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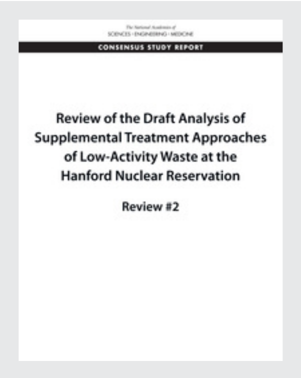

Review of the Draft Analysis of Supplemental Treatment Approaches of Low-Activity Waste at the Hanford Nuclear Reservation: Review #2 (2018)

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

Review #2

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

Nuclear and Radiation Studies Board

Division on Earth and Life Studies

A Consensus Study Report of
The National Academies of
SCIENCES • ENGINEERING • MEDICINE

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Preface

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

DOE's current plan for treating the nearly 56 million gallons of radioactive and heterogeneous 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 in the LAW stream. Once the under-construction Waste Treatment and Immobilization Plant (WTP) becomes operational, it will vitrify the HLW stream and at least one-third to perhaps one-half of the LAW stream. The excess LAW that still needs to be treated is called supplemental LAW (SLAW). DOE, the Washington State Department of Ecology, and the U.S. Environmental Protection Agency—the three parties under the legally binding 1989 Tri-Party Agreement—have yet to agree on the SLAW treatment method.

The use of a technology other than vitrification for *any* LAW is controversial for use 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 (FY) 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 to undertake a concurrent, 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 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 which—together with stakeholder comments—is intended to ultimately lead to a final report on which DOE can rely in reaching a decision on the management of SLAW. This second committee report is an interim report that provides the committee's review of the FFRDC team's draft report, dated July 15, 2018.

The FFRDC team has presented its work to the review committee three times: once in an introductory meeting in Washington, DC, on December 12-13, 2017, once in a meeting describing the status of the FFRDC's draft analysis held in Richland, Washington, on February 28 and March 1, 2018, and most recently in a meeting describing the FFRDC's draft report held in Richland, Washington, on July 23-24, 2018. The committee is most 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. Between the second and third meetings, as the review indicates, the FFRDC team has made significant progress. We all recognize, however, that much more remains to be done, and that a comprehensive and final

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committee evaluation must await the comprehensive and final FFRDC team report. Accordingly, the committee's review report makes relatively few formal findings and recommendations, and the bulk of this review, like the previous review, consists of observations and suggestions that are intended to provide the FFRDC team members with guidance and assistance—should they decide to take it—in developing their final report.

We hope that the present review will provide a useful guide to the work that has been completed to date, and additional guidance as it progresses. The committee will meet two more times in Washington State (the next time is in late November), and we look forward to continued dialogue with the FFRDC team, interested government representatives, Hanford 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

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Rob Seifert, DOE-EM
Linda Suttora, DOE-EM

The committee also thanks the presenters and speakers who gave high-quality presentations during the three public meetings as listed in Appendix D. In particular, for the most recent third public meeting, on July 23-24, 2018, the committee is pleased to note the several very informative presentations given by Alex Smith of the Washington State Department of Ecology, Alfrieda Peters of the Yakama Nation, 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 of Sciences, Engineering, and Medicine staff in preparing the report. The chair and vice-chair are also thankful for the time and energy devoted by the committee members.

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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:

Lake H. Barrett, independent consultant, Venice, Florida
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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. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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APPENDIXES

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Summary

Section 3134 of the National Defense Authorization Act for Fiscal Year 2017 (P.L. 114-328) (Sec. 3134) calls for a Federally Funded Research and Development Center (FFRDC) "to conduct an analysis of approaches for treating the portion of low-activity waste (LAW) at the Hanford Nuclear Reservation" intended for supplemental treatment.[1] The U.S. Department of Energy (DOE) has contracted with Savannah River National Laboratory (SRNL), an FFRDC, to provide the called-for analysis. SRNL then 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 Section 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 second of four to be issued by the National Academies to address the congressional mandate, focuses on the Statement of Task's study charge 4: "Results of the assessments, including the formulation and presentation of conclusions and the characterization and treatment of uncertainties." The committee's review is based on the FFRDC's draft report of 197 pages submitted to the committee on July 16, 2018, and a set of about 200 slides produced by the FFRDC and presented at the public meeting on July 23-24, 2018, in Richland, Washington, as well as other public presentations at that meeting.

The committee's overarching task is to provide a concurrent, independent *peer review* of the ongoing FFRDC analysis. The committee is neither charged to analyze the supplemental treatment approaches, nor to recommend any particular approach over another. 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 itself will not identify a preferred option for supplemental treatment, but instead will evaluate the treatment alternatives against the baseline as well as against one another. It will provide (existing) data and analysis to enable DOE, with congressional oversight, to make an informed decision whether to use vitrification, grouting, fluidized bed steam reforming, or other identified treatment approaches to process supplemental LAW (SLAW) into waste forms for disposal.

Given that the FFRDC's draft report has many chapters and sections for the summaries of the analytic results labeled "TBD," and given other gaps in the draft report, this review report makes relatively few formal findings and recommendations. The bulk of this review, like the previous review, consists of observations and suggestions that are intended to provide the FFRDC team members with guidance and assistance—should they decide to take it—in developing their final report. In general, the committee intends for the suggestions to provide useful guidance for the FFRDC in the next phase of its analysis and for the recommendations to be actions that the FFRDC should definitely carry out to meet the congressional

[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 as part of the WTP. See Chapter 1 for more details and Chapter 4 on details about the waste classification and Waste Incidental to Reprocessing determination.

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mandate in Sec. 3134. This review also has some conclusions to show what the FFRDC needs to have in its final report to meet the congressional mandate.

THE NEED FOR A COMPARATIVE ANALYSIS

The committee's fundamental conclusion at this juncture is that the FFRDC's final report needs to provide a structured comparative analysis that can form the basis for selection among the treatment alternatives. Comparative analysis is the essence of the congressionally mandated task. The committee suggests that a useful final report be fundamentally structured around a common set of factors to guide decision-makers. In particular, the committee suggests that the FFRDC's final report:

- Give consideration to the sources, consequences, and probabilities of the several types of risks (health, environment, social, and regulatory) posed and avoided by each alternative approach;
- Assess the reliability (the likelihood that it can be made to operate and then continue to produce waste forms of the intended quality, at the expected rate, on a sustained basis) of the technology underlying the approach;
- Estimate the full lifetime costs of approaches, as both present value and timeline estimates; and
- Prioritize the information and analysis for decision-makers by asking some relevant questions:
    - What information will be of most salience to DOE and its stakeholders?
    - What information would be "show-stoppers" or trigger no-go decisions?
    - What information makes little difference to the final decision, either because it is relatively unimportant, or because there is little meaningful difference between the alternatives in that respect?
    - Where do uncertainties overwhelm the results of the analysis?

Cost-Benefit Analysis

To meet the congressional mandate (see Appendix A), the final report is required to provide a cost-benefit analysis. The committee observes that the draft report provides cost-estimation analysis, which is one component, but does not discuss or list the benefits for consideration of each treatment option; thus, the draft report does not provide a cost-benefit analysis. (See Chapter 2 for more details.)

Finding 2-1

The information compiled by the FFRDC team does not guide the reader to the Sec. 3134 factors and criteria that are most likely to distinguish one treatment approach from another. Especially in view of the volume of information (in more than 150 pages of appendixes) and the number of approaches and variations, it will be difficult for DOE and stakeholders to make the most effective use of the report as presently configured, which has all of the "summary" chapters labeled as "To Be Determined."

Finding 2-2

The FFRDC's current draft report emphasizes information and analysis concerning the treatment approaches in isolation from each other, making a direct comparison of them difficult for decision-makers. The information presented in the draft report lacks meaningful integration for the purpose of comparison. For example, the approaches to supplemental waste treatment are presented separately and not as a comparative analysis. Because the fundamental purpose of the FFRDC analysis is to form the basis for making choices among alternatives, a direct comparison for each factor will greatly improve the utility of the report for decision-making.

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Recommendation 2-1

In order to distinguish one treatment approach from another, in its final report the FFRDC should identify the distinctive aspects of the chosen approaches in a comparative analysis. Moreover, the FFRDC needs to present that information in a manner consistent with cost-benefit analysis practice, adapted to the case where benefits are presented in non-monetized terms.

Recommendation 2-2

The final report should emphasize and describe in detail the most important differences among the alternatives with respect to the decision-relevant attributes, and present the areas of difference in a parallel format that enables ready and accurate comparison for the purposes of the selection of a preferred alternative by the decision-maker.

ANALYSIS OF THE ALTERNATIVE TREATMENT APPROACHES

The FFRDC team presents three primary alternatives, together with variants on each: vitrification, grouting, and steam reforming. As discussed in Review #1, the committee observes that the FFRDC team has appropriately limited its analysis to these three alternatives and key variants. Therefore, as described in Chapter 2, the task for the FFRDC team is to gather the information and provide the analytical results necessary for a decision-maker to distinguish, weigh, and ultimately choose among these particular alternatives. As mentioned above, the draft report has major gaps, especially in the “summary” chapters.

Finding 3-1

As a compilation of information, the FFRDC draft report has collected and documented an impressive amount of material that is relevant to a decision regarding the treatment and disposal of SLAW. Nevertheless, there remain gaps in data and analysis results that have been acknowledged by the FFRDC team that will be required for DOE’s decision-making.

Finding 3-2

The FFRDC’s draft report limits its detailed consideration to three main approaches (vitrification, grout, and steam reforming)—those explicitly identified in Sec. 3134—and variations of those alternatives. The limitation to these three main approaches is justified by the current state of the relevant technologies, and the inclusion of variations takes into account opportunities to improve the effectiveness of each approach and to take advantage of opportunities created by each approach.

Recommendation 3-1

Before finalizing its report, the FFRDC should identify and provide the information and analysis that are critical for a decision by DOE. If it is impossible to gather the necessary information within the time permitted by the authorizing statute, the FFRDC team should clearly identify the gaps and assess their potential impact on the analysis.

Waste Form Performance Following Disposal

A fundamental issue is how well the disposal of the waste forms from the alternatives meets the performance requirements for the disposal sites. Each waste form would have to be understood in enough detail

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(including materials description, location of key radionuclides and metals [as listed under the Resource Conservation and Recovery Act (RCRA)] in the waste form, radionuclides' chemical form, and release mechanisms) such that a decision-maker would know the basis for the performance assessment (PA) in the relevant disposal site. DOE has finished its PA for the Integrated Disposal Facility (IDF) at Hanford, but as of the writing of this review report in mid-September 2018, the PA had not been made publicly available. Nonetheless, during the February 28, 2018, public meeting, the committee received a briefing about the PA and useful data on the inventory of iodine-129 and technetium-99. The PA is based on the assumptions that the LAW would be vitrified and the secondary waste generated from the LAW vitrification process would be grouted.

As discussed in the FFRDC's draft report, waste acceptance criteria are the primary means to determine if a waste form is acceptable for a disposal site. The FFRDC recognizes that while the waste acceptance criteria have been established for the off-site facility at Waste Control Specialists (WCS) near Andrews, Texas, at this time, there are only draft waste acceptance criteria for the IDF at Hanford, and those draft criteria are only for a vitrified LAW waste form. To make a comparison among the various waste forms for the IDF, the FFRDC proposes on page 27 of its draft report that it will perform an analysis that will include "documentation of the waste form release mechanisms, waste form and disposal site assumptions including configuration, inventory of key contaminants, recharge/infiltration, barrier life, waste form release rate parameters, values, and basis, and modeling/assessment tools employed." The committee agrees with this analytic approach and suggests that the FFRDC's final report provide a clear description of this analysis (including assumptions and approximations) for the different waste forms. (See Chapter 3 for more details.)

Costs of Waste Form Processes

In the draft report, the FFRDC discusses that it has selected specific facilities as analogies for the cost estimation for the three treatment approaches and their variants. The analogous facilities are the Defense Waste Processing Facility at Savannah River Site and the WTP's LAW treatment facility for vitrification, the Saltstone processing at Savannah River Site for grouting, and the Integrated Waste Treatment Unit (IWTU) at Idaho National Laboratory for fluidized bed steam reforming (FBSR). The committee observes that the draft report does not list references for the cost-estimation data and does not provide much detail as to why these analogous facilities were chosen. For example, while the FFRDC acknowledges that the IWTU produces a different mineralized waste form than what would be produced with Hanford waste if FBSR were used, the FFRDC does not discuss other FBSR facilities that might be better analogies or at least mention other facilities it may have considered. Thus, the committee suggests that the FFRDC's final report provide more details into the rationale for selecting the best analogous facilities for the FFRDC's cost estimation and provide a list of references to the cost data. The committee also suggests any discussion of uncertainty in the report's cost estimates address the question of asymmetry in the uncertainty, for example, what percentage error around the base estimate can be expected in the upward and downward direction. In addition, and particularly important, the committee suggests the FFRDC try to identify whether those ranges of uncertainty are larger for some of the options than for others. Doing so would more clearly allow decision-makers to gain insight to the robustness of the individual cost estimates. (See Chapter 3 for more details.)

Regulatory Compliance

For obvious reasons, regulatory compliance is a fundamental requirement for any treatment approach that DOE chooses. An analysis of compliance is also mandated by Sec. 3134, which requires the FFRDC to analyze the compliance of the various treatment approaches "with applicable technical standards associated with and contained in" relevant regulations. (See Appendix A for the list of regulations.) The

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committee observes and appreciates that the draft report's Appendix J has an extensive discussion of regulatory compliance issues and that Appendix H on Disposal Site Considerations and Appendix I on Transportation Considerations include discussions of relevant regulations affecting these issues.

As mentioned above, based on the outline in pages 27 and 28 of its draft report, the FFRDC proposes to perform an analysis of the various waste forms for the IDF. In order to have meaningful comparisons, it is important that similar degrees of conservatism in data and assumptions be used in these comparison analyses. It is also important in the FFRDC's final report to describe and discuss the conceptual models and supporting data underpinning the treatment of barriers. The committee also suggests that in the FFRDC's assessment of alternatives that require transportation of nuclear wastes through multiple states, the team consider concerns of potential opposition of local stakeholders along the transportation routes. (See Chapter 3 for more details.)

Finding 3-3

The regulatory environment for the Hanford tank waste is complex and contested. While the committee does not express an opinion on the correct legal interpretations and policy choices, especially with respect to the "as good as glass" issue, it finds that contested regulatory standards represent a significant program risk to any approach.

Recommendation 3-2

The FFRDC report should define to the extent possible the contested regulatory issues with regard to each approach it considers, and describe to the extent possible the impact of the likely outcomes on the choice of approach and program schedule.

ADDITIONAL PROCESSES AFFECTING THE ALTERNATIVE TREATMENT APPROACHES

Among the challenges for the FFRDC team is that the alternative treatment technologies or approaches for SLAW interface with an existing and planned system that begins with waste in tanks that is itself characterized by numerous uncertainties, and ends with a number of different disposal configurations and locations. *The system in which the treatment technology is embedded impacts the choice of technology, and at the same time the choice of technology determines the characteristics and performance requirements of the system.* Consideration of the alternative SLAW approaches in isolation from the systems in which they would operate could lead to poor decisions and is almost certain to miss opportunities to adjust other aspects of the SLAW and the system to achieve a faster, safer, more reliable, and less expensive tank remediation. (See Chapter 4 for more details about the specific additional processes that affect the alternative treatment approaches.)

Finding 4-1

It is reasonable to bound the FFRDC's scope by having it begin with a pre-treated feed stream from the Waste Treatment and Immobilization Plant's pre-treatment plant or the Low-Activity Waste Pretreatment System because it is impractical to re-invent the numerous system-wide studies of the Hanford tank waste situation. However, it is important to recognize that some changes external to the FFRDC's scope could have important downstream impacts on SLAW that are essential to understand when deciding on the preferred SLAW approach.

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Recommendation 4-1

The FFRDC report should consider the impact of these four processes—pre-treatment, off-gas treatment, secondary waste generation treatment, and load leveling and waste blending—on the treatment rate, reliability, performance of secondary waste following disposal, and cost of alternative approaches to SLAW treatment.

THE ANALYTIC HIERARCHY PROCESS AND EXPERT ELICITATION

The Analytic Hierarchy Process (AHP) is a well-known process to help decision-makers create a structured numerical framework reflecting their objectives in choosing an option from among several where the choice involves trade-offs among multiple attributes or "criteria." The hallmark of AHP is that once the structuring steps are completed, AHP guides each decision-maker through a sequence of one-on-one comparisons of the criteria, eliciting *from the decision-maker* what he or she feels is the relative importance of each criterion in maximizing the defined objective. Once all possible pairwise ratings are completed, the AHP software computes a set of relative weights that it will apply to the scores on each criterion (which are assigned in the following step of the process) to produce a rank-ordering of the decision options in terms of how well they meet the overall objective for the decision. Importantly, these weights—and the resulting rank-ordering—necessarily reflect the preferences of the decision-maker. The expressed purpose of the FFRDC's expert elicitation, consistent with use of AHP methodology, was to identify the specific treatment and disposal options to be considered, and to establish a ranking of these options based on consideration of multiple different attributes.

The question of concern to this committee's review is whether AHP is a useful tool for responding to the requirements of Sec. 3134. On that question, the critical point is that the AHP method is intended for use by the decision-makers themselves, perhaps with supporting input from technical experts, to rank alternatives to support making a specific choice among them. The role of the FFRDC team is not to choose or recommend an option but only to provide decision-relevant information about the costs, benefits, risks, and uncertainties of the options. However, in its use of AHP, the FFRDC team has had to incorporate its own set of preferences into the process. (See Chapter 5 for more details.)

Finding 5-1

The FFRDC's role in the Sec. 3134 congressional mandate is to produce a comparison of the costs, benefits, and risk trade-offs necessary to support a well-informed public policy decision-making process by DOE and others, but the implementation of the AHP did not lead to a defensible ranking of the alternatives.

Recommendation 5-1

In its final report, the FFRDC should focus on the decision factors identified by Sec. 3134 as the basis for its analysis. The remainder of the main body of the final report should be structured so as to permit direct comparison of the approaches (including SLAW treatment and pre-treatment variants) according to direct estimation of what is known about each of those factors.

Recommendation 5-2

While ranking alternative approaches according to individual criteria, as the FFRDC has done in the draft report, may inform the decision-maker, the FFRDC's final report should refrain from attempting or presenting a single or unified ranking of alternatives, or assigning priorities or weights to the criteria—and thus avoid supplanting the role of the decision-maker.

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Context and Setting

The nation's biggest and most complex nuclear cleanup challenge is at the Hanford Nuclear Reservation, which has its origins in plutonium production, starting in 1943, during the Manhattan Project. By 1987, when the last and ninth 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 significant amounts of radioactive and other hazardous wastes as well as substantial amounts of airborne, surface, subsurface, and groundwater contamination. 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 a variety of 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 recovery of cesium-137 and strontium-90, 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 and the U.S. Environmental Protection Agency.

In the committee's first review report, the emphasis in the introductory chapter was on the congressional mandate in Section 3134 of the National Defense Authorization Act of Fiscal Year 2017 (Sec. 3134) (see Appendix A). The committee continues to underscore the fundamental importance of this mandate, and thus, this chapter also provides a brief introduction about the study's mandate to set the stage for this review.

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

The salient points for understanding the proposed treatment plan and the congressional mandate are the following. 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 to yield 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.

To treat these two waste streams, the plan is to use vitrification, or immobilization in glass waste forms, for all of the HLW stream and for at least one-third and perhaps all of the LAW stream (depending on analysis yet to be completed and decisions yet to be made). Due to capacity limits in the LAW vitrification facility portion of the Waste Treatment and Immobilization Plant (WTP), which is under construction, DOE-EM anticipates that there will be substantial amounts of low-activity waste that the WTP cannot process. The WTP's design would allow for at least one-third and perhaps about one-half of the LAW to be vitrified. To increase LAW treatment capacity, DOE-EM intends to decide on a supplemental treatment approach and build another treatment facility to implement it. The supplemental low-activity waste (SLAW) to be treated would be similar in composition to the LAW to be treated in the WTP. The LAW—whether from the WTP or the SLAW facility—is intended to be disposed in near-surface facilities, which

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can include the Integrated Disposal Facility (IDF) at Hanford, or off-site such as at the Waste Control Specialists (WCS) facility near Andrews, Texas.

DOE-EM has yet to select a supplemental treatment approach. To help with that selection, Congress has 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), which can produce a calcined powder or a monolithic crystalline ceramic waste form.

Sec. 3134 also asks for identification by DOE of additional alternative approaches, if appropriate. At this stage of the study, neither DOE nor the FFRDC has identified additional primary alternative approaches. As discussed in the FFRDC's draft report, dated July 15, 2018, there are nine variants of these primary three alternatives being considered. Also, to implement the three currently identified approaches, 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.

In parallel to selecting the FFRDC, DOE was directed 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 in order for the review results 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 national laboratories. The charge to the FFRDC team from Sec. 3134 is in Appendix A. The Statement of Task is in Appendix B.

STUDY PROCESS

In this second review, the committee discusses its observations and provides its peer review of the FFRDC's draft report, dated July 15, 2018,[2] and the FFRDC's presentations at the public meeting in Richland, Washington, on July 23-24, 2018.[3] Table 1-1 lists the FFRDC's presentations from this meeting. The webcast videos of the three public meetings are archived and available for viewing.[4]

During the three public meetings, the committee received briefings from several presenters not from the team, as listed in Appendix D. In addition, 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

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

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

[3]For this (the third) public meeting's presentations, see http://dels.nas.edu/Past-Events/Meeting-Supplemental-Treatment/DELS-NRSB-17-02/9944.

[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.

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second and third public meetings from the Washington State 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 scheduled for November 29-30, 2018.

TABLE 1-1 List of the FFRDC's Presentations, given on July 23-24, 2018, in Richland, Washington

Presentation No.	Title
1	FFRDC Team Overview—Bill Bates
2	Baseline, Feed Vector, Uncertainties—Michael Stone
3	Analysis Approach—Tom Brouns
4	Base and Variant Case Overview—Michael Stone
5	Pretreatment Approaches—Michael Stone
6	"Other" Considerations—Tom Brouns
7	Vitrification Cases—Alex Cozzi
8	Grout Cases—George Guthrie
9	Steam Reforming Cases—Nick Soelberg
10	Transportation and Disposal Site Considerations—Paul Shoemaker
11	Estimate Methodology and Results—Frank Sinclair
12	Analysis Results—Sharon Robinson
13	Summary—Bill Bates

TABLE 1-2 Planned Schedule of Forthcoming Public Meetings, FFRDC Reports, and Committee Reviews

Timing	Activity
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-September 2018	The committee's second review report is prepared and reviewed.
October 2018	The FFRDC receives committee's review to take into account during its work on its final draft report. Committee's review report is published.
November 2018	The FFRDC sends third draft report to the committee.
November 29-30, 2018	Public meeting #4 in Richland, Washington, to discuss the second review report and the third draft FFRDC report, as well as to hear from stakeholders
December 2018-January 2019	The committee's third review report is prepared and reviewed.
February-April 2019	Period for review and comments by stakeholders and the interested public on the FFRDC's fourth draft report and the committee's third review report.
April 2019	Convene public meeting in Richland, Washington, for the committee to receive presentations from the FFRDC on its final report, as well as comments from stakeholders and interested members of the public.
April-June 2019	The FFRDC releases its final report to the public, and the committee's final review report is prepared and published.
June-July 2019	Final briefings to Congress, DOE, and other stakeholders.

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To perform the peer review task, the National Academies formed a committee composed of 13 experts 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 other DOE-EM sites. Appendix E 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 conditioning, 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.

THE HANFORD REGION'S ENVIRONMENT AND THE TRIBAL NATIONS

Knowing the vital role of the Columbia River and the surrounding environment is essential to understanding the Hanford Nuclear Reservation. The Columbia River is the fourth largest river in the United States by flow volume and has its headwaters in Canada. After making a journey of more than 1,200 miles, its waters flow into the Pacific Ocean at the border between the states of Washington and Oregon. A free-flowing section of the Columbia River, the Hanford Reach, forms the northern boundary of the Hanford Nuclear Reservation.

The availability of electricity from the Grand Coulee Dam on the Columbia River was a major factor in choosing the Hanford Site during the Manhattan Project. Equally important, water from the Columbia River was necessary to cool the plutonium production reactors. In the absence of the Columbia River, the Hanford Site would not have been given the mission to produce plutonium for nuclear weapons. The waste cleanup legacy from this mission affects the quality of Columbia River water and the surrounding environment.

Today, stakeholders and other members of the public speak, at times passionately, to the importance of the Columbia River for the well-being of those who live in the region. Indicative of the strength of this public sentiment, this review notes some particular comments received during the information-gathering sessions[5]:

- The river is the economic and ecological heart of the region, and the ancestral and modern-day home to tribes.
- This river's importance to our state, our region, and our identity is not debatable.
- The Columbia River must be protected.

For thousands of years, several tribes have lived by the Columbia River; these tribal nations include the Yakama, the Umatilla, the Nez Pierce, and the Wanapum. Members of these tribes are among today's stakeholders. Their comments have informed both this review report and the previous review report.

In 1943, the U.S. Army arrived at the site that was to become the Hanford Nuclear Reservation. The Army's task was to clear the land of inhabitants and begin construction of the facilities needed to produce plutonium. In addition to ranchers and farmers who had more recently settled on the land, members of the Wanapum were still in the area, and they fished and gathered food along the Columbia River. Along with the ranchers and farmers, in 1943 the Wanapum were forced to abandon their lands along the river so that construction at the Hanford Site could begin.

This committee's first report (hereafter referred to as Review #1) published June 8, 2018, included comments from Matthew Johnson, a representative of the Confederated Tribes of the Umatilla Indian Reservation. Although he reported that his tribe had ceded to the United States 6.4 million acres in the Treaty of 1855, the tribe has retained certain rights to hunt, gather, and pasture animals and to fish at usual and accustomed places, which include parts of the Hanford Nuclear Reservation.

[5]These comments and those below have been paraphrased from the stakeholders' presentations. To view the videos of these presentations, see http://www.tvworldwide.com/events/nas/180723/.

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He further noted:

- Tribal health and culture is based on the ability to access and safely use traditional foods, known as First Foods.
- We are a food-based culture and need safe access to those foods.
- We want the natural and cultural resources to be protected, restored, clean, and safe to use.

He also emphasized that members of his tribe do not view Hanford with the same time perspective as do many others, stating, “We have been here for 10,000 years.”

This review report adds the voice of Alfrieda Peters, a representative of the Yakama Nation, who also spoke of the tribal and personal connections to the Columbia River and of the importance she gave to the land surrounding it:

- Since time immemorial, our ancestors fished, hunted, and gathered food on this land.
- The Yakamas are inseparable from this land. This land and all its resources have been our homeland.
- We are here to express our opinion about leaving high-activity waste near the Columbia.
- We are opposed to DOE’s reclassifying of the high-level waste and want all wastes to be removed from the site.

THE WASTE TANKS AND THEIR CONDITION

In relatively close proximity to the Columbia River, the presence of radioactive waste is highly problematic to those living in the area today, as indicated by the Yakama Nation representative’s comments. As mentioned earlier, the cleanup challenge centers today and for the coming decades on the waste tanks. According to DOE-EM, DOE’s Office of River Protection (DOE-ORP) is charged with the mission: “To safeguard the nuclear waste stored in Hanford’s 177 underground tanks, and to manage the waste safely and responsibly until it can be treated in the Waste Treatment and Immobilization Plant for final disposition” (DOE-EM, 2015). These tanks are aging, and many are operating well beyond their design life. More than sixty tanks may have already leaked more than 1 million gallons of waste into the ground, according to DOE’s estimates (GAO, 2017). As time passes, more tanks are likely to leak; however, mitigating this risk is that practically all of the liquids able to be pumped from the single-shell tanks have been removed and placed in the double-shell tanks. The tank degradation time clock is running, thus adding urgency to all of the information presented in this review and the overall tank remediation effort. Failure to retrieve, treat, and store waste from these tanks could eventually result in environmental, economic, and public health consequences to those living in the region. A failure also represents a broken TPA commitment to safely remove waste from the tanks in a timely manner.

As part of its fact-finding in July, the committee visited one of the tank farms and entered an aboveground mock-up of one of the tanks—part of the Cold Test Facility—to better appreciate the massive size of a tank and to learn about the technologies used to remove the waste contents. The presentations given by DOE-ORP and Washington River Protection Systems provided the following information concerning tank remediation:

- Several technologies have been used to retrieve waste out of several single-shell tanks, including a “sluicer” (nozzle jet) that sprays high-pressure liquid, including recycled waste, to create slurries that are pumped out of the tanks.
- All of the retrieved waste subsequently goes to an evaporator to reduce its volume by removing excess water. Next, this waste is added to a double-shell tank.
- The available capacity in the existing 28 double-shell tanks is not sufficient to hold all of the waste now contained in the 149 single-shell tanks, although the capacity of an individual double-shell

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tank is typically significantly bigger than a single-shell tank. As noted above, the liquids able to be pumped from the single-shell tanks have been placed into the double-shell tanks. Once the WTP is operational, it will take waste from the double-shell tanks to free up capacity in order to allow more retrieval from the single-shell tanks. Thus, waste retrieval from all of the single-shell tanks depends on an operational WTP, according to DOE-EM's current treatment plan.

- To date, waste has been removed from 18 single-shell tanks, leaving no more than half of an inch of residual waste in each of these tank bottoms.
- DOE-ORP intends to back-fill the nearly empty tanks with grout that contains additives to retain any remaining radionuclides.

While maintaining the integrity of the tanks and retrieving waste from the tanks are important for managing risks, the committee notes what is not in the scope of the FFRDC's analysis and the committee's review, namely, tank waste management and retrieval, HLW processing and treatment, and the WTP's design, construction, and operations. Nonetheless, decisions about how and when to treat the SLAW affect the overarching systemic risks, and as noted above, the SLAW will derive from processing the tank waste in the WTP pre-treatment facility.

VITRIFICATION, THE CONCEPT OF "AS GOOD AS GLASS" FOR OTHER WASTE FORMS, AND WASTE DISPOSAL OPTIONS

During the three public meetings, the committee heard strong views, especially from representatives of the Washington State Department of Ecology, in favor of using a vitrified waste form for SLAW. Because the selection of the SLAW treatment approach is central to this study, this section provides context for the Washington State Department of Ecology's position. The committee notes that this section is not a detailed history, but interested readers can delve into the references in the Washington State Department of Ecology's public presentations as well as the relevant sections of the 2011 National Research Council Consensus Study Report *Waste Forms Technology and Performance* (NRC, 2011).

The Washington State Department of Ecology has expressed two main concerns about waste forms other than glass: inferior waste form performance (specifically, degradation rates and the release rates of radionuclides and some chemicals) and increased waste volume. The increased waste volume concern is directed at grout waste forms, which would be about twice the volume of glass waste forms for the projected volume of low-activity waste to be treated, according to the Washington State Department of Ecology. Indeed, the FFRDC's draft report (see Table F-14) posits that the volume for a grouted waste form would increase by a factor of 1.8. The Washington State Department of Ecology has told DOE that it has assessed that this increased volume "would create increased disposal needs and associated costs" (DOE, 2012).

As to waste form performance, the Washington State Department of Ecology has stated that any non-vitrified waste forms would have to be "as good as glass." This regulatory agency has pointed to the definition of "as good as glass" given by Roy Schepens, then Site Manager at DOE-ORP, in a June 12, 2003, letter to Mike Wilson of the Washington State Department of Ecology:

> The waste form resulting from treatment must meet the same qualifications of those imposed for the expected glass form produced by the Waste Treatment Plant (WTP). We expect all waste forms produced from any supplemental technology to: (1) perform over the specified time period as well as, or better than WTP vitrified waste; (2) be equally protective of the environment as WTP glass; (3) meet LDR [land disposal restrictions] requirements for hazardous waste constituents; (4) meet or exceed all appropriate performance requirements for glass, including those identified in the WTP contract, Immobilized Low-Activity Waste (ILAW) Interface Control Documents, and ILAW Performance Assessment. (Schepens, 2003; DOE, 2012)

The committee points out that it is not endorsing this view. The concept of "good as glass" is based on a history of discussions among DOE, the State of Washington, and others. There is undeniable ambiguity

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and disagreement about DOE's acceptance of the concept, to say nothing of its precise meaning. More importantly, the concept has not, to the committee's knowledge, been adopted as a formal regulation or guidance by the federal government. While it is neither the FFRDC's nor the committee's role to define or urge adoption or rejection of a particular legal or regulatory standard, the FFRDC and committee would be remiss in ignoring the issue. "Good as glass" is fundamental to the interaction of DOE with the State of Washington, the Tribal Nations, and a large number of stakeholders. Agreement that such a concept—however defined—has been met would presumably go a long way to removing regulatory uncertainties and speeding implementation of a non-vitrification approach. On the other hand, the lack of agreement that a non-vitrification approach is "as good as glass" (again: however defined) will unquestionably increase uncertainty and may well extend the time to implementation. The committee cannot resolve the question—that is a matter for political and possibly judicial bodies—but the committee urges the FFRDC to elaborate the issues involved as a basis for the committee's review in the next review report.

Data in DOE's *Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington*, dated November 2012, appear to support the Washington State Department of Ecology's position that the non-vitrified waste forms being considered for SLAW treatment are not "as good as glass" or have significant uncertainties as to whether they are "as good as glass." For example, page S-75 of the Environmental Impact Statement states:

> Because the release rates for [Immobilized] glass are low and are supported by experiment, there is less uncertainty regarding this waste form compared to bulk vitrification glass, cast stone waste [grout-type waste form], and steam reforming waste. Of these supplemental treatment [Immobilized LAW] forms, the least amount of characterization and testing has been performed for steam reforming waste. Thus, the greatest degree of uncertainty relative to waste form performance is associated with the steam reforming waste. (DOE, 2012)

In addition, the Environmental Impact Statement, on page S-132, states that the radiological risk to a member of the public for steam-reformed LAW waste form is about an order of magnitude greater than a LAW glass waste form due to projected releases of the radionuclides technetium-99 and iodine-129 (DOE, 2012). The November 2012 Environmental Impact Statement is the most recently published document that the Washington State Department of Ecology has cited at the committee's July 23, 2018, public meeting to support its position on "as good as glass," though the document is capable of less prescriptive interpretations.

The current congressionally mandated study is an opportunity to bring new analysis to bear on the issue of "as good as glass." In Review #1, the committee suggested "that the FFRDC's analysis discuss what would be required for the non-vitrified waste forms being assessed to be considered 'as good as glass' in the context of the current state of technology for waste forms other than glass from a technical and human health risk perspective" (NASEM, 2018, p. 2). The FFRDC's draft report, dated July 15, 2018, does not provide this analysis. The committee reiterates its previous suggestion that the FFRDC provide this analysis in its forthcoming report.

An essential related issue is which disposal facility or facilities would accept various waste forms. DOE has recently evaluated the IDF's performance by assuming the LAW per se was vitrified and the secondary waste was in a grout waste form. (As of the writing of this review report in mid-September 2018, the performance assessment had not been released, but the committee received a briefing on aspects of this assessment at the second public meeting.) Notably, there has not been a performance assessment for the IDF that considers non-vitrified SLAW waste forms. The committee is not aware of plans for such a performance assessment. That being the case, any primary non-vitrified waste forms for SLAW would not be permitted in the IDF until a performance assessment including such waste forms was completed and waste acceptance criteria based on the assessment are established by DOE and the Washington State Department of Ecology.

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If any selected off-site facility, e.g., WCS, declines to accept non-vitrified waste (assuming that this is chosen to treat the SLAW) from Hanford at any time during the decades of SLAW treatment, this treatment could come to a halt and that would also most likely affect the continued treatment of the HLW, which would likely have ripple effects throughout the cleanup mission at Hanford. The committee notes that the Washington State Department of Ecology's presentation on July 23, 2018, mentioned that the need for SLAW could be overtaken by events, for example: "If DOE optimizes the operation of current facilities and glass loading." Alternatively: "If DOE foregoes pretreatment and replaces it with Direct Feed HLW." And finally: "If DOE considers off-site (out of state) disposal of LAW at Waste Control Specialists in Texas." As a major party to the TPA and as the Washington State environmental regulatory agency, the Washington State Department of Ecology and the State officials to which it reports obviously have a key role, if not *the* key role, in determining whether to permit non-vitrified waste forms in the IDF.

For an expanded range of disposal options, the Washington State Department of Ecology and some stakeholders have expressed the view that DOE must show that the non-vitrified SLAW forms must meet the "as good as glass" performance concept. Without expressing a view on whether DOE is legally or otherwise obligated to make such a demonstration, the committee notes that this is a contested regulatory issue and has been for quite a long time; therefore, the committee restates its advice from Review #1 to the FFRDC to provide its technical analysis on durability, protectiveness, leachability, and other performance criteria for the non-vitrified waste forms.

Another major consideration and motivation for this study is the cost for various SLAW treatment approaches. As Jonathan Epstein, a professional staff member of the Senate Armed Services Committee, explained to the National Academies committee during the first public meeting in December 2017, a major rationale for the congressional mandate is to "fully inform" Congress, DOE, and other decision-makers about the costs for the various treatment technologies. In particular, he emphasized that a recent U.S. Government Accountability Office (GAO) report indicated significant cost savings for the grout treatment approach as compared to vitrification based on the experience of the Savannah River Site's use of grout for about 4 million gallons of LAW (GAO, 2017). However, he pointed out that the chemical composition of the LAW at the Savannah River Site is not as complex as the LAW at Hanford, and this could affect the cost of using grout treatment at Hanford. He then underscored the importance of Sec. 3134 in ensuring that a credible analytic study is performed by the FFRDC to include a cost-benefit analysis for each treatment approach. Notably, the GAO report 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."

REVIEW REPORT ORGANIZATION

The remainder of this review report is structured as follows:

- Chapter 2 provides the committee's basic description of the draft report and its organization, identification of self-evident gaps, and discussion of the importance of and the need for a comparative analysis, including a cost-benefit analysis.
- Chapter 3 is the centerpiece of this review report in that it examines whether and how the FFRDC's draft report analyzes the four critical issues for decision-makers and other stakeholders of (1) the safety of an alternative approach following waste disposal and the risks of the treatment technology, (2) confidence in whether each waste form production technology will work, (3) costs of the waste formation processes and comparison to each other, and (4) whether the waste form will comply with applicable laws and regulations.

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- Chapter 4 discusses four (at first glance peripheral, but actually integral) additional processes that need to be considered for all treatment technologies. These four processes are additional SLAW pre-treatment, off-gas treatment, secondary waste, and load (SLAW feed rate) leveling and waste blending.
- Chapter 5 examines the FFRDC's use of the analytic hierarchy process for its expert elicitation, which appears to be the FFRDC's intended approach for a comparative analysis of the alternatives, and examines what is needed for a comparative analysis that will be helpful for decision-makers.

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2

The Committee's Major Observations and Overarching Assessment of the FFRDC's Draft Report

This chapter has two parts: overall observations concerning the Federally Funded Research and Development Center's (FFRDC's) draft report of July 15, 2018, including identification of work still to be done, and discussion of the importance of and need for a comparative analysis of the supplemental low-activity waste (SLAW) treatment options, including a cost-benefit analysis. The committee received the team's second draft report on July 16, 2018. This draft report formed the basis for discussion at the public meeting at Richland, Washington, held July 23-24, 2018. Table 2-1 lists the contents of the draft report, and Table 1-1 lists the FFRDC's presentations shown at the public meeting.

OVERALL OBSERVATIONS

The committee offers several general observations about the (1) overall structure of the draft report and its completeness, (2) compilation and presentation of information, (3) clarity of the writing for decision-makers, (4) adequacy of the executive summary, and (5) identification of key risks and characterization of those risks.

Table 2-1 lists the contents of the FFRDC's draft report. The committee's first observation is that the draft report clearly remains a work in progress. It is also clear that the FFRDC has done significant work, under tight deadlines, since the first set of draft working documents the FFRDC sent the committee in mid-February 2018. Nevertheless, a great deal of work has yet to be done, primarily in the area of integrating a large amount of information for enabling the comparison of alternatives in a decision-relevant format—the central purpose of the FFRDC's report.

The overall structure of the draft report is that it first briefly discusses "Parameters of the Analysis," including sections on "Strategy," "Scope," "Uncertainties," "Technical Challenges," and "Cost-Estimation Summary." It then gives an overview of the proposed processes at Hanford for treatment of LAW and SLAW. Next, it has a section on "Analysis Risk Assessment," which is essentially an outline of the components of the intended risk assessment for the types of risk to be considered (project, alternatives, and environmental); it does not contain the results of any actual risk assessments.

These initial chapters are followed by chapters that will address, in summary form, the specific elements of the task before the FFRDC: the technologies assessed by the team (i.e., pre-treatment, vitrification, steam reforming, grout, and other approaches) (Chapter 4), disposal site (Chapter 5), transportation (Chapter 6), and finally a comparative analysis of approaches (Chapter 7). These summaries do not appear in the report and had yet to be written by the time of the committee's public meeting on July 23-24, 2018. Instead, placeholder phrases refer the reader to a series of appendixes, A-K, which provide detailed discussions of the relevant materials, technologies, regulations, cost, and comparison methodologies. The appendixes are descriptive, as opposed to evaluative or analytical. Thus, the appendixes contain more than 150 pages of valuable supporting information and a foundation for the summary chapters; however, each appendix functions essentially as a stand-alone document, and its essential information still has to be integrated into the main body of the report.

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In the chapters to be completed, the FFRDC would have to integrate, analyze, and compare the alternatives being considered in its analysis. At the July public meeting, the FFRDC team leader told the committee that the FFRDC will provide a complete final draft report before the next public meeting on November 29-30, 2018.

The committee's second set of observations is about the compilation of information in the draft report. The report contains an impressive amount of information, but the authors have not prioritized this information according to either the general significance of the information, or—more importantly—the extent to which particular factors distinguish between alternatives and thus form the basis for choosing among them. For example, facts and findings are not distinguished according to their significance or influence on the choice among approaches. In addition, this information lacks meaningful integration. For example, the approaches to SLAW treatment are presented separately and not as a comparative analysis. A comparative analysis—presumably to be supplied in the future report in the summary chapters—would most usefully serve the needs of decision-makers.

The committee's third area of observations concerns the ways in which the draft report communicates information and analysis. This is especially true for the choices on whether to primarily use very technical language or laypersons' terms. This is important because many readers of the final report will not be engineers and scientists. Moreover, many decision-makers and stakeholders are not technical experts in the complex subject matter of SLAW treatment. Thus, decision-makers would benefit from a final report that uses transparent plain English (as much as possible), with clear explanations of complex technical issues where required.

TABLE 2-1 List of the Chapters and Appendixes in the FFRDC Draft Report, "Report of Analysis of Approaches to Supplemental Treatment of Low-Activity Waste at the Hanford Nuclear Reservation," Dated July 15, 2018

Chapter No.	Title
0	Executive Summary
1	Parameters of the Analysis
2	Hanford LAW Overview
3	Analysis Risk Assessment
4	Assessment Area Summaries (to be provided)
5	Summary of Disposal Site Considerations (to be provided)
6	Summary of Transportation Considerations (to be provided)
7	Comparative Analysis of Approaches Summary (to be provided)
Appendix A	Expanded Discussion—Pretreatment
Appendix B	Expanded Discussion—Vitrification
Appendix C	Expanded Discussion—Steam Reforming
Appendix D	Expanded Discussion—Grout
Appendix E	Expanded Discussion—Other Approaches
Appendix F	Expanded Discussion—Comparative Analysis of Approaches
Appendix G	Expanded Discussion—Cost-Estimate Methodology and Basis
Appendix H	Expanded Discussion—Disposal Site Considerations
Appendix I	Expanded Discussion—Transportation Considerations
Appendix J	Expanded Discussion—Regulatory Compliance
Appendix K	Expanded Discussion—Feed Vector
Appendix L	Bibliography

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The committee's fourth observation is that the executive summary neither reflects key findings of the draft report, nor does it adequately characterize the alternatives, explain systemic risks, or in any way provide the important information needed by decision-makers. The executive summary would have to serve this purpose, as it is often the most widely read part of a document.

The committee has also observed that the FFRDC team has done a credible job identifying individual key risks (and assumptions—which by their nature can represent uncertainties in the risks) associated with the overall tank farm cleanup and its potential impact on SLAW composition and feed rates. The team has also identified key risks and assumptions with the three primary SLAW processing approaches and variants within the approaches. Significant work, however, remains to be done in characterizing those risks and their impacts on the alternative approaches to treating SLAW both individually and comparatively. It is particularly important for the FFRDC to explain, characterize, and transparently present information on alternative approaches to SLAW treatment (and their relationship to the larger tank remediation effort) to help decision-makers understand the highly complex nature of the SLAW treatment system and how their decisions can impact future outcomes. The FFRDC's draft report as currently configured does not achieve this goal.

The introductory chapter, "Parameters of the Analysis," could usefully be structured as a more traditional introduction to present what the team is trying to do in the rest of the report (focusing on comparing SLAW treatment alternatives), why the team is doing it (meeting the congressional mandate in Section [Sec.] 3134), and how the team is doing it (defining the scope of the SLAW treatment, identifying main process alternatives, developing flowsheets for each alternative, obtaining or creating data for each criterion of each alternative, juxtaposing the data, and evaluating the juxtaposition to support the comparison among alternatives). Some of these steps are listed in the draft report. But the trail leading to the evaluation of the juxtaposition of alternatives is too brief and is camouflaged by the early introduction and extensive discussion of the GAO "best practices." Some specific suggestions for improving this section are as follows:

- Here and in the rest of the report the sequence of thought and analysis need to be transparent to readers who may be unfamiliar with the details of the Hanford cleanup effort or possibly even nuclear technology.
- Move the "best practices" table to an appendix with a short description of how they were used, including discussion of why the U.S. Department of Energy (DOE) orders, guides, and standards were not used.
- Associate the discussion of uncertainties, technical challenges, and cost estimation with related sections in the main body or appendixes.
- Identify previous studies of and experience with SLAW treatment and pre-treatment technologies, summarize their results, and discuss any important differences between the previous and current results. For example, specifically, previous bulk-vitrification work has been explored at Hanford. While there are important differences between the bulk and currently proposed vitrification processes, that experience could yield valuable insights into technical and cost aspects of the proposed SLAW process.

THE NEED FOR A COMPARATIVE ANALYSIS

According to Sec. 3134 (see Appendix A), the task set by Congress for the FFRDC team is to perform "an analysis of approaches" that will provide the technical and analytical basis on which DOE, in consultation with the Washington State Department of Ecology and other stakeholders, can make a well-informed choice among the technologies available for treating SLAW for permanent disposal. This is not a simple task. Within a very constrained amount of time, the team is required to gather and present a very large amount of information, created over many years, about three basic approaches to treatment of SLAW; and to present that information in a way that enables decision-makers to make an informed and respected choice in a context of intense public scrutiny and even skepticism. At the same time, because the team is neither the decision-maker, nor has it been asked to recommend a particular choice among alternatives, the team's

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report has to be careful to provide an analysis in which the particular strengths and weaknesses of each approach are clearly and fairly represented. The team's role is to facilitate the choice, but not preordain or make the choice. To facilitate decision-making, the committee offers this overarching guidance for all future reports of the FFRDC:

- Assemble and frame information in ways that will clearly convey useful information to decision-makers.
- Find and use communications experts and a technical editor in assembling and framing information to be accessible to non-technical readers.
- Provide analyses that will make it relatively easy for decision-makers to compare the various aspects of the treatment approaches without preordaining the conclusion.
- Ensure that the graphs and images are designed and selected to facilitate interpretation and guide decision-makers, for example, by showing a projected timeline of construction and operations for each approach with projected costs per year.

More fundamentally, the committee suggests that the final report provide a structured comparative analysis that can form the basis for selection among alternatives. Sec. 3134 (see Appendix A) provides criteria for the FFRDC to use:

- The risks of each approach,
- Their costs and benefits,
- The anticipated schedules,
- Compliance of each approach with applicable laws and regulations, and
- Any obstacles to implementation.

While a comparative table appears in Appendix F (see Table F-2) of the draft report, comparative analysis is the essence of the congressionally mandated task, and the committee suggests that the FFRDC consider it as the organizing structure. A useful final report would be fundamentally structured around a common set of factors. For example, there is no clear parallelism in the presentation of each approach in the appendixes in accordance with these criteria. This is more than a rhetorical misdemeanor or a mere convenience for the reader. It deprives the user of the report—and indeed the *authors* of the report—of a direct side-by-side comparison of alternatives that informs deciding among them. If this is not done, key features are likely to be missed, and comparisons are likely to be inconsistent. While detailed descriptions of each approach are unquestionably important, they would most usefully be presented with the comparative task and the ultimate objective.

Likewise, the criteria would need to be characterized so as to respond to decision-makers' questions, and not general exposition. The committee suggests that the final report consider the sources, consequences, and probabilities of the several types of risks (health, environment, social, and regulatory) posed and avoided by each approach; assess the reliability (the likelihood that it can be made to operate and then continue to produce waste forms of the intended quality, at the expected rate, on a sustained basis) of the technology underlying the approach; and estimate the full lifetime costs of approaches.

A comparative analysis would have to recognize that not every criterion is equally important, and that some criteria are more meaningful discriminators among approaches than others. Up to the point of the draft report, the FFRDC team has, quite reasonably, focused on comprehensive information gathering and technical assessment of each approach, as the summary-and-appendix structure of the draft report clearly reflects. This structure is both sensible and commendable, as comprehensiveness has utility and is essential to the added value and the credibility of the present study.

The committee suggests, however, that in the forthcoming final report, the team prioritize the information and analysis for decision-makers by asking some relevant questions:

- What information will be of most salience to DOE and its stakeholders?

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- What information would be "show-stoppers" or trigger no-go decisions?
- What information makes little difference to the final decision, either because it is relatively unimportant, or because there is little meaningful difference between the alternatives in that respect?
- Where do uncertainties overwhelm the results of the analysis?

This kind of analysis is not foreign to the team, because in its comparison section the team rejected for further consideration several variants of the three basic approaches. This was a useful and desirable step in the comparison process, in order to winnow down the alternatives to a manageable number for decision-makers. According to its presentation at the July public meeting, the team used criteria such as exorbitant cost, technological infeasibility, and not differentiating among the approaches or variants as a basis for winnowing. The team's winnowing results seem sensible; however, the winnowing process is not well described and is essentially tacked onto, rather than being integral to, the draft report.

Cost-Benefit Analysis

An essential part of the comparative analysis is a cost-benefit analysis. Sec. 3134 requires the FFRDC to analyze "the benefits and costs of such approaches," where the approaches are the various technologies for the treatment of SLAW. The committee notes that the FFRDC's draft report does not explicitly discuss cost-benefit analysis. However, the draft report does present cost estimation, which is a necessary input to a cost-benefit analysis. A cost-benefit analysis sums the total costs of an activity (in this study, a treatment approach) and compares it against its total benefits. For ease of comparison, a cost-benefit analysis typically places a value on each benefit. But in practice, many of the key benefits are often not possible to monetize, and that is the case here too. Nevertheless, all important benefits need to be identified and estimated, even if not in a monetized form, so that one can assess the nature and degree of trade-offs between the costs of alternative options and the benefits (or risks) associated with those options. Indeed, a clear and well-structured list of the important categories of costs and benefits that could arise from consideration of each treatment approach can provide very useful input for decision-making and for strategizing; providing an analysis-based summary of their relative magnitudes (even if in non-monetized form) is, however, a hallmark of good cost-benefit analysis.

On the benefits side of the ledger, there will be many commonly shared benefits for the different treatment approaches. For example, each approach will provide the benefit of a vastly safer and healthier environment in the Hanford region compared to current conditions. It is clear that this benefit can vary depending on the waste form, chosen disposal site, and disposal performance, and the challenge for decision-making is in understanding the qualitative and quantitative differences in these benefits for different SLAW options. Thus, the main qualitative dimensions of these benefits need to be explained in understandable terms, and within those benefit dimensions the relative performance of each option needs to be reported in terms that allow direct comparison to each other. It is important to explain not just that the options differ in their expected waste performance, but by how much. For example, risk to the most exposed individual over time should be illustrated for each option, even if broad uncertainty bands are placed on each. The same can be done regarding differences in cleanup schedule and its uncertainties. Only in this way can decision-makers make informed decisions about how much additional cost is "worth it" from a societal perspective.

As the FFRDC has already recognized, the costs can certainly vary significantly for different treatment approaches (as discussed in Appendix G of the draft report and Chapter 3 of this review). However, an important and essential technique of cost-benefit analysis is to present the present value of the costs, and to present the timeline of the costs that comprise that present value to understand its implications from a budgetary risk, as well. Present value is a quantitative means to recognize that costs occurring in the future are weighted less than costs incurred today. This is accomplished by discounting future costs in the spending timeline to compare them to near-term costs. The U.S. Office of Management and Budget recommends that

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cost-benefit analyses use both a 3 percent and 7 percent discount rate when comparing alternative regulatory options, to help understand how sensitive the total costs are to a range of discount rates that may be appropriate for societal decisions. In section 1.1, page 13 of the draft report, it is noted that the U.S. Government Accountability Office (GAO) best practice is to give "the life-cycle cost estimate in present value terms" and discuss the reason for choosing a specific discount rate. The team mentions that it "presented life-cycle costs in present value terms," but it does not mention what discount rate it chose and why a particular discount rate was chosen or not chosen. Also, the report does not provide the associated timeline of spending, which would have to be exactly consistent with the present value estimates, and are important for understanding if some of the options involve very different budgetary challenges.

The above discussion of present values is stated only in terms of the cost element, because the committee does not expect that the benefits that the FFRDC needs to characterize will or can be done in a monetized format. If they could be, then discounting would apply to benefits estimates, and the present value of net benefits (i.e., benefits minus costs) would be appropriate to compute as well. However, note that the suggestion to present risks over time reflects a similar informational objective.

Finding 2-1

The information compiled by the FFRDC team does not guide the reader to the Sec. 3134 factors and criteria that are most likely to distinguish one treatment approach from another. Especially in view of the volume of information (in more than 150 pages of appendixes) and the number of approaches and variations, it will be difficult for DOE and stakeholders to make the most effective use of the report as presently configured, which has all of the "summary" chapters labeled as "To Be Determined."

Finding 2-2

The FFRDC's draft report emphasizes information and analysis concerning the treatment approaches in isolation from each other, making a direct comparison of them difficult for decision-makers. At this point in the drafting process, the information presented in the draft report lacks meaningful integration for the purpose of comparison. For example, the approaches to supplemental waste treatment are presented separately and not as a comparative analysis. Because the fundamental purpose of the FFRDC analysis is to form the basis for making choices among alternatives, a direct comparison for each factor will greatly improve the utility of the report for decision-making.

Recommendation 2-1

In order to distinguish one treatment approach from another, in its final report the FFRDC should identify the distinctive aspects of the chosen approaches in a comparative analysis. Moreover, the FFRDC needs to present that information in a manner consistent with cost-benefit analysis practice, adapted to the case where benefits are presented in non-monetized terms.

Recommendation 2-2

The final report should emphasize and describe in detail the most important differences among the alternatives with respect to the decision-relevant attributes, and present the areas of difference in a parallel format that enables ready and accurate comparison for the purposes of the selection of a preferred alternative by the decision-maker.

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3

Analysis of the Alternative Treatment Approaches

The Federally Funded Research and Development Center (FFRDC) team presents three primary treatment alternatives, together with variants on each: vitrification, grouting, and steam reforming. As discussed in Review #1, the committee observes that the FFRDC team has appropriately limited its analysis to these three alternatives and key variants due to technical maturity. Therefore, as described in Chapter 2, the task for the team is to gather the information and provide analytical results necessary for a decision-maker to distinguish, weigh, and ultimately choose among these particular alternatives. (More fundamental alternatives—such as no-action, not separating high-level waste [HLW] and low-activity waste [LAW], or redesigning the treatment system currently under construction to eliminate the need for supplement LAW [SLAW] treatment—are beyond the scope of the team's task and thus beyond the committee's scope as well.)

Finding 3-1

As a compilation of information, the FFRDC draft report has collected and documented an impressive amount of material that is relevant to a decision regarding the treatment and disposal of SLAW. Nevertheless, there remain gaps in data and analysis results that have been acknowledged by the FFRDC team that will be required for the U.S. Department of Energy's (DOE's) decision-making.

Finding 3-2

The FFRDC's draft report limits its detailed consideration to three main approaches (vitrification, grout, and steam reforming)—those explicitly identified in Section (Sec.) 3134—and variations of those alternatives. The limitation to these three main approaches is justified by the current state of the relevant technologies, and the inclusion of variations takes into account opportunities to improve the effectiveness of each approach and to take advantage of opportunities created by each approach.

Recommendation 3-1

Before finalizing its report, the FFRDC should identify and provide the information and analysis that are critical for a decision by DOE. If it is impossible to gather the necessary information within the time permitted by the authorizing statute, the FFRDC team should clearly identify the gaps and assess their potential impact on the analysis.

The four sections of this chapter are intended to reflect in general terms the approach recommended above. Put informally, the core questions for decision-makers concerning the selection of the treatment approach and the corresponding waste form are:

- *How safe is an alternative in comparison to others following waste disposal?*
- *What is the level of confidence that each waste form production process will work?* For example, are these technologies safe, reliable, and feasible?
- *How much will each waste formation process cost?* In addition, how do the costs for the various waste formation processes compare to each other, and what are the effects of funding constraints?

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- *Will the waste form comply with applicable laws and regulations?*

By presenting these issues comparatively, the FFRDC's final report can provide invaluable assistance to DOE, the regulators, Congress, and stakeholders in seeking the best approach to the management of SLAW.

SAFETY OF THE ALTERNATIVES FOLLOWING WASTE DISPOSAL

How safe is an alternative in comparison to others following waste disposal? This section considers essential issues for understanding how waste form performance affects safety with the view toward what the FFRDC needs to address in its forthcoming report. The performance assessments of the waste disposal sites are fundamental documents for determining what waste forms are acceptable for a particular site or sites. As mentioned in Chapter 1 of this review, DOE has finished its performance assessment (PA) of the Integrated Disposal Facility (IDF) at Hanford, but as of July 15, 2018, the release date of the FFRDC's draft report, DOE had not yet made the PA publicly available and had not done so during the time of the committee's writing of this review. However, at the public meeting on February 28, 2018, the committee and the FFRDC received briefings relevant to the PA.

While these briefings were useful, the committee observes that it would improve the FFRDC's report to describe the source term, that is, a description of the types, chemical forms, and amounts of radioactive or hazardous materials released from the waste form, which is fundamental for any PA. In addition to describing the source term, it would be useful for the FFRDC's final report to discuss what percentage of the total inventory of radionuclides of concern (e.g., iodine-129 and technetium-99) will end up in the LAW stream. The committee appreciates that Table H-2 in the draft report shows the radiological content (in curies per cubic meter) of the radionuclides for April 2060, based on computer simulation of the LAW stream from the Waste Treatment and Immobilization Plant's (WTP's) pre-treatment facility, and the committee suggests it would be relatively easy to use these data to provide percentages of each radionuclide in the total inventory of the stream.

The presentation on the IDF's performance assessment from the second public meeting has useful data on the inventory and concentrations of iodine-129 and technetium-99, as shown in Table 3-1, but it is important to have similar data for any other radionuclides of concern. Recognizing that compositions will vary over time and from tank to tank, the committee suggests it would be helpful for the report to contain data on the average and expected range of compositions and chemical forms and for the FFRDC to discuss these data in its final report.

Because the underlying question is how well the disposal of the waste forms from the alternatives meets the performance requirements, the committee suggests that the final report describe the waste form in enough detail (including materials description, location of key radionuclides and metals [as listed in the Resource Conservation and Recovery Act] in the waste form, radionuclides' chemical form, and release mechanisms) such that a decision-maker can understand the basis for analysis of performance in the relevant disposal site. The discussion of release mechanisms is very important to understanding the basis of the risk assessment or "mini-PA" that the FFRDC mentioned it will perform to compare the various waste forms that could be considered for the IDF. Section 3.3.2 of the draft report provides a brief description of the methodology that the FFRDC proposes it will use in its mini-PA.

As to descriptions of the waste forms, the draft report provides the most detailed information on the fluidized bed steam reforming (FBSR) waste forms in Appendix C, but the data are presented without analysis and a cogent summary. Appendix B discusses vitrification but provides no information on the glass waste forms. Appendix D discusses the grout approach and has a section on the cast stone waste forms with a brief discussion about how these compare to earlier grout formations for Hanford LAW. The committee observes that this is a useful discussion and suggests that the FFRDC's final report provide further analysis that addresses the issues above and a thoughtful summary.

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TABLE 3-1 Inventory and Concentrations of Iodine-129 and Technetium-99

Waste Stream	Waste Volume[1] (m^3)	As-disposed waste volume[2]	^{99}Tc Inventory (Ci)	^{99}Tc Concentration (Ci/m^3)	^{129}I Inventory (Ci)	^{129}I Concentration (Ci/m^3)
ILAW glass	278,797	278,797	26,400	$9.47x10^{-2}$	16.5	$5.92x10^{-5}$
LSW	18,900	18,900	0.229	$1.21x10^{-5}$	$6.42x10^{-2}$	$3.40x10^{-6}$
SSW	41,447	11,436	21.2	$1.85x10^{-3}$	12.1	$1.06x10^{-3}$
SSW – HEPA (debris)	*1,832*	*183.2*	*17.45*	$9.53x10^{-2}$	*0.13*	$7.10x10^{-4}$
SSW – other debris	*26,546*	*5,309*	*0.11*	$2.07x10^{-5}$	*0*	*0*
SSW – IX resin	*686*	*1,029*	*2.36*	$2.29x10^{-3}$	*0.02*	$1.94x10^{-5}$
SSW – carbon adsorber (GAC)	*1,137*	*1,706*	*0*	*0*	*4.42*	$2.59x10^{-3}$
SSW – Ag mordenite	*104*	*156*	*0*	*0*	*7.56*	$4.85x10^{-2}$
Secondary waste management	*9,489*	*1,898*	*0.0992*	$5.23x10^{-5}$	$1.43x10^{-5}$	$7.53x10^{-9}$
FFTF	*1,030*	*1,030*	*0.015*	$1.46x10^{-5}$	*0*	*0*
On site non CERCLA non tank	*623*	*125*	*1.21*	$9.68x10^{-3}$	$1.32x10^{-3}$	$1.06x10^{-5}$

NOTE: Ag = silver; CERCLA = Comprehensive Environmental Response, Compensation, and Liability Act of 1980; FFTF = Fast Flux Test Facility; GAC = Granular Activated Carbon; HEPA = high-efficiency particulate air filter; ILAW = immobilized low-activity waste; IX = ion exchange; LSW = liquid secondary waste; SSW = solid secondary waste.

[1]The waste volume is an estimate of the as-generated waste volume.

[2]The waste volume is an estimate of the as-disposed waste volume of secondary solid waste after it has been compacted or solidified.

SOURCE: Washington River Protections Solutions, LLC, TOC-PRES-18-0441-VA, Rev. 0 (p. 4).

Finally, the committee mentions for the FFRDC's awareness that the comparison of waste forms has a long history (e.g., Chapter 12 in Lutze and Ewing, 1988). It is not easy to make such comparisons because the results depend on the disposal environment. The unique opportunity in this study is that the disposal environments, whether the IDF at Hanford or the Waste Control Specialists (WCS) facility in Texas, are well defined—perfect for making a defensible comparison.

CONFIDENCE IN WASTE FORM PRODUCTION TECHNOLOGIES

What is the level of confidence that each waste form production process will work? This section focuses on the practicalities of producing each waste form. Because the production processes for the three waste forms differ significantly, the specific questions that need to be addressed are not necessarily the same for each of them. Nonetheless, the committee points out here common themes it suggests the FFRDC address for each production process.

First, provide a qualitative comparison of the important hazards to workers and the public assuming that production facilities would be designed to meet regulatory and DOE standards. While the expert elicitation discussed in Appendix F of the draft report considered, as criteria, hazards and safety to workers and the public, the draft report does not provide underlying discussion of the hazards for each of the production processes. For example, hazards associated with materials common to grout and concrete production in the construction industry include exposure to nuisance dust, silica dust, and chemical burns due to the high alkalinity of portland cement-based grout.

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Second, list the experience with each production technology in radioactive applications. The draft report gives a well-informed discussion for the fluidized bed steam reforming production's experience with radioactive applications but not as well for the other two primary production alternatives.

Third, provide a high-level analysis of the technical readiness levels and technology maturity requirements for each production process. In the subsections below, the committee highlights significant issues concerning reliability and feasibility of the production processes, and the committee offers observations and suggestions to the FFRDC for help in improving the final report.

Programmatic risk is a fundamental issue at the Hanford Nuclear Reservation. The combination of extremely hazardous and heterogenous waste forms, high-cost storage facilities (e.g., the tanks), a history of false starts and missed deadlines, a history of regulatory and policy disagreements, and the prospect of decades of waste treatment as the best case—all indicate that there are very significant programmatic risks going forward for any technical approach. While all have significant programmatic risks, they are not necessarily identical in their nature or extent, and this section outlines the committee's observations in this regard.

Vitrification

Reliability

Vitrification is a high-temperature process with multiple steps. Each step must work properly for the operation as a whole to function. This multi-step process raises concerns about the effects of periodic shutdowns that would be necessary for repair and maintenance. In general, it is expected that the more system operations that occur, the greater the operational risk. Even if most shutdowns are due to scheduled maintenance, there will be some that are unforeseen. The FFRDC appears to recognize these concerns, and in the section on "Risks" in Appendix B, it states: "The current assumptions for LAW WTP facility availability [70 percent] are higher than achievable in actual operation." But the committee suggests that in the final report the FFRDC provide a detailed discussion of reliability concerns in general and the basis for a value of 70 percent availability being higher than achievable.

The baseline vitrification facility has two melters and four primary and secondary off gas handling systems. What are the consequences to scheduled throughput if and when one of the melters would need replacing or when the high-efficiency particulate air (HEPA) filters need to be replaced? Here again, the committee observes the FFRDC has not included a detailed discussion of such operational risks in the draft report and the final report would benefit from including such a discussion. Notably, the draft report, however, does mention on page 46: "The design life of a melter is five years. Bubbler replacement is expected to be the most frequent maintenance requirement, with each bubbler having an estimated life span of 26 weeks." The draft report does not discuss how challenging it would be to replace the bubblers or a melter, and the committee suggests that the FFRDC discuss this issue in its final report.

Feasibility

The committee observes that the draft report does not discuss prior experiences with similar or comparable vitrification processes but suggests the FFRDC do so in its final report. It is worth observing that supporters of the technology are quick to cite successful deployment, and critics are equally quick to cite failures. Consideration of U.S. and international precedents will greatly increase the report's credibility.

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Fluidized Bed Steam Reforming

Reliability

Similar to vitrification, FBSR is a multi-step, sequential process. The committee suggests that the FFRDC's final report address similar concerns regarding possible causes of shutdown, ease of shutdown or idling if necessary, ease of restart, and the potential length and cost of likely delays. The committee observes that pages 84-89 of the draft report have an extensive discussion of the startup challenges of the Idaho National Laboratory's (INL's) Integrated Waste Treatment Unit (IWTU) and how these challenges have been addressed or will be addressed. However, the draft report mentions on page 89 that

> some of the design and function of a Hanford SLAW treatment process would by necessity need to be different than in the IWTU because of the goal to produce the durable mineral waste form from the Hanford SLAW, versus the carbonate-based product to be produced at the IWTU.

The committee suggests that the FFRDC summarize these important points in the main body of its final report.

Feasibility

FBSR has been extensively tested at various facilities and at various scales and has demonstrated success in eliminating organics, nitrates/nitrites, sulfates, chlorides, fluorides, and other contaminants from waste streams. As the draft report states, FBSR is a continuous process that needs little or no additional pre-treatment of the waste stream beyond that already planned to take place in the WTP and Direct Feed LAW facilities. It seems likely that the aluminosilicate process could be used for Hanford SLAW but may not be as high on the technical readiness level (TRL) scale as the other options. The committee suggests the FFRDC summarize these important points in the main body of its final report.

The committee notes that the reliance on a foreign supply of coal to operate the FBSR is particularly vulnerable to loss of supply. The committee suggests the FFRDC mention this issue in its final report.

Grout

Reliability

Based on the draft report's description of the flowsheet for grouting, this production process is much simpler than the other proposed methods. From an operations standpoint, it thus appears to be inherently more reliable. Even so, components do require routine maintenance as well as repair and eventual replacement. For example, in the construction industry, equipment that is less robust such as concrete pumps may require spares on hand to permit continuing operations. Also, in the construction industry, the use of chemical admixtures allows for such measures as set retardation should a pump fail. The committee understands that chemical admixtures are not used in waste form grouts. If not, what other measures can be employed in such circumstances? The committee suggests the FFRDC provide a discussion of how operational reliability would be addressed for a potential grouting program.

The shortage of fly ash for grout formulations is not an immediate risk to a grouting program, but the risk will grow as inefficient coal-fired plants are shut down. Because fly ash is a byproduct, supply and demand works differently than for manufactured products: shortages cause price increases, but high prices do not provide incentives to increase the supply. Organizations such as the American Concrete Institute, as well as private corporations, are exploring the development of alternative supplementary cementitious materials; the committee suggests that the FFRDC consider such action as well. While the committee agrees with the FFRDC that stockpiling of materials would provide insurance against occasional shortages of key

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materials, it believes that systemic changes to the market will make fly ash increasingly scarce and suggests the FFRDC briefly discuss these material shortage issues and consider this eventuality in its comparative analysis.

Feasibility

The committee recognizes that page 105 of the draft report identifies the risk that:

> Construction and start-up testing of a facility will not be met within budget or timeline. This risk was evaluated to be low due to extensive experience constructing similar facilities (i.e., DOE's grouting experience) and based on it being a simple facility/process (ambient temperature, minimal off-gas, commercially available reagents).

The committee also notes the construction industry has developed techniques, equipment, and practices that could prove instructive.

The committee suggests that the team consider the potential benefits of using rectangular blocks or vaults for the grout. Rectangular blocks might more completely and efficiently fill the space in a landfill and might hinder the ingress of water between blocks.

COSTS OF WASTE FORMATION PROCESSES

How much will each waste formation process cost? In this section, the committee provides observations about the FFRDC's cost estimations for the waste treatment processes and makes suggestions about how the FFRDC could improve cost estimates in its final report. In the draft report, section 1.5 "Cost-Estimation Summary" mentions the FFRDC used cost data from analogous facilities where the various treatment technologies have been developed and the team's subject-matter experts then "identified technical and/or programmatic gaps between selected facility analog and the pertinent technology." While section 1.5 gives a brief summary of the methodology, it does not provide a summary of the cost estimates, which the committee believes would be useful in the section near the beginning of the report so that decision-makers could have these cost estimates readily accessible. The draft report provides a more in-depth discussion and a table of cost estimates in Appendix G.

Appendix G starts by explaining that the team is just providing a "Rough Order of Magnitude (ROM) Class 5 Planning Estimate for research and development, design, construction, lifecycle costs including transportation and disposal." As Appendix G notes, these estimates "have the least project definition available … and therefore have wide accuracy ranges." In Review #1, the committee suggested "that the FFRDC team in its forthcoming analysis [its second draft report, dated July 15, 2018] discuss how order of magnitude (which is significantly uncertain) cost estimates could be useful to decision-makers." However, the FFRDC has not provided this discussion in the second draft report. Thus, the committee reiterates its suggestion for the FFRDC to discuss this issue in the final report.

The committee also suggests that any discussion of uncertainty in the report's cost estimates would have to address the question of asymmetry in the uncertainty, for example, what percentage error around the base estimate can be expected in the upward and downward direction. In addition, and particularly important, the committee suggests the FFRDC try to identify whether those ranges of uncertainty are larger for some of the options than for others. Even if every option is costed only to a ROM Class 5 level, it seems unlikely that they will all, in actuality, have similar uncertainty ranges when accounting for the differences in their TRLs and system complexities, among other factors. It would also be useful for the factors that may make one option's cost estimate more inherently subject to surprise increases (or decreases) to be discussed and summarized in terms of their overall impact on the magnitude of each option's cost contingency.

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In its review of Appendix G, the committee appreciates the detailed listings of items relevant for the estimates' scope and assumptions. The committee observes that these lists appear comprehensive. Appendix G then briefly mentions the analogous facilities used for the cost estimates. In particular, the FFRDC team has selected WTP's LAW facility and associated Effluent Management Facility (EMF) as the best analogy for SLAW vitrification. The draft report also mentions the Defense Waste Processing Facility (DWPF) at the Savannah River Site as another useful analog.

The FFRDC has selected the saltstone method applied at the Savannah River Site as the analog for the grout treatment cost estimate and notes that this method "can produce at the same scale as required for Supplemental LAW grout … but significant handling, pretreatment (in some of the variants), and logistical unit operations must be included." As with the vitrification analog, it would be helpful for the FFRDC's report to discuss more fully why the team has chosen this grout treatment method in its cost estimation. The FFRDC has selected the IWTU at INL as the analog for the FBSR treatment cost estimate, but the draft report notes the IWTU is nominally half the capacity required for SLAW processing and will produce a different mineral (aluminosilicate proposed for Hanford versus sodium carbonate in IWTU) form, and the IWTU has been built for more highly radioactive material. Nonetheless, the FFRDC believes the IWTU "is the best available analog." It would have been useful for the FFRDC to have discussed whether there are more suitable analogous facilities for its cost estimation. The committee notes that including more than one analog could help with giving a range of cost estimates based on actual construction and operational experience.

The committee observes that the draft report does not list references for the cost-estimation data and does not provide much detail as to why these analogous facilities were chosen. For example, while the FFRDC acknowledges the IWTU produces a different mineralized waste form than what would be produced with Hanford waste if FBSR were used, the FFRDC does not discuss other FBSR facilities that might be better analogies or at least mention other facilities it may have considered. Furthermore, the DWPF facility for HLW vitrification has significantly different requirements than for SLAW, and the WTP LAW vitrification facility has encountered numerous difficulties and is not yet operating. Thus, the committee suggests that the FFRDC in its final report provide more details into the rationale for selecting the best analogous facilities for the FFRDC's cost-estimation, address the uncertainties entailed in the selection of these facilities, and provide a list of references to the cost data.

The committee understands that tank integrity is outside the scope of the FFRDC's tasking. Nonetheless, the committee notes that early tank failures represent a cost uncertainty. In particular, a sudden loss of double tank shell capability could result in dramatic increase in the time it takes to transfer waste for treatment. Thus, the committee suggests that the FFRDC consider the potential of tank failure in the context of the time required to develop and deploy the various treatment alternatives and variants (longer development and deployment times increases the chances of tank failures).

REGULATORY COMPLIANCE

The committee's fourth fundamental question is: *Will the waste form comply with applicable laws and regulations?* For obvious reasons, compliance is a fundamental requirement for any approach that DOE chooses, but such an analysis is also mandated by Sec. 3134, which requires the FFRDC to analyze the compliance of the various treatment approaches "with applicable technical standards associated with and contained in" relevant regulations. (See Appendix A for the list of regulations.) The committee observes and appreciates that the draft report's Appendix J has an extensive discussion of regulatory compliance issues and that Appendix H on Disposal Site Considerations and Appendix I on Transportation Considerations include discussions of relevant regulations affecting these issues.

The committee calls attention to the important issue of designation of Hanford waste that the FFRDC team discusses on page 166 of Appendix J, which mentions that in 1997, DOE and the U.S. Nuclear Regulatory Commission (U.S. NRC) "provisionally agreed that the vast majority of waste from Hanford tanks is not high-level waste, but rather is low-level waste that is not subject to the NRC's licensing authority."

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However, to be managed under DOE's regulatory authority, the waste designated as LAW has to meet the Waste Incidental to Reprocessing (WIR) criteria in DOE M 435.1-1 (DOE, 2011). The criteria as paraphrased from page 166 of the draft report are:

- Processed to remove key radionuclides to the maximum extent that is technically and economically practical;
- Managed to meet safety requirements comparable to performance objectives in Title 10 Code of Federal Regulations Part 61, Subpart C, "Performance Objectives"; and
- Managed pursuant to DOE's authority under the Atomic Energy Act of 1954, as amended, and in accordance with provisions in DOE M 435.1-1, Chapter IV, provided the waste will be incorporated in a solid physical form at a concentration that does not exceed the applicable concentration limits for Class C low-level waste, as specified in 10 CFR 61.55, or will meet alternative requirements for waste classification and characterization as DOE may authorize.

Before waste is emplaced in the IDF, it will have to meet a WIR determination.

In Review #1, the committee suggested the FFRDC's analysis discuss what would be required for the non-vitrified waste forms being assessed to be considered "as good as glass" in the context of the current state of technology for waste forms other than glass from a technical and human health risk perspective. As Chapter 1 of this review has noted, the FFRDC's draft report does not provide this analysis.

Regulatory Compliance and the Performance Assessments for Waste Disposal Facilities

In Review #1, the committee also suggested the FFRDC's analysis discuss how consideration of [additional] pre-treatment processing alternatives to remove radionuclides such as technetium-99 and iodine-129 could expand on-site and off-site disposal options, taking into account compliance with applicable laws and regulations, and the extent to which various treatment (immobilization) options affect the need for pre-treatment to remove key radionuclides.

Appendix A of the draft report has an expanded discussion on pre-treatment and shows results of calculations of how strontium removal would affect the waste classification for the three waste forms, which is potentially relevant to disposal at WCS. Appendix A on page 34 also provides information on the removal levels in percentages required for technetium and iodine to meet the EPA groundwater protection requirements for the IDF based on the PA. While recognizing these data are useful to have, the committee underscores that the PA has not yet been released and calculations to assess the performance of grout and FBSR waste forms for SLAW have not been presented or provided to the committee. Due to these limitations, the draft report does not provide comparisons of the post-disposal performance of the three supplemental LAW waste form alternatives being evaluated although it does state on pages 27-28 that a "mini-PA" will be performed to provide a basis for comparing the three waste forms for the IDF.

As the draft report makes clear, the FFRDC has identified WCS, a commercial low-level waste disposal site near Andrews, Texas, as a potential off-site disposal facility for the final waste forms of SLAW. WCS has been licensed to receive Class A, B, and C low-level waste (LLW) and mixed low-level waste (MLLW). The FFRDC has analyzed the radionuclide concentrations in a grout waste form and compared these concentrations with radionuclide concentration limits in the WCS waste acceptance criteria (WAC). The FFRDC has found the grouted SLAW can easily be accepted under this WAC.

Interestingly, there are different regulatory requirements for the IDF and commercial LLW disposal facilities. The IDF is regulated by DOE Order 435.1 and includes performance objectives of not only dose requirements, but also having to meet EPA groundwater standards as well as specifying a compliance time frame (1,000 years) and a point of compliance. Commercial LLW facilities are regulated under U.S. NRC Title 10 of the Code of Federal Regulations Part 61 (U.S. NRC 10 CFR Part 61) or agreement states that have acquired this authority. (Texas is an agreement state and thus regulates disposal of LLW within its borders; the Texas LLW law has to be at least as restrictive as 10 CFR Part 61, but can be more restrictive.)

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This regulation defines classes of waste (Class A, B, and C) based on radionuclide-specific concentration limits and performance objectives consisting of dose limits, but no groundwater protection requirements, and the point of compliance is defined on a case-by-case basis.

From the July FFRDC presentation by Robert Jubin and Michael Stone on "Pretreatment Approaches," in order to comply with the safe drinking water requirements in the groundwater, an overall technetium-99 removal of 92 percent and an overall iodine-129 removal of 48-57 percent are required.[1] Even in the case where LAW is vitrified, the performance of IDF in terms of meeting the groundwater standard is dominated by iodine-129 and technetium-99 present in the grouted secondary wastes, not the vitrified LAW per se. Yet, the FFRDC's February presentation by John Cochran on the WCS disposal facility indicates that for the same waste composition but in grouted waste form, the average concentration of technetium-99 is about 1 percent of the Class C limit of 10 CFR Part 61, and iodine-129 concentration is about 0.1 percent of the Class C limit.[2] With such large margins below Class C limits, it is natural to consider whether the potential need for additional treatment of SLAW to remove iodine-129 and technetium-99 could be avoided if WCS disposal is selected. It is important to note that the 10 CFR Part 61 waste class definitions are driven mainly based on the intruder scenarios; PA analyses are still required to demonstrate compliance with the performance objectives (dose requirements).

Based on the technetium-99 and iodine-129 removal requirements for the IDF, it appears that the IDF has more stringent compliance requirements than WCS; however, it is not clear if this is because the WCS site characteristics can provide much better waste isolation, or the IDF PA may have used very conservative assumptions and data, or a combination of both.

The committee was not provided the PA information on WCS. However, a WCS document as part of its license application indicated PA analyses were performed for 100,000 years after facility closure and 10 CFR Part 61 performance objectives were met for its license application inventory (WCS, 2011). This indicates the availability of PA calculations for WCS.

As noted on pages 27-28 of the FFRDC's draft report, the FFRDC proposes to perform analyses of the waste forms that could be considered for the IDF. In order to have meaningful comparisons, it is desirable that best-estimate data and assumptions are used to the extent possible, and that similar degrees of conservatism in data and assumptions are used when necessary in these analyses. It is also important to understand the conceptual models and data supporting the treatment of barriers, preferably from the publicly released IDF PA with a short summary in the team's report. Questions include:

- Which IDF barriers are modeled in the PA?
- For barriers not included in the PA, are there analyses that show these barriers are not important to long-term performance, or are they excluded due to lack of information to support a credible analysis?
- Are barriers assumed to fail instantly, or is there a time-related degradation of performance?

Other Important Regulatory Issues

Resource Conservation and Recovery Act of 1976

Wastes that would be disposed of in the IDF are subject to regulation by both the Resource Conservation and Recovery Act of 1976 (RCRA) and DOE Order 435.1. The Washington Department of Ecology is the regulator for RCRA issues, and a permit is required before the IDF can be operated. Currently, there is a draft permit for disposal of vitrified LAW in the IDF, but no other waste forms are authorized, and WAC acceptable to both DOE and Washington Ecology have not been finalized.

RCRA requirements do not address radionuclides. The requirements for disposal of the radionuclides in LAW or SLAW are defined in DOE Order 435.1. These requirements establish dose limits of 10 millirem (mrem) per year by an air pathway and of 25 mrem per year from all pathways to someone at the accessible

[1]See slide 62 in http://dels.nas.edu/resources/static-assets/nrsb/miscellaneous/hanford3-bates.pdf.
[2]See slide 98 in http://dels.nas.edu/resources/static-assets/nrsb/miscellaneous/Hanford2/hanford11.pdf.

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environment, defined to be 100 meters downgradient from the disposal site. This order also establishes higher acute and chronic dose limits for an on-site intruder. These requirements apply for 1,000 years after site closure although the IDF PA results shown in the public presentations extend to much longer times.

Transportation

If the final SLAW waste will be disposed of at WCS, major transportation activities would be involved. Appendix I of the draft report and the FFRDC presentation during the July public meeting included regulatory and operational analysis of potential transportation. The FFRDC showed in its analysis the feasibility of transporting grouted and steam-reformed wastes from Hanford to WCS using a maximum of 26 gondola railcar loads per month for slightly less than 30 years. The analysis was based on the assumption that dedicated trains would be used. Appendix I stated that a shipping program of this scale will most likely require the development of an Environmental Impact Statement (EIS) under the National Environmental Policy Act (NEPA). The EIS process includes input and involvement of stakeholders along the rail lines. The committee suggests that in the assessment of alternatives that require transportation of nuclear wastes through multiple states, the FFRDC consider concerns of potential opposition of local stakeholders along the transportation routes.

Finding 3-3

The regulatory environment for the Hanford tank waste is complex and contested. While the committee does not express an opinion on the correct legal interpretations and policy choices, especially with respect to the “as good as glass” issue, it finds that contested regulatory standards represent a significant program risk to any approach.

Recommendation 3-2

The FFRDC report should define to the extent possible the contested regulatory issues with regard to each approach it considers, and describe to the extent possible the impact of the likely outcomes on the choice of approach and program schedule.

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4

Additional Processes Affecting the Alternative Treatment Approaches

Among the challenges for the Federally Funded Research and Development Center (FFRDC) team is that the alternative treatment technologies or approaches for supplemental low-activity waste (SLAW) interface with an existing and planned system beginning with waste in tanks, which is itself characterized by numerous uncertainties, and ending with a number of different disposal configurations and locations. *The system in which the treatment technology is embedded impacts the choice of technology, and at the same time the choice of technology determines the characteristics and performance requirements of the system.* Consideration of the alternative SLAW approaches in isolation from the systems in which they would operate could lead to poor decisions and is almost certain to miss opportunities to adjust other aspects of the SLAW and the system to achieve a faster, safer, more reliable, and less expensive tank remediation.

Finding 4-1

It is reasonable to bound the FFRDC's scope by having it begin with a pre-treated feed stream from the Waste Treatment and Immobilization Plant's pre-treatment plant or the Low-Activity Waste Pretreatment System because it is impractical to re-invent the numerous system-wide studies of the Hanford tank waste situation. However, it is important to recognize that some changes external to the FFRDC's scope could have important downstream impacts on SLAW that are essential to understand when deciding on the preferred SLAW approach.

Sec. 3134 requires an analysis of "further processing of the low-activity waste to remove long-lived radioactive constituents." In line with that requirement, this chapter addresses four processes integral to the overall objective to treat and dispose of the SLAW, but not necessarily specific to one treatment technology. The four processes are additional SLAW pre-treatment, off-gas treatment, secondary waste generation rate and treatment, and load leveling and waste blending. While at first glance these processes may seem peripheral, in several cases the best available treatment technology strongly depends on the success of effectively applying one or more of these processes. These processes were addressed in the draft report, but to varying degrees. In this chapter, the committee suggests areas concerning these processes that the FFRDC could address in its final report.

ADDITIONAL SLAW PRE-TREATMENT

The draft report in Appendix A states that additional pre-treatment of SLAW to remove strontium can impact the low-level waste classification of the SLAW. This could be significant, but insufficient information was given as to determine whether one would want to remove strontium from SLAW. In particular, while Tables A-1 and A-2 of the draft report list the number of months during the treatment duration that strontium removal would affect the waste classification for the three primary treatment approaches, Appendix A does not discuss how these changes in waste classification would affect whether the waste could be disposed on-site or off-site and how these changes would affect the costs and risks of the disposal options. While this information was discussed in the FFRDC presentations in July 2018, the committee suggests the FFRDC include it in the final report to help decision-makers.

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In comparison, presentation of the pre-treatment options for technetium in Appendix A of the draft report seems to be sufficient to make an informed decision relative to the potential removal efficiency of technetium from the waste stream. However, the cost-benefit analysis of that treatment is not presented in Appendix A. Removal of technetium is more impactful for some treatment technologies than others. The final report would benefit from clearly presenting the cost-benefit analysis for technetium pre-treatment for each of the SLAW treatment options to help decision-makers.

The committee observes that presentation of the pre-treatment options for iodine, RCRA metals, and organic compounds are not covered sufficiently—especially in the form of a cost-benefit analysis—in the draft report, and it suggests the FFRDC's final report provide this information to help decision-makers.

OFF-GAS TREATMENT

The need for off-gas treatment is mentioned in the draft report in Chapters 1 and 2, Appendix B on "Vitrification," Appendix C on "Steam Reforming," and Appendix K on "Feed Vector." The choice and extent of off-gas treatment depend on the pre-treatment and SLAW treatment options that are selected. Decision-makers would benefit from understanding the off-gas treatment that is needed for additional SLAW pre-treatment and SLAW treatment options. To better inform non-technical decision-makers, the committee suggests the FFRDC more clearly present the concept of "flywheel" recycling of the effluent from off-gas treatment. The cost-benefit analysis of additional radionuclide pre-treatment relative to off-gas treatment is not covered in the draft report and would be useful for decision-making for it to be covered in the final report.

SECONDARY WASTE

During the second and third public meetings, the committee heard presentations from Washington River Protection System contractors and the FFRDC team that discuss the baseline of vitrification of LAW with grouting of secondary waste with both waste forms to be disposed at the Integrated Disposal Facility at Hanford. This is one option that the FFRDC is considering for treatment of SLAW and associated secondary waste. The FFRDC presentations from the July meeting and the draft report (mostly in the appendixes) also consider other options for secondary waste such as grouting and shipping it to Waste Control Specialists. Notably, page 49 of Appendix B on "Vitrification" lists a couple of risks that the FFRDC has identified; these are (1) the integrated flowsheet models do not consider the impact of melter idling on secondary waste volume generation, and (2) the flowsheet for immobilized low-activity waste underestimates the volume of liquid secondary waste that will likely be produced. The committee commends the FFRDC for identifying these risks. The committee suggests that the FFRDC clearly present and summarize the secondary waste production considerations in the main body of its final report and consider this issue as part of the cost-benefit analysis.

LOAD LEVELING AND WASTE BLENDING

Variability of feed rate and feed composition can pose problems for SLAW treatment. Table C-6 on page 61 of the draft report shows data that indicate the high variability of both feed rate and feed composition. Load leveling and waste blending have the potential to have a profound impact on the overall cost of the SLAW treatment. Prior work by others resulted in calculation of the System Plan 8 feed vector (ORP, 2017), which is assumed to be the waste stream entering the SLAW treatment process. But the committee is still unclear about what specific scenario(s) from System Plan 8 was used to determine the feed vector and where the feed vector is defined. Furthermore, it is not clear why there are significant fluctuations in flow rate, radioactivity concentration, and some other constituents over the lifetime of the SLAW treatment facilities. If one could make the flow rate level, then it seems that the average throughput of the SLAW treatment facility would be about one-half that of the peak that would exist in the current System Plan 8.

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Review of Draft Analysis of Supplemental Treatment Approaches of LAW at Hanford Nuclear Reservation: Review #2

There is certainly a reason for the proposed feed vector, but without that information there seems to be options that could result in a lower lifecycle cost for SLAW treatment. The FFRDC's next report offers an opportunity to include all of the feed vector assumptions and justifications for those assumptions that are relevant to the cost and risk of the SLAW treatment and how they affect each alternative.

Recommendation 4-1

The FFRDC report should consider the impact of these four processes—pre-treatment, off-gas treatment, secondary waste generation treatment, and load leveling and waste blending—on the treatment rate, reliability, performance of secondary waste following disposal, and cost of alternative approaches to SLAW treatment.

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5

The Analytic Hierarchy Process and Expert Elicitation

As the committee has previously noted, the team has a very difficult task: on the one hand, the team must provide detailed information and analysis of alternative approaches in a way that a decision-maker can readily and accurately compare the alternatives; on the other hand, the team must avoid allowing itself to assign weight to relevant criteria or itself to make the comparison, as this is the province of the decision-maker. The committee's overall view is that the draft report does not provide a sufficient orientation toward providing information in terms that are informative for decision-makers. As this review has already noted, the basic questions that need to be answered for each of the options under consideration are: "How much will each treatment process cost?"; "Can the process be expected to be implemented successfully?"; and "What will be the relative performance of the resulting waste forms, and will they meet regulatory compliance?" Although other attributes may be useful to summarize as well, these central questions also represent the foundation for a cost-benefit evaluation, which is mandated by Section (Sec.) 3134. The preceding sections of this review make it clear that the Federally Funded Research and Development Center's (FFRDC's) current draft report does not provide clear answers to these questions.

At the same time, however, the team, as discussed in Appendix F of the draft report, undertook a detailed exercise that resulted in a hierarchically arranged comparison of approaches, using factors and weights of the team's choosing. Moreover, the committee is left to believe the FFRDC intends to provide a comparison of the SLAW options based on the team's Analytic Hierarchy Process (AHP) exercise, given that Appendix F contains only the documentation of the outcomes of that exercise (which the FFRDC also refers to as its "expert elicitation"). The committee notes that two of its members and the National Academies of Sciences, Engineering, and Medicine's study director were welcomed by the FFRDC to observe the AHP exercise, and the following peer review comments are thus informed by more than just a reading of Appendix F. However, the committee emphasizes that the following observations and findings regarding how the FFRDC needs to craft a useful comparative analysis section reflects the consensus views of the entire committee, not just those who observed the AHP. Based on the direct observations of the AHP exercise and the resulting discussion in the draft report, the committee believes that the exercise was conducted in good faith, without motivational biases, and without any effort to skew the results toward a particular conclusion. The committee further notes its comments are concerned with the appropriateness of AHP for providing decision-makers with a useful comparative analysis of alternative SLAW options. In brief, the committee believes the team's draft report provides too little information in meaningful comparative formats useful to support decision-makers' evaluations, while its use of its AHP results would supplant (or at least anticipate) the decision-makers' evaluation by performing one of its own.

OBSERVATIONS REGARDING THE APPROPRIATENESS OF AHP FOR THE SECTION 3134 REPORT

AHP is a well-known process to help decision-makers create a structured numerical framework reflecting their objectives in choosing an option from among several where the choice involves trade-offs among multiple attributes or "criteria" (Saaty, 2008). The standard steps of AHP are helpfully outlined in the figure on slide 41 of the FFRDC's presentation materials for the July meetings in Richland (and as reproduced in Figure 5-1). The hallmark of AHP is that once a set of evaluation-structuring steps are completed, AHP guides each decision-maker through a sequence of one-on-one comparisons of the criteria,

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eliciting *from the decision-maker* what he or she feels is the relative importance of each criterion in maximizing the defined objective. Once all possible pairwise ratings are completed, the AHP software computes a set of relative weights that it will apply to the scores on each criterion (which are assigned in the following step of the process) to produce a rank-ordering of the decision options in terms of how well they meet the overall objective for the decision. Importantly, these weights—and the resulting rank-ordering—necessarily reflect the preferences of the decision-maker.[1]

The FFRDC team and several affiliated experts met in person in an office building at Savannah River Site for three full days (May 1-3, 2018) to work through an AHP process aimed at comparing the relative merits of identified SLAW immobilization and disposal options. Approximately 20 FFRDC individuals participated (excluding the committee's observers, who did not participate except to occasionally ask clarifying questions). The expressed purpose of the exercise, consistent with use of AHP methodology, was to identify the specific treatment/disposal options to be considered, and to establish a ranking of them based on consideration of multiple different attributes.

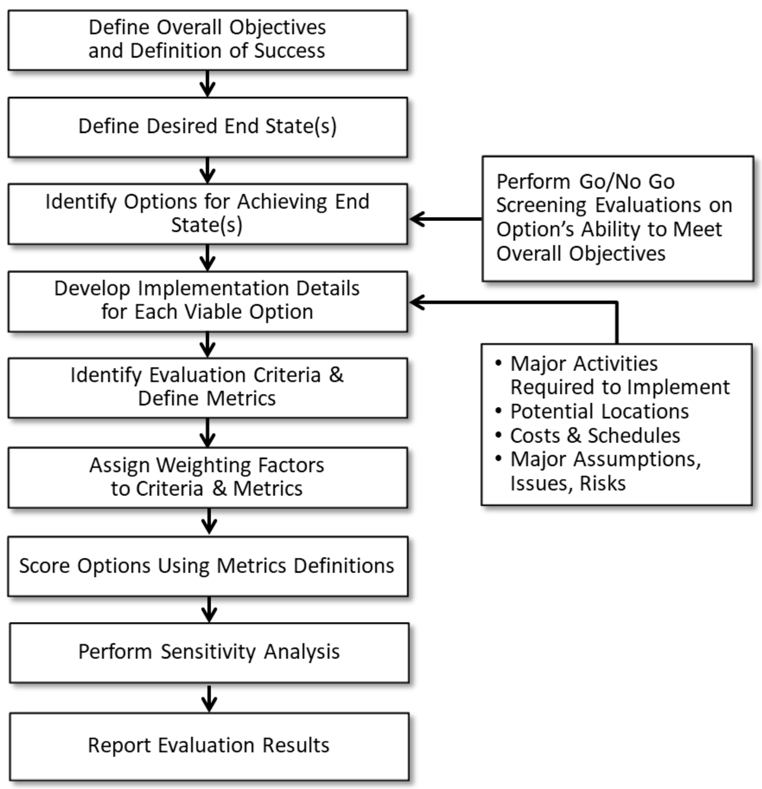

FIGURE 5-1 AHP options analysis process.
SOURCE: R. T. Jubin, Oak Ridge National Laboratory.

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[1]In the case of a public policy decision (as opposed to a private-sector or personal decision), a societal perspective on the desirability of the various trade-offs is needed. The preference elicitation process of AHP is not well suited to supporting decisions on major policies because its ranking outcomes lack transparency regarding the trade-offs that are implicitly being made. A more transparent way of supporting a public policy decision would be for the experts to present information about key options and their respective key criteria in a direct and comparative manner, enabling the decision/policy-makers to understand the nature and extent of the trade-offs faced, and to be able to articulate the justification for their decisions in terms of the trade-offs they consider to be in the public interest.

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The question of concern to this committee's review is whether AHP is a useful tool for responding to the requirements of Sec. 3134. On that question, the critical point is that the AHP method is intended for use by the decision-makers themselves, perhaps with supporting input from technical experts, to rank alternatives to support making a specific choice among them. As described above, this is not the role of the FFRDC study (or, indeed, of this committee's review). The role of the FFRDC team is not to choose or recommend an option but only to provide decision-relevant information about the costs, benefits, and risks/uncertainties of the options. However, in its use of AHP, the FFRDC team has had to incorporate its own set of preferences into the process.

Furthermore, the committee observes that the AHP software used by the FFRDC only allows for a single point estimate of a score, and does not allow for representation of uncertainty about how well an option will perform with respect to a criterion. Thus, it is not a good tool for handling situations marked by significant uncertainty in the outcomes, and is rather more designed for handling decision situations that are made complex by the need to grapple with multiple different attributes of concern. The committee expects that comparisons of the options of concern in the Sec. 3134 report will be strongly affected by uncertainty in (i.e., lack of precise knowledge about) costs and waste form performance, in addition to the fact that there are multiple types of trade-offs to be considered. Thus, lack of features in the tool to accommodate direct representation of uncertainty in criteria scores is another reason the committee believes that the AHP tool is not well suited for responding to the requirements of Sec. 3134. Moreover, although it might be possible to modify an AHP process to input uncertainty ranges on scores, and then to produce uncertainty ranges on rankings, this was not done. Rather, the FFRDC team defined a number of its criteria to reflect concerns with uncertainty on cost and schedule, to name two important issues. This is not a standard method for addressing uncertainty in a cost-benefit or risk analysis.

Thus, while the FFRDC's AHP exercise has been characterized as "expert elicitation," the committee notes that it was not a traditional expert elicitation, which is a set of formal procedures to help experts extract from their professional knowledge and experience a subjective judgment about the potential *range* over which the true value of some parameter or future outcome may fall. Uncertainty was not what was elicited, but merely a "best point estimate." The fact that the point estimate needed to be only a score of 1 to 5 exacerbates the inappropriate precision that is usually associated with any point estimate on an unknown value, but the scores are nevertheless deterministic values without accompanying uncertainty ranges.

Relatedly, the results of the AHP presented in Appendix F give an unwarranted appearance of authoritativeness and certainty due, respectively, to the numerical complexity of the calculations and the ordinal simplicity of the conclusions. In fact, the complex numerical calculations leading to the rankings is viewed by the committee as a step in the wrong direction for a report that is supposed to identify and communicate the key attribute differences that imply trade-offs that decision-makers ultimately must make when choosing among SLAW options. To an extent, these concerns exist simply because of the appearance that the FFRDC is relying on numerical calculations rather than plain English summaries of what they have ascertained about the differences among the treatment options in terms of the relative magnitudes of their dollar costs (however uncertain) and their risks (however uncertain). Such plain English summaries are what the committee would expect to ultimately appear in Chapter 7 of the final report, rather than further synopsis of the AHP outputs themselves.

Finding 5-1

The FFRDC's role in the Sec. 3134 congressional mandate is to produce a comparison of the costs, benefits, and risk trade-offs necessary to support a well-informed public policy decision-making process by the U.S. Department of Energy and others, but the implementation of the AHP did not lead to a defensible ranking of the alternatives.

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Although the committee is uncomfortable with the use of the AHP process as the basis for the comparative analysis that should be provided in the final report, it does feel that this was probably a very useful exercise for the team members to have gone through, individually and as a group, to help them recognize where there remained important, decision-relevant gaps in their information as of that point in their investigation, and what aspects of the multiple criteria they discussed may be most important to communicate to the decision-makers who will be a primary audience for their final report. The committee urges the FFRDC to now put those insights to use to organize its "Comparative Assessment" chapter (see Chapter 7) to provide a structured comparison of the options according to the central questions outlined above, providing direct cost and risk estimates (with quantified representation of the magnitude and direction of uncertainties) for each option rather than mere scores.

Recommendation 5-1

In its final report, the FFRDC should focus on the decision factors identified by Sec. 3134 as the basis for its analysis. The remainder of the main body of the final report should be structured so as to permit direct comparison of the approaches (including SLAW treatment and pre-treatment variants) according to direct estimation of what is known about each of those factors.

Recommendation 5-2

While ranking alternative approaches according to individual criteria, as the FFRDC has done in the draft report, may inform the decision-maker, the FFRDC's final report should refrain from attempting or presenting a single or unified ranking of alternatives, or assigning priorities or weights to the criteria—and thus avoid supplanting the role of the decision-maker.

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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.

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(c) REVIEW OF ANALYSIS.—

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

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

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

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

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

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

(e) SUBMISSION TO CONGRESS.—

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

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

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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.

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Appendix C

Suggestions from the Committee's Review #1 and How the FFRDC Responded

Due to the draft and incomplete nature of the Federally Funded Research and Development Center's (FFRDC's) working documents presented in mid-February 2018 to the committee, Review #1 did not have required recommendations for the FFRDC's next draft report. However, Review #1 provided guidance in the form of suggestions to the FFRDC team. This appendix has the purposes of documenting those suggestions and of describing the committee's observations (shown in italics after each suggestion) of whether and how the FFRDC has responded. The suggestions follow the structure of the tasking in Review #1; see Appendix B for that tasking.

RISK ASSESSMENT METHODOLOGIES

The committee suggests that the FFRDC specify and explain in its forthcoming report what type of probabilistic risk assessment will be used, the parts of the supplemental low-activity waste (SLAW) system to which it will be applied, and the basis for not applying it to other parts of the SLAW system, as well as the basis for selecting the risk analysis techniques applied to other parts of this system.

The committee has not observed a response to this suggestion in the draft report.

It will also be useful for the FFRDC to discuss which risks can be quantified and which can be analyzed using qualitative assessments, e.g., legal and regulatory risks.

On pages 26 and 27 of the Section on "Application of Risk Assessment Techniques," the FFRDC has some discussion about how it has applied quantitative and qualitative assessments in its analysis and draft report.

The FFRDC has not fully described how it will carry out this [expert] elicitation. As to understanding lines of inquiry, the committee suggests that the forthcoming analytic report discuss more fully how lines of inquiry and associated criteria are determined and defined.

The draft report describes the expert elicitation in Appendix F, which along with Section 3.3.1, provides information about the lines of inquiry and associated criteria used in the elicitation.

The committee also suggests that the FFRDC consider a complete set of risks, including health risks and high-level legal issues, associated with shipping waste forms off the Hanford Site. While the committee notes that political risks will be an important consideration for the U.S. Department of Energy (DOE), the committee understands that there is little, beyond identifying such risks, that can be done within the FFRDC's scope.

The draft report in Appendix I on "Transportation Considerations" discusses "the programs that will be needed to transport primary and secondary WFs [waste forms] from the Hanford Reservation to

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the WCS [Waste Control Specialists] disposal facilities in west Texas." Also, Appendix H on "Disposal Site Considerations" provides relevant information for both the Integrated Disposal Facility (IDF) and WCS, but the front sections of the draft report concerning "Summary of Disposal Site Considerations" and "Summary of Transportation Considerations" are "TBD."

COST ESTIMATION

The cost estimation figures based on System Plan 8 are not detailed or precise enough for decision-making. The committee suggests that the FFRDC team in its forthcoming analysis discuss how order of magnitude (which is significantly uncertain) cost estimates could be useful to decision-makers.

The draft report does not discuss "how order of magnitude (which is significantly uncertain) cost estimates could be useful to decision-makers."

The committee also suggests that the team consider use of DOE's "Cost Estimating Guide" because it provides guidance on methods and procedures that are to be used in programs at DOE for preparing cost estimates.

Based on the references and text of the draft report, it does not appear that the FFRDC used DOE's "Cost Estimating Guide." Appendix G mentions use of "the criteria found in the Association for the Advancement of Cost Engineering, International (AACEI), recommended practices."

SCHEDULE ASSESSMENTS

Given the importance of schedule as a reason for commissioning the FFRDC study and the increasing danger of tank leakage over time, schedule risk must be a central consideration.… The committee suggests that the FFRDC's forthcoming analysis examine the important interrelationships among technical and schedule risks as well as safety and costs.

Page 26 of the draft report states that: "The effect [of project risks] is frequently on project costs and schedule. Identifying risks and their potential impact, as well as risk mitigation approaches is important to project planning and execution." While the draft report has little discussion on these project risks, it does include project risks as part of the criteria in the FFRDC's data tables for the analytic hierarchy process used in the expert elicitation as included in Appendix F.

In particular, a better understanding of scheduling risks could include considering an incremental approach that would have the SLAW treatment choice be made after the Waste Treatment and Immobilization Plant (WTP) is operational, keeping in mind the WTP's start date, in order to take advantage of the additional knowledge gained from experience with the actual operation of the waste transport, pre-treatment, and treatment technologies and facilities.

On page 134, the draft report notes that: "Project schedule assumes results of the Analysis of Alternatives (AoA) and a Project Requirements Document (PRD) will be completed in a timely fashion to support completion of technology development, design, construction and startup activities to support a startup of SLAW to support WTP operations schedule." The committee has not seen in the draft report an explicit discussion of having the SLAW choice be made after the WTP is operational. The committee notes that on page 17, it is mentioned that: "In addition to the potential differences in the feed vector, evaluations are in progress that could change the way Hanford tank waste is processed. Rather than list each of the possible changes, it should be assumed that many aspects of tank waste retrieval and immobilization could change from the current assumptions. These changes have the

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potential to minimize the need for a single Supplemental LAW facility tied directly to the WTP facility as assumed in this evaluation and could potentially include smaller, modular systems designed to treat the waste at the individual tank farms or even individual tanks within a farm."

It is also worth considering performance of a sensitivity analysis of the likely downtimes or failures of essential equipment as well as of the potential for using modular equipment that could be switched out in the event of equipment breakdowns. The sensitivity analysis would include assessment of the optimistic assumption of 70 percent availability for the feed material into the SLAW facility.

As Appendix F shows, the FFRDC performed a sensitivity analysis that was a variance of the weightings of the criteria used in the expert elicitation. As to consideration of equipment breakdowns, page 27 of the draft report notes that the technology readiness level (TRL) and complexity line of inquiry (LOI) include the challenges of major equipment replacement. Appendix F includes these LOIs in the expert elicitation results. On page 17, the draft report mentions: "It was assumed that the throughput through the current WTP LAW is not likely to change dramatically as the models used in the Integrated Flowsheet contain most of the expected improvement in waste loading. The model assumes 70% attainment and operation at nameplate capacity; two conditions that the WTP LAW facility is not likely to exceed. Thus, the throughput through the WTP LAW facility should not be expected to be higher than assumed in the flowsheet and that the amount of feed to Supplemental LAW will not decrease if the LAW mission schedule is not changed." While the FFRDC has not apparently done a sensitivity analysis of the 70 percent availability assumption, it recognizes that this is an optimistic assumption.

While schedules can be accelerated or delayed depending on the budgetary assumptions and actual receipt of funds to manage a project, the FFRDC team should consider whether it would be helpful to acknowledge the existence of such risks and their impacts on its analysis so that DOE can take them into account in its decision-making.

Page 18 of the draft report states that: "The funding assumptions in the System Plan assume that funding is increased (unconstrained) whenever needed to perform capital projects to construct or upgrade facilities while operating existing facilities. The annual funding needed to support this assumption represents funding increases that could be double or triple the current annual expenditures. If the funding profile remains flat, then the required facilities to perform System Plan 8 will not be available when required. Thus, the mission need for Supplemental LAW could change depending on the actual funding levels provided."

REGULATORY COMPLIANCE ASSESSMENT

The committee suggests that the FFRDC's analysis discuss what would be required for the non-vitrified waste forms being assessed to be considered "as good as glass" in the context of the current state of technology for waste forms other than glass from a technical and human health risk perspective.

The committee does not observe this analysis in the draft report.

The committee also suggests that the FFRDC's analysis discuss how consideration of pre-treatment processing alternatives to remove radionuclides such as technetium-99 and iodine-129 could expand on-site and off-site disposal options, taking into account compliance with applicable laws and regulations, and the extent to which various treatment (immobilization) options affect the need for pre-treatment to remove key radionuclides.

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Appendix A of the draft report has an expanded discussion on pre-treatment and shows results of calculations of how strontium removal would affect the waste classification for the three waste forms, which is potentially relevant to disposal at WCS. Appendix A on page 34 also provides information on the removal levels in percentages required for technetium and iodine to meet the U.S. Environmental Protection Agency groundwater protection requirements for the IDF based on the PA that has not yet been released.

The committee suggests that the FFRDC's analysis discuss differences in requirements concerning time-of-compliance, and the impacts of various assumptions on lines of inquiry such as cost, schedule, and risk.

Appendix J on "Regulatory Compliance" provides much useful information relevant for time-of-compliance but does not give a discussion of "the impacts of various assumptions on lines of inquiry such as cost, schedule, and risk."

Finally, the committee suggests that the FFRDC's analysis define the flowsheets that would be compared from the waste receipt tank showing the steps of blending, conditioning, treatment, transportation, and disposal. Also, the committee would like to know the material balances for the key radionuclides in each flowsheet.

Appendixes B, C, and D for the three primary treatment alternatives provide information about the flowsheets developed and considered by the FFRDC. But the data in these appendixes do not fully address the committee's suggestions such as a comparison from the waste receipt tank showing the steps of blending, conditioning, treatment, transportation, and disposal and the listing of the material balances for the key radionuclides.

WASTE CONDITIONING AND SUPPLEMENTAL TREATMENT APPROACHES

Regarding each of the primary treatment technologies, the committee suggests that the FFRDC clarify the relationship between the low-medium-high TRL levels used in the FFRDC draft report to the traditional nine-level TRL scale and the reason the traditional scale was not used.

Of the technical appendixes on the three primary treatment alternatives, Appendix C on "Steam Reforming" provides a detailed discussion.

The committee suggests that the FFRDC include its assessment of the potential problems and technical challenges of each of these treatment technologies as well as the potential barriers to acceptance of any of these technologies and the resulting waste forms for disposal sites under consideration.

There is some consideration of potential barriers to acceptance, but as discussed in the main text of this review, the committee suggests that the FFRDC perform additional analysis.

Because it was not clear to the committee whether the FFRDC considers these technologies to be major alternatives to the three major SLAW options, or variations within one or more of these three, the committee suggests that the FFRDC clarify whether there are other major alternatives or a variation of or supplement to one of the major three baseline SLAW approaches.

The FFRDC has specified in the draft report which nine variations the FFRDC is considering and has some discussion as to the rationale for these choices.

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The committee suggests that it would be useful for the FFRDC to identify promising upstream technologies or processes and use them to perform a sensitivity analysis on their effect on treatment flowsheets.

The draft report does not show that the FFRDC has identified promising upstream technologies or processes and done a sensitivity analysis on their effect on treatment flowsheets.

Consideration can be given to removal of radionuclides of concern, such as technetium-99, iodine-129, and strontium-90, as well as methods of blending tank wastes. The analysis would benefit by having clear explanations of the reasons for such pre-treatment, for example, to remove certain radionuclides and other hazardous chemicals to meet waste acceptance criteria at certain disposal sites or to produce a releasable effluent.

The FFRDC has considered a number of these relevant issues concerning pre-treatment in Appendix A.

The committee also suggests that the team could usefully consider, at least briefly, whether certain *combinations* of immobilization technologies could confer particular advantages.

The committee does not observe such a consideration in the draft report.

KEY INFORMATION AND DATA SOURCES BEING USED

The committee suggests that the FFRDC explicitly identify, discuss, and document the underlying assumptions in the One System Integrated Flowsheet and System Plan 8 that could impact its analysis.

Page 18 of the draft report has a discussion of several "programmatic challenges with using System Plan 8." Pages 18 and 19 also have a discussion of other relevant "technical challenges."

The committee also suggests that the team, if it has not done so, obtain and analyze credible existing studies and data on long-term waste form performance to inform analysis of the "as good as glass" issue.

As mentioned earlier, the draft report does not provide an analysis of the "as good as glass" issue.

GENERAL COMMENTS

The committee suggests that the FFRDC's forthcoming analytic report include:

- An accessible organizational structure of the analytic approach that presents clear choices and their consequences to decision-makers, with the recognition that the FFRDC will not select a preferred supplemental treatment option.

As discussed earlier in this review, the FFRDC needs to provide an accessible structure for a comparative analysis in its final report.

- A complete and consistent set of supplemental treatment alternatives specifying clearly whether just the major three supplemental treatment approaches are being assessed or whether there are any variations on these three to consider, including the processing, transportation, and disposal options in each alternative. Likewise, the committee suggests that the FFRDC consider identifying and describing opportunities to improve the performance, cost, and rate of implementation of the alternatives through pre-treatment to disposal, even if some are strictly outside the scope of the SLAW facility.

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As mentioned earlier, the FFRDC has done this work as shown in the draft report.

- Lines of inquiry to include, among other issues:
  - Safety (including nuclear safety, chemical safety, and physical safety of workers and the public)
  - Technical readiness of each option
  - Waste form performance for each option
  - Secondary wastes and effluents produced for each option
  - Cost of each option
  - Schedule of each option
  - Overall regulatory compliance

Appendix F provides relevant information on lines of inquiry.

- A characterization of uncertainties for each line of inquiry.

See the committee's assessment in Chapter 5 of this review.

- The use of appropriate assessment methodologies implemented using best practices for the comparisons within the lines of inquiry.

See the committee's assessment in Chapter 5 of this review.

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Appendix D

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 Presentations

- *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

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- *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

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

Invited Presentations
Committee Members' Presentations

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

Stakeholder Presentation

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

FFRDC Team's Presentations

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

Stakeholder Presentation

- Alfrieda Peters, Yakama Nation

Public Comment

- Mark Hall, Hanford Solutions and a former DOE employee

Submitted Written Comment to the National Academies

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

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Appendix E

Biographical Sketches of the Committee and Technical Adviser

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 engineer degree (1974) from the Massachusetts Institute of Technology, and an MBA (1981) from the University of Tennessee.

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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 is a board member of the National Academies' Nuclear and Radiation Studies Board, a member of the Advisory Committee of Reactor Safeguards at the U.S. Nuclear Regulatory Commission, and a member of the Nuclear Energy Advisory Committee at DOE. 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.

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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, 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, a 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' Emeritus Professor 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

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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 and the Integrated Liberal Studies Program (Howe Bascom Professor), University of Wisconsin–Madison. Since 2015, she has also served as the interim director for academics and research for the 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. Other recognition from ACS includes being elected as a fellow (2009) and receiving national awards for incorporating sustainability into the chemistry curriculum (2011), for encouraging women in careers in the chemical sciences (2003), and for fostering diversity (2001). Over the past 20 years, Dr. Middlecamp has designed, supervised, and taught in a number of programs for students under-represented in the sciences, both collegiate and pre-collegiate. In addition, she has edited and contributed chapters to monographs on teaching and learning sustainability in the chemistry curriculum. 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 a 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 Nuclear Technology R&D 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 in-

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ternship 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, of which he is a member. He was elected to membership in the National Academy of Engineering (NAE) in 2001. 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 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

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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.

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Appendix F

Acronyms and Abbreviations

AHP	Analytic Hierarchy Process
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980
CFR	Code of Federal Regulations
Ci	curie
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
DWPF	Defense Waste Processing Facility
EIS	Environmental Impact Statement
EMF	Effluent Management Facility
FBSR	fluidized bed steam reforming
FFRDC	Federally Funded Research and Development Center
FFTF	Fast Flux Test Facility
GAC	granular activated carbon
GAO	U.S. Government Accountability Office
HEPA	high-efficiency particulate air filter
HLW	high-level waste
I	iodine
IDF	Integrated Disposal Facility
ILAW	immobilized low-activity waste
INL	Idaho National Laboratory
IWTU	Integrated Waste Treatment Unit
LAW	low-activity waste
LLW	low-level waste
LSW	liquid secondary waste
m	meter
MLLW	mixed low-level waste
mrem	millirem [Roentgen Equivalent Man]
NDAA	National Defense Authorization Act
NEPA	National Environmental Policy Act
PA	performance assessment
PNNL	Pacific Northwest National Laboratory
PRA	probabilistic risk assessment
RCRA	Resource Conservation and Recovery Act of 1976
ROM	Rough Order of Magnitude
SLAW	supplemental low-activity waste
SRNL	Savannah River National Laboratory
SSW	solid secondary waste
TBD	to be determined
Tc	technetium
TPA	Tri-Party Agreement
TRIDEC	Tri-City Development Council

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TRL	technical readiness level
U.S. NRC	U.S. Nuclear Regulatory Commission
WAC	waste acceptance criteria
WCS	Waste Control Specialists
WIR	Waste Incidental to Reprocessing
WTP	Waste Treatment and Immobilization Plant

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