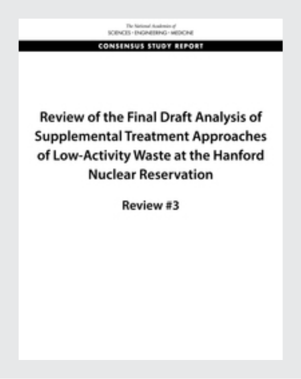
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CONSENSUS STUDY REPORT

Review of the Final Draft Analysis of Supplemental Treatment Approaches of Low-Activity Waste at the Hanford Nuclear Reservation

Review #3

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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 cleanup 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. Notably, DOE's determination as to whether a volume of waste is 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*. But this processing could still leave significant amounts 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. According to DOE's plan, once the under-construction Waste Treatment and Immobilization Plant becomes operational, it will vitrify (treat) the HLW stream and 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 (the 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 a technology other than vitrification for *any* LAW is controversial at Hanford—though it has been adopted at other DOE-EM sites—and such use 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, and fluidized bed steam reforming—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 when the report is complete, but also at certain points during the effort. 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 on in reaching a decision on 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. This third review report provides 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 six 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; and most recently in a meeting discussing the final draft report, held in Kennewick, Washington, on May 16, 2019. (It is the final draft that the committee will fully review; however, the document itself is labeled "Preliminary Draft.") The committee is grateful for the time and effort that went into the team's presentations, as well as the presentations by other interested government agencies, stakeholders, and members of the public. The Department of Ecology, in particular, presented in detail and responded to the committee's questions at every public meeting in Richland and Kennewick. Between the fifth and sixth meetings, as this review indicates, the FFRDC team has continued to make significant progress. The committee's review 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.

We hope that the present review will provide a useful guide to the FFRDC's final draft analysis for decision-makers, other stakeholders, and interested members of the public. The committee will meet one more time in Washington State in late October. That public meeting will focus on receiving final comments from the Department of Ecology, tribal nations, and other stakeholders at the end of a congressionally mandated minimum 60-day public comment period, which starts immediately after publication of this review report, and we anticipate that the FFRDC will have issued a final published report by then. We look forward to continued dialogue with interested government representatives, Hanford area 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:

Kaylin Burnett, DOE-Office of River Protection (ORP)
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Naomi Jaschke, DOE-ORP
Beth Moore, DOE-EM
Rob Seifert, DOE-EM
Linda Suttora, DOE-EM

The committee also thanks the presenters and speakers who gave high-quality presentations during the public meetings as listed in Appendix C. In particular, for the most recent public meeting on May 16, 2019, the committee is pleased to note the very informative presentations given by John Plodinec, vice chair, the National Academies of Sciences, Engineering, and Medicine's Committee on the Independent Assessment of Science and Technology for DOE's Defense Environmental Cleanup Program; Suzanne Dahl, section manager of tank waste treatment in the Washington State Department of Ecology; and the team members of the Federally Funded Research and Development Center led by the Savannah River National Laboratory. In addition, the committee is grateful for other submitted public comments, which were useful in helping the committee better understand the public's concerns and views.

The committee is grateful for the outstanding assistance provided by the National Academies staff in organizing the committee meetings and preparing the report. The chair and vice-chair are also 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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Ian L. Pegg, The Catholic University of America, Washington, DC
Kevin Smith, independent consultant, Richland, Washington

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.

Contents

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 A, and the Statement of Task for the National Academies review is provided in Appendix B.

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 C) 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

[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.

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 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 radionuclindes (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.

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.

Review of Final Draft Analysis of Treatment Approaches of LAW at Hanford Nuclear Reservation: Review #3

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.

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 A). 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 A. The Statement of Task for the National Academies of Sciences, Engineering, and Medicine's (the National Academies') committee is in Appendix B.

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 C. 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.

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

[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.

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.
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.

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 D 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 will be made available in the study's Public Access File.[5]

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

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 recommendaton 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 B). 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.

2

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

For this review, the Statement of Task (see Appendix B) 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 A). 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.

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

[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.

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 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.

[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.

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, 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 under-pinning 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 A) 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.

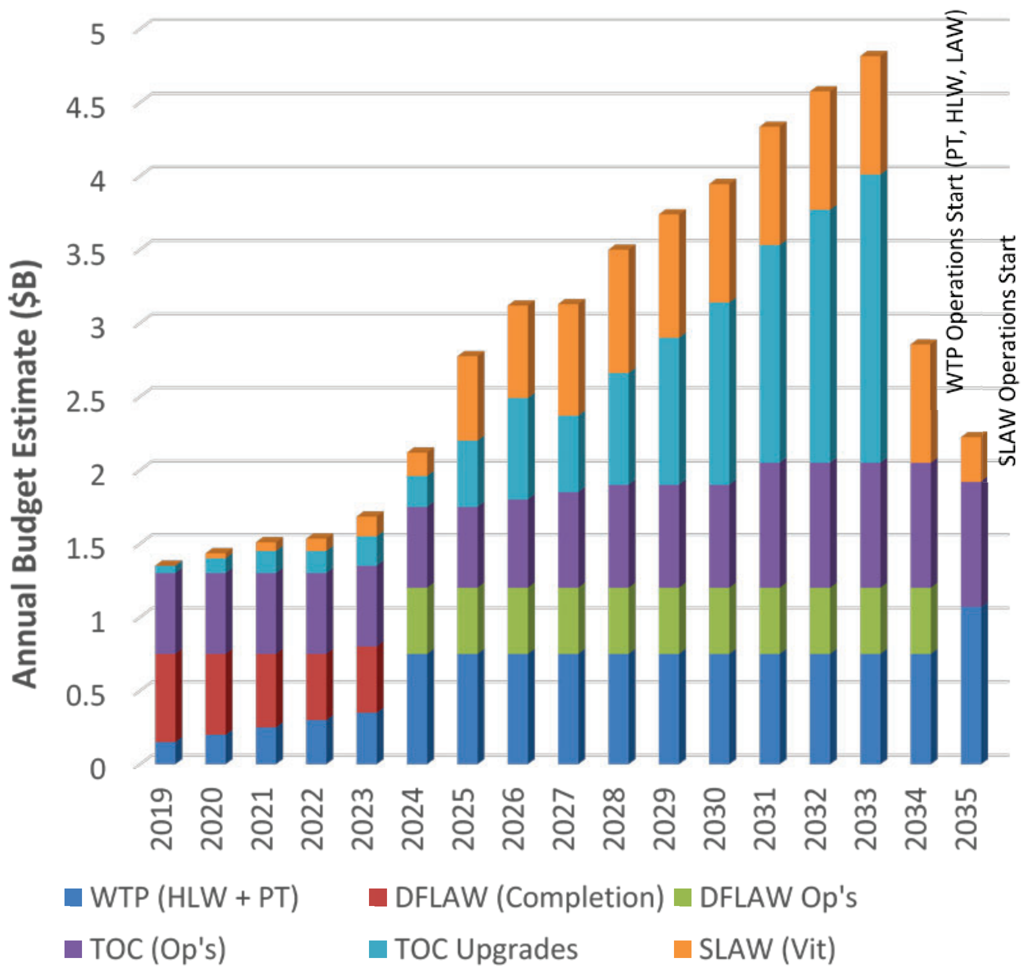

FIGURE 2-1 Near- and mid-term budget for SLAW vitrification in conjunction with key Hanford mission facilities and operations.
NOTE: DFLAW = Direct Feed Low-Activity Waste; TOC = Tank Operations Contract; WTP = Waste Treatment and Immobilization Plant.
SOURCE: Reprinted by permission from the FFRDC's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

[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 Pub-lication 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 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

[7] Page 166 of the FFRDC report.

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 threatment 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 radionuclindes (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 A). 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 requiements 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.

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Appendix A

Section 3134 of the 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.—

Appendix A

(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 B

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 C

Presentations at the Committee's Information-Gathering Meetings

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.

Appendix C

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.

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)
- *Onsite Disposal Performance Evaluation (IDF)*, Tom Brouns
- *Offsite 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 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.

Appendix D

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 1986 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 E

Acronyms and Abbreviations

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
EPA	U.S. Environmental Protection Agency
FBSR	fluidized bed steam reforming
FFRDC	Federally Funded Research and Development Center
GAO	U.S. Government Accountability Office
HEPA	high-efficiency particulate air filter
HLW	high-level waste
I	iodine
IDF	Integrated Disposal Facility
INL	Idaho National Laboratory
LAW	low-activity waste
LDR	land disposal restriction
mrem	millirem [roentgen equivalent man]
PA	Performance Assessment
PE	Performance Evaluation
R&D	research and development
RCRA	Resource Conservation and Recovery Act of 1976
Se	selenium
SLAW	supplemental low-activity waste
SRNL	Savannah River National Laboratory
SRS	Savannah River Site
Tc	technetium
TPA	Tri-Party Agreement
WCS	Waste Control Specialists
WTP	Waste Treatment and Immobilization Plant