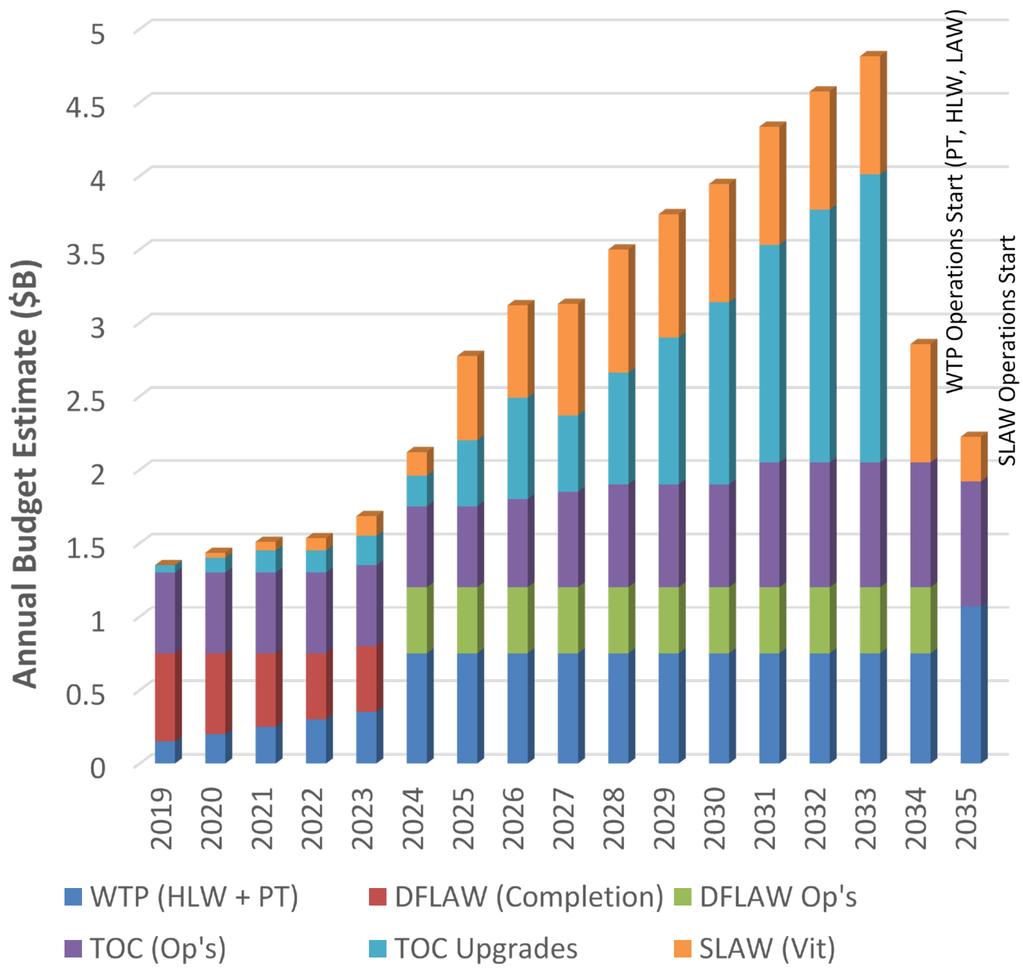

FIGURE 2-1 Near- and mid-term budget for SLAW vitrification in conjunction with key Hanford mission facilities and operations.
NOTE: DFLAW = Direct Feed Low-Activity Waste; TOC = Tank Operations Contract; WTP = Waste Treatment and Immobilization Plant.
SOURCE: Reprinted by permission from the FFRDC's final draft report's Figure 1.

The FFRDC's analysis assumes that funding would be made available to meet the schedule's order and scale of operations indicated in the annual funding requirement graph. However, on p. 24, the report points out "project funding has often been 'capped,' i.e., annual funding limited, independent of the project estimate." If this continues to be the case, SLAW technology development, facility design, and facility construction would compete for priority and funding with other large capital expenditures at Hanford including Direct Feed Low-Activity Waste treatment, WTP's major construction projects, tank waste retrieval, and other operations involving the tanks. Thus, the duration of the Hanford tank cleanup mission would inevitably be substantially increased.

Regulatory Compliance

The FFRDC report (see Section 3.2.7, p. 39; Section 3.3.7, p. 45; Section 3.4.7, pp. 51-52; and corresponding sections in Appendixes B, C, and D) considers the three waste form options from the perspective of their capabilities to meet applicable regulatory standards.[6] For disposal in the IDF, the regulatory drivers for determining compliance are groundwater concentration limits for radionuclides developed by the U.S. Environmental Protection Agency (EPA) under the Safe Drinking Water Act, which are part of the DOE orders under which the IDF is regulated. Such requirements are not applicable at the Waste Control Specialists (WCS) site because this site is licensed under the U.S. Nuclear Regulatory Commission's regulations (10 CFR part 61), which do not require compliance with the Safe Drinking Water Act. Both sites will be required to meet disposal standards (LDRs) under the Resource Conservation and Recovery Act (RCRA) concerning wastes containing hazardous chemicals. Meeting the RCRA requirements typically requires waste treatment to destroy or immobilize hazardous chemicals. The FFRDC team in its report did not directly discuss environmental and human health risks but in effect considered these in its analysis of regulatory compliance.

The use of the radionuclide drinking water concentration limits is a reasonable surrogate for human health risk as a first order of approximation. Moreover, for any of the alternatives to be feasible, it must be capable of complying with the applicable regulations such as drinking water standards. A thorough risk assessment and cost-benefit analysis would need to evaluate other exposure pathways (even if only to assure that the drinking water concentration is at least as protective), and to evaluate the benefits to be gained from additional protective actions or lost by other alternatives.

WASTE CONDITIONING AND SUPPLEMENTAL PRE-TREATMENT APPROACHES CONSIDERED IN THE ASSESSMENTS, INCLUDING ANY APPROACHES NOT IDENTIFIED BY CONGRESS

Sec. 3134 directed the FFRDC to perform an analysis of the risks, benefits, costs, schedules, and obstacles for removal of iodine-129 and technetium-99 from the SLAW for immobilization with the HLW. This highlights the fact that the identified approaches—vitrification, grouting, and steam reforming—are part of a larger system that provides the LAW feed and considers multiple potential disposal locations. In addition to the LAW feed from other parts of the tank waste remediation system, the SLAW facility will produce and have to manage its own secondary wastes and may include pre-treatment to make the SLAW more suitable for treatment or disposal. While these aspects precede and follow the central treatment approach, respectively, they can have a profound impact on the risk, cost, and benefit of the central approach.

Broader Waste Management System

The SLAW treatment technology is a relatively small part of a large, interrelated system that includes subsystems for treatment of the HLW and primary LAW, as well as tank operations. Following the congressional mandate, the FFRDC has focused its analysis within this relatively narrow scope of supplemental treatment of the LAW. The FFRDC team has analyzed three immobilization technologies identified in Sec. 3134: vitrification, grouting, and steam reforming.

Vitrification

This is a high-temperature technology that blends the SLAW with glass forming materials at about 1,150 °C, incorporating most of the radionuclides and metals into a glass waste form. The vitrification and off-gas systems destroy the LDR organics and some of the nitrates. Water is not incorporated into the glass, so it is treated in an effluent management facility to yield a large volume of grouted secondary waste. Solid secondary wastes (e.g., off-gas filters) that are generated are grouted (see separate discussion of secondary wastes below).

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[6]See Appendix A of this review report for the list of relevant standards as specified in the congressional mandate and Appendixes F and I of the FFRDC report for more detailed information.

Grouting

Grouting technology operates at room temperature (≈25 °C) and blends the liquid SLAW with dry inorganic materials to produce a cementitious waste form. All radionuclides, metals, and organics are incorporated into the grout, producing a very small amount of secondary wastes from filters and used equipment. Pre-treatment (see separate discussion below) to remove or destroy LDR organics may be needed.

Steam Reforming

This high-temperature technology blends the liquid SLAW with dry inorganic materials at 750 °C, forming dry granular mineral particles with a chemical structure that retains the radionuclides and metals. The particles can be mixed with additives to produce a monolithic solid waste form. This process also generates secondary wastes that the FFRDC assumed would be grouted.

In previous reviews, the committee accepted the FFRDC's choice to study only these three primary treatment options. As implied by the congressional directive to study these particular technologies, they are familiar and relatively well understood—which is not to say completely understood—technologies, and so the FFRDC's choice has merit especially given the looming Tri-Party Agreement milestones. At the same time, it is inevitable that further use of these technologies over time, whether at Hanford or elsewhere, will result in better understanding and improvements in the process and output—all the more so because the Hanford cleanup project is to last for decades. Moreover, given the need for waste disposal in many settings (beyond DOE, beyond nuclear), it is entirely possible, even likely, that entirely or partially new technologies will emerge that would be useful for the SLAW. Therefore, because new technologies, improved existing technologies, or new combinations of existing, improved, and new technologies may represent the best way to address the SLAW as the project develops over the next decades, it would behoove DOE to make choices now that do not foreclose the testing and adoption of treatment approaches that are not apparent or whose large-scale adoption is not yet warranted.

In addition to the three primary treatment options, the FFRDC also identified two near-surface land disposal options to analyze and compare. The IDF located at Hanford is considered as the "baseline" LAW disposal facility. In this baseline option, the liquid LAW will be solidified using vitrification, and the secondary waste will be grouted. DOE plans to dispose of both types of waste at the IDF, but the Washington State Department of Ecology (the Department of Ecology) has yet to approve waste acceptance criteria that would allow disposal of grouted secondary waste or even the primary vitrified LAW. The second disposal site analyzed is operated by WCS, located near Andrews, Texas. WCS is sited in an arid and isolated region of western Texas and has become an active commercial low-level waste disposal facility in recent years. Also, the report briefly mentions (see Appendix F, p. 155) the possible use of the EnergySolutions facility near Clive, Utah, especially if pre-treatment to remove sufficient strontium-90 can produce Class A waste, which is required for acceptance at that facility.

The Major Role of Pre-Treatment

Sec. 3134 directed the FFRDC to perform an analysis of the risks, benefits, costs, schedules, and obstacles for removal of iodine-129 and technetium-99 from the SLAW for immobilization with the HLW. (See sidebars on iodine-129 and technetium-99 for contextual discussion about characteristics of these radionuclides.) Instead, the FFRDC performed an analysis of whether removal of these radionuclides is needed to comply with the relevant waste acceptance criteria and examined the status of technologies for removing these radionuclides from the SLAW feed stream. Section 3.1 and Appendix A of the FFRDC report has a fairly complete review of the pre-treatment techniques and options that are available for these waste streams.

Besides the possibility of pre-treatment to remove technetium (Tc) and iodine (I) as specified by Sec. 3134, there is discussion of the need to pre-treat for organic materials to meet the LDR for waste acceptance of grouted SLAW, as well as the pre-treatment of the SLAW to remove strontium-90 to reclassify as Class A low-level waste for off-site disposal to possibly reduce disposal cost at the WCS site.

During the information-gathering meeting on May 16, 2019, slide #37 presented by the FFRDC team concluded:

- Treatment for LDR organics may be required for some of the waste for both on-site and out-of-state disposal.
- Technetium and iodine removal is not needed for out-of-state disposal of grouted or steam reformed waste forms.
- Technetium and iodine removal is not needed for on-site disposal of grouted or steam reformed waste forms, assuming high-performing grouted and steam-reformed waste forms.

For radioactive waste disposal, the committee notes that the two mobile and long-lived radionuclides iodine-129 and technetium-99 are consistently important risk contributors. Two important questions for this analysis are (1) whether it makes sense to remove these two radionuclides from the SLAW and immobilize them with the HLW streams, and (2) whether technetium and iodine will meet EPA's drinking water standard and, presumably, the yet to be determined waste acceptance criteria for the IDF.

Both the unpublished IDF PA and the FFRDC's Performance Evaluation (PE) attempted to answer the second question. According to the PA results described by Pat Lee of Orano Federal Services at the information-gathering meeting on February 28, 2018 (Lee, 2018), and the summary of those results in the FFRDC report (see p. 166), the immobilized (vitrified) low-activity waste form "is projected in the PA to contain the majority of ^{99}Tc and ^{129}I." Moreover, the report (p. 166) notes: "No performance objectives or measures were exceeded within the 1,000-year DOE compliance period." However, according to the PA's simulations, the release of iodine-129 would exceed the drinking water standard approximately 7,000 years after site closure. In comparison, the FFRDC's PE concluded that on-site IDF disposal would not require the removal of these radionuclides. The differing conclusions in the PA and PE analyses concerning iodine-129 point to the importance of revealing the modeling assumptions. In particular, the committee believes there are large uncertainties associated with the unvalidated waste form degradation models and data used in the FFRDC's PE analysis. Furthermore, what differentiates a "low-performing grout" from a "high-performing grout" from a "projected best" grout would have to be specified. Therefore, the conclusions from the FFRDC's PE that removal of iodine-129 and technetium-99 for on-site IDF disposal are not necessary would benefit from further evaluation and validation. If it turns out that iodine-129 can be removed from the current LAW or otherwise mitigated by engineered disposal barriers such as getters (which are added materials that can retain contaminants of concern) or isotopic dilution, resulting in much more benign LAW streams, other disposal options may open up for the disposal of these radionuclides as well as the waste from the treatment process.

Similarly with respect to selenium-79 (see sidebar for contextual discussion), without the proper supporting documentation for the FFRDC PE, or the IDF PA on which the PE was based, the committee is unable to assess the potential significance of ^{79}Se and any other long-lived fission products. It would have been useful for the FFRDC to include the risk over time for ^{79}Se and all of the long-lived radionuclides that are indicated in Table F-2 of the report.

SIDEBAR 1 Iodine

Nuclear fission creates a number of different isotopes of iodine. Most of these isotopes are very short-lived, with half-lives of hours or days. However, one isotope, ^{129}I, has a very long half-life of—some 16 million years and thus has a low amount of radioactivity per unit mass. Despite its low activity, ^{129}I is one of a limited number of long-lived fission products that are produced in significant amounts in nuclear fuels and remain as an important constituent during waste processing.

Iodine is relatively volatile so that the high-temperature processing of nuclear waste, such as in vitrification, inevitably causes a fraction (the actual value for this fraction will not be known until operation of the treatment plant, as noted in the FFRDC report [p. 37]) of it to be released into off-gas streams where it is collected and some of it ends up in secondary waste streams. These secondary waste streams may be handled by direct disposal (which was assumed in the analysis) or by further processing for incorporation into waste forms designed for iodine.

The geochemistry and mobility of iodine are sensitive to the degree to which the subsurface environment is oxidizing. This is because iodine travels as a negatively charged chemical species (iodide [I^-] and iodate [IO_3^-]). It is not sorbed onto the negatively charged mineral surfaces, particularly in an oxidizing environment. Iodine-129's relative abundance among long-lived fission products, very long half-life, biological significance, geochemical mobility, and being an essential mineral make it an important contributor to human health risk.

SIDEBAR 2 Technetium

Technetium has isotopes from ^{85}Tc to ^{120}Tc, where the longest-lived isotopes are ^{97}Tc (half-life of 4.2 million years), ^{98}Tc (half-life of 4.2 million years), and ^{99}Tc (half-life of 210,000 years). Isotopes with an atomic weight of 99 have a relatively high yield from the fission of ^{235}U, but the other two isotopes do not; therefore, technetium is present in Hanford waste, mainly as ^{99}Tc, while the other two isotopes are present in insignificant amounts.

Technetium exhibits valence states ranging from –1 to +7. However, due to its radioactivity and the fact that it does not occur naturally because it has no stable isotopes, there is relatively little known about its chemistry in comparison with the neighboring stable elements (Cotton et al., 1999; Sattelberger, 2005).The paucity of fundamental technetium chemistry is an impediment for understanding its behavior in tank waste, separations, waste forms, and the environment.

The primary stable solution form of technetium in an oxidizing environment is the negatively charged pertechnetate ion TcO_4^-. In the environment, TcO_4^- is mobile and is a significant contributor to the calculated dose rate a member of the public could receive from disposal of radioactive waste (Darab and Smith, 1996). In the Hanford tanks, the chemistry of technetium is more complex. In some instances, ion exchange treatment of tank waste was unsuccessful for isolating technetium. It was found that TcO_4^- was not the main chemical form (Schroeder et al., 1998), but rather a reduced Tc^{+1} species that was observed (Lukens et al., 2004). During high-temperature treatment a small fraction of the technetium is volatized and is collected on filters that are then managed as a secondary waste. Separations of technetium from radioactive waste and nuclear fuel removes the TcO_4^- or the reduced Tc^{4+} species. The Tc^{4+} species chemically differs from TcO_4^-; the Tc^{4+} is less soluble, less volatile, and has different properties during chemical separations. Controlling the technetium oxidation state can be important for removal of this element and for separate treatment and disposal.

SIDEBAR 3 Selenium

Selenium-79 is another long-lived[a] fission product that forms a negatively charged species when in an oxidizing environment. This species, $^{79}SeO_4^{2-}$, exhibits limited sorption to common subsurface sediments under oxidizing conditions, and so it is highly mobile. Selenium-79 can be a contributor to calculated waste disposal risk based on numerous PAs for deep geologic disposal in multiple media, including the oxidizing media at Yucca Mountain (e.g., Croff and Krahn, 2015; Helton et al., 2014).

The FFRDC report (see Table F-2) states that the average ^{79}Se radioactivity concentration in anticipated SLAW feed is nearly 20 times higher than that of ^{129}I. As a result, the committee inquired on multiple occasions in public meetings about the calculated dose rate from ^{79}Se. The FFRDC draft report (p. 166) does not provide a quantitative estimate of the dose rate from ^{79}Se but states that "radionuclides [other than ^{99}Tc and ^{129}I] are insignificant contributors to the total dose" despite having no supporting evidence. Furthermore, as reported by Fuhrmann and Schwartzman (2008), there is a discrepancy in a frequently referenced paper on partitioning coefficients that determine the mobility of ^{79}Se in the subsurface (Sheppard and Thibault, 1990). The incorrect partitioning coefficients reported by Sheppard and Thibault are two to three orders of magnitude higher than Fuhrmann and Schwartzman, which means that the mobility of ^{79}Se may be much greater than the unknown value used in the FFRDC's PE analysis.

[a]DOE in its PA used the value of 295,000 years for the half-life based on the GoldSim library values from ICRP Publication 107 "Nuclear Decay Data for Dosimetric Calculations." The half-life has been reported as several different values of 65,000 years, 295,000 years, 327,000 years, 480,000 years, 650,000 years, and 1.13 million years. [https://www.ptb.de/cms/en/ptb/fachabteilungen/abt6/forschungsnachrichtenabt6/news-from-the-annual-report.html?tx_news_pi1%5Bnews%5D=3589]. Evaluation of the available data by the National Nuclear Data Center [https://www.nndc.bnl.gov/ensdf] led to a currently adopted value of 327,000 years, as of May 2016.

The Major Role of Secondary Waste

While the FFRDC report mentions the challenges of secondary waste in the Executive Summary and explains its origins in Appendix F, the committee believes that the FFRDC does not emphasize strongly enough to decision-makers the central role that secondary waste plays in meeting disposal waste acceptance criteria. Secondary waste is produced during the treatment (and pre-treatment if used) of the SLAW in differing amounts depending on the treatment method used and can include solid (such as HEPA filters) and liquid wastes produced during primary processing which are then assumed to be grouted. In particular, high-temperature processes volatize iodine and a small fraction of it is present in the grouted secondary waste forms.

Indeed, the grouted secondary waste has a disproportionate impact on the IDF performance and results in it being the dominant contributor to calculated dose during a 10,000-year period. Specifically, long-lived and mobile iodine-129 dominates the long-term health risks for all three treatment technologies. As shown in Lee's presentation from the February 28, 2018, public meeting on the IDF PA, the time of peak dose for iodine-129 occurs in the 7,000 to 8,000 year period after emplacement in the IDF (Lee, 2018). Thus, the production of secondary waste streams for high-temperature processes (vitrification and steam reforming)—if left unmitigated—becomes an important decision factor among the alternatives.

Given the fact that the grouted secondary waste streams drive IDF performance (except for grout, where less iodine is in the secondary wastes and the dose from the primary waste dominates), it is surprising that the FFRDC did not spend more time analyzing mitigation actions both on the secondary waste form, but also in the IDF design (which, for example, takes no credit for using engineered fill materials as a radionuclide migration barrier). Accomplishing either of these mitigation actions could have a significant impact on performance of the IDF LAW disposal system (including waste form, fill material, liners, and caps) and potentially streamline the decision-making process. However, the FFRDC's report does mention the possibility of shipping grouted secondary waste to WCS while keeping vitrified primary waste at the IDF. Waste acceptance criteria at WCS are less restrictive than at the IDF because, in contrast to the IDF, WCS lacks an aquifer containing potable water under the disposal site.

OTHER KEY INFORMATION AND DATA USED IN THE ASSESSMENTS

Performance Assessment and Performance Evaluation of Waste Disposal

The compliance of primary (WTP) vitrified LAW disposal at the IDF relies on PA calculations (as specified in DOE Order 435.1; DOE, 2011b). The PA evaluated the performance of vitrified primary waste and grouted secondary wastes in the IDF, but did not address the performance of the IDF containing waste from the grouting and steam reforming alternatives. The report on p. 166 states the PA results for vitrified LAW as follows:

- No [DOE] performance objectives or measures were exceeded within the 1,000-year DOE compliance period. The highest calculated dose projected was for the chronic inadvertent intruder scenario where interception of four ILAW [immobilized low-activity waste] glass cylinders occurs from well drilling at the end of the institutional control period. In this case the dose is <50% of the 100 mrem/yr [milli-roentgen equivalent man/year] maximum dose rate performance objective.
- For the air and groundwater exposure pathways, the predicted dose during the DOE compliance period, is dominated by the air pathway for gaseous radionuclides, but is a factor of 50 below the 10 mrem/yr performance objective.
- Only the groundwater protection measure (beta-gamma dose equivalent) is exceeded during the post-compliance period (>1,000 years), where dose calculated using the EPA dosimetry method projects a dose rate of 4.9 mrem/yr (versus 0.4 mrem/yr beta-gamma standard) resulting from ^{99}Tc and ^{129}I within solid secondary waste, specifically the grouted granular activated carbon (GAC) and HEPA filters solid secondary waste (SSW).

To assess potential compliance of the SLAW and secondary waste disposal at the IDF from the grouting and steam reforming options, the FFRDC team conducted PE analyses that are similar to the PA methodology, and they validated the PE against the PA. The FFRDC team also conducted a PE of vitrified SLAW and secondary waste disposal using its own waste form models and assumptions. As discussed on p. 166 of the report, the results of the PE for all three waste disposal systems at the IDF extending to 500,000 years were that the calculated peak dose was less than 50 percent of the 100 mrem/yr dose rate performance objective. "After more than 200,000 years, radium-226 becomes a dominant dose contributor, but less so than the earlier peak doses from technetium-99 and iodine-129."[7] Thus, iodine-129 and technetium-99 were the only significant contributors to the peak dose, which occurred several thousand years after disposal site closure. The committee notes that preparation and release of PAs is beyond the scope of the FFRDC's charge or resources. However, it is evident from the most recent report that the FFRDC has had access to draft PA analyses and results. The committee did not have access to the PA data and analyses, thereby, making it impossible for the committee to critically review the disposal performances of the three waste disposal systems. Moreover, the technical bases for waste degradation models and mechanisms used in the PE analyses for the IDF by the FFRDC team are not well documented and justified.

Consideration of Experience at Relevant Sites

In a number of places the report mentions experience relevant to the SLAW, especially at DOE sites other than Hanford. Examples include the vitrification and grouting at the SRS, vitrification at the West

[7]Page 166 of the FFRDC report.

Valley Demonstration Project, and the steam reforming unit under development at INL. However, the mentions are just that. There is no analysis of what aspects of the experience are relevant to the SLAW or not, why this is the case, and the implications for the readiness of the various technologies for deployment. For example, extensive information exists on the design, cost, production, and performance of Saltstone at the SRS accumulated over nearly three decades. This information was used by the FFRDC to inform their cost estimates for the grout alternative. Because of the similarities in some of the wastes, the committee believes that there are lessons to be learned from the activities at other sites that are not reflected in the FFRDC report, not only regarding the design and operation of these similar facilities, but also regarding the performance of the grout waste form, which has been widely used to immobilize radioactive and chemically hazardous wastes. Discussion of this experience would help inform decision-makers. In addition, it would help to consider other useful, relevant experience at non-DOE sites to include commercial facilities, such as the operating steam reforming facility in Erwin, Tennessee. This would include analysis of pre-treatment and treatment alternatives for operations similar to those being consider for treatment of SLAW at Hanford.

While there undeniably are relevant differences among the sites' respective waste streams, physical environments, regulatory requirements, and other factors, there are also similarities. Success or lack of success at another site does not directly translate to the same outcome at Hanford, but every experience offers lessons to be learned, and the FFRDC report would be strengthened by a candid assessment of such lessons. The committee recognizes that there is often cultural resistance to assessments, but DOE, like all other organizations, would benefit from learning from its own experiences across the DOE complex. Moreover, as suggested in Recommendation 3-1 (see Chapter 3), the long duration of the Hanford cleanup lends itself to a concerted effort to learn from experience at other DOE sites, at locations in other countries where these technologies are used, and from Hanford's own experience over multiple decades.

In a similar vein, the report has a brief comparative discussion of differences among the current efforts and previous performance assessments (see Appendix F.4.3.3) and a very brief acknowledgment of previous comparative evaluations of technologies relevant to the SLAW treatment (Sec. 3.5). A few documents in both categories are referenced in the report. The committee believes that there is a need to systematically and transparently identify and compare the differences among the various historical documents at both levels to provide the basis for determining the credibility and shortcomings of the current analysis.

Other Needed Information

Meeting the Requirements of the Resource Conservation and Recovery Act of 1976

An important aspect of regulatory compliance is meeting the requirements of the RCRA. Some metals and organic chemicals that are known or suspected to be in the SLAW waste stream are regulated under the RCRA, which sets stringent land disposal restrictions for these materials based on their potential to leach into groundwater. Other chemicals suspected to be in the SLAW, such as nitrates, are regulated to prevent groundwater contamination. If these materials are destroyed or removed during the processing of the waste, or adequately immobilized in waste form, then near-surface disposal is not an LDR issue. However, if they remain, the LDRs represent a regulatory hurdle, and one which is in the control of state regulators under the terms of the Federal Facilities Compliance Act. Although the FFRDC report mentions the possibility that the LAW might require pre-treatment to meet LDR, its analysis of mitigation options is terse, and it is unclear whether or when mitigation will be needed and how the need will be assessed.

Enhanced Engineered Barriers for Iodine-129

Because of its characteristics (see sidebar), iodine-129 poses a particular challenge for disposal in either a near-surface facility or a geologic repository. Over the very long term, iodine-129 becomes an important contributor to dose calculations. For this reason, there has been a substantial amount of research, mostly funded by DOE, to investigate new materials for the selective removal of iodine from the HLW waste streams, its incorporation into durable waste forms, and the development of getters to capture released iodine in the near-field of the disposal environment.

Although the report raises the possibility of using getters in the grout, the report does not provide an explanation or analysis of the materials that would be used, nor is the possibility of isotopic dilution discussed. Finally, the report does not consider a strategy for augmenting the design of the disposal site, for example, the IDF, to use getters in the fill material as a barrier to iodine release.

PRESENTATION OF ASSESSMENT RESULTS

Comparative Assessment of Waste Form Performance

In Review #2, the committee emphasized the need for a comparative assessment (NASEM, 2018b). One distinct element of the decision-making process will be to answer the question of whether the performance of the different waste forms has a significant impact on the performance of the disposal system. The answer to this question lies in an evaluation of the comparative material properties of the waste forms, their performance in the near-surface, disposal environment, and an understanding of how all of the elements of the disposal system actually functions individually and how they interact.

The FFRDC's final draft analysis attempts to do this, but there are deficiencies to the FFRDC's approach. Most noteworthy is the lack of a truly parallel analysis of the three waste forms. A parallel, comparative analysis would consist of three clearly presented and discussed steps:

- A clear **definition of the waste feed stream** (also called a feed vector) for each waste form. Although some data are given (e.g., Tables F-1 and F-2), these data represent examples at a specific time or global averages. In order to understand waste form performance, particularly of key radionuclides like iodine-129 and technetium-99, the analysis has to provide envelopes of composition that capture variations in the waste stream during processing. This may be important in determining whether the waste form can incorporate or encapsulate the waste stream's radionuclides. More importantly, the type of processing, such as high-temperature vitrification versus low-temperature grouting, can change the immobilized waste stream composition. In the case of vitrification, small fractions of volatile elements, such as I (a few to 25 percent) and Tc (a fraction of a percent), are projected to be in the secondary waste streams, which are assumed to be grouted. Thus, the final disposal evaluation needs to consider not only the performance of the three waste forms, but also the performance of radionuclides in the secondary waste streams. Options for the treatment of the secondary waste streams also need to be described and evaluated.
- A **comparison of material properties** of the three waste forms. This should consist of four types of information:
  - A description of the basic waste form properties (e.g., waste loading and density), particularly properties that will affect performance, such as the composition of the glass, whether additional engineered barriers will be used in the grout, the permeability of the grout, and the microtexture of the glass ceramic that will result from steam reforming.
  - A description of the distribution and chemical speciation of key radionuclides within each waste form, particularly their redox state and the identification of other components that may change or control the redox state within the waste form.
  - A description of the radionuclide release mechanisms for each waste form, and a discussion of alternative mechanisms and why they were not adopted. The understanding of the mechanisms of release and retardation is a critical aspect of the models that were used in the PA.
- The last step in the **comparison is the performance assessments of the waste forms in the disposal environment.** If the PA and the PE calculations for the IDF had been available for the committee's review, four issues would have been of critical interest:

- How is the waste form's release of radionuclides modeled?
- What other near-field geochemical or hydrologic processes (e.g., solubility limits or sorption) slow the release and/or decrease the mobility of radionuclides?
- How do assumptions about future conditions, (e.g., climate or the geologic medium) affect the PA results?
- How do the principal components in the IDF interact with one another? The scenario analyzed in the PA involves two types of waste in the IDF: glass for primary LAW and grout for secondary waste. Are there coupled mechanisms at play, such as the effect of grout on the pH of water reaching the waste form and then interacting with the glass? Glass corrosion is very pH dependent. (If the vitrified and grouted waste forms are co-located in the IDF, high-pH leachate from the grout would corrode the glass.)

The committee notes the following key points:

- A modeled demonstration of compliance is only the first step in a performance assessment or a performance evaluation. One also needs to develop a strong understanding of how the disposal system functions as a whole and be able to make a compelling argument for the selection of one waste form over another (what is sometimes known as the safety case). Even if all three waste forms comply with the regulations, that still does not mean that the differences in waste form performance have been captured by the analysis. Other parameters, such as the time to reach the peak radiation dose rate and the time for dose rates to diminish, may be relevant to the decision-maker's consideration of the three technologies and their waste forms. The committee acknowledges that the FFRDC has made a valiant effort to compile and compare data on the different waste forms. Still, the lack of a fully transparent comparison between the three waste forms hinders the analysis.
- As noted above, the FFRDC report has very limited discussion of the Saltstone that is in use at the SRS (see pp. 93-94 in Appendix C). More details on the similarities and differences between the grout to be used at Hanford and the Saltstone at SRS would have added greatly to understanding how the grout is being modeled at the IDF at Hanford.

In summary, the FFRDC report fails to muster the extensive data in the literature on the different waste forms and present a comparison that highlights the pros and cons of each. The committee notes that this is attempted, as an example for grout (p. 92 in Appendix C), but this bulleted list is really just composed of assertions without reference to data or citations to relevant literature.

The "As Good as Glass" Conundrum

Much has been made, particularly by the Department of Ecology, of a supposed commitment by DOE that any treatment technology for the SLAW be "as good as glass." While not found in so many words in federal or state law or regulation, the "as good as glass" concept has taken on a life of its own at Hanford. Some stakeholder groups advocate for it; the Department of Ecology and others have developed a set of legal arguments for "as good as glass"; and the Department of Ecology has offered some tentative criteria (see the presentation of Alex Smith, Washington State Department of Ecology, at the July 23, 2018, public meeting) by which another technology might be determined to be as good as (or not as good as) glass. In theory, the "as good as" formulation would allow DOE to pursue a treatment technology *other than* glass (vitrification). In practical terms, however, "as good as glass" forces DOE to adopt vitrification because the content and contours of the concept are undefined. The conundrum is that "as good as glass" can mean different things—often without a clear awareness of the differences by users of the term. The committee has heard discussions during its information-gathering meetings that imply at least three different meanings, as follows:

- First, in its narrow technical sense, it refers to the waste isolation capacity of the SLAW immobilization medium (e.g., glass or grout). This is fundamentally a question of materials science and chemistry. It is informed by laboratory experiment and mechanisms of isolation, and it can be evaluated based on a considerable technical literature with varying degrees of uncertainty.
- Second, in a technical but broader sense, "as good as glass" refers to the disposal system—not just the waste form itself, but the waste isolation effectiveness of the waste form, packaging, fill material surrounding the packages in the disposal trenches, the engineered barriers such as liners and caps that surround the trenches, and the natural environment surrounding this engineered system. Thus, the engineering of the waste disposal facility is relevant, as is the geology, geochemistry, climate, and hydrology of the environment in which the disposal facility is located.
- Third, "as good as glass" can refer to the overarching decision that DOE has to make among treatment technologies and disposal locations. That is, it can refer to the comparison of the baseline alternative involving vitrified SLAW, grouted secondary waste, and disposal in the IDF to grouting and steam reforming alternatives with disposal in the IDF and/or WCS on a multi-attribute basis. This, however, requires consideration of not only the physical characteristics of the waste, its form, and its placement, but all of the factors that will be considered by the decision-makers when selecting a preferred alternative. This means that, *in addition* to physical characteristics of the waste form and disposal site identified in the previous two bullets, one has to consider a range of quasi-technical factors including cost, reliability of technology, technological readiness, schedule, and safety, and their relative importance, i.e., "all things considered." Additionally, it is important to note that there are secondary wastes from the vitrification and steam reforming processes that were projected to contain significant amounts of ^{99}Tc and ^{129}I, so this waste stream is the most important contributor to calculated dose rate as compared to the immobilized SLAW per se. In other words, "as good as glass" could mean the primary *and* secondary waste forms.

As can be understood from the above steps in the analysis of waste form performance, the judgment of whether other waste forms are "as good as glass" may be made at different levels: (1) the evaluation and comparison of the release rates from each of the waste forms based on laboratory data; (2) the waste form performance in the disposal system modeled over time; and (3) multi-attribute comparison of alternative disposal systems that include consideration of quasi-technical factors. At each step, the factors to be considered are different and increase in number.

The committee believes that waste form performance would have to be based on the comparison of waste form performance in the disposal sites over relevant periods, e.g., out to the time of the peak dose rate. All other points of comparison, e.g., materials properties, are components of the larger PA analysis. It is essential that the analyses supporting the selection of a preferred treatment alternative clearly distinguish among, and provide the necessary information for, analyzing all of these meanings of "as good as glass." The technical assessment of the waste form per se and the technical assessment of the waste form in situ are essential elements of the larger decision but are far from the only elements that need to be considered.

The committee also notes that there may be opportunities to engage productively with the Department of Ecology to reach an agreement on the "as good as glass" issue. While this issue falls outside the scope of the FFRDC's mandate, it is germane to the committee's scope because Sec. 3134 requires the National Academies to "provide an opportunity for public comment, with sufficient notice, to inform and improve the quality of the review." The Department of Ecology is a major stakeholder and a decision-maker because of its role as the state regulator with the authority to issue permits for the Hanford Site's facilities such as the IDF, the WTP, and the SLAW treatment—or not. Department of Ecology representatives have provided substantive comments at every public meeting that the committee has held in the Hanford area. At the most recent public meeting on May 16, 2019, Suzanne Dahl, section manager of tank waste for the Department of Ecology, described the FFRDC's final draft report as a "feasibility study" and as a "potential first stepping stone to changing SLAW treatment." She also noted several new pieces of information in the report, including the "cost of nearly complete LAW vitrification plant," (sic) "WCS as new candidate waste disposal site," "new high performance grout waste form performance data," and "new FBSR [fluidized bed steam reforming] crystalline ceramic waste form performance data." As to the high performance grout, she noted that the report indicates that this type of grout performs "better than the vitrification waste form performance." She mentioned that these "results are contrary to 30 years of previous results" and that "Ecology has no comment on these results. Ecology has not completed evaluation of underlying studies and would need to complete a significant effort before concurring with the latest results." The committee observes that Ms. Dahl's remarks suggest an opportunity for DOE and the Department of Ecology to work together to take the next steps that she has outlined.

THE COMMITTEE'S FINDINGS

Overall Assessment

Finding 1-1

The purpose of the committee's review is to advise whether DOE, Congress, regulators, and other stakeholders can rely on the FFRDC report to evaluate and decide on a treatment approach for the SLAW. The committee finds that, in its current iteration, the FFRDC's analysis:

a. When taken alone, does not yet provide a complete technical basis needed to support a final decision on a treatment approach;
b. Does not yet clearly lay out a framework of decisions to be made among treatment technologies, waste forms, and disposal locations; but
c. Can form the basis for further work as described below in the committee's findings and recommendations.

Analysis of Costs, Benefits, and Risks

Finding 2-1

The cost estimates in the FFRDC report are based on technologies that, for the most part, have not yet been fully developed, tested, or deployed for Hanford's particular, and particularly complex, tank wastes, and instead use costs from similar technologies. As a result, there are large attendant uncertainties, suggesting that costs could be much higher than estimated, but are unlikely to be much lower.

Finding 2-2

The cost estimates in the FFRDC report are based on continuing funding at and beyond current levels to optimize the waste treatment technologies and speed of progress. These involve very large annual appropriations, which are inevitably uncertain over the planned decades of activity, especially because current planning assumptions anticipate a two- or three-fold increase in expenditures at certain points in the SLAW treatment process. This, too, introduces the possibility that funding shortfalls will lead to longer schedules, increased total costs, and higher chances of additional tank leaks or structural failures, which will themselves increase costs as well as health and environmental risks.

Finding 2-3

The report's analysis of costs does not enable the reader to analyze key trade-offs among specific alternatives or variations of major alternatives.

Disposal Risk Assessment

Finding 3-1

Assessment of the waste forms' performance would have to include consideration of the characteristics of the disposal sites and the transport pathways to receptors over the relevant periods of time, as well as be based on the inherent characteristics of the waste form.

Finding 3-2

The committee did not have access to the 2017 IDF Performance Assessment (PA) that has been prepared by DOE or to the Performance Evaluation (PE) data and analysis prepared by the FFRDC. Therefore, it was impossible for the committee to critically review the differences in the performances of the three waste forms and their associated disposal systems over time. Additionally, the technical bases for waste degradation models and mechanisms used in the PE analyses for the IDF by the FFRDC team are not well documented and justified.

Finding 3-3

Without the proper supporting documentation for the FFRDC's PE, or the IDF PA on which it was based, the committee is unable to assess the potential significance of mobile, long-lived fission products such as iodine-129, technetium-99, and other long-lived radionuclides (possibly selenium-79 and others). It would have been useful for the FFRDC to include the human health risk estimates (dose) over time for all of the long-lived radionuclides that are listed in Table F-2 of their report, not just iodine-129 and technetium-99.

Finding 3-4

The FFRDC report gives little consideration in its analysis to the environmental, health, and safety consequences of hastening or further delaying remediation of the Hanford waste storage tanks, which is related to the probability that additional tank leaks or structural failures will occur over the long time period expected for the removal and treatment of the waste in the tanks.

Pre-Treatment to Remove Iodine-129 and Technetium-99

Finding 4-1

The FFRDC performed an analysis of whether removal of iodine-129 and technetium-99 was needed to comply with the disposal waste acceptance criteria, and examined the status of technologies for removing these radionuclides from the SLAW feed stream, but the FFRDC report does not respond fully to the congressional direction (in Sec. 3134) because the report does not address immobilization of the iodine-129 and technetium-99 recovered from the LAW as part of the separate high-level glass waste form to be produced in the WTP.

Other Observations

Finding 5-1

The report makes little use of the experience with grouting and other technologies at other DOE sites and commercial operations. While there are unquestionably meaningful differences among the waste forms, technologies, and disposal environments as compared to Hanford, the extensive experience gained at Savannah River Site, in particular, is an invaluable source of insight.

Finding 5-2

The committee was repeatedly told that the selection and implementation of an approach to tank waste was hampered by the insistence by the State of Washington and some other stakeholders that any approach other than vitrification must be "as good as glass." The term "as good as glass" is not defined in law, regulation, or agreement, and it is only tentatively defined by its advocates. The analysis in and the public presentations of the draft FFRDC reports offer a follow-on opportunity for DOE to engage with its regulators and stakeholders to identify performance standards based on existing regulatory requirements for waste form disposal and to pursue a holistic approach to selecting a treatment technology.

Comparisons

Finding 6-1

Over multiple iterations, the FFRDC report has increasingly enabled side-by-side comparisons among the SLAW treatment approaches, exemplified by the table of alternatives and criteria. It remains difficult, however, for the reader to see comparisons and trade-offs in the supporting narrative.

The FFRDC Report's Steps Forward

Finding 7-1

The report represents useful steps forward by:

a. Confirming that versions of vitrification, grouting, and steam reforming are treatment technologies that merit further consideration for the SLAW;
b. Establishing the likelihood that vitrification, grouting, or steam reforming are capable of meeting existing or expected regulatory standards for near-surface disposal albeit with varying amounts of pre-treatment being required;
c. Highlighting the important contribution of the iodine-129 in the secondary waste streams disposed at the IDF to the total estimated radiation dose rate to the receptors;
d. Underscoring the regulatory and acceptance uncertainties regarding approaches other than vitrification technology for processing the SLAW; and
e. Opening the door to serious consideration of other disposal locations, specifically the WCS facility near Andrews, Texas, and possibly the EnergySolutions facility near Clive, Utah.

3

The Committee's Assessment of the Usefulness for Decision-Makers of the FFRDC's Final Draft Analysis

The Federally Funded Research and Development Center (FFRDC) team was assigned a very large task in a short period of time, that is, to review a long history and large technical literature on three or more very different treatment technologies and, as the analysis developed, the permanent disposition of waste material in two (or potentially three) different disposal sites. As the committee has noted in previous reports and above, the choice among treatment approaches cannot meaningfully be made without consideration of the disposal environment and the quasi-technical factors identified earlier. The FFRDC team has, as the committee has also noted, worked very hard to grapple with the task it was assigned. It has gathered a large amount of information, performed various analyses on it, and adjusted its approach and presentation in response to comments. Nevertheless, as Chapter 2 demonstrates, there are significant technical limitations to the conclusions that can be drawn from the team's work, especially regarding the analyses of costs and risks, as well as the uncertainties surrounding the technologies themselves, costs, and several important programmatic risks.

The committee's review is constrained, it goes without saying, by the Statement of Task, which expressly calls for the committee to "evaluate the technical quality and completeness" of the FFRDC report on the treatment options for supplemental low-activity waste (SLAW). This is a double limitation: the committee's report is to be "technical," and the committee's scope (following the FFRDC's) includes treatment approaches to the SLAW plus the directly related ancillary processes such as pre-treatment and secondary waste management. Neither the FFRDC nor the committee was tasked to offer views on broader policy issues or on the overall system for managing tank waste at Hanford. While one may quite reasonably find such limitations frustrating and sometimes even question-begging, they represent Congress's commendable effort to obtain a well-informed and reliable technical answer to a particular and important question before it.

Within the committee's task of technical review, it may also be helpful to identify the ways in which the extensive information and analysis in the FFRDC report may best be used by Congress, the U.S. Department of Energy (DOE), and stakeholders, together with additional considerations that users should bring to the analysis. The committee's overarching assessment is that the FFRDC report is a valuable feasibility or scoping (in a non-technical sense) report, which identifies the key alternatives *as of now*, and paves the way for more detailed evaluations. It also paves the way for adopting a more iterative approach to technology at Hanford, taking advantage of the distant time horizons to build in flexibility and learning. Such an approach could help to avoid the tank waste management project finding itself, in 2030, at the outer limits of available funding and schedule and yet bound by vintage technologies of 2020 with decades of waste management and disposal to go. Put another way, the high degree of difficulty and uncertainty in the FFRDC's analysis at *this* point in time ought to counsel caution and humility in making expensive or even irrevocable choices for the long-term future.

This chapter focuses on the usefulness of the FFRDC's final draft report to decision-makers. In effect, this congressionally mandated study resulted in an FFRDC report that provides an assessment of three major alternatives for supplemental treatment of low-activity waste (LAW) derived from material in the Hanford tanks as described in the FFRDC's mandate. As mentioned earlier, the FFRDC team did not identify a preferred option by design, because it was not in their mandated scope, and the committee agrees with the team's decision. The committee envisions that decision-makers will ask themselves a series of questions during the decision-making process. This chapter provides the committee's views on questions that decision-makers are likely to ask and the committee's assessment of information available from the FFRDC's April 5, 2019, report, and the FFRDC presentation slides from the public meeting on May 16, 2019, that could address these questions and what additional information is needed.

The committee assumes the decision-makers are senior policy-makers in the federal government (Congress and DOE's executive management) and the state regulator (the Washington State Department of Ecology [the Department of Ecology]). They are also the primary audience of the FFRDC report, and that their decisions will be at the policy level. That is, they will be examining the relative priorities of the factors (decision criteria or "lines of inquiry") analyzed in the report in the context of broader government priorities and available resources leading to identification of a preferred alternative or guidance on additional analyses needed to allow such an alternative to be pursued. Thus, what follows is essentially a guide to the report from the standpoint of decision-makers.

CONSIDERATIONS FOR DECISION-MAKERS

At the end of this chapter, the committee offers four recommendations: first, a general recommendation on the best way to understand and thus make productive use of the FFRDC report; second, specific issues around which a full decisional document should be organized; third, organizational structure to improve its usefulness to decision-makers; and fourth, using the FFRDC report as the basis for considering a more flexible approach to the SLAW (and possibly other aspects of tank waste management) that makes productive use of the long time horizon for cleanup.

While Congress did not specify that either the FFRDC team or the committee undertake formal risk assessments or cost-benefit analyses, such formal analyses, conducted with rigor, would greatly help to elucidate the relevant issues, choices, and uncertainties for well-defined paths forward. There are, and DOE and others have calculated them in the past, baseline risks and costs of the current situation with the Hanford tanks. That is, the risks, costs, and uncertainties of maintaining the waste at a level that minimizes the likelihood of release of tank waste to the extent feasible *in their current configuration.*

These baseline results provide a point of comparison with other pathways for waste management, specifically moving and treating the waste so as to achieve greater reduction of risk than is allowed by leaving the wastes in their present configuration. Additionally, DOE and others have performed analyses to support conclusions concerning the amount of waste that can be left in the tanks; this is the justification for constructing the multi-billion-dollar facilities to retrieve, store, and treat the tank waste. DOE has made the further decision to construct the multi-billion-dollar facilities on the basis of separating high-activity waste and LAW streams, and the particular flowchart on which these facilities are based requires the separate treatment of the SLAW.

The decision to adopt an approach that not only divides tank waste into high-activity wastes and LAWs, but also requires separate treatment of the SLAW, is the starting point of the FFRDC team and thus of the committee. As complex as the SLAW treatment question is, it is far less complex than the overall question of what to do about tank waste as a whole in its current configuration. Accordingly, it should be possible for a manageable number of pathways for treating and disposing of the SLAW to be identified and rigorously analyzed. The techniques of risk assessment, cost-benefit analysis, and uncertainty analysis are well suited for this task.

As stated in Chapter 2 of this review, the FFRDC team addresses the elements of such analyses for a reasonable selection of alternative pathways, but there are important gaps and omissions. Moreover, because the team was not directed to, and did not, perform rigorous analyses of risk, cost, benefit, and uncertainty, a decision-maker is not in a position to make a decision among pathways (technology approach and disposal site) solely on the basis of the FFRDC report. The following considerations therefore highlight the specific areas that a decisional analysis would need to address in detail and with rigor and, where possible, with quantification.

Are the Alternatives Adequately Defined and Described?

The FFRDC in its report considers three waste treatment immobilization processes (vitrification, grouting, and steam reforming) for the primary SLAW stream, and further possible pre-treatment processing to remove technetium-99 and iodine-129 to meet the requirements stated in the congressional mandate (see Appendix C). Additionally, during the course of the FFRDC's work, the FFRDC identified the possibility of SLAW disposal at the Waste Control Specialists (WCS) near-surface disposal site near Andrews, Texas, and this is considered in the FFRDC report. The committee believes that this was a desirable addition to the scope of the analysis.

The committee has a number of concerns about the definition and description of the alternatives, as follows:

- There are many possible combinations of pre-treatment, treatment (immobilization), and disposal options. This fact, combined with waste acceptance criteria that differ at the two disposal sites considered (the Integrated Disposal Facility [IDF] and WCS) and, in the case of the IDF, are not yet approved, results in a confusing array of alternatives. In particular, the committee believes it will not be clear to the reader when and what type of pre-treatment is required or desirable for the various waste form-disposal destination combinations.
- The two high-temperature technologies (vitrification and steam reforming) produce secondary wastes (e.g., high-efficiency filters, liquids not suitable for release, and charcoal adsorbent beds) separate from the primary SLAW stream. In comparison, as a low-temperature process, grouting produces relatively minimal amounts of secondary waste; see p. 103 of the FFRDC report. The secondary wastes are assumed to be grouted and disposed of in the IDF in these alternatives, although the FFRDC does briefly discuss the possibility of sending this grouted secondary waste to WCS. In its report, the FFRDC mentions that vitrification produces the largest volume and the highest radioactivity content of secondary waste of the high-temperature primary treatment technologies, and that this secondary waste is the dominant source of radiation doses to a public receptor according to calculations examining a 10,000-year period at the IDF.
- The congressional mandate to the FFRDC calls for the analysis to include consideration of "Further processing of the low-activity waste to remove long-lived radioactive constituents, particularly technetium-99 and iodine-129, for immobilization with high level waste." As noted in Chapter 2 of this review, further processing (pre-treatment) to remove these radionuclides is considered only from the perspective of SLAW regulatory compliance or changing the SLAW classification from the U.S. Nuclear Regulatory Commission's Class B or C to Class A to reduce disposal costs at the WCS facility or possibly make the SLAW acceptable for disposal at the EnergySolutions facility near Clive, Utah. The possibility of moving these two radionuclides into the high-level waste (HLW) stream was not evaluated by the FFRDC in the report. In addition, doses from other long-lived, mobile radionuclides were not provided—selenium-79, in particular.

Taking these concerns together, decision-makers will need to carefully read the main report and possibly selected appendixes to understand the comparative advantages and disadvantages of the alternatives. This is especially the case when one considers the many externalities that are outside the FFRDC's scope (see FFRDC report p. 11, "Significant Funding Needs," and p. 13, "Emergent Studies and Future Scenarios"), but which could profoundly affect decisions on the SLAW treatment.

What Is the Level of Confidence That Each Treatment Alternative Will Meet Performance Requirements?

The FFRDC, in its final draft analysis, discusses the level of confidence that each alternative will meet its performance requirements in terms of its "technical maturity," which is typically measured on a scale of technology readiness levels beginning with basic research and ending with commercial deployment of the technology (DOE, 2011a). The FFRDC's discussion is presented briefly, in qualitative terms, and without reference to an established scale. Some key aspects of the FFRDC's discussion are discussed below.

The FFRDC report has neither a side-by-side comparison of the technical maturity of the major alternatives, nor a comparative discussion of the technical maturity assessment process used. If work on the analysis continues, it would be useful to include such discussion. The summary comparison tables (Table 2, p. 14, and Table 10, p. 61) state that vitrification is the most mature, FBSR the least mature, and, by inference, grout is intermediate. The committee offers the following observations on the FFRDC's views:

- Technical maturity is an imprecise measure of the level of confidence as to how well a technology will perform. Whether a technology will perform depends on the competence of the designers, constructors, and operators, as well as the inherent characteristics of the technology. At this point, the committee believes technical maturity is not an appropriate measure, because there is no design, construction, or operation.
- The committee questions the FFRDC's assessment that vitrification is the most technically mature technology for Hanford LAW. The FFRDC cites the Waste Treatment and Immobilization Plant (WTP) LAW vitrification facility as evidence. However, this facility has neither been completed, nor has it been operated. Radioactive waste has been vitrified at "industrial scale" at the Savannah River Site (SRS), with a somewhat different and more homogenous feed composition than at Hanford; it has also been vitrified at a few reprocessing plants around the world with a significantly different feed composition. The committee believes that the best evidence of the technical maturity for LAW immobilization is at SRS, where large volumes of low-activity alkaline salt-laden waste have been immobilized using grouting in near-surface vaults for years. Thus, the committee points to this evidence that grouting similar LAW appears more mature than vitrification but agrees with the FFRDC that fluidized bed steam reforming (FBSR) is the least mature immobilization technology.
- The FFRDC's "bottom line" assessment of technical maturity is focused on the immobilization technology per se. However, the maturity of other aspects of each alternative needs to be taken into account. In particular, each alternative treatment technology requires pre-treatment of the feed stream and management of secondary wastes to varying degrees. The maturing of the necessary pre-treatment technologies does not seem to have been taken into account in the FFRDC's assessment. The maturity of candidate pre-treatment technologies is summarized in Section (Sec.) 3.1 and detailed in Appendix A of the FFRDC report. In general, the committee believes that the pre-treatment methodologies are less mature than vitrification and grouting, and perhaps even FBSR. However, while many component technologies to implement these pre-treatment options have been the subject of some research and development, the committee notes that the most challenging part of completing the WTP at Hanford has been the LAW pre-treatment facility.
- In addition to technical maturity (the current development state of the process), an important consideration when assessing whether a technology that has not been implemented can succeed is the technology's complexity. Complexity is basically measured by how many things must simultaneously function properly for the technology to operate. The FFRDC does address complexity in its summary tables: vitrification is the most complex, grout the least complex, and FBSR intermediate. The committee accepts that grout is least complex. However, as with technical maturity, there is no side-by-side discussion of how complexity was assessed. Additional information on the complexity assessment would be useful.
- Finally, technical maturity is informed by experience elsewhere with similar materials. For the Hanford tank waste, the obvious analogy is the reprocessing waste at SRS. Indeed, the progress at SRS is a driver of Congress's interest in an assessment of alternative approaches for Hanford SLAW. SRS has used both vitrification and grouting, and Idaho National Laboratory (INL) has used steam reforming. Careful analysis of each of these experiences is essential to a thorough review of technical maturity—with the important caveat that success or failure elsewhere is unlikely

to be absolutely determinative of results at Hanford. For example, the composition of the vitrification feed stock at SRS was relatively uniform as compared to Hanford, and it is quite possible that each new batch at Hanford will have a different composition that will require individual adjustment. Moreover, the sheer complexity of the vitrification system operations mandates a lower technical maturity level than is currently projected. Likewise, the difficulties that steam reforming have encountered with INL's calcined waste may suggest a fundamental difficulty with the technology, or after careful analysis, may be less relevant to Hanford's waste or may be, in effect, the pilot phase of the technology that enables problems to be identified and resolved. In sum, technical maturity will be usefully informed by other, similar experiences, but will require careful analysis to assess.

How Will Each Waste Form Perform in Isolating Constituents of Concern?

The performance of each waste form *as such* depends on the materials science of the incorporation, corrosion, and release mechanisms. There are sizable technical literatures on each waste form based on theoretical work, laboratory testing, and experience in the field. It is not clear how the FFRDC used the available literature in its analysis or how they modeled the waste form performance. The committee also reminds the reader of the earlier discussion in this review that the waste form is just one component of the waste disposal system that includes other barriers to radionuclide transport.

How Will Each Waste Form Perform Over Time in the Expected Disposal Environments?

The FFRDC team identified two disposal options, and suggested the possibility of a third option at the facility near Clive, Utah. These represent a range of geologic, hydrologic, and other qualities that will have an effect on the transport and fate of any radionuclides that the waste form fails to isolate permanently. For each waste form, the decision-maker needs to understand how each disposal system will function over time in providing a barrier to the release of key radionuclides to the accessible environment, including technetium-99 and iodine-129. The FFRDC essentially concludes that all of the waste forms and their associated waste disposal systems can meet regulatory requirements with varying degrees of pre-treatment that have not yet been determined.

**What Are the Estimated Costs? How Reliable Are They?
and How Do They Compare to Other Known Costs at Hanford?**

The FFRDC report has estimated costs for the alternatives (three treatment technologies, two disposal sites, five cases in all). The "bottom-line" results are in the summary tables of the FFRDC report (see Table 2, p. 14, and Table 10, p. 61) and in this review (see earlier section on "Consideration of Costs"); some discussion is in the main body of the report (Sec. 2.3); and more details are provided in Appendix H. However, the committee observes that additional cost uncertainty was characterized in the "semi-quantitative risk assessment," described in Appendix E, but finds that these uncertainties have not been incorporated into these cost ranges. The reported cost ranges, as wide as they are, therefore appear to be more certain than the FFRDC team has actually determined. In Chapter 2 of this review, the committee has some detailed comments on the cost analysis. To make the most (or best use) of the FFRDC report, the committee offers the following points:

- The cost estimates are based on technologies that, for the most part, have not yet been fully developed or deployed at Hanford, and are based on costs from similar technologies, and assuming ideal funding conditions (i.e., no funding caps) and no redirection during a multi-year effort. Thus, there are large attendant uncertainties, suggesting that costs could be much higher than estimated, but are unlikely to be much lower.

- The FFRDC cost estimates (see pp. 11-12 of the report and Figure 2-1 of this review) indicate that Hanford tank waste cleanup (Office of River Protection budget) funding would have to increase two to three times the current budget level of approximately $1.3 billion per year to support any of the alternatives analyzed. In addition to this, the budget for non-tank-related cleanup (Richland Office budget) at Hanford typically adds almost $1 billion per year to expenditures at Hanford.
- Operational idiosyncrasies in the treatment processes are an important consideration in estimating costs. The assumed feed stream rate and composition to the SLAW treatment facility is currently projected to be highly variable and thus requires the facility to operate at varying levels or even be in standby mode for significant periods. The vitrification process must be "always on" to keep the glass in the melter from solidifying, whereas grouting and FBSR can be readily shut down and restarted as the situation demands.

Do the Alternatives Meet Safety Requirements?

Whether an alternative meets safety requirements is a false dichotomy. Engineered systems can virtually always be made to meet safety requirements, as they are expected to be, albeit at a cost that may include very high expenses, system complexity, and occupational risks. Thus, while the report concludes that "A viable SLAW treatment and disposal option can be developed for each of the three technologies evaluated" (p. 15, first bullet), and "all three primary waste forms can meet applicable DOE requirements for disposal at IDF or WCS" (Sec. 4.1.5)—this is not an especially useful conclusion. The real issue, as noted in the section in Chapter 2 of this review on cost-benefit analysis, is the cost and risk of the additions and their alternatives.

Therefore, some caveats have to be attached to the claims that fall into the category of the "additional cost" mentioned in the previous paragraph, as follows:

- All three alternatives involving disposal at the IDF may require mitigation measures for iodine-129 in the secondary wastes to meet U.S. Environmental Protection Agency (EPA) groundwater requirements. This is not an issue for disposal at WCS because this site is not classified as having a drinking water aquifer.
- Mitigation measures to meet EPA land disposal restrictions (LDRs) for organic chemicals may be required for a grouted waste form. This is not an issue for high-temperature processes such as vitrification and steam reforming because the organic chemicals are destroyed.
- The grouting and steam reforming alternatives that involved disposing of the primary SLAW waste at the IDF would need to overcome the stated preference of the Department of Ecology for a glass waste form (see the subsection in Chapter 2 on the "As Good as Glass" Conundrum).

What Are the Schedules for Implementation and the Uncertainties?

The FFRDC report has estimated schedule ranges for the time period to construct and to ready for operations for the three treatment technologies. As summarized in the report's Tables 2 and 10, the estimated schedule ranges are 10-15 years for vitrification, 8-13 years for grouting, and 10-15 years for steam reforming. The report notes that: "The window to startup of any Hanford SLAW immobilization facility is 15 years (to 2034)." That is, according to the amended milestones of the Tri-Party Agreement, the WTP's HLW treatment should begin by 2034 and the SLAW treatment should start concurrently. As this review states in Chapter 2, the subsection on "Schedule," the FFRDC based these estimates on similar DOE capital projects. The ranges of the estimated schedules suggest that there are significant uncertainties in these estimates. Notably, the committee observes that additional schedule uncertainty was characterized in the "semi-quantitative risk assessment" described in Appendix E, but finds that these uncertainties have not been incorporated into the cost ranges that have some dependency on the duration of cleanup. The schedule ranges, as wide as they are, therefore appear to be more certain than the FFRDC team has actually determined.

The SLAW facility would be an integral part of the overall tank cleanup effort and, as a consequence, the nominal schedule for the SLAW is determined by its relationship to a number of other facilities and activities. The FFRDC adopted System Plan 8 (DOE-ORP, 2017) as its baseline for the schedule of major tank cleanup facilities and activities (see bullet points in the report on p. 12). For this baseline—which assumes that primary SLAW waste is vitrified—the planned start date of the SLAW operations would be 2034.

However, for the purposes of the FFRDC report—providing information to support a decision on the SLAW treatment alternative to be pursued—the more relevant information is the comparative time that would be required to bring each alternative from its current state of development to deployment in a facility ready to operate. The FFRDC developed information concerning the time required to bring each alternative to the point that it was ready for operation as part of its risk assessment using expert elicitation (see the report on p. 278 and Appendix E), which are summarized at the beginning of this section.

There are many attendant uncertainties in the schedule estimates, as follows:

- The estimates assume the tank cleanup program is fully funded as shown in Figure 2-1 of the report. Schedules will increase to the extent that the program is less than fully funded (see programmatic risks below).
- As noted above, the SLAW facility would be part of an integrated system of facilities and activities. To the extent that other facilities are delayed for whatever reason, this could affect the schedule for the SLAW treatment facility directly or by diverting funding.
- All three of the waste immobilization technologies per se (vitrification, grouting, steam reforming) require further research and development (R&D) to varying degrees. The time required to complete this R&D is unpredictable and, while this unpredictability was considered in the expert elicitation, it introduces uncertainty into the schedule. While grout may appear to be the most mature technology based on experience at SRS, vitrification and steam reforming have also been used in analogous settings. The differences among settings inevitably creates a level of uncertainty.
- Uncertainties remain concerning the extent to which pre-treatment will be needed to address LDR organic chemicals, LDR metals, iodine-129, and possibly other constituents. As described in the report (see Appendix A) most of the required processes will require further R&D to be ready for deployment.
- Regulatory issues introduce uncertainties into the schedules. Examples are permitting the IDF for disposal of primary and secondary treated LAW wastes, the acceptability of waste forms other than glass for disposal in the IDF, and the continued acceptability of the SLAW wastes for transport to and disposal at WCS.

The committee notes that the schedule uncertainties are likely to be biased toward being longer rather than shorter, i.e., do not count on events that would significantly reduce the schedule. The report briefly addresses schedule urgency, i.e., when decisions have to be made on which SLAW alternative to pursue. The FFRDC's view on p. 22 of the report is: "For some [alternatives], the required time for construction and startup require an immediate start to allow completion by the required startup date" with the target startup date being 2034 based on System Plan 8. This means that delays in selecting and pursuing some alternatives would result in a commensurate increase in the startup date.

What Are the Major Programmatic Risks?

This question addresses major programmatic risks, which are defined as non-technical risks outside the control of the DOE program. In the committee's view, the major programmatic risks are:

- **Funding needs:** The annual funding needs to develop, design, and build SLAW facilities, plus the future annual costs for the other components of Hanford tank waste cleanup, are estimated by the

FFRDC to increase from the current approximately $1.3 billion per year to more than $4.5 billion per year (see p. 11 in the report). This is due to the simultaneous capital costs to complete the WTP, build the SLAW facilities, and build tank farm infrastructure to deliver wastes to the WTP. While there are significant uncertainties in the magnitude of the increase, it is clear that a substantial and possibly unrealistic increase in annual spending would be required. The cost estimates shown assume that the LAW is treated by vitrification, which is the most expensive of the three treatment alternatives. Treatment by grouting or FBSR could reduce the annual cost requirements through 2034 somewhat, but the SLAW construction cost is estimated by the FFRDC to be a significant fraction of the total annual spending requirements. The committee estimates the peak annual expenditure might be reduced by approximately $0.5 billion per year if the least expensive treatment option (grouting) were adopted. Building the necessary facilities sequentially could lower the peak funding requirements but at the cost of substantially increasing the duration and life-cycle cost of Hanford tank cleanup, as well as the increased chance of failures in tanks that are already beyond their design lifetime. Notably, the funding requirement profile in the FFRDC report does not include the annual cleanup cost for the Hanford site's other waste legacies, such as decontamination and decommissioning of buildings, waste burial ground cleanup, and subsurface plume management, which has typically been about $1 billion per year.[1]

- **Waste disposal impediments:** The SLAW facility plans to produce two major immobilized wastes: the SLAW in the form of glass, grout, or a steam reformed product; and grouted secondary wastes. Currently, the SLAW glass is planned to be disposed of in the IDF, and grouted SLAW and steam reformed SLAW could be disposed of at the IDF or WCS. IDF disposal is planned for grouted secondary waste generated during vitrification of the primary LAW at the WTP and the SLAW, although this grouted waste could ultimately be sent to WCS or elsewhere. However, there are existing or potential impediments to any of these plans:

  WCS is presently an operating waste disposal site that has waste acceptance criteria approved by the state of Texas. Although there are no major technical or safety issues regarding transportation to WCS, there is the potential for stakeholders in Texas or along transportation routes from Hanford to Texas to block the large-scale shipments or disposal of the waste by WCS. Thus, the committee believes that it would benefit DOE to address these stakeholder concerns early in the project.

  The IDF, a disposal facility planned for Hanford-treated SLAW and secondary waste, is presently not accepting any wastes. The IDF safety analyses and related documentation are based on vitrified SLAW and grouted secondary wastes. However, the Department of Ecology has not issued the permits required for either of these wastes. Furthermore, in multiple public meetings during the course of this study, Department of Ecology representatives have indicated resistance to considering any waste form other than glass for the SLAW, based on their belief that DOE committed to a glass waste form for the SLAW many years ago. (See the subsection on the "As Good as Glass" Conundrum in Chapter 2 of this review for details on the Department of Ecology's most recent views.) This situation poses two impediments. The first is that primary and secondary SLAW cannot be disposed of at the IDF until the permits are issued. The second is that the Department of Ecology could decline to issue permits if decision-makers choose to treat the SLAW by grouting or FBSR. In either case, the SLAW facility would not be able to operate. Notably, the first impediment would also affect the operation of the WTP, which is planned to send vitrified LAW and grouted secondary wastes to the IDF.

Programmatic risks also include some factors outside the scope of or are not explicitly mentioned in the congressional mandate in Sec. 3134 that would affect the selection of a technology and waste form. These include:

[1]However, in the current budget cycle, this amount has dropped to about $800 million.

- The increased chance of tanks failing (all 149 single-shell tanks have exceeded their design life);
- DOE's proposed reinterpretation of the definition of the HLW waste could change the SLAW size and performance requirements by altering the feed volume and composition depending on how the reinterpretation is implemented; and
- DOE has also proposed expanding the Test Bed Initiative, which would have the next phase involve grout treatment of 2,000 gallons of LAW and shipment to WCS (the first phase involved a proof of concept treatment of 3 gallons of LAW that was sent to WCS) (DOE-EM, 2018).

Are There Opportunities for Innovation in Hybrid SLAW Treatment Approaches?

Even during the pendency of the FFRDC report and committee review, several new opportunities for managing SLAW came to light, including the potential of the WCS facility near Andrews, Texas, and the EnergySolutions facility near Clive, Utah. These opportunities remind decision-makers that technologies and waste management options will not stand still during the decades that managing the Hanford tank waste will take, even under the most optimistic estimates. While the length of the cleanup period is undoubtedly frustrating, it also offers opportunities to learn from experience and new information to improve the effectiveness, efficiency, and possibly the speed and cost of the Hanford tank waste management effort.

In this connection, the committee observes that some of the treatment approaches may be considered to be hybrids even though only a single treatment (immobilization) process is involved. For example, treatment by grouting may require pre-treatment (processing) to destroy or remove organic chemicals to meet EPA land disposal restrictions, and additional pre-treatment to remove strontium may be cost-effective if the SLAW disposal at WCS or at the EnergySolutions facility is pursued. However, in this section, the focus is on hybrid treatment approaches involving multiple immobilization technologies, and the combination of treatment and pre-treatment options is addressed in earlier subsections on Broader Waste Management System and The Major Role of Pre-Treatment.

A hybrid approach to treating the SLAW would involve deploying more than one treatment alternative and routing a portion of liquid SLAW (e.g., from a single tank) to the alternative that is most appropriate for that particular waste composition. Thus, the advantage of hybrid approaches is that they are better able to accommodate the highly variable waste compositions in the Hanford tanks (see discussions of variability on pp. 11, 37, 93, and 109 of the FFRDC report), perhaps by routing wastes containing higher concentrations of hazardous or difficult-to-process wastes to a low-capacity but relatively expensive treatment (e.g., more extensive pre-treatment and vitrification) process and lower-hazard wastes through a high-capacity but relatively inexpensive process (e.g., grouting).

The disadvantage of a hybrid approach is that more than one process must be developed, built, and operated, which means increased system complexity as well as increased cost in what may be a cost-constrained situation. More extensive and detailed analyses based on more accurate knowledge of the composition of the wastes in the various Hanford tanks would be needed to provide adequate information to decide whether such approaches should be pursued and which alternatives to include in the hybrid approach.

It is a truism, but also an important truth, that the perfect can become the enemy of the good. The search for the one best solution can take on a life of its own, excluding other important practical or corollary considerations. This observation has particular force when the relevant timeline is very long, as at Hanford, where the most optimistic cost estimates run to many billions of dollars in capital and operating costs and the most optimistic scenarios for tank waste remediation stretch for decades. Even if one were to identify the perfect waste treatment for the SLAW today, it may appear far less than perfect in a decade or less, so leaving DOE with a sub-optimal approach and an enormous stranded investment in that approach. For example, DOE and others may learn things about that technology that render it far from perfect, or even unworkable or otherwise unacceptable. Also, fundamental improvements or new technologies may be developed that render the chosen approach and its huge fixed costs outdated. In an environment that contains many substantial uncertainties, as described in Chapters 2 and 3 of this review, it is a virtual certainty that important new information will emerge—at least some of it from experience in implementing the very decisions made today—that will call into question or alter what appeared at one time to be the best decision.

Moreover, intervening external occurrences—lower funding, further tank failures that demand urgent management, problems with other parts of an extremely complex system (waste retrieval, the HLW and the LAW, the WTP vitrification in the WTP, and the WTP pre-treatment, to mention only the most obvious)—could similarly render the selected SLAW approach redundant, undesirable, sub-optimal, or even obsolete. The longer the time between selection and completion, the more likely such scenarios are to occur.

Indeed, one could take a lesson from the Manhattan Project itself. In order to assure the production of sufficient fissile material for an atomic bomb that could be deployed before an anticipated Nazi bomb, the Manhattan Project created facilities for gaseous diffusion and electromagnetic separation to produce highly enriched uranium, and nuclear reactors coupled with a series of chemical separation processes to produce plutonium. The development of parallel tracks for waste treatment at Hanford could minimize the impact of disappointing results, which is not an unknown phenomenon in the Environmental Management program or any complex and novel engineering program; it could also maximize the likelihood that cleanup will at least proceed at some level, which is of great importance in view of the risks of tank failure. It would be extremely unrealistic to think that the nature of the Hanford tank waste easily or inexpensively lends itself to multiple treatment options; on the other hand, the uncertainty of current technologies and the length of time of the management project suggest, respectively, the need for and the opportunity to experiment with parallel, sequential, or hybrid approaches.

Could Developments Outside the Scope of This Study Affect the Use of the FFRDC's Report and the Committee's Review?

The report notes on p. 13 and Sec. 1.4, subsection 7, that "numerous alternative concepts for tank waste processing at Hanford have been proposed in various levels of detail, which, if adopted, could impact the SLAW assumptions used to perform this analysis. Examples include:

- Direct Feed HLW,
- At-Tank Treatment Alternatives,
- HLW Definition Clarifications, [and]
- Improved LAW glass or process models.

Any of these examples would result in direct or indirect impacts on the assumptions in this analysis. It is not possible in this study to evaluate each potential future scenario as many of the scenarios have not been defined sufficiently well to allow a definitive impact evaluation. If these scenarios progress, the impact on the SLAW mission needs to be considered."

The committee observes that if any of these developments were to occur, the scope and scale of the SLAW treatment could be profoundly affected, and the need for treating the SLAW could be eliminated albeit at a cost of unknown magnitude and duration. The committee suggests that decision-makers view these possible developments as uncertainties to be considered when deciding how to proceed with the SLAW treatment.

THE COMMITTEE'S RECOMMENDATIONS

Use the FFRDC Report as a Pilot or Scoping Study

Recommendation 1-1

The committee recommends that the "Preliminary Draft" FFRDC report reviewed by the committee (dated April 5, 2019) be accepted as a pilot or scoping study for a full comparative analysis of the SLAW treatment alternatives, including:

- Vitrification, grouting, and steam reforming as treatments for the SLAW;
- Pre-treatment to remove iodine-129, technetium-99, and other radionuclides (e.g., selenium-79) to ensure that regulations are met or reduce cost, and pre-treatment to assure that the waste product meets land disposal requirements;
- Pre-treatment of strontium-90, if it is not removed during the cesium-137 pre-treatment process; and
- Disposal at the IDF, WCS, and (possibly) the EnergySolutions facility.

The draft report should either be substantially revised and supplemented (though the committee understands that the FFRDC team's funding may not permit this), or be followed by a more comprehensive analysis effort and associated decisional document, which needs to involve the decision-makers or their representatives.

Organize the Report or Decisional Document Around Four Interrelated Areas

Recommendation 2-1

The final FFRDC report or follow-on decisional document should provide technical data and analysis to provide the basis for addressing four interrelated areas, as follows:

(a) Selection of a technology that will produce an effective waste form. This has two parts:

- The treatment (immobilization) technology:
  - How well will it work? Is the technology well understood, tested or used under real-world conditions, dependent on other technologies, or relatively simple?
  - What types and volumes of secondary waste are created by each technology?
  - What is the lifetime cost and duration and uncertainties therein?
  - What are the risks (e.g., programmatic and safety) and uncertainties therein?
- The waste forms and associated disposal sites:
  - How effective is each waste form in immobilizing the waste (e.g., the materials science of the incorporation, corrosion, and release processes) and over what time periods?
  - What is their performance under the expected disposal conditions (e.g., release from the disposal facility and transport through the geosphere to a receptor)?
  - How do the waste form performances actually differ? This goes further than simply demonstrating compliance, but rather demonstrates an understanding of how the waste forms and disposal environments actually interact.

(b) Selection among available disposal sites. The report describes the IDF and WCS, and it briefly mentions the EnergySolutions facility near Clive, Utah. Selection requires an understanding of how each site will "work" over time in providing a barrier to the release and migration rate of key radionuclides, especially and specifically technetium-99 and iodine-129.

- What is the role of the hydrogeology at each site (the IDF and WCS) in preventing/slowing radionuclide release and migration?
- How might the disposal facility design be modified to enhance the performance of each waste form?

Important site related-issues include regulatory compliance, public acceptance, cost, safety, expected radiation dose to the maximally exposed individual over time, and differences among the disposal environments.

(c) Determining how much and what type of pre-treatment is needed to meet regulatory requirements regarding mobile, long-lived radionuclides and hazardous chemicals, and possibly to reduce disposal costs. The congressional charge specifically mentions technetium-99 and iodine-129, but other long-lived radionuclides, such as selenium-79, may be relevant. The analysis should consider both:

- Leaving the technetium (Tc), iodine (I), and other long-lived radionuclides in the waste form for the SLAW, with possible use of enhanced engineered barriers such as getters, which are added materials that can better retain the contaminants of concern; and
- Removing the Tc and I (and possibly other radionuclides) to create a new waste stream with its own (and possibly different) form of immobilization and final disposition, including incorporating it into the separate vitrified HLW stream.

(d) Other relevant factors. Other factors that would affect the selection of a SLAW treatment alternative include:

- The costs and risks of delays in making decisions or funding shortfalls in terms of additional resource requirements and the increased chance of tank leaks or structural failures over time and the need to address the consequences (notably, all 149 single-shell tanks have exceeded their design life and the 28 double-shell tanks will have exceeded their design life before the waste is slated to be removed);
- DOE's proposed reinterpretation of the definition of HLW waste could change the SLAW size and performance requirements by altering the feed volume and composition depending on how the reinterpretation is implemented;
- Thorough consideration of the experience of other DOE sites (e.g., the SRS) and relevant commercial facilities; and
- Outcomes of DOE's proposed Test Bed Initiative, the second phase of which would have involved (and perhaps still could involve) grout treatment of 2,000 gallons of LAW and shipment to WCS (the first phase involved a proof of concept treatment of 3 gallons of LAW that was sent to WCS and completed in December 2017). The future of the second phase of the Initiative is now in doubt due to DOE's withdrawal in late May 2019 of the state permit application.

Need Direct Comparisons of Alternatives to Aid Decision-Making

Recommendation 3-1

The analysis in the final FFRDC report and/or a comprehensive follow-on decisional document needs to adopt a structure throughout that enables the decision-maker to make direct comparisons of alternatives concerning the criteria that are relevant to the decision and which most clearly differentiate the alternatives.

Consideration of Parallel Approaches

Recommendation 4-1

The FFRDC report could also provide the springboard for serious consideration of adopting an approach of multiple, parallel, and smaller scale technologies, which would have the potential for:

a. Faster startup to reduce risks from tank leaks or structural failures if adequate funding is available to support parallel approaches;
b. Resilience through redundancy (like the parallel uranium enrichment and plutonium separation methods during the Manhattan Project);

c. Taking positive advantage of the unavoidably long remediation period to improve existing technologies and adopt new ones; and
d. Potentially lower overall cost and program risk by creating the ability to move more quickly from less successful to more successful technologies, with less stranded cost in the form of large capital facilities that are inefficient or shuttered before the end of their planned lifetime.

Appendix A

References

Cotton, F.A., G. Wilkinson, C.A. Murillo, and M. Bochmann. 1999. *Advanced Inorganic Chemistry*, 6th ed. New York: John Wiley and Sons.

Croff, A.G., and S.L. Krahn. 2015. A Simple Improved Measure of Risk from a Geologic Repository. Proceedings of the 15th International High-Level Radioactive Waste Conference, Charleston, South Carolina, April 12-16, 2015.

Darab, J.G., and P.A. Smith. 1996. The chemistry of technetium and rhenium species during low-level radioactive waste vitrification. *Chemistry of Materials* 8(5):1004.

DNFSB (Defense Nuclear Facilities Safety Board). 1990a. DNFSB Recommendation 90-3, "Future Monitoring Programs at Hanford's HLW Tanks." *Federal Register* Notice Vol. 55, No. 62, March 30, 1990.

DNFSB. 1990b. DNFSB Recommendation 90-7, "Implementation Plan for Recommendation 90-3 at the Department of Energy's Hanford Site, WA." *Federal Register* Notice Vol. 55, No. 202, October 18, 1990.

DOE (U.S. Department of Energy). 1988. *Disposal of Hanford Defense High-Level, Transuranic, and Tank Waste, Hanford Site, Richland, Washington*. Record of Decision (ROD) for DOE/EIS-0113, April 8, 1988.

DOE. 2011a. *Technology Readiness Assessment Guide*, DOE G 413.3-4A, September 15, 2011.

DOE. 2011b. *Radioactive Waste Management Manual*, DOE M 435.1-1, Change 2.

DOE. 2013. *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington*. Record of Decision. *Federal Register* Notice Vol. 78, No. 240, December 13, 2013.

DOE-EM (U.S. Department of Energy's Office of Environmental Management). 2018. Hanford Test Bed Initiative. Fact Sheet and FAQ. July 2018.

DOE-ORP (U.S. Department of Energy's Office of River Protection). 2017. *River Protection Project System Plan*, Revision 8, ORP-11242, Prepared for the U.S. Department of Energy's Assistant Secretary for Environmental Management, October 2017.

Dunning, D. 2016. History of Vitrification at Hanford. Presentation to Oregon Hanford Cleanup Board. May 16, 2016.

Fuhrmann, M., and A.L. Schwartzman. 2008. Corrected K_d values for selenium. *Health Physics* 94(2):192.

GAO (U.S. General Accounting Office). 1991. *Nuclear Waste: Pretreatment Modifications at DOE Hanford's B Plant Should Be Stopped*, Report to the Chairman, Environment, Energy, and Natural Resources Subcommittee, Committee on Government Operations, House of Representatives, GAO/RCED-91-165, June 1991.

GAO (U.S. Government Accountability Office). 2014. *Hanford Cleanup: Condition of Tanks May Further Limit DOE's Ability to Respond to Leaks and Intrusions*, Report to the Honorable Ron Wyden, U.S. Senate, GAO-15-40, November 2014.

GAO. 2015. *Hanford Waste Treatment: DOE Needs to Evaluate Alternatives to Recently Proposed Projects and Address Technical and Management Challenges*, Report to the Committee on Armed Service, U.S. Senate, GAO-15-354, May 2015.

GAO. 2017. *Nuclear Waste: Opportunities Exist to Reduce Risks and Costs by Evaluating Different Waste Treatment Approaches at Hanford*, Report to Congressional Addressees, GAO-17-306, May 2017.

Helton, J.C., C.W. Hansen, and C.J. Sallaberry. 2014. Expected dose for the nominal scenario class in the 2008 performance assessment for the proposed high-level radioactive waste repository at Yucca Mountain, Nevada. *Reliability Engineering and System Safety* 122:267-271.

Lee, P. 2018. "Overview of the 2017 IDF Performance Assessment for LAW," Washington River Protection Solutions, Public Meeting, Richland, Washington, February 28, 2018. http://dels.nas.edu/resources/static-assets/nrsb/miscellaneous/Hanford2/hanford8.pdf (accessed August 9, 2019).

Lukens, W., D.K. Shuh, N.C. Schroeder, and K.R. Ashley. 2004. Identification of the non-pertechnetate species in Hanford Waste Tanks, Tc(I)-carbonyl complexes. *Environmental Science & Technology* 38:229-233.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2018a. *Review of the Analysis of Supplemental Treatment Approaches of Low-Activity Waste at the Hanford Nuclear Reservation: Review #1*. Washington, DC: The National Academies Press.

NASEM. 2018b. *Review of the Draft Analysis of Supplemental Treatment Approaches of Low-Activity Waste at the Hanford Nuclear Reservation: Review #2*. Washington, DC: The National Academies Press.

Peterson, R.A., E.C. Buck, J. Chun, R.C. Daniel, D.L. Herting, E.S. Ilton, G.J. Lumetta, and S.B. Clark. 2018. Review of the scientific understanding of radioactive waste at the U.S. DOE Hanford Site. *Environmental Science & Technology* 52(2):381-396.

Roberson, J. 2001. Memorandum from Assistant Secretary for Environmental Management Jessie Roberson sent a memorandum to the Director of Office of Management, Budget, and Evaluation, Department of Energy. November 14, 2001.

Sattelberger, A.P. 2005. Technetium Compounds. In *Multiple Bonds Between Metal Atoms*, 3rd ed. F.A. Cotton, C.A. Murillo, and R.A. Walton, editors. New York: Springer. Chapter 7.

Schroeder, N.C., S.D. Radzinski, K.R. Ashley, A.P. Truong, and P.A. Sczcepaniak. 1998. Technitium Oxidation State Adjustment for Hanford Waste Processing. In *Science and Technology for Disposal of Radioactive Tank Wastes*, W.W. Schulz and N.J. Lombardo, editors. New York: Plenum Press. P. 301.

Sheppard, M., and D.H. Thibault. 1990. Default soil solid/liquid partition coefficients, K_ds, for four major soil types: A compendium. *Health Phys*ics 59:471-482.

WRPS (Washington River Protection Solutions). 2018. "The Tanks." https://wrpstoc.com/tank-operations/the-tanks (accessed June 12, 2019).

Appendix B

Executive Summary from the Federally Funded Research and Development Center's Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation

INTRODUCTION

Section 3134 of the National Defense Authorization Act for Fiscal Year 2017 (NDAA17) stipulates that a Federally Funded Research and Development Center (FFRDC) team conduct an analysis of technologies for treating and solidifying what is generally called "Supplemental Low Activity Waste" at the Department of Energy's (DOE's) Hanford Nuclear Reservation. The focus of the analysis is technical, and the FFRDC team is made up of technical experts in appropriate disciplines from the national laboratories. The NDAA17 also requires a concurrent review of the analysis by a committee of technical experts selected by the National Academies of Science, Engineering, and Medicine.

Hanford tank waste processing is currently planned to complete in 2063. Supplemental Low Activity Waste (SLAW) is treated Hanford liquid radioactive waste that cannot be treated and solidified by the currently planned first Low Activity Waste (LAW) systems within the Waste Treatment and Immobilization Plant (WTP) without extension of processing and tank storage durations. Under current planning expectations, the projected volume of SLAW (~54,000,000 gallons) will be similar to the volume of waste currently stored in the tanks due to the need to add water while removing the waste from the tanks, transferring it, and pretreating to remove key radionuclides. A decision on how to treat the SLAW is anticipated in the future and this report is expected to assist in those future decisions.

This report describes the FFRDC team's analysis results, which are intended to inform the decision-makers who will ultimately select approaches and technologies for the SLAW treatment.

SCOPE & CASES ANALYZED

The NDAA17 section 3134 calls for analysis of further processing of SLAW to remove long-lived isotopes such as technetium and iodine to immobilize with High Level Waste (HLW). It also calls for analysis of vitrification, grouting, and fluidized bed steam reforming and other approaches identified by the DOE for immobilizing LAW. These technologies are described in detail in the report. Each of these technologies was analyzed against the following parameters as specified in the NDAA:

- Risks related to treatment and final disposition
- Benefits and costs
- Anticipated schedules
- Regulatory compliance
- Obstacles that would inhibit pursuit of the approaches

The study developed numerous cases for initial analysis (including off-site out-of-state disposal) and ultimately simplified them to five. These five cases are:

1. Vitrification with On-site Disposal
2. Grouting with On-site Disposal
3. Grouting with Out-of-state Disposal
4. Steam Reforming with On-site Disposal
5. Steam Reforming with Out-of-state Disposal

Off-site disposal was considered because the geology and waste acceptance requirements of the off-site disposal facility are different from those of the on-site disposal facility and offer a disposal path for wasteforms that may be deemed unsuitable for on-site disposal.

The grout process is a room temperature process that is much lower temperature than the other technologies. Low temperature can be beneficial: heating waste to high temperature drives off volatile chemicals, creating liquid secondary waste and air emissions, which are not created in a low temperature process. However, low temperature treatment does not destroy all hazardous organic chemicals that are typically restricted from land disposal.

Without pretreatment, organics present in some of the waste will remain in the grout and some waste may be prohibited from disposal unless granted an exemption. Before grouting, pretreatment to remove or reduce organics would be required on the waste with high organic content. Thus, Pretreatment to remove or destroy these organics prior to grouting was conservatively assumed to be required for the low temperature alternatives.

Each of these five cases addresses primary and secondary wastes. Secondary waste is generated during treatment of primary waste and may include solid and liquid forms. For example, offgas treatment during vitrification produces liquid secondary waste that requires additional treatment and disposal. Grouting and steam reforming produce no liquid secondary waste from the offgas systems. Each technology will produce solid secondary waste.

The study found that disposal of secondary waste generated by these cases may be viable for off-site disposal. There is also potential for "combination" treatment and disposal scenarios, such as disposal of a primary waste on-site and off-site disposal of secondary waste. Such cases were not explored in detail.

HIGH LEVEL RESULTS

Table 1 includes a high level summary of results. There are many details, assumptions, and technical explanations behind this high level summary, which are addressed in this report.

CONCLUSIONS

The following conclusions resulted from the FFRDC analysis of the SLAW treatment technologies:

- A viable SLAW treatment and disposal option can be developed for each of the three technologies evaluated (vitrification, grouting, and steam reforming).
- For grouting, both on-site and out-of-state disposal will likely require treatment of select organics if found in the waste, and additional flowsheet studies will be needed to define that treatment.
- Removal of technetium and iodine is not needed for out-of-state disposal of grouted or steam reformed wasteforms.
- Technetium removal is not needed for on-site disposal of grouted or steam reformed wasteforms, assuming high performing grouted and steam reformed wasteforms.
- Iodine removal is not needed for on-site disposal of grouted or steam reformed wasteforms, assuming best performing grouted and high performing steam reformed wasteforms.
- Grouting and steam reforming offer significant cost benefits over vitrification. Grout is the least expensive option, with FBSR and vitrification options ranging 2.5 to 5× and 4 to 10× higher, respectively, which is comparable to recent Government Accountability Office reporting.

TABLE 1 High-Level Comparison of the Five Representative Cases for Immobilization of Hanford SLAW per the Analysis Criteria Specified in NDAA17

NDAA CRITERIA	VITRIFICATION CASE: DISPOSAL ON-SITE AT HANFORD	GROUTING CASE 1: DISPOSAL ON-SITE AT HANFORD	GROUTING CASE 2: DISPOSAL OUT OF STATE AT WASTE CONTROL SPECIALISTS (WCS)	STEAM REFORMING CASE 1: SOLID MONOLITH PRODUCT DISPOSAL ON-SITE AT HANFORD	STEAM REFORMING CASE 2: GRANULAR PRODUCT DISPOSAL OUT OF STATE AT WCS
SKS/OBSTACLES	• Difficult to build and operate because highly complex process	• Requires pretreatment of organics • Requires wasteform validation	• Requires pretreatment of organics	• Requires most technology maturation • Requires wasteform validation	• Requires most technology maturation
BENEFITS	• Similar to technology being built for first LAW	• Low integrated complexity • No liquid secondary waste	• Low integrated complexity • No liquid secondary waste	• No liquid secondary waste	• No liquid secondary waste
COST	~$20B to ~36B	~$2B to ~$3B	~$5B to ~$8B	~$6B to ~$12B	~$9B to ~$17B
YEARS NEEDED BEFORE STARTUP	10-15 years	8-13 years	8-13 years	10-15 years	10-15 years
REGULATORY COMPLIANCE	• Primary waste is compliant • Secondary waste may require Iodine mitigation	• Likely meets requirements after organics pretreatment • May require iodine mitigation	• Compliant following organics pretreatment	• Likely meets technical requirements	• Compliant

- A near-term decision on SLAW treatment technology is needed to meet DOE mission completion goals.
- Implementing any of the SLAW treatment technologies will exceed current funding levels when combined with required spending for all WTP and tank projects concurrent with SLAW treatment.
- Secondary waste generated from vitrification will require additional wasteform development and treatment capabilities.

Several key aspects of this study may benefit from further verification and technical analysis to increase confidence in several cases. These include the following:

- Treatment of organics restricted from land disposal (on-site and off-site grout cases)
- Treatment of technetium and iodine (on-site grout case)
- Treatment of liquid secondary wastes (vitrification case)
- Performance of grouted waste forms (on-site grout case)
- Performance of steam reformed waste forms (on-site SR case).

It is clear from the analysis that increased levels of funding will be needed in all cases, based on the integration with other Hanford tank waste disposition efforts. It is important that a decision on the SLAW treatment technology (or a baseline/alternate) be made quickly and commencement of technical maturation be started without delay to allow the completion of a facility to treat the SLAW by the time the facility will be needed. If the SLAW facility is not ready when needed, the treatment of tank waste could be delayed, thus extending tank waste storage duration (and resulting in increased storage risks).

The remainder of the FFRDC report is intended to provide a deeper review of each analyzed case by defining it and explaining the risks and the areas recommended for further study and analysis.

Appendix C

Section 3134 of Fiscal Year 2017 National Defense Authorization Act

SEC. 3134. ANALYSIS OF APPROACHES FOR SUPPLEMENTAL TREATMENT OF LOW-ACTIVITY WASTE AT HANFORD NUCLEAR RESERVATION.

(a) IN GENERAL.—Not later than 60 days after the date of the enactment of this Act, the Secretary of Energy shall enter into an arrangement with a federally funded research and development center to conduct an analysis of approaches for treating the portion of low-activity waste at the Hanford Nuclear Reservation, Richland, Washington, that, as of such date of enactment, is intended for supplemental treatment.

(b) ELEMENTS.—The analysis required by subsection (a) shall include the following:

(1) An analysis of, at a minimum, the following approaches for treating the low-activity waste described in subsection (a):

(A) Further processing of the low-activity waste to remove long-lived radioactive constituents, particularly technetium-99 and iodine-129, for immobilization with high level waste.

(B) Vitrification, grouting, and steam reforming, and other alternative approaches identified by the Department of Energy for immobilizing the low-activity waste.

(2) An analysis of the following:

(A) The risks of the approaches described in paragraph (1) relating to treatment and final disposition.

(B) The benefits and costs of such approaches.

(C) Anticipated schedules for such approaches, including the time needed to complete necessary construction and to begin treatment operations.

(D) The compliance of such approaches with applicable technical standards associated with and contained in regulations prescribed pursuant to the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (42 U.S.C. 9601 et seq.), the Solid Waste Disposal Act (42 U.S.C. 6901 et seq.) (commonly referred to as the “Resource Conservation and Recovery Act of 1976”), the Federal Water Pollution Control Act (33 U.S.C. 1251 et seq.) (commonly referred to as the “Clean Water Act”), and the Clean Air Act (42 U.S.C. 7401 et seq.).

(E) Any obstacles that would inhibit the ability of the Department of Energy to pursue such approaches.

(c) REVIEW OF ANALYSIS.—

(1) IN GENERAL.—Concurrent with entering into an arrangement with a federally funded research and development center under subsection (a), the Secretary shall enter into an arrangement with the National Academies of Sciences, Engineering, and Medicine to conduct a review of the analysis conducted by the federally funded research and development center.

(2) METHOD OF REVIEW.—The review required by paragraph (1) shall be conducted concurrent with the analysis required by subsection (a), and in a manner that is parallel to that analysis, so that the results of the review may be used to improve the quality of the analysis.

(3) PUBLIC REVIEW.—In conducting the review required paragraph (1), the National Academies of Sciences, Engineering, and Medicine shall provide an opportunity for public comment, with sufficient notice, to inform and improve the quality of the review.

(d) CONSULTATION WITH STATE.—Prior to the submission in accordance with subsection (e)(2) of the analysis required by subsection (a) and the review of the analysis required by subsection (c), the federally funded research and development center and the National Academies of Sciences, Engineering, and Medicine shall provide to the State of Washington—

(1) the analysis and review in draft form; and

(2) an opportunity to comment on the analysis and review for a period of not less than 60 days.

(e) SUBMISSION TO CONGRESS.—

(1) BRIEFINGS ON PROGRESS.—Not later than 180 days after the date of the enactment of this Act, and every 180 days thereafter until the materials described in paragraph (2) are submitted in accordance with that paragraph, the Secretary shall provide to the congressional defense committees a briefing on the progress being made on the analysis required by subsection (a) and the review of the analysis required by subsection (c).

(2) COMPLETED ANALYSIS AND REVIEW.—Not later than two years after the date of the enactment of this Act, the Secretary shall submit to the congressional defense committees the analysis required by subsection (a), the review of the analysis required by subsection (c), any comments of the State of Washington under subsection (d)(2), and any comments of the Secretary on the analysis or the review of the analysis.

(f) Limitations.—

(1) Secretary of energy.—This section does not conflict with or impair the obligation of the Secretary to comply with any requirement of—

(A) the amended consent decree in Washington v. Moniz, No. 2:08-CV-5085-RMP (E.D. Wash.); or

(B) the Hanford Federal Facility Agreement and Consent Order.

(2) State of Washington.—This section does not conflict with or impair the regulatory authority of the State of Washington under the Solid Waste Disposal Act (42 U.S.C. 6901 et seq.) (commonly referred to as the "Resource Conservation and Recovery Act of 1976") and any corresponding State law.

Appendix D

Statement of Task

The National Academies of Sciences, Engineering, and Medicine will review the analysis carried out by the U.S. Department of Energy's Office of Environmental Management (DOE-EM) selected Federally Funded Research and Development Center (FFRDC) on approaches for supplemental treatment of low-activity waste at the Hanford Nuclear Reservation. The review will evaluate the technical quality and completeness of the following:

1. Methods used to conduct the risk, cost-benefit, schedule, and regulatory compliance assessments and their implementation;
2. Waste conditioning and supplemental treatment approaches considered in the assessments, including any approaches not identified by DOE-EM;
3. Other key information and data used in the assessments; and
4. Results of the assessments, including the formulation and presentation of conclusions and the characterization and treatment of uncertainties.

The review will be carried out concurrently with the FFRDC's analysis with opportunities for input from the Washington State Department of Ecology, other principal Hanford stakeholders, and members of the public. The study will produce up to four review reports with findings and recommendations. The first report will focus on study charges 1-3; the second report will focus on study charge 4; the third report will provide the committee's overall assessment; and the fourth report will provide a summary of public comments on the third committee report and the committee's views, if any, on these comments and whether they change any of the findings or recommendations in that report.

Appendix E

Presentations at the Committee's Information-Gathering Meetings and List and Summary of Comments Received During the Public Comment Period

PUBLIC MEETING #1: WASHINGTON, DC, DECEMBER 12-13, 2017

Invited Presentations

- *Congressional Perspectives on the Tasking,* Jonathan Epstein, professional staff member, Senate Armed Services Committee
- *Overview of the Department of Energy-Environmental Management (DOE-EM)'s Program and Perspective on the Committee's Tasking*, Betsy Connell, Director, EM Regulatory, Intergovernmental, and Stakeholder Affairs
- *DOE's Office of River Protection (DOE-ORP): Program Scope and Status*, Delmar Noyes, Assistant Manager WTP Start-Up, Commissioning, and Integration, DOE-ORP
- *Presentations by members of the Federally Funded Research and Development Center (FFRDC) Team, led by Savannah River National Laboratory (SRNL)*, Bill Bates, project leader, SRNL, with Michael Stone, SRNL, and Thomas Brouns, Pacific Northwest National Laboratory
- *Perspective Regarding Congressional Interests about Cleanup at the Hanford Site*, David Bearden, Congressional Research Service
- *Perspective from Government Accountability Office's Reports on Treatment Options for Low-Activity Waste at the Hanford Site*, David Trimble and Nathan Anderson, U.S. Government Accountability Office
- *Independent Assessment of Challenges Concerning Cleanup at the Hanford Site*, Robert Alvarez, Senior Scholar, Institute for Policy Studies

Public Comments

- John Greeves, independent consultant
- Suzanne Dahl, Washington State Department of Ecology
- Geoff Fettus, Natural Resources Defense Council
- Ian Pegg, Vitreous State Laboratory, The Catholic University of America

PUBLIC MEETING #2: RICHLAND, WASHINGTON, FEBRUARY 28-MARCH 1, 2018

Invited Presentation

- *Introductory Remarks on DOE-ORP*, Jon Peschong, DOE-ORP

Presentations by Washington River Protection System's Contractors

- *Introduction*, Jason Vitali
- *Hanford Low-Activity Waste Historical Overview*, Dave Swanberg
- *System Plan 8 Baseline Case SLAW Sizing*, Jeremy Belsher
- *History of Supplemental LAW Treatment Reviews*, Dave Swanberg

- *History of Supplemental LAW Cost Comparison*, Dave Swanberg
- *Advanced Glass Program*, John Vienna
- *ILAW Glass Testing Program Status*, Elvie Brown
- *Overview of the 2017 IDF Performance Assessment for LAW*, Pat Lee
- *Radioactive Waste Test Bed Initiative*, Stephanie Doll
- *Cementitious Waste Form Formulation and Testing Status*, Dave Swanberg

FFRDC Team's Presentations

- *Introduction to Study and Lines of Inquiry Table and Schedule Overview*, Bill Bates (SRNL)
- *Process Flowsheet Overview and Feed Vector Overview*, Michael Stone (SRNL)
- *Baseline and Vit Flowsheets and Preliminary Technical Readiness Levels (TRLs)*, Alex Cozzi (SRNL)
- *Grout Flowsheets and Waste Forms and Preliminary TRLs*, George Guthrie (Los Alamos National Laboratory)
- *Steam Reforming and Waste Forms and Preliminary TRLs*, Nicholas Soelberg (Idaho National Laboratory)
- *Technologies Considered and Not Included*, Thomas Brouns (Pacific Northwest National Laboratory)
- *Disposal Facilities Overview, Waste Acceptance Criteria, and Transportation*, John Cochran (Sandia National Laboratories)
- *Analytic Approach to Risk*, Thomas Brouns
- *Cost Estimating Methodology*, Frank Sinclair (SRNL)
- *Wrap Up*, Bill Bates

Stakeholders' Presentations

- Alex Smith, Washington State Department of Ecology
- Dave Bartus, U.S. Environmental Protection Agency Regional Office
- Ken Niles, State of Oregon Department of Energy
- Susan Leckband, Chair, Hanford Advisory Board
- David Reeploeg, Vice President, Tri-City Development Council (TRIDEC)
- Pam Larsen, President, Hanford Communities
- Matthew Johnson, Confederated Tribes of the Umatilla Indian Reservation (CTUIR)

Public Comments

- Paul Flaherty, CHC Consulting, LLC, who made an oral presentation and submitted a written comment on behalf of Knauf Insulation
- Vince Panesko, Retired from the Hanford Site
- Don Alexander, Retired from DOE

Submitted Written Comments at the Public Meeting

- John Vienna, Pacific Northwest National Laboratory
- John Williford, Chrysalis Technology Group, Ltd.
- Tom Carpenter, Hanford Challenge

Submitted Written Comments to the National Academies of Sciences, Engineering, and Medicine
Darryl Siemer, a consulting scientist who is retired from the Idaho National Laboratory, submitted a number of comments via e-mail.

PUBLIC MEETING #3: RICHLAND, WASHINGTON, JULY 23-24, 2018

Invited Presentations
Committee Members' Presentations

- Observations from the committee's Hanford Site tour during the morning of July 23, 2018, John S. Applegate (chair)
- Observations by two committee members and study director of the FFRDC's expert elicitation on May 1-3, 2018, Anne E. Smith (member)

Stakeholder Presentation

- *Agency's Comments on the First FFRDC Draft Report and the Committee's First Review Report*, Alex Smith, Washington State Department of Ecology

FFRDC Team's Presentations

- *FFRDC Team Overview*, Bill Bates (SRNL)
- *Baseline, Feed Vector, Uncertainties*, Michael Stone (SRNL)
- *Analysis Approach*, Tom Brouns (Pacific Northwest National Laboratory)
- *Base and Variant Case Overview*, Michael Stone
- *Pretreatment Approaches*, Michael Stone
- *"Other" Considerations*, Tom Brouns
- *Vitrification Cases*, Alex Cozzi (SRNL)
- *Grout Cases*, George Guthrie (Los Alamos National Laboratory)
- *Steam Reforming Cases*, Nick Soelberg (Idaho National Laboratory)
- *Transportation and Disposal Site Considerations*, Paul Shoemaker (Sandia National Laboratories)
- *Estimate Methodology and Results*, Frank Sinclair with William "Gene" Ramsey (SRNL)
- *Analysis Results*, Sharon Robinson (Oak Ridge National Laboratory)
- *Summary*, Bill Bates

Stakeholder Presentation

- Alfrieda Peters, Yakama Nation

Public Comment

- Mark Hall, Hanford Solutions and a former DOE employee

Submitted Written Comment to the National Academies

- Tom Galioto, long-term Tri-Cities resident, a former Hanford employee, and a current member of the Environmental Management Site Specific Advisory Board (EM SSAB) at Hanford that advises DOE on cleanup activities; he contacted the committee in his capacity as a private citizen and not as a member of the advisory board.
- John F. Williford, President, Chrysalis Technology Group, Ltd., Richland, Washington, submitted on July 22, 2018, a report that he wrote and titled, "Commercial Viability Assessment of Iron Phosphate Glass for Immobilization of Low-Activity Nuclear Waste for MO-SCI Corporation," Chrysalis Technology Group, Ltd., December 8, 2002; he also submitted an opinion piece that proposes the idea of "treating all the tank waste without separation by vitrification." The opinion piece's citation is John F. Williford, "Is there a better way to treat tank waste?" *Tri-City Herald*, June 21, 2015.

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PUBLIC MEETING #4: RICHLAND, WASHINGTON, NOVEMBER 29-30, 2018

Invited Presentations
Committee Member's Presentation

- *Observations on the FFRDC Working Meeting in Albuquerque, New Mexico, on October 16-17, 2018*, Rachel Detwiler, Committee Member

Stakeholders' Presentations

- *Washington State Department of Ecology's Perspective on the Most Recent FFRDC's Draft Report and the Committee's Review Report*, Suzanne Dahl and Alex Smith, Washington State Department of Ecology
- *Perspective from Hanford Advisory Board's Chair on the Recent Report*, Susan Leckband
- *Perspective from the Hanford Communities' Executive Director on the Recent Report*, Pam Larsen
- *Perspective of the Nez Perce Tribal Nation*, Jack Bell, Director of Environmental Restoration and Waste Management Program

FFRDC Team's Presentations

- *Introduction of FFRDC Team Study*, Bill Bates (SRNL)
- *Process Overview and Major Assumptions/Bases*, Michael Stone (SRNL)
- *Analysis Approach*, Tom Brouns (PNNL)
- *Pertinent Pretreatment Technologies and Maturities*, Robert Jubin (ORNL)
- *Vitrification Case*, Alex Cozzi (SRNL)
- *Grout Cases 1 and 2*, George Guthrie (LANL)
- *Steam Reforming Cases 1 and 2*, Nick Soelberg (INL)
- *On-site Disposal Performance Evaluation (IDF)*, Tom Brouns
- *Off-site Transportation & Disposal (WCS)*, John Cochran (SNL)
- *Risk Analysis*, Steve Unwin (PNNL)
- *NDAA—Hanford Supplemental LAW Evaluation Cost Estimate Status*, William "Gene" Ramsey (SRNL)
- *Additional Discussion with the FFRDC Team*

PUBLIC MEETING #5: ATLANTA, GEORGIA, JANUARY 8, 2019

There were no formal presentations. The FFRDC team and the National Academies committee had a 3-hour long discussion about the FFRDC's incomplete draft report and next steps toward completing the report.

PUBLIC MEETING #6: KENNEWICK, WASHINGTON, MAY 16, 2019

Invited Presentations
Committee Member's Presentation

- *Independent Assessment of Science and Technology for the Department of Energy's Defense Environmental Cleanup Program*, John Plodinec, Vice Chair of the Committee on Independent Assessment of Science and Technology for the U.S. Department of Energy's Defense Environmental Cleanup Program.

Stakeholder Presentation

- *FFRDC Draft Report*, Suzanne Dahl, Section Manager of Tank Waste Treatment, Washington State Department of Ecology

FFRDC Team's Presentations

- *Introduction of FFRDC Team Study & Final Draft Report*, Bill Bates (SRNL)
- *Performance Evaluation (PE) Inputs &Overview*, Tom Brouns (PNNL)
- *Performance Evaluation Results*, Tom Brouns (PNNL)
- *FFRDC Conclusions*, Michael Stone (SRNL)
- Additional Discussion with the FFRDC Team

Public Comment

- Allyn Boldt, e-mailed submitted comment that was read at the public meeting.

PUBLIC MEETING #7: RICHLAND, WASHINGTON, OCTOBER 31, 2019

Comments received at this meeting from stakeholders and members of the public are included in the congressionally mandated comment period.

Invited Presentations
Committee Member's Presentation

- *Description of the Scope of the Committee's Final Task and Summary of the Main Findings, Recommendations, and Observations of the Committee's Review #3*, John S. Applegate, Committee Chair

FFRDC Team's Presentations

- *FFRDC Overview—Final Report on Analysis of Supplemental Treatment Approaches for Low-Activity Waste at the Hanford Nuclear Reservation*, Bill Bates (SRNL)
- *Evaluation of Supplemental Low-Activity Waste Treatment Options: Performance Evaluation and Other Options*, Thomas M. Brouns (PNNL)
- *Key Updates, Conclusions, & Areas for Further Study*, Michael Stone (SRNL)

Stakeholders' Presentations

- *Perspective from Tri-City Development Council (TRIDEC)*, David Reeploeg, Vice President, TRIDEC
- *FFRDC Draft Report & NAS Review #3*, Alex Smith, Program Manager, and Suzanne Dahl, Section Manager of Tank Waste Treatment, Washington State Department of Ecology
- *Perspective from the Hanford Communities and the Energy Communities Alliance*, Pam Larsen, Executive Director, Hanford Communities
- *Office of River Protection Glass Science Program*, Albert A. Kruger, Office of River Protection (presentation by invitation of the Executive Director of Hanford Communities)
- *Perspective from the Hanford Advisory Board*, Susan Leckband, Chair, Hanford Advisory Board
- *Perspective from Oregon Department of Energy*, Jeff Burright, Nuclear Waste Remediation Specialist, Oregon Department of Energy
- *Perspective of the Wanapum Tribe*, Rex Buck, Jr., Chief of the Priest Rapids Band

Public Comment

- *Perspective of the Yakama Nation*, McClure Tosch, Remediation & Restoration Specialist, Yakama Nation Fisheries

Appendix E

WRITTEN COMMENTS RECEIVED DURING THE COMMENT PERIOD FROM AUGUST 15, 2019, TO NOVEMBER 20, 2019

- Anonymous, as a final summary, the FFRDC should provide a qualitative, relative risk assessment of the viable treatment technologies over time, as compared to the increasing risk of potential tank ruptures and radioactive leaks to the subsurface. The NAS should review, comment, and recommend best future options for decision-makers to mitigate further environmental contamination at Hanford. This includes new tank construction to empty tanks that are high risk for rupture/leakage and treatment options that offer a quicker pathway for waste removal from tanks that are high risk for failure, August 19, 2019.
- Anonymous, asks if the study is surveying cancer incidence east and northeast of the plant over many years past; also expresses concern about rail transport through Hanford, August 28, 2019.
- Steven Fine, sent e-mailed comments on different dates; raises concern about whether the vitrification plant will be completed on time and if so, will it operate safely and effectively; cautions that "time is the enemy" and that further delays increase risks and that there is a chance for "a black swan event" happening such as a major flood or earthquake; asks to examine the options "in a total cost way"; emphasizes the Perma Fix technology that can treat low-activity waste as grout that can be shipped to WCS in Texas, September 3, 4, and 5, 2019.
- Anonymous, draws attention to the potential treatment of some waste streams including from the Effluent Management Facility and the Effluent Treatment Facility as commercial-treatment streams and that these "streams can contain significant ^{99}Tc and other isotopes. If processed as proposed, this waste would be transported as a liquid to a commercial facility in Richland ("Perma-Fix") which is within just a mile or two of local food processing facilities [as well as] local residential areas and schools"; would appreciate if the risks of this inside the city limits approach could be considered in comparison to grouting the effluent/wastes in the Hanford 200 Areas (where it belongs). The lesson here is from the contamination found at a local school in Portsmouth, Ohio, from DOE waste remediation of a gaseous diffusion facility"; raises concern about the new disposal dilemma posed by the plan to place cesium-137 in ion exchange columns; asks if the number of curies of iodine-129 is overcounted because of the multiple evaporation passes in the tank farms have resulted in iodine releases and whether it makes sense to salt with non-radioactive iodine to reduce the potential exposure to the public; asks that the "all-glass" approach at Hanford be reconsidered in light of the "proliferation of secondary wastes, brines, and effluents that must now be treated," September 4, 2019.
- Catherine Lee, expresses the position that the incomplete study does not yet provide the complete technical basis needed for a decision; asks that a final decision not be based on "least expensive" considerations but instead favor "most likely to contain radioactivity effectively for long periods of time"; in addition, asks for a decision to take into consideration what is acceptable for disposal outside of Washington state and notes that she is from Texas, September 5, 2019.
- Steve March, chair, and Dan Solitz, vice chair, Oregon Hanford Cleanup Board, who sent a letter dated September 3, 2019, which referenced a briefing and paper from the Oregon Department of Energy's staff (the National Academies also received that paper on August 14, 2019, and Jeff Burright of the Oregon Department of Energy presented about the topics of this paper to the committee at the public meeting on October 31, 2019; that paper is part of the record for the comment period); the main positions from the letter from the Oregon Hanford Cleanup Board are (1) Hanford tank wastes pose an inherent hazard to the Columbia River; (2) decisions about waste forms should proceed from an ethical foundation of precaution; (3) there remains significant uncertainty regarding the performance of a grouted waste form disposed of at Hanford; (4) removal of technetium-99 and iodine-129 from low-activity waste would make a grouted waste form safer and more feasible for Hanford; and (5) if these radionuclides stay in the LAW, vitrification appears to remain the option most likely to result in long-term safety if disposed of at Hanford.

- Geoff Daly, an engineer, mentions consideration of the syn-rock project that was applied to about 25,000 pounds of low and high activity waste products and that immobilized this material into "a fully vitrified mass" at Oak Ridge; asks that this and potentially other additional methods be considered and for Hanford's engineers to "think outside the box"; also suggests that Washington Department of Ecology should convene a public seminar to collect additional ideas, September 5, 2019.
- Anonymous, notes that the effort to recover from the loss of the WTP Pretreatment Facility, which was supposed to feed supplemental LAW, has resulted in a number of patchwork facilities that will create even more waste; also, no one should underestimate or gloss over the costs associated with high temperature process off-gas treatment; steam reforming off-gas, for example, will have similar design, safety, and cost issues as vitrification, September 9, 2019.
- Anonymous, expresses concern about the steam reforming facility being developed at Idaho National Laboratory that "has had both technical and project management failures, which are continuing"; cites as evidence the recent U.S. Government Accountability Office report on this facility (GAO-19-494); "would appreciate if the National Academies committee will consider the exponential savings that are possible by not having a technically complex process and by not having a high temperature off-gas process," September 17, 2019.
- Don Meyers, recommends (1) getting all the authors of the TPA together to revisit, evaluate, and update the existing very stringent TPA requirements, (2) planning how to meet those updated and more realistic requirements, sell the plan to Congress and obtain the needed time and funding to finish the cleanup, (3) retrieving high risk liquid wastes from tanks, basins, cribs, etc. with past, proven Hanford methods, i.e., sluicing and evaporating, (4) disposing of structures/solid waste volumes in place, (5) completing cleanup with funds separate from the WTP, October 1, 2019.
- Richard O. Zimmerman, retired Hanford safety professional, mentions that the Hanford site's railroad system is not cited in the FFRDC final draft report or in Review #3 and that there is a need to understand what are the applicable federal railroad regulations, October 4, 2019.
- FFRDC team's comments on Review #3, see Chapter 2 for the summary and committee's responses, October 10, 2019.
- Harry D. Harmon, Ph.D., retired nuclear processing consultant, mentions that bulk vitrification has not received much attention in the FFRDC's analysis and specifically cites GeoMelt's melters that have been treating nuclear and hazardous wastes since the 1990s and have produced more than 26,000 metric tons of glass for disposal in the United States and other countries; DOE's technical concerns from 2006, when a technical assessment of bulk vitrification was published, were that during the melting process, "some of the technetium in the waste feed deposits in the refractory material as a soluble salt. In the performance assessment, the salt has the potential to create a technetium peak in the groundwater concentration"; "Metal inclusions have been observed in the resulting glass product. It is unknown whether these inclusions have a deleterious effect on the long-term performance of the waste"; mentions that all three studied options have remaining technical issues; asks for the specific glass composition that was used for the FFRDC performance evaluation be described; supports Review #3's finding about learning valuable lessons and studying data in more depth from other sites, especially the Savannah River Site; points out that it is difficult to understand the bases for the schedules for implementation of the three technologies and that a schedule table with time required for technology development, design and construction, start-up, etc. would be helpful; add the Direct Feed LAW facility to the list of facilities that could affect future implementation of SLAW treatment; finally, points out the negative impact on the progress toward SLAW treatment by the frequent changes in direction which create further delays and increase costs, October 10, 2019.
- Tom Carpenter, executive director, Hanford Challenge, and Marco Kaltofen, Ph.D., engineering consultant to Hanford Challenge, wants "to be clear that Hanford Challenge considers Hanford's tank waste to be high-level waste as defined by the Nuclear Waste Policy Act"; expresses concern

that the cleanup "challenges tilts decision making towards faster, cheaper solutions at the expense of environmental protectiveness and human health and safety"; efforts to find alternatives to vitrification "have all ended with the conclusion that nothing proposed is 'as good as glass'"; "firmly believes that waste containing long-lived radioactive toxins that will take millions of years to decay should not be buried at Hanford above an aquifer that feeds into the Columbia River" and "that cost savings should not be the dominating factor that drives cleanup decisions … and can often be deceptive"; for example, "if further research shows that the getters are not guaranteed to confine the technetium-99 and iodine-129 in grout form and pretreatment is required to remove these radionuclides prior to putting it in grout form, those cost savings could quickly disappear"; expresses concern about DOE's "enthusiasm" for grout for SLAW, "despite the need for further research and development" and "seems premature to declare that there is a clear scientifically defensible path forward for grout … under the assumption that further study and research will confirm the best-case scenarios"; their technical concerns include: that "the grout form proposed by the FFRDC report is itself toxic and a potential threat to the environment"; "long-term integrity of grout is untested"; grouting "will not effectively bind residual high-level waste components such as iodine-129 and technetium-99"; "Hanford's climatic and soil environments are particularly harsh for grout monoliths"; "Grout performance and the rate of groundwater flow through the grout monolith is critically dependent on near-perfect, fracture-free, installation"; "Future use scenarios assume continuous institutional controls over the entire life of the project, including unrealistic restrictions on land uses"; "Climatic scenarios exclude dam failures, Columbia River flooding, concentrated rainfall events, glacial flooding/damming, and climate change-induced alterations in evapotranspiration/rainfall, all of which are plausible and even predictable events for this region," October 25, 2019.

- Paul Flaherty, CHC Consulting, LLC, expresses concern that Review #3 does not provide a clear determination that "the FFRDC performance evaluation has a poor technical basis for waste degradation model and mechanisms"; does not see that "any new technologies were identified or considered" by the FFRDC and is thus concerned about whether the FFRDC followed the congressional mandate; cautions that "the predicted degradation on the structural integrity of the landfill [IDF] will ultimately lead to adverse groundwater impacts" and "modeling variables should also consider daily operational activities during the active life of" the IDF "prior to capping of the landfill"; recommends considering the impacts of weather events on the structural integrity; also believes that the federal government should "provide post-closure integrity assurance into perpetuity"; mentions that at a previous public meeting he briefed the committee and the FFRDC team on a new vitrification technology that should be considered but that he "was never contacted by the FFRDC" despite providing his contact information; fully supports Recommendation 4-1 in Review #3, October 29, 2019.
- Julie Reddick, points out a potential risk that the ILAW flowsheet underestimates the volume of liquid secondary waste that will be produced; suggests that an unreliable water balance is a substantial uncertainty and risk, which should not be outside the scope of the task; the "add-on" cesium removal systems do not have disposal decisions approved by regulatory authority; "ETF is easily overwhelmed if liquid feed goes up. A flowsheet with the uncertainty in liquid volumes included is needed"; cites the GAO report *DOE and NNSA Should Improve Their Lessons-Learned Process for Capital Asset Projects*, GAO-19-25, December 2018; "The cost estimates in the FFRDC report are for only limited portions of the complete scope. The FFRDC report provides part of the picture, but does not examine the overall life cycle costs"; evaluate "the beyond the scope topics" for risk; there is a need for rebaselining of the waste treatment project using root cause analysis, which would meet the requirements of DOE Order 413.3B; expresses concern about tritium releases, October 29, 2019.
- Jean Wynn, opposes use of grout for Hanford's tank waste disposed of at Hanford; requests use of glass because of its long-term durability, October 29, 2019.

- Nancy Arbuckle, opposes putting Hanford's tank waste in grout; SLAW should have long-lived radionuclides removed and immobilized in glass; do not dispose of grouted SLAW at Hanford site, October 30, 2019.
- Steven Fine, "grouting is a misnomer for the process that Perma Fix would use"; "Once the neutralized state is reached, then the whole container that has been processed will be encompassed by a special concrete mixture, that folks like Hanford Challenge [have] simply addressed as grouting as if the product coming in would just be encompassed with grouting without extensive neutralization"; "Then the encapsulated sample would appropriately by rail car be shipped to WCS in Texas, a process that has been affirmed. This process would save some 15 to 20 billion dollars and cost less than 1/3 of what the vitrified low rad product would cost to process"; characterizes Hanford Challenge's opposition to the grouting process as "a scare tactic," October 30, 2019.
- Julie Reddick, follow-on to previous message in order to send a steam reforming technology report that "confirms that both tritium and carbon-14 are not abated, but are discharged in bulk up the stack in the steam reforming ventilation system," as shown on page 12 of THOR Treatment Technologies, LLC, *THOR Steam Reforming Process for Hazardous and Radioactive Wastes*, Technology Report, TR-SR02-1, Rev. 1, [undated], October 31, 2019.
- Gary A. Cooke, provides a link https://www.osti.gov/biblio/1523279 to an assessment of over 100,000 analyses of organic compounds in Hanford tank waste, concentrating on double-shell tank supernate. "It will be discussed in December's Cementitous Waste Technical Exchange at SRNL," October 31, 2019.
- Sandra Witherup Hankins, opposes putting Hanford's tank waste in grout; SLAW should have long-lived radionuclides removed and immobilized in glass; do not dispose of grouted SLAW at Hanford site, October 31, 2019.
- Robert V. Masterson, Ph.D., opposes use of grout for disposal at Hanford, expresses concern about safely storing long-lived radionuclides, October 31, 2019.
- Dan Solitz, expresses appreciation for the "diligent attention to this matter" and the quality of the meetings that he viewed via webinar; wants to know what is the "cost of mining a full failed tank and processing the tailings to meet a waste acceptance criteria"; also seems to him that "there is time, as it will take a while to formulate good as glass grout," October 31, 2019.
- James E. Strick, Professor, Dept. of Earth and Environment, Franklin and Marshall College, opposes putting Hanford's tank waste in grout; SLAW should have long-lived radionuclides removed and immobilized in glass; do not dispose of grouted SLAW at Hanford site, October 31, 2019.
- James P. Thomas, notes in his comment that he has "been involved with Hanford environmental issues since 1984" and that he is "currently writing a book on the history of Hanford's plutonium processing and the resulting environmental harm," opposes putting Hanford's tank waste in grout; "vitrification of the waste and deep geologic burial is the only way to adequately protect future generations," October 31, 2019.
- Patricia Janesh, Ph.D., M.P.H., opposes grout and believes that the "use of glass appears to be the most effective" treatment approach," October 31, 2019.
- Laura Feldman, opposes putting Hanford's tank waste in grout; SLAW should have long-lived radionuclides removed and immobilized in glass; do not dispose of grouted SLAW at Hanford site, October 31, 2019.
- Alexandra K. Smith, Program Manager, Nuclear Waste Program, Washington Department of Ecology (this is a summary of the Department of Ecology's submitted written comments, which address several of the same as well as additional themes presented by the in-person presentation by Suzanne Dahl at the public meeting on October 31, 2019), (1) staff of the Department of Ecology "appreciate the enormous body of information that underlies the scope of the FFRDC study, and acknowledge that it is virtually impossible for the FFRDC to address every issue for every audience in this report"; (2) "the greatest disappointment of this report was the terse discussion of pretreatment for Tc-99 and/or I-129 removal upstream of supplemental low-activity waste (SLAW) treatment …

[and] was perplexed that the study did not include an obvious alternative involving pretreatment, [in particular] an alternative with Tc-99 removal pretreatment using ion exchange resin, as described in Section 3.1.2.3 [of the FFRDC report], and separate waste stream management. That alternative, combined with enhanced grout with an iodine getter (e.g., layered bismuth hydroxides, in a Portland cement-based grout formulation) would eliminate the chemical competition to maintain a reducing environment to Tc-99 retention within an otherwise oxidizing environment"; (3) "While the research results for enhanced grout and ceramic waste form FBSR since the 2012 Tank Closure and Waste Management Environmental Impact Statement (TC&WM EIS) are encouraging, the State considers these two waste forms in the research and development stage … [and] still require additional development and long-term testing before they can be considered proven"; (4) "the figure in Appendix F [of the FFRDC report] presents the data in a way that makes it appear vitrified waste, rather than the secondary waste from the vitrification process, contributes most of the I-129 to groundwater. The State believes that this should be corrected. … since the 2012 TC&WM EIS it has been known that "some of the secondary waste would have to be treated with improved grout formulations. Vitrification alternatives analysis should not be unfairly penalized by treating the secondary waste with lesser performing grout"; (5) "while it may be possible to control future releases of chromium, nitrate, Tc-99, and I-129 from IDF (by controlling the waste forms, limiting [what] is disposed of in IDF, or both), there is little to no possibility of controlling the future release of [these contaminants] from waste already disposed of to the soils across the Hanford Site. These additional contributions are why the State is looking for results that are significantly lower than the EPA drinking water MCLs"; (6) "agree that the term ['as good as glass'] needs to be objectively defined. A detailed approach to this definition was developed in 2003 timeframe when the 'as good as glass' term was first coined and agreed to between Ecology and the United States Department of Energy (DOE). The State would welcome an opportunity to rekindle the discussion around a comprehensive working definition with DOE and DOE's selected technical community representatives"; (7) "would have appreciated it if the FFRDC had estimated the quantity of low activity waste that might require Land Disposal Restriction (LDR) pretreatment for LDR organics and LDR metals" and what are the fractional amounts of various types of waste considering the different potential waste forms that may need additional treatments to be compliant with LDR requirements; (8) Review #3 "appeared to advocate consideration of enhancing the disposal facility design to enhance the performance of each waste form.… If there is a proven basis for considering these kinds of disposal facility enhancements in relation to long term performance, (e.g., substantially greater than 1,000 years), the State asks that the Committee refer that basis. If there is none, the State asks that these comments be removed from the NAS's review"; (9) "The most significant new element that could change SLAW technology selection is the potential availability of an out-of-state commercial disposal facility, Waste Control Specialists (WCS) in Texas. The state of Washington is cautiously optimistic about the WCS facility and its potential as a disposal site for Hanford's SLAW"; (10) agree with the committee that the specifics on the Performance Evaluation "analysis were not transparent, and would require disclosure of more specific information prior to State acceptance"; (11) "concur with the Committee's comments regarding the consideration of risk in the FFRDC report" and particularly appreciated the comments that "the cost estimates did not include consideration of identified risks, e.g., increasing the estimate uncertainty range, and the risk induced by funding uncertainty" and that "the study does not consider the legal regulatory documents that would need to be changed and the cost and schedule risks if a technology other than vitrification is used"; (12) there might be significant delays—at least a decade—in the need for SLAW facilities because of the September 4, 2019, DOE notification that the High Level Waste (HLW) Facility and Pretreatment (PT) Facility could be delayed beyond the milestones contained in current version of a consent decree," the pending results of DOE's analysis of alternatives, discussions about the continued need for sludge washing, and the potential for Direct Feed LAW operations creating additional available tank volume in the time before startup of HLW processing; (13) "While this FFRDC study might be a valuable first stepping stone toward

selection of a SLAW treatment technology other than vitrification as a general proposition, it is not sufficient to be acceptable as the basis for selection of a SLAW treatment technology other than vitrification for on-site disposal. This is because the enhanced grout and FBSR waste forms have not yet proven to have long-term performance"; (14) "was heartened that NAS included the 'Considerations for Decision-Makers' in their review"; highlights that there has been one double-shell tank failure, AY-102, and three years were required to retrieve the contents; four more double-shell tanks are in similar condition; in addition, double-shell tanks' availability will further decrease during DFLAW operations and due to Tank Side Cesium Removal pretreatment; therefore, the state of Washington wants to avoid "any technology that will require additional research and development where possible, because the evidence is mounting that the existing tank infrastructure is running out of capacity and time," October 31, 2019.

- Pam Larsen, Executive Director, Hanford Communities (this is a summary of her submitted written remarks, which address the themes in her in-person presentation at the public meeting on October 31, 2019), points out that the parties of the Tri-Party Agreement have agreed that the low-activity waste will be vitrified and that there is a Federal Court Consent Degree to that effect; as to the treatment of SLAW, steam reforming was studied extensively at Hanford at the cost of hundreds of millions of dollars and "was not found to be acceptable"; as to the grout option, she had previously spoken to the committee about the Test Bed Initiative (TBI), a process for separating the cesium and solids from low-activity waste, grouting the remaining other material and shipping it to WCS for disposal; she expressed disappoint in how the TBI is addressed in Review #3; while the TRU permit request "has been temporarily withdrawn for timing, not technology reasons, TBI offers a low tech, low cost option to remove waste from tanks, grout it and [send] it to an appropriate landfill"; in addition, she expressed that there are historic concerns about grouting waste and burying it at Hanford because "previous studies have demonstrated that some constituents of Hanford waste leach out of grout"; wants to make sure that members of Congress and their staff understand that appropriate cost comparisons about treatment options and especially consider the relatively low cost of TBI, October 31, 2019.
- Laurene Contreras, Program Manager, and McClure Tosch, NRIA Lead, Yakama Nation ERWM (many of the themes in the summary of these written comments were presented by Mr. Tosch at the public meeting on October 31, 2019), requests an extension of the comment period in light of new information presented at the public meeting [the National Academies subsequently extended the comment period to November 20, 2019], emphasizes that the Hanford area "holds cultural significance for many reasons" such as providing "foods and medicines that cannot be found anywhere else"; underscores that under the Treaty of 1855 the Yakama Nation was established and "ceded over 12 million acres of land to the United States," but preserved rights for the Yakama people to, among other usages, "right of taking fish at all usual and accustomed places" to include places on the Columbia River; notes the vital importance of this river to the Yakama Nation; notes that Review #3 makes it "very apparent that the committee has found substantial uncertainties in the technologies for waste treatment and disposal" as analyzed by the FFRDC; believes that the committee "should include a recommendation for evaluation of impacts to Tribal people and resources in recommendations 2-1 and 3-1"; states their view that leaving waste on the Hanford site is not an acceptable alternative because it will restrict their access to their "accustomed places," impacting their Treaty rights, and notes that the Hanford Challenge's submitted comments supports their position; suggests "the committee add Tribal, State, and Other Entities opposition as a bullet point to Recommendation 2-1 (d)"; "shares the concerns with Hanford Challenge regarding the threats posed to groundwater, the use of impractical long ranged institutional controls, and the potential effects of climate change and severe weather events that could compromise the protection of human health and the environment from long lived radionuclides present in this waste stream," October 31, 2019.
- Anonymous, do not re-classify radioactive waste as low-activity waste; take it to a geological formation and away from the river, October 31, 2019.

- James Byron, states that he is anxious to hear of the findings, October 31, 2019.
- Rob Roy Rowley, "I do not believe the leaking tank waste or its by-product should be put into grout. It is already a sin what has been done in the Columbia Basin"; "do the right thing and clean up properly and stop making waste," October 31, 2019.
- Adam Romero, Ph.D., University of Washington, concerned by the FFRDC's recommendation that Hanford's tank waste be immobilized in grout. Hanford's Supplemental Low-Activity Waste (SLAW) should have long-lived radionuclides removed and then be immobilized in glass to ensure protection of future generations. "Protection of the environment and people is my priority, not short term cost savings," October 31, 2019.
- The Hayden Family, sent by Melissa Bethke, opposes putting Hanford's tank waste in grout; SLAW should have long-lived radionuclides removed and immobilized in glass; do not dispose of grouted SLAW at Hanford site, October 31, 2019.
- Caroline Bryant, opposes putting Hanford's tank waste in grout; SLAW should have long-lived radionuclides removed and immobilized in glass; do not dispose of grouted SLAW at Hanford site, October 31, 2019.
- Steven G. Gilbert, Ph.D., Institute of Neurotoxicology & Neurological Disorders, Seattle, Washington, opposes putting Hanford's tank waste in grout; SLAW should have long-lived radionuclides removed and immobilized in glass; do not dispose of grouted SLAW at Hanford site, October 31, 2019.
- Ted Granger, opposes putting Hanford's tank waste in grout; SLAW should have long-lived radionuclides removed and immobilized in glass; do not dispose of grouted SLAW at Hanford site; he also noted in his comment that "This is the stock text from Hanford Challenge, which is fine, but perhaps too mild in reacting to the absurdity of encasing nuclear waste in concrete or grout." He also mentioned his 60 years of experience in construction, mostly as a registered architect, with extensive experience in dealing with concrete, October 31, 2019.
- Gail Grinnell, opposes putting Hanford's tank waste in grout; SLAW should have long-lived radionuclides removed and immobilized in glass; do not dispose of grouted SLAW at Hanford site, October 31, 2019.
- Judith Klayman, opposes putting Hanford's tank waste in grout; SLAW should have long-lived radionuclides removed and immobileized in glass; do not dispose of grouted SLAW at Hanford site, October 31, 2019.
- Jenna McLellan, opposes putting Hanford's tank waste in grout; SLAW should have long-lived radionuclides removed and immobilized in glass; do not dispose of grouted SLAW at Hanford site, October 31, 2019.
- James P. Milbauer, "a concerned Hanford worker," opposes putting Hanford's tank waste in grout; SLAW should have long-lived radionuclides removed and immobilized in glass; do not dispose of grouted SLAW at Hanford site, October 31, 2019.
- Patricia Morton, opposes putting Hanford's tank waste in grout; SLAW should have long-lived radionuclides removed and immobilized in glass; do not dispose of grouted SLAW at Hanford site, October 31, 2019.
- Kelly Norton, opposes putting Hanford's tank waste in grout; SLAW should have long-lived radionuclides removed and immobilized in glass; do not dispose of grouted SLAW at Hanford site, October 31, 2019.
- Jeanne Poirier, do not take short-cuts to save money today; opposes grout and favors glass, October 31, 2019.
- Beth Sanders, opposes putting Hanford's tank waste in grout; SLAW should have long-lived radionuclides removed and immobilized in glass; do not dispose of grouted SLAW at Hanford site, October 31, 2019.

- Carol Shaffer, opposes putting Hanford's tank waste in grout; SLAW should have long-lived radionuclides removed and immobilized in glass; do not dispose of grouted SLAW at Hanford site, October 31, 2019.
- John L. Swanson, troubled by the use of the word "supplemental"; it is sometimes used as "supplemental treatment of LAW" and other times as "treatment of supplemental LAW"; such phrases do not mean the same thing; he recommends correcting imprecision in terms in final reports, October 31, 2019.
- Randolph W. Urmston, opposes putting Hanford's tank waste in grout; SLAW should have long-lived radionuclides removed and immobilized in glass; do not dispose of grouted SLAW at Hanford site, October 31, 2019.
- John Wolcott, opposes putting Hanford's tank waste in grout; SLAW should have long-lived radionuclides removed and immobilized in glass; do not dispose of grouted SLAW at Hanford site, October 31, 2019.
- Kathleen M. Saul, Ph.D., expresses anger about the many years and many dollars spent in trying to develop a new technology while very little progress has been made in cleaning up the waste; opposes use of grout because experience "around the world has shown that concrete type materials degrade over time and due [to] the heat and radiation from the materials surrounded by the concrete; believes that the SLAW should have the long-lived radionuclides removed and be immobilized in glass to ensure protection of future generations," October 31, 2019.
- Chuck Broscious, President of the Board, Environmental Defense Institute, agrees with Hanford Challenge's concerns about the use of grout for Hanford waste and that grouted SLAW should not be disposed of at Hanford; also cautions that the technical and management problems over several years in trying to treat Idaho National Laboratory's waste using steam reforming should serve as a lesson for Hanford; expresses concern about the many billions of dollars that "have been wasted on quick-and-cheap solutions," October 31, 2019.
- David Kosson (Principal Investigator), Craig Benson, Kevin Brown, Kathy Higley, Andrew Garrabrants, Jane Stewart, Richard Stewart, and Hans van der Sloot, members of the Consortium for Risk Evaluation with Stakeholder Participation (CRESP), recognize the fundamental goal of protecting human health and the environment and that "Hanford tank waste cleanup is fundamentally different and more complex and costly than ever imagined during the development [of] the current complex web of federal and state laws and regulations governing nuclear waste and environmental management. Current cost and schedule estimates should only be considered coarse estimates, with cost and schedule growth inevitable, as has been shown to be typical for federal projects of this magnitude"; this "leads to a fundamental choice: (i) continue along the current plan of record, or (ii) chart a course that results in more rapid and cost effective cleanup while assuring tank waste management is consistent with expectations of adequate protection of human health and the environment that is applied elsewhere in the country"; the "Tank Closure and Waste Management EIS (2012) and Record of Decision (2013), which provide the foundation for the current plan of record, are predicated on overly conservative and bounding assumptions (biased towards overestimating risk). Similarly, performance assessments carried out under DOE 435.1 are biased towards overestimating risk and with bounding assumptions to demonstrate that the proposed action is adequately protective, rather than providing best estimates of performance based on the best available science and engineering with uncertainty"; supports the committee's point in Review #3 "that having start/stop capability may be particularly important because … the receipt rate [of the SLAW] is projected to be highly variable"; "suggests that the focus should not be on any specific waste form (e.g., glass versus others) but instead on defining the necessary technical performance requirements of any waste form that would be used for low-level waste burial in the IDF"; "suggests that these potential worsening conditions [of the integrity of the tanks] and delays be considered more directly in future decision making concerning the Hanford tank wastes"; "would like to reinforce the opin-

ion that the R&D will be an ongoing need during development and operation of the treatment facilities, and that the current investment in directly supporting R&D is insufficient"; "encourages the Committee to recognize that Hanford also competes for resources across the entire DOE Environmental Management mission, and greater expenditures at Hanford will likely slow progress at other sites"; believe that it would be incomplete for the committee "*not* to include analysis of options for SLAW disposition using the *current HLW definition adopted by the Department*" [in the *Federal Register* notice in June 2019], but they note that this definition has yet to be implemented at Hanford; highlights that Review #3 "begins with the premise that there is a 'perceived agreement' that the final waste form for tank SLAW will be vitrification or another final waste form that is 'as good as glass'"; "DOE has not entered into any such agreement, and CRESP urges that this error in [Review #3] be corrected" and "should make clear that the Hanford Federal Facility Agreement (FFA), which is the legally binding agreement, … contains no such agreement"; Review #3 "does not address the important issue of regulatory authority over mixed waste, and its implications for regulation of SLAW. RCRA regulators have the authority to regulate the chemically hazardous aspects of mixed waste, whereas regulators with nuclear regulatory authority—here DOE—have authority over the radioactive components. Under this allocation, RCRA regulators do not have authority to impose different regulatory requirements depending on the radioactivity of mixed wastes unless those differences affect the chemically hazardous character of the wastes"; "Developing an adequately protective and cost-effective treatment plan for non-HLW SLAW wastes requires that DOE, Washington state, and EPA fully and carefully consider the potential applicability of all available LDR flexibility mechanisms…. The analysis should evaluate the prospects for each major category of non-HLW SLAW waste stream to meet the criteria required for regulatory approval for use of each of the RCRA LDR flexibility mechanisms.… If the analysis is not possible for this Report, we strongly recommend that it be considered for a follow-on NAS study"; there is the need for a more accurate inventory of RCRA tank wastes and that the current operating assumption is that all of the tanks contain all of the hazardous materials under RCRA, thus substantially increasing the costs for cleanup; there is a need to understand the impact of RCRA tank closure requirements on SLAW volume; the report "should evaluate a full range of disposal site options, both on-site and off-site" and in particular, should consider "the Nevada National Security Site (NNSS) as a potential disposal site for Hanford SLAW"; underscores the noncompliance with the Federal Facility Compliance Act (FFCA) at the IDF such that the FFCA provides that requirements to federal facilities apply "in the same manner, and to the same extent" as requirements applicable to private parties and to "impose on Hanford a requirement that LAW be vitrified or the equivalent, when no such requirement is imposed on private LAW disposal sites, could constitute a violation of the parity requirement of FFCA," October 31, 2019.

- Shannon Cram, Ph.D., University of Washington, as a member of Hanford's Advisory Board, "I would like to voice my opposition to putting Hanford's tank waste in grout. Instead, I would like Hanford's long-lived radionuclides to be removed from its Supplemental Low-Activity Waste (SLAW) and immobilized in glass. We need to prioritize long-term human and environmental health over short-term cost savings. I am very concerned that the FFRDC is recommending grout for Hanford's SLAW. Not only is this recommendation myopic, it could set a dangerous precedent for other waste management areas on site," November 1, 2019.
- Gary Peterson, retired from Hanford, expresses concern that the "as good as glass" concept is not defined in law and that trying to vitrify all the waste in Hanford's tanks would take too long and cost too much money; mentions the estimated significant cost savings for use of grout and the option for shipping that waste form to WCS in Texas, November 6, 2019.
- Anonymous, "I saw the presentation from the October 31, 2019 meeting regarding the Office of River Protection Glass Science Program. The ORP Glass Program provided the perspective that better glass formulations have the 'potential to realize nearly the entire soda inventory in the WTP LAW Facility and within an acceptable mission duration.' I believe this perspective requires the flow sheet and mass balance to be closed around all of the WTP equipment, not just the melters. If

the process duration is compressed that means the tank waste feed is being treated at a rate much faster than was used as the basis for design of the WTP LAW Off-Gas treatment system, or the tank waste effluents management system. The promise of an easy fix with good glass must be evaluated in terms of the concentrations in the off-gas effluents, and whether the increased off-gas burden creates equipment capacity problems, including at ETF, or equipment corrosion problems, due to higher concentrations of halides, for example. It may be premature to suggest relying on better glass as a basis for deleting secondary LAW treatment. This will be especially true if the DFLAW off-gas and effluents systems do not perform as advertised," November 6, 2019.

- Carlgh, expresses concern that the FFRDC report seems to confuse terms of high-level, low-activity, and supplemental low-activity waste, and that this apparent confusion appears to contradict the legal definition of HLW as defined by the Atomic Energy Act, as amended, November 7, 2019.
- Leah Boehm Brady, do not reclassify radioactive waste; "keep this poison away from the river"; "protect the Columbia River," November 7, 2019.
- Carol Davis, has the committee investigated best practices of European countries such as those presented at the 43rd Annual Symposium on the Scientific Basis for Nuclear Waste Management, held October 21-24 in Vienna, Austria, November 18, 2019.

Appendix F

Biographical Sketches of the Committee, Technical Adviser, and Study Director

COMMITTEE

John S. Applegate (*Chair*) is executive vice president of University Academic Affairs of Indiana University (IU) and the Walter W. Foskett Professor of Law in the IU Maurer School of Law. He has served as a vice president for IU since 2008. He teaches and has written extensively in the fields of environmental law, administrative law, regulation of chemicals and hazardous wastes, international environmental law, risk assessment, and the management of radioactive waste. He chaired the Fernald Citizens Advisory Board at the U.S. Department of Energy's (DOE's) Fernald facility in Ohio from 1993-1998, and he served on the DOE Environmental Management Advisory Board from 1994-2001. He has also served on several National Academies of Sciences, Engineering, and Medicine studies. A member of the American Law Institute, Professor Applegate has also taught at the University of Paris (Panthéon-Assas) and the University of Erlangen-Nürnberg and has been a research fellow at Cardiff University. Before moving to Indiana, he was the James B. Helmer, Jr., Professor of Law at the University of Cincinnati's College of Law and was a visiting professor at the Vanderbilt University Law School. He was a judicial law clerk for the U.S. Court of Appeals for the Federal Circuit and an attorney in private practice in Washington, DC. He has served as a board member of the National Academies' Nuclear and Radiation Studies Board; he was chair of the National Academies' workshop on Low-Level Radioactive Waste Management and Disposition; and he has served on several National Academies' committees. Professor Applegate received his BA in English from Haverford College in 1978 and his JD from Harvard Law School in 1981.

Allen G. Croff (*Vice-Chair*) is an adjunct professor of nuclear and environmental engineering in the Department of Civil and Environmental Engineering at Vanderbilt University. He is also a member of the U.S. Nuclear Waste Technical Review Board, appointed to this position by the president in February 2015, and a distinguished emeritus member of the National Council on Radiation Protection and Measurements. Mr. Croff has 29 years of technical and program management experience at the Oak Ridge National Laboratory. He was subsequently vice-chairman of the Advisory Committee on Nuclear Waste in the U.S. Nuclear Regulatory Commission and a senior technical advisor to the Blue Ribbon Commission on America's Nuclear Future. He has led or participated in numerous multi-disciplinary national and international technical and review committees for the National Academies of Sciences, Engineering, and Medicine; the National Council on Radiation Protection and Measurements; the Nuclear Energy Research Advisory Committee; and the Nuclear Development Committee of the Nuclear Energy Agency. Mr. Croff's technical accomplishments include creation of the ORIGEN2 computer code used worldwide to calculate the radioactive characteristics of nuclear materials for use in nuclear material and waste characterization, risk analyses, and nuclear fuel cycle analysis; developing and evaluating comprehensive, risk-based waste classification systems, including changing the boundary defining transuranic waste from 10 to 100 nCi/g; technical, economic, and systems analysis of current and advanced nuclear fuel/material cycles from uranium mining through waste disposal; and conceiving, analyzing, and reviewing actinide partitioning-transmutation (P-T) concepts beginning with the first comprehensive analysis of P-T from 1976 to 1980 through subsequent cycles of renewed interest in the concept up to the present. Mr. Croff received a BS (1971) in chemical engineering from Michigan State University, a nuclear engineering degree (1974) from the Massachusetts Institute of Technology, and an MBA (1981) from the University of Tennessee.

Margaret S. Y. Chu provides consulting services to domestic and international clients in nuclear waste management, nuclear fuel cycle analysis, nuclear security analysis, and research and development. Her entire career has been devoted to promoting safe nuclear energy and nuclear fuel cycles. She has extensive experience in successfully managing large, multi-disciplinary projects and in negotiating with customers, regulators, and stakeholders. She has more than 20 years of experience serving at Sandia National Laboratories in several capacities, including director of the Nuclear Waste Management Program Center, manager of the Environmental Risk Assessment and Waste Management Department, and deputy manager of the Waste Isolation Pilot Project (WIPP) and Technical Integration Department. In 2002, she was appointed by President George W. Bush as director of the U.S. Department of Energy's (DOE's) Office of Civilian Radioactive Waste Management, which is responsible for developing the nation's waste disposal system for spent nuclear fuel and high-level radioactive waste at Yucca Mountain. She has authored nearly 50 publications and has received numerous awards, including the Secretary of Energy's Gold Award (2005), DOE's highest honor, and Team Lead of the Lockheed Martin Nova Award (1998). She served as a board member of the National Academies' Nuclear and Radiation Studies Board and a member of the Nuclear Energy Advisory Committee at DOE. Dr. Chu is a member of the Advisory Committee of Reactor Safeguards at the U.S. Nuclear Regulatory Commission. She is a member of the National Academy of Engineering. She holds a BS degree from Purdue University in chemistry and a PhD from the University of Minnesota in physical (quantum) chemistry.

Kenneth R. Czerwinski is a professor in the radiochemistry program at the University of Nevada, Las Vegas, and director of the radiochemistry PhD program. His current research is centered on understanding the chemical speciation and coordination of actinides and technetium compounds for exploratory and applied studies. His fundamental research focuses on coordination chemistry and evaluating electronic structure. By understanding radioelement containing systems, one can determine relevant species, study their behavior, verify results, inform computational efforts, and incorporate the latest concepts into education. Current projects include speciation of actinides in spent fuel, chemical speciation of actinides in separations, nuclear forensics, and radioelement compounds and material synthesis. Dr. Czerwinski has been an associate professor in the Nuclear Engineering Department at the Massachusetts Institute of Technology and an associate research scientist for the Institut für Radiochemie Technische Universität München. He has been accorded the Presidential Early Career Award in Science and Engineering and was elected fellow of the American Association for the Advancement of Science in 2012 for his distinguished contributions to actinide and fission product chemistry. Dr. Czerwinski obtained his BA from Knox College in Russian language and chemistry and his PhD in nuclear chemistry from the University of California, Berkeley.

Rachel J. Detwiler is a principal engineer at Beton Consulting Engineers, LLC. Her areas of expertise are construction troubleshooting, concrete durability, transport properties, microstructure, and test methods for concrete and cement-based materials. Dr. Detwiler previously worked as an associate and a senior engineer at Braun Intertec Corporation; a principal engineer at Construction Technology Laboratories; an assistant professor at the University of Toronto; and a design and materials engineer with ABAM Engineers, Inc. She is a fellow of the American Concrete Institute, where she served as chair of Committee 227 on Radioactive and Hazardous Waste Management and as a member of the Publications Committee. She is a member and a past chair of Committee 234 on Silica Fume in Concrete and a member of Committee 201 on Durability of Concrete. She also served in an advisory role until 1996 for the initial development of a formulation of grout for the stabilization of radioactive and hazardous waste in underground storage tanks at the Savannah River Site. Dr. Detwiler has published more than 60 technical papers related to concrete microscopy, durability, and testing. Dr. Detwiler has served on several National Academies committees. Dr. Detwiler holds a BS in civil engineering, an MS in structural engineering, and a PhD in civil engineering materials from the University of California, Berkeley. She was also a postdoctoral fellow at the Institute for Building Materials at the Norges Tekniske Høgskole, Trondheim, Norway.

Timothy A. DeVol is the Toshiba Professor of Nuclear Engineering and the director of the Nuclear Environmental Engineering Sciences and Radioactive Waste Management Center at Clemson University. Dr. DeVol's primary teaching responsibilities are in the areas of radiation detection and measurement, environmental risk assessment, and introduction to nuclear engineering and radiological sciences. Dr. DeVol oversees the Accreditation Board for Engineering and Technology Applied and Natural Science Accreditation Commission's accredited Environmental Health Physics educational program in the Environmental Engineering and Earth Sciences Department at Clemson University. Dr. DeVol's research interests are in the areas of radiological environmental measurements, environmental health physics, statistical methods, homeland security, nuclear forensics, and in situ and field portable analytical instrumentation for radioactive environmental contaminant quantification. Dr. DeVol has more than 60 refereed publications and more than 160 presentations in the field of detection of radioactive materials. He holds three U.S. patents on the development of methods and materials for the detection of radioactivity in the environment. Additionally, Dr. DeVol has helped to bring in more than $8 million in externally funded research, of which $4.5 million was directly attributed to him in his more than 20 years on the faculty at Clemson University. Dr. DeVol is also the recipient of the 2003 and the 2011 Clemson University Innovation awards and the 2004 Elda E. Anderson award from the Health Physics Society. He is a member of the American Nuclear Society, the Health Physics Society, and the Institute of Electrical and Electronics Engineering Society. Dr. DeVol is an American Board of Health Physics certified health physicist. He holds an MS and a PhD, respectively, in nuclear engineering from the University of Michigan, Ann Arbor, and a BS in engineering physics from The Ohio State University, Columbus.

Rodney C. Ewing is the Frank Stanton Professor in Nuclear Security and co-director of the Center for International Security and Cooperation in the Freeman Spogli Institute for International Studies, and a professor in the Department of Geological Sciences in the School of Earth, Energy and Environmental Sciences at Stanford University. In addition, he is the Edward H. Kraus Distinguished University Professor Emeritus at the University of Michigan, where he was in three departments: Earth & Environmental Sciences, Nuclear Engineering & Radiological Sciences, and Materials Science and Engineering. He is also a Regents' Professor Emeritus at the University of New Mexico. His professional interests are in mineralogy and materials science, and his research has focused on radiation effects in complex ceramic materials and the long-term durability of radioactive waste forms. He is a fellow of the American Association for the Advancement of Science, the American Ceramic Society, The Geochemical Society, the Geological Society of America, the Mineralogical Society of America, and the Materials Research Society. He is a past president of the International Union of Materials Research Societies and the Mineralogical Society of America. In 2006, he was awarded the Lomonosov Great Gold Medal of the Russian Academy of Sciences, and in 2007, he was named an Honorary Doctor of Université Pierre et Marie Curie. He is a member of the National Academy of Engineering. He received MS and PhD degrees in geology from Stanford University.

Craig S. Hansen is an independent business consultant with 27 years of executive and senior-level experience in facility/site management; business and product line management; executing large and complex nuclear plant manufacturing, construction, decommissioning, and nuclear reactor servicing contracts; and in successful leadership of complex technical projects facing a wide range of stakeholder challenges. Mr. Hansen has extensive experience with BWXT, formerly the nuclear technology business of the Babcock & Wilcox Company (B&W). His most recent service was as president and board member (2013-2014) at B&W's American Centrifuge Manufacturing, LLC (ACM), where he was responsible for management and operations of the American Centrifuge Technology and Manufacturing Center located in Oak Ridge, Tennessee, overseeing direction, management, and operation through bankruptcy and program re-alignment; managed a sophisticated technical manufacturing operation in a highly automated facility; and led product line diversification and demobilization due to government funding cuts. In B&W's nuclear manufacturing division (2008-2013), he was the vice president of nuclear equipment where he was responsible for B&W's global commercial nuclear equipment business along with U.S. and Canadian manufacturing sites, worldwide contracts, and product lines. From 2003 through 2008, Mr. Hansen organized and managed B&W's

government relations team. As B&W's deputy site manager (2001-2003), he accelerated the cleanup and public relations at the U.S. Department of Energy Miamisburg Environmental Management Project (Mound Plant), a site on the National Priorities List since 1989 due to past disposal practices and releases to the environment. Prior to B&W he worked on the Naval Nuclear Propulsion Program in Washington, DC, and Idaho (1988-2001) in a series of progressively responsible positions at the nuclear reactor headquarters and naval reactor site management. He also served as the first chairman of the U.S. Department of Commerce Civil Nuclear Trade Advisory Committee. Mr. Hansen has a BA from Eastern Washington University in operations management.

Cathy Middlecamp is a professor at the Nelson Institute for Environmental Studies, University of Wisconsin–Madison and the director for education and research of the UW Office of Sustainability. She has been recognized on campus, state-wide, and nationally for her excellence in teaching and service to a diverse group of students. From 2007 to 2016, she was the editor-in-chief for *Chemistry in Context*, a project of the American Chemical Society (ACS), and has served as the lead author for the chapters on nuclear energy, air quality, stratospheric ozone depletion, acid rain, and polymers. From the ACS, she also received the George C. Pimentel Award for Chemical Education (2019), was elected as a fellow (2009), and received national awards for encouraging women into careers in the chemical sciences (2006), for incorporating sustainability into the chemistry curriculum (2011), and for encouraging disadvantaged students into careers in the chemical sciences (2015). Her recognition by the American Association for Advancement of Science includes being named a fellow (2003) and being elected the chair of Section Q, Education (2015). Dr. Middlecamp graduated with distinction in all subjects and Phi Beta Kappa from Cornell University (1972), earned her PhD in chemistry from the University of Wisconsin–Madison (1976), and also holds a master's degree in counseling psychology and counselor education from the University of Wisconsin–Madison (1989).

Alfred P. Sattelberger retired in 2017 from the Argonne National Laboratory, where he most recently was deputy lab director for Programs, the chief research officer, and the senior intelligence official. Prior to his appointment as an associate lab director at Argonne in 2006, he was a senior laboratory fellow and former head of the Chemistry Division and the Science and Technology Base Program Office at the Los Alamos National Laboratory (LANL). Dr. Sattelberger's research interests include actinide coordination and organometallic chemistry, technetium chemistry, homogeneous and heterogeneous catalysis, and nuclear energy. Before joining LANL in 1984, Dr. Sattelberger held a faculty appointment in the Chemistry Department at the University of Michigan. He is a former chair of the Inorganic Chemistry Division of the American Chemical Society (ACS) and the Chemistry Section of the American Association for the Advancement of Science (AAAS). He served as a member of the 1996 Environmental Management Science Program merit review panel. He was elected as a fellow of AAAS in 2002 in recognition of his scientific contributions to early transition metal and f-element chemistry, and a fellow of ACS in 2010. He has also served as a member of several National Academies committees examining radioactive waste management issues at the U.S. Department of Energy (DOE) and is currently the chair of the Fuel Cycle and Infrastructure Subcommittee of the DOE Nuclear Energy Advisory Committee. Dr. Sattelberger received a BA in chemistry at Rutgers College in 1970 and obtained a PhD in inorganic chemistry from Indiana University in 1975.

Barry E. Scheetz is recognized for his expertise in the chemistry of cementitious systems for waste forms and environmental remediation. He is a retired professor of materials, civil, and nuclear engineering at The Pennsylvania State University. His work includes environmental waste management programs such as remediation of mine lands by the use of industrial byproducts, focusing on large-volume usage of fly-ash-based cementitious grouts. Other programs include developments of radioactive waste forms based on vitrifiable hydroceramics and sodium zirconium phosphate structures. Dr. Scheetz received a national internship from the Argonne National Laboratory in 1972 and he was a National Academy of Sciences visiting scholar to China in 1989. He served as a member of the Board on Radioactive Waste Management Committees on Idaho National Engineering and Environmental Laboratory High-Level Waste Alternative

Treatments, and Cesium Processing Alternatives for High-Level Waste at the Savannah River Site. Dr. Scheetz is the author of more than 240 scientific publications and holds 40 U.S. and world patents. He received a BS in chemical education from Bloomsburg State College and an MS and a PhD in geochemistry from The Pennsylvania State University.

Anne E. Smith is a managing director and co-chair of National Economic Research Associates, Inc.'s (NERA's) Global Environment Practice. Trained in economics, decision sciences, and mathematical modeling, she has applied this expertise to issues including air quality, climate change, contaminated sites, food safety, and nuclear waste management. She has also conducted training courses in health risk assessment and risk management for staff of corporations and government agencies. In addition to her consulting activities, Dr. Smith has served on committees of the National Academies of Sciences, Engineering, and Medicine; the United Nations (UN) Economic Commission for Europe; the UN's Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection; and the U.S. Environmental Protection Agency's (EPA's) Board of Scientific Counselors. She is a member of many different professional societies, performs peer reviews for journal articles, and served on the Board of Directors of the Society for Benefit-Cost Analysis in 2013 and 2014. Prior to joining NERA, Dr. Smith was a practice leader of climate and sustainability at Charles River Associates. She was also a vice president and a policy analysis practice leader at Decision Focus Incorporated, and served as an economist in the Office of Policy Planning and Evaluation at EPA. Dr. Smith graduated summa cum laude from Duke University with a BA in economics and from Stanford University with an MA and a PhD in economics, as well as a PhD minor in engineering-economic systems.

Chris G. Whipple has 40 years of experience in managing risks to human health and the environment. The major emphases of his work have been radioactive wastes, hazardous air pollutants, and environmental mercury. He has served on numerous national committees addressing radioactive waste management, including committees of the National Academies of Sciences, Engineering, and Medicine; the U.S. Environmental Protection Agency; and the National Council on Radiation Protection and Measurements. He has chaired the National Academies' Board on Radioactive Waste Management, as well as National Academies committees on the Review of the Hanford Site's Environmental Remediation Science and Technology Plan; Models in the Regulatory Decision Process; Medical Isotope Production Without Highly Enriched Uranium; and Understanding and Managing Risk in Security Systems for the U.S. Department of Energy Nuclear Weapons Complex. He also co-chaired the National Academies' Report Review Committee from 2008-2016. He was a charter member and the second president of the Society for Risk Analysis and is a fellow of the American Academy for the Advancement of Science. He is a member of the National Academy of Engineering. He received a PhD and an MS in engineering science from the California Institute of Technology and a BS in engineering science from Purdue University. In 2004, he received Purdue's Distinguished Engineering Alumni Award.

TECHNICAL ADVISER

David W. Johnson, Jr., is a retired editor-in-chief for the *Journal of the American Ceramic Society*. He is the retired director of materials research at Bell Laboratories, Lucent Technologies, and a former adjunct professor of materials science at Stevens Institute of Technology. His research activities included fabrication and processing of glass and ceramics with emphasis on materials for electronic and photonic applications. He is a member of several professional societies, including a fellow, distinguished life member, and past president of the American Ceramic Society. Dr. Johnson won the Taylor Lecture Award and the Distinguished Alumni Award from The Pennsylvania State University; the Ross Coffin Purdy Award for the best paper in ceramic literature; the Fulrath Award; the John Jeppson Award; the Orton Lecture Award from the American Ceramic Society; and the International Ceramics Prize for Industrial Research from the World Academy of Ceramics. He is a member of the National Academy of Engineering and the World

Academy of Ceramics. He holds 46 U.S. patents and has published numerous papers on materials sciences. He earned a BS in ceramic technology and a PhD in ceramic science from The Pennsylvania State University.

STUDY DIRECTOR

Charles D. Ferguson is the director of the Nuclear and Radiation Studies Board in the Division on Earth and Life Studies at the National Academies of Sciences, Engineering, and Medicine. Previously, he was the president of the Federation of American Scientists (FAS). Prior to FAS, he worked as the Philip D. Reed senior fellow for science and technology at the Council on Foreign Relations (CFR), where he specialized in nuclear issues, and served as project director for the Independent Task Force on U.S. Nuclear Weapons Policy chaired by William J. Perry and Brent Scowcroft. Before CFR, he was the scientist-in-residence at the Monterey Institute's Center for Nonproliferation Studies, where he co-authored the book *The Four Faces of Nuclear Terrorism* (Routledge, 2005) and was lead author of the January 2003 report *Commercial Radioactive Sources: Surveying the Security Risks*. For his work on security of radioactive sources, he was awarded the Robert S. Landauer Memorial Lecture Award from the Health Physics Society in 2003. He is also the author of *Nuclear Energy: What Everyone Needs to Know* (Oxford University Press, 2011). In addition, he has worked as a physical scientist in the Office of Nuclear Safety at the U.S. Department of State, and he has served as a nuclear engineering officer and submarine officer in the U.S. Navy. He is an elected fellow of the American Physical Society in recognition of his service to public policy and public education on nuclear issues. Dr. Ferguson earned a BS in physics with distinction from the U.S. Naval Academy and MA and PhD degrees, also in physics, from Boston University.

Appendix G

Acronyms and Abbreviations

CRESP	Consortium for Risk Evaluation with Stakeholder Participation
DFLAW	Direct Feed Low-Activity Waste
DNFSB	Defense Nuclear Facilities Safety Board
DOE	U.S. Department of Energy
DOE-EM	U.S. Department of Energy's Office of Environmental Management
DOE-ORP	U.S. Department of Energy's Office of River Protection
DWS	drinking water standard
EPA	U.S. Environmental Protection Agency
FBSR	fluidized bed steam reforming
FFCA	Federal Facility Compliance Act
FFRDC	Federally Funded Research and Development Center
GAC	granular activated carbon
GAO	U.S. Government Accountability Office
HEPA	high-efficiency particulate air
HLW	high-level waste
I	iodine
ICRP	International Commission on Radiological Protection
IDF	Integrated Disposal Facility
INL	Idaho National Laboratory
LAW	low-activity waste
LDR	land disposal restriction
NAE	National Academy of Engineering
NAS	National Academies of Sciences
NASEM	National Academies of Sciences, Engineering, and Medicine
MCL	maximum contaminant level
mrem	millirem [roentgen equivalent man]
PA	Performance Assessment
PE	Performance Evaluation
R&D	research and development
RCRA	Resource Conservation and Recovery Act of 1976

SLAW	supplemental low-activity waste
SRNL	Savannah River National Laboratory
SRS	Savannah River Site
SSW	solid secondary waste
Tc	technetium
TOC	tank operations contract
TPA	Tri-Party Agreement
WCS	Waste Control Specialists
WIPP	Waste Isolation Pilot Plant
WTP	Waste Treatment and Immobilization Plant