An End State Methodology for Identifying Technology Needs for Environmental Management, with an Example from the Hanford Site Tanks

Committee on Technologies for Cleanup of High-Level Waste in Tanks in the DOE Weapons Complex
Board on Radioactive Waste Management
Commission on Geosciences, Environment, and Resources
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This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council (NRC) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals, who are neither officials nor employees of the NRC, for their participation in the review of this report:

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Summary

A major issue in the cleanup of this country's nuclear weapons complex is how to dispose of the radioactive waste resulting primarily from the chemical processing operations for the recovery of plutonium and other defense strategic nuclear materials. The wastes are stored in hundreds of large underground tanks at four U.S. Department of Energy (DOE) sites throughout the United States. The tanks contain hundreds of thousands of cubic meters of radioactive and hazardous waste. Most of it is high-level waste (HLW), some of it is transuranic (TRU) or low-level waste (LLW), and essentially all containing significant amounts of chemicals deemed hazardous. Of the 278 tanks involved, about 70 are known or assumed to have leaked some of their contents to the environment. The remediation of the tanks and their contents requires the development of new technologies to enable cleanup and minimize costs while meeting various health, safety, and environmental objectives.

While DOE has a process based on stakeholder participation for screening and formulating technology needs, it lacks transparency (in terms of being apparent to all concerned decision makers and other interested parties) and a systematic basis (in terms of identifying end states for the contaminants and developing pathways to these states from the present conditions). The primary purpose of this study is to describe an approach for identifying technology development needs that is both systematic and transparent to enhance the cleanup and remediation of the tank contents and their sites.[1] The committee believes that the recommended end state based approach can be applied to DOE waste management in general, not just to waste in tanks. The approach is illustrated through an example based on the tanks at the DOE Hanford Site in southeastern Washington state, the location of some 60 percent by volume of the tank waste residues.

THE APPROACH

The approach proposed for identifying technology development needs for the remediation of high-level waste in tanks is essentially an application of systems engineering. The essence of the approach is the structuring of remediation scenarios (i.e., a reference scenario and several alternatives) to identify the technologies required to reliably achieve the goals of radioactive waste management in the face of uncertainties about the future. Identification of technology needs is based on specifying remediation goals in terms of the desired *end state* of

[1] The information used by the committee for this study is, for the most part, current as of mid-1998, although a few more recent documents were reviewed and have been cited.

specific wastes. As used in this report, an *end state* is defined as the final product of a waste processing, remediation, or management scenario characterized well enough in terms of chemical, physical, and radioactive attributes to allow details of scenarios to be specified. In addition to chemical and physical properties, specifications of end states may include location, legal, regulatory, societal, and institutional factors. Owing to the emphasis on the specification of end states, the approach is referred to as the *end state based approach.* For the DOE Hanford waste in large underground tanks, used as an illustration of the end state based approach, three general waste end states are considered; (1) immobilized HLW, (2) immobilized low-activity waste (LAW), and (3) closed tank farms containing some amount of radioactive material.

The recommended approach consists of the following steps:

1) characterize the initial state or condition of the wastes and site to be remediated,
2) identify reference and alternative scenarios to accomplish the general remediation objective,
3) specify the waste forms and environmental conditions as the desired end states,
4) define the functional flowsheets required to transform the initial waste or waste site into the desired end states,
5) combine essentially identical functions in the flowsheets into a unique set of functions,
6) allocate end state specifications to each processing function as functional requirements, and
7) assess the respective development or deployment status of the technology required for each function to yield technology needs.

A *scenario* is defined for this report as a qualitative description of the transition path of waste from its initial state to a specific end state.

The key to successful application of the recommended approach is in the scoping and specification of end states and functional flowsheets. Note that there may be appropriate interim products as a result of phasing or modularizing the overall remediation process. One of the most important steps in the approach is the development of a *functional flowsheet,* a generalized description of processing operations (functions) linked to effect transformation of the initial radioactive waste to an end state.

The advantages of the end state based approach are many. Technology development needs are tied to specific end states (goals), and the underlying bases are easily visible. There is a traceable path from the problem to the solution through specifying the initial states or conditions, defining a reference goal and alternatives to accommodate uncertainties, identifying functional approaches to move from the initial problem to the solution, assessing the adequacy of existing technology, and implementing technology development only in those areas where technology is unsatisfactory (e.g., too costly) or inadequate to accomplish technical goals. *Technical adequacy* refers to the ability to reach a prescribed end state in a cost-effective manner. The existence of this traceable path is believed to be very important to the technology sponsor and users, and in gaining public support. A significant benefit of the end state approach should be a better chance of passing the scrutiny of review and oversight groups, including the U.S. Congress.

The explicit connection of the technology development program to the desired end states of the wastes is intended to provide logic and efficiency for the technology development program. The need for support of each significant technology development project may be derived from a specification of the satisfactory and plausible end state to be achieved and an assessment to determine whether additional technology development is required. If technology to achieve the end state already exists, then justification of additional technology development would require that such development lead to increased benefits, such as reduction of implementation cost or risk, that would compensate for the projected cost of the development.

AN EXAMPLE

A limited application of the end state based method was developed to demonstrate the identification of technology development needs to remediate high-level waste tanks at the Hanford Site in Washington state. The results of the example are illustrative only and are based on information accessible to the committee.

The total radioactivity content of the Hanford tanks is approximately 198 million curies, with about two-thirds of it in the tank solids. The principal radioactivity of the waste comes from cesium-137 and strontium-90 and their decay products. The tanks contain solids of various types (e.g., sludge, saltcake, slurry) and supernatant liquid. The chemical constituents of the solids are mostly precipitated iron, aluminum, and other hydrated metal oxides. Saltcake is primarily crystalline sodium nitrate, and the supernatant liquid contains large amounts of dissolved sodium salts, especially nitrates, nitrites, and hydroxides.

For the Hanford tanks example, end states were postulated by the committee for three products; HLW, LAW, and closed tanks. The end state assumed for HLW is immobilization in borosilicate glass logs stored in a passively cooled, on-site temporary storage facility, and certified for transport to and acceptance in a deep geologic repository.[2] The end state for LAW for the committee's reference scenario in the example is an immobilized form containing most of the bulk chemicals from the tanks and a small amount of radionuclides. The LAW is assumed to be disposed of in on-site near-surface facilities. The end states for the tanks and tank farms are in situ stabilization, with or without waste in the tanks.

Three scenarios were postulated for the example. The *committee's reference scenario* represents the essence of DOE's currently planned approach (i.e., the *Hanford baseline scenario).* The committee would have chosen Hanford's baseline scenario as its reference scenario except that a well-defined baseline did not exist because of its dependence on technology yet to be provided by a private contractor. The committee defines an *in situ disposal scenario* as representing a budget-restricted, cost-risk balanced remediation approach. To further reduce radionuclides in the LAW, the committee developed an *extensive separations scenario* which reduces risk, reduces the volume of HLW, or both. The diverse nature of the waste in the Hanford tanks suggests that use of various scenarios may allow optimization of costs, schedules, and other factors, resulting in different scenarios being applied based on the initial attributes of the tank wastes.

The essence of the committee's reference scenario is to retrieve most of the waste from each of the tanks. The tanks would then be filled with gravel, capped with a multilayer barrier to prevent water ingress, and subjected to occasional maintenance and surveillance. This scenario would result in the tank farm area being perpetually unsuitable for unrestricted use. The retrieved waste would be converted into two products; (1) vitrified HLW suitable for interim on-site storage, to be followed by disposal in a deep geologic repository, and (2) immobilized LAW, containing most of the chemicals and a small amount of radionuclides, which is suitable for onsite, near-surface disposal. Functional steps in the scenario are characterization of waste in the

[2] The use of such end states should not preclude consideration of the costs of subsequent operations (e.g., transportation and disposal) in evaluating remediation scenarios.

tanks, mobilization and retrieval of the wastes, initial solids washing and waste transfer, enhanced sludge washing, radionuclide separation and recovery functions, waste immobilization, vitrifier offgas processing, storage operations, and tank stabilization and closure. None of the committee's scenarios include transportation of waste to or disposal at an off-site repository.

In addition to the committee's reference scenario, two alternative scenarios are considered. The first is the *in situ disposal scenario,* which may be used if tank cleanup cost estimates exceed allocated budgets (assuming that in situ disposal, including consideration of possible increased characterization and change in regulations, is indeed less costly than other remediation options) or if it is found that some tanks can be remediated at relatively low risk using in situ techniques that do not include waste retrieval. The end state of this scenario is tanks with contents immobilized to the extent practical, completely filled with solid material to prevent tank collapse, and surrounded with protective barriers. Some functions for this scenario, such as the characterization of the tanks and their contents and secondary waste treatment, are the same as in the committee's reference scenario. Added functions include risk analysis for the selection of tanks suitable for in situ remediation, the stabilization of tanks and tank contents, and the application of enhanced barriers to reduce both the amount of water contacting the stabilized tank and radionuclide migration.

The other alternative scenario, *extensive separations,* could be applicable if a need exists to further reduce radionuclide contents in the LAW and/or to reduce the volume of HLW. The end states for this scenario are the same as in the committee's reference scenario except for the relative volumes of the two waste streams, and the low-activity waste that will contain significantly lower levels of radionuclides. This scenario uses all functions of the reference scenario. Additional functions include analyses required for deciding which tank waste should be subject to extensive processing, a solids dissolution step, enhanced cesium removal, separation of radionuclides, and destruction of nitrate and acids.

The three scenarios in this example involve a number of process steps that are, at this point in the description of the approach, identified only by specification of the functions to be performed. The next step in applying the end state based approach is to determine the technology requirements to implement each function in the various remediation scenarios. This step requires an examination of the functions to identify technology requirements. The final step in the application of the approach compares the requirements with available technologies to establish specific technology development needs, which is a major objective of the end state based approach.

Since the only purpose of this example is to illustrate the approach, the committee limited the detailed consideration of the functional steps in the three scenarios to a few functional process steps selected for their likely importance to the overall process and the anticipated importance of technology development to those functions. The functions selected for examination from the committee's reference and extensive separations scenarios were enhanced sludge washing and vitrifier offgas processing. The functions selected from the in situ disposal scenario were stabilization of tanks and their contents and use of enhanced barriers. The technology status for each selected function was assessed and compared to the requirements of the postulated end states to yield technology development needs. The Office of Environmental Management (EM) technology development program was then examined and evaluated in the context of these needs.

For enhanced sludge washing, the technology development needs include additional investigations on colloid formation, identification of the broader range of sludges likely to be encountered during the processing steps or waste retrieval, and reaction rates. Regarding vitrifier offgas streams, technology development needs include engineering response to information on the specification and quantities of materials evolving from the vitrifier, including development of processes for the treatment of these streams and secondary waste. Technology development needs are also influenced by requirements for remote operations and maintenance and the effectiveness of offgas cleanup and pollution abatement.

The EM tank waste remediation programs have not defined, and the EM technology development program is not addressing, technology needs related to tank stabilization and enhanced barriers for tanks from which wastes have not been retrieved. As a result, new technology development activities would likely be required if DOE were to pursue the in situ disposal scenario.

CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations, while considerable with respect to what was learned from the Hanford example, are primarily directed at the major purpose of the committee's study, that is, to describe a broadly applicable end state based method for identifying technology development needs. The example was created only for illustrative purposes, and the conclusions and recommendations based on the example should be considered in this context.

There are several major differences between the application of the approach to identification of technology needs as recommended by the committee (i.e., use of end states) and as used by the DOE. An important difference is the consideration by the committee of end states other than those for the baseline scenario as codified at a given site in various site-specific compliance agreements. The committee believes strongly that scenarios involving alternative end states may need to be considered for reasons including life cycle costs, technical failures, changing requirements, and delays in meeting schedules when originally selected end states present problems. The committee recognizes that such alternative end states are largely outside of the present plans of both the DOE remediation programs and the DOE technology development organization. However, the committee believes that DOE management and legislative decision makers should change their approach by expanding the scope of consideration of alternative end states that may be needed in the future and reflecting this in the DOE remediation and technology development programs.

At present, many public stakeholders at Hanford apparently want DOE to follow the current compliance-driven Hanford baseline approach, and they view investment of significant resources in technology development for alternative scenarios as a diversion from that effort. Some stakeholders do apparently recognize that readjustments to the Hanford baseline may become necessary if a particular approach proves to be infeasible for whatever reason (whether technical, programmatic, economic, or political). However, stakeholders generally appear to prefer DOE to limit such investments. Nevertheless, more explicit consideration of alternatives as proposed herein and greater organizational commitment to a risk-based approach could make the overall DOE program more robust with respect to unexpected developments, as well as provide a more transparent rationale for a particular approach to eventually be adopted from among the candidate approaches.

Conclusions

- The committee observes that technology development typically requires several years to produce deployable results, depending on the initial technology status. In contrast, regulations and stakeholder values concerning remediation issues and decisions often change much more rapidly.
- An end state based approach that includes a range of plausible scenarios can identify technology gaps in a reference flowsheet and technology development needs associated with credible alternative flowsheets.
- The committee concludes that an end state based approach for identifying technology development needs would greatly facilitate the efficiency and visibility of the DOE EM efforts to provide technologies required to remediate the HLW in tanks throughout the DOE complex, thereby providing rationale and background for appropriate funding. The committee concludes that (1) attention should be given to the development of alternative scenarios for such reasons as providing viable contingencies in case of operational problems or changes in remediation guidelines or regulations, (2) these alternatives should be pursued by application of an end state methodology, and (3) if an end state methodology is carefully applied, the overall increase in funding necessary to support technology development for alternative scenarios may be relatively modest.
- End state specifications can be grouped into those related to human health and ecological risk (e.g., safety, hazard), to cost and schedules (e.g., process reliability, performance, efficiency), and to societal externalities (e.g., policy on allowable risk, desirable end state specifications, the role of privatization). To form the basis for a technology development program, these specifications must be translated into specific requirements for each function. Some type of risk or cost assessment, together with a decision analysis, is necessary to convert broad end state requirements into quantitative end state specifications pertinent to scenario analysis.
- The committee found the EM tank waste technology development program to have a substantial but incomplete end state approach for the Hanford baseline scenario. In particular, there was no significant consideration of different alternative scenarios with associated end states, primarily because of the absence of their identification by the problem owners.
- Several health and safety risk studies have been conducted on remediation strategies under consideration. The committee was unable to find evidence that such quantitative risk studies have had an effect on the choice of remediation strategies.
- The committee is confident that the end state based approach proposed in this report and illustrated by the Hanford tanks would greatly facilitate the identification of technology development needs, thereby highlighting the technical basis of the technology development program. This can be done even though substantial uncertainties exist in the end state specifications, and the real drivers of the program may be non-technical factors. The committee believes that such an approach is critical to gaining public support and acceptance for the remediation program.
- The Hanford tank example was effective in illustrating the identification of specific technology development needs in selected functional areas and the relationship of those needs to achieving the desired end states.
- Examples of additional technology development needs, derived from the committee's scenarios and the DOE technology development program for the Hanford tanks wastes, are improved understanding of enhanced sludge processing reaction times, better information on colloid formation during sludge processing, and an improved means for preventing buildup of solids and radioactivity in the offgas system of the vitrification process.

- The privatization initiative diverts DOE attention from addressing some tank technology development needs (e.g., vitrification offgas). DOE has not explicitly stated its strategy and policy concerning its role in technology development in light of privatization of tank remediation operations. This obscures the scenarios and functions that are the targets for the technology development program and confuses the process for identifying and prioritizing needs.
- Finally, the process for making decisions related to technology needed for the remediation of radioactive waste in tanks must consider factors other than purely scientific and technical ones. These other considerations, referred to in this report as external factors, include the constraints on decision making that come from organizational changes, regulations, stakeholder agreements, congressional actions, etc. While external factors were not a focus of the committee's study, such issues as privatization and DOE's organization have a major influence on technical decisions.

Recommendations

- Implementation of an end state based approach is recommended for determining an appropriate technology development program to support DOE's remediation efforts for the radioactive waste in tanks. In particular, this approach should encompass a range of plausible scenarios, as opposed to only a preferred baseline approach as used at Hanford. Depending on the extent to which waste remediation has been completed, alternative scenarios may not be needed for some remediation problems. Examples of this situation could be cases where the best remediation option is obvious or where regulations mandate a particular approach with no recourse to alternatives.
- If initial conditions cannot be adequately characterized and end states cannot be completely specified for waste-containing systems to be remediated, it is recommended that, in the interim, provisional assumptions that allow scenario development and identification of technology needs to proceed should be clearly stated, preferably by problem owners, but by technology providers if necessary. A plan leading to the timely resolution of the 'open items' should be prepared and executed.
- The committee recommends that the end state based approach be applied by DOE on a much broader scale than currently apparent, consistent with a total systems approach to the remediation of contaminated sites. The success of such a strategy is dependent on the support for it from legislators and stakeholders. The need to apply the end state based approach is highlighted by the extensive uncertainty surrounding the entire tank cleanup program, including the role and responsibilities of DOE and contractors that may be part of the privatization program.
- The various steps taken in implementing the end state based approach should be documented in detail for the custodians of the waste and those persons engaged in technology development. Documentation should be the basis of reviews by oversight groups. In addition, executive-level documentation appropriate for decision makers, including DOE upper management, regulators, Congress, and the interested public, should be provided.
- The committee recommends a limited parallel pursuit of alternatives (including end states) to the current strategy of the remediation of the radioactive waste tanks developed by the privatization contractors. It is not considered prudent to rely totally on the success of the privatization process. The uncertainties and costs are great and the chances for unacceptable results are too high not to pursue viable alternatives.

The committee provides in this report a description and an example of application of an end state methodology that can lead to a rationalized technology development program. The committee believes it is highly desirable for DOE to apply such a methodology to waste remediation activities and other comparable assignments to define technology development needs clearly, conserve resources, meet schedules and cost targets, reduce risk of technology failures, and provide visibility to stakeholders of the course of action being taken to remediate sites and facilities.

1

Introduction

The Committee on Technologies for Cleanup of High-Level Waste in Tanks was one of several committees formed at the request of the Assistant Secretary for Environmental Management, U.S. Department of Energy (DOE). The task of this committee was to provide independent review and recommendations to the office of Environmental Management (EM) on scientific and technical issues relevant to technology development to accomplish the environmental management of the DOE nuclear weapons complex (Appendix C). It is the purpose of this committee to provide findings, conclusions, and recommendations on an approach for identifying technology development needs for remediating the radioactive waste, especially the high-level waste (HLW) in large underground tanks in the DOE nuclear weapons complex. This report is based on information gathered through mid-1998. The scope of the study includes the wastes in the tanks and the final disposition of the tanks. Much of the waste is from development and implementation of separation processes associated with plutonium and tritium production.

The thrust of the committee's report is primarily to propose a methodology for identifying technology requirements to remediate stored tank wastes, and a limited example based on the HLW in the Hanford Site tanks (located near Richland, Washington) is presented to illustrate the approach. Currently, technology needs are formulated at each of the four DOE sites through their respective Site Technology Coordination Groups.[1] While the technology needs are carefully screened, there is little evidence that the process is based on a clear-cut systems approach. The committee recommends a systematic and transparent generic approach that is considered applicable to any of the waste tank farms throughout the DOE nuclear weapons complex. In fact, the approach is widely applicable to many EM problems when there are significant uncertainties in the end state of the waste streams and technology development is needed for remediation. The approach involves the analysis of end state based remediation scenarios to highlight the technology needs to achieve specified goals. For this report, a *scenario* is defined as a qualitative description of the transition path of waste from its initial state to a specified end state.[2]

[1] The Site Technology Coordination Group (STCG) is a group consisting of stakeholders, technology users, and DOE representatives at each specific site. The group is responsible for coordinating regulatory and stakeholder interactions at each tank site and facilitating interactions among these groups and the Tank Focus Area.

[2] This definition of a scenario is more general than the one used in the probabilistic risk assessment (PRA) field. In particular, PRA models generally consider a scenario as a single path (initiating event to an end state) through a multi-branched event tree.

The approach has been termed *end state based* because it is driven by the desired final state of the waste stream under consideration. An *end state* is defined as the final product of a waste processing, remediation, or management scenario characterized well enough in terms of chemical, physical, and radioactive attributes to allow details of scenarios to be specified. For example, in the case of waste in large underground tanks there are three principal potential categories of final waste end states; (1) immobilized HLW, (2) immobilized low-activity waste (LAW), and (3) residual radioactive materials contained and stabilized in the tank farms (i.e., the tanks themselves and surrounding contaminated soils). The committee believes that scenarios to achieve predefined end states for the waste are an effective framework in which to consider technology development needs for the implementation of cleanup operations. End states are defined in terms of planned composition, configuration, performance, and location of a particular waste at the completion of a major phase of processing and management activities. Consequently, end states play a major role in the findings, conclusions, and recommendations of this study.

HIGH-LEVEL WASTE TANKS

The tanks considered in this study are large underground storage tanks that contain over 100 million gallons (380,000 m^3) of radioactive wastes in 278 individual tanks distributed among four DOE sites. These sites are the Hanford Site near Richland, Washington; the Savannah River Site near Aiken, South Carolina; the Idaho National Engineering and Environmental Laboratory (INEEL) near Idaho Falls, Idaho; and the Oak Ridge National Laboratory (ORNL) near Oak Ridge, Tennessee (Figure 1). Tanks at the demonstration project site in West Valley, New York, are owned by the state of New York and, thus, are not discussed in this report. Of the 278 tanks in the complex, 177 are at Hanford and contain over 60 percent by volume of the DOE tank waste (U.S. Department of Energy, 1995). By comparison, the Savannah River Site tanks contain about 36 percent by volume of the waste, while the INEEL and ORNL tanks together contain less than 3 percent. Not all the tanks contain waste designated as HLW (e.g., the tanks at Oak Ridge), but all contain radioactive wastes of varying characteristics and amounts. The tanks also vary in design, but they can generally be described as single-shell or double-shell, the double-shell tanks having an annular space between an inner and outer steel tank shell (see Figure 2). Both single-shell and double-shell tanks are found at Hanford. Table 1 describes the tanks by site.

Not all underground waste storage tanks are included in this study. For example, not listed in Table 1 under the Hanford Site are 63 tanks classified as miscellaneous underground storage tanks (MUSTs), either used in the past or currently being used for a variety of purposes. Eighteen of these tanks are in active use and 45 are inactive (Hanlon, 1998). These tanks vary in capacity from 900 gallons (3.4 m^3) to 50,000 gallons (190 m^3) and are part of the Hanford tank waste system.

The tank wastes at the four DOE sites differ in quantity, radioactivity level, storage mode, originating process, chemical composition, and physical attributes. The non-sodium-bearing liquid wastes in the INEEL tanks remained acidic prior to being calcined and stored as solid granules, whereas most of the tanks at other sites contain wastes that were originally acidic solutions but were stored in the tanks in a strong caustic (i.e., high pH) medium. The caustic wastes are composed of solids associated with the supernatant liquid. At some sites, wastes were processed to concentrate solutions and reduce volumes, resulting in precipitated solid components of the waste also being present in tanks. Processing of the original waste at some

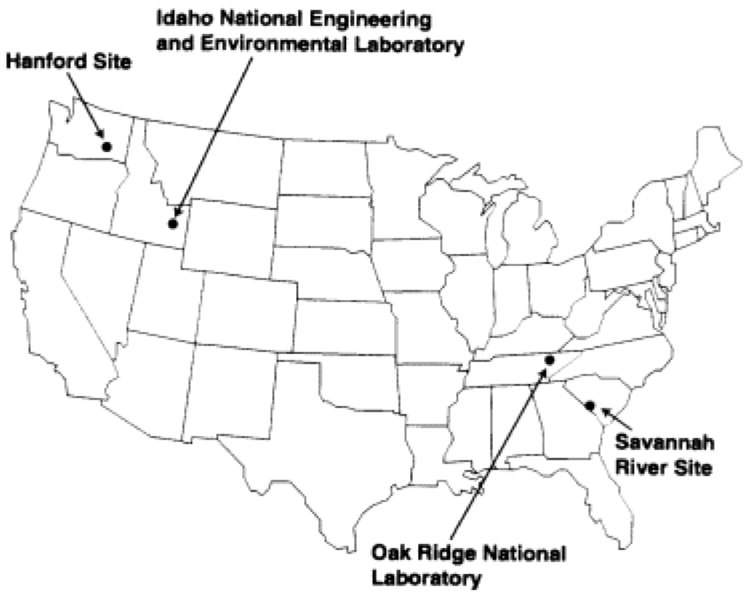

Figure 1.
DOE Tank Sites

Table 1 Waste Tanks in the DOE EM Remediation Area Program by Siteb

Site	Number Of Tanks	Type Of Tanks	Waste Volume, million gal (m^3)	Activity, million Ci
Hanford	177	Single and double-shell	54 (203,000)	198
INEEL	11	Single-shell	2 (7,600)	2
{calcine bin sets}	{7}		{1 (3,800)}	{50}
ORNL	34	Single and double-shell	0.6 (2,300)	0.2
Savannah River Site	49[a]	Double-shell	33 (125,000)	534
Total	278		92 (350,000)	784

NOTES: INEEL = Idaho National Engineering and Environmental Laboratory; ORNL = Oak Ridge National Laboratory.
[a] Two tanks at the Savannah River Site were closed recently, leaving 49 tanks to be remediated and the wastes vitrified.
[b] List does not include many small underground storage and process tanks at the sites.
Sources: Pacific Northwest National Laboratory (1998); for Hanford Site, Hanlon (1998).

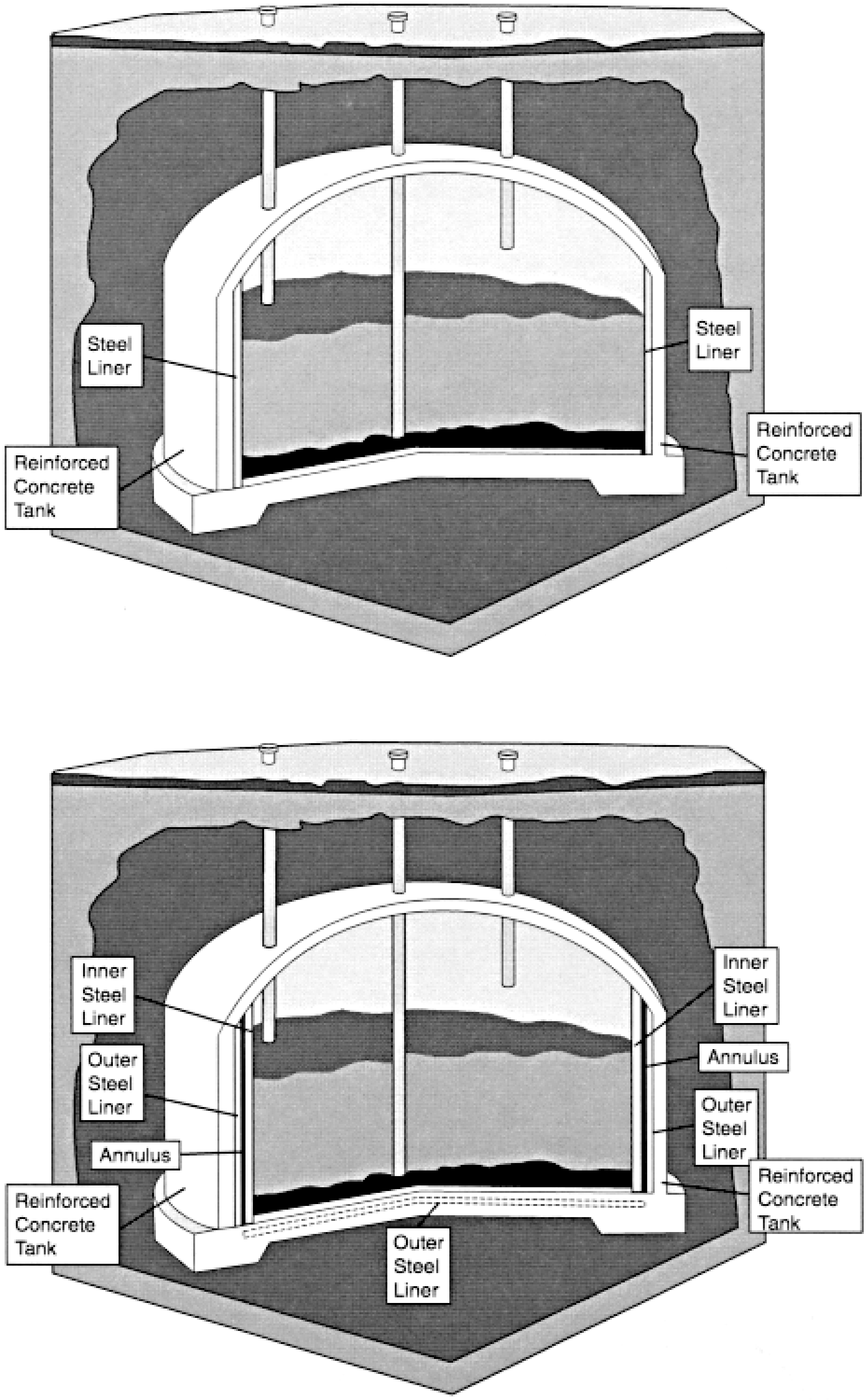

Figure 2.
Two Basic Types of Hanford Tanks—Above, a Single-Shell Tank; Below, a Double-Shell Tank

sites removed selected components by processes different from those that produced the original waste.[3] The resulting tank wastes are a heterogeneous mixture of solutions, sludges, saltcakes, and other phases. Many of the tanks have exceeded their design life, and some have leaked, contaminating the soil surrounding the tanks, and possibly the ground water. Since the Hanford tanks have been selected for an illustrative application of the committee's proposed methodology for identifying technology development needs, a brief description of these tanks follows.

The Hanford tanks contain components of the waste streams from the chemical separations processes and various radionuclide recovery processes that took place between 1943 and 1989. The wastes are currently stored in 177 underground tanks in the 200 Areas of the Hanford Site. There are 149 single-shell tanks and 28 double-shell tanks (Figure 2). The 149 single-shell tanks constructed between 1943 and 1964 are made from reinforced concrete with carbon steel liners. The single-shell tanks vary in capacity from 210 to 3,800 m^3 (55,000 to 1 million gallons) and currently contain approximately 134,000 m^3 (35 million gallons) of saltcake, sludge, and liquid. Since 1956, 67 single-shell tanks have leaked waste into the surrounding soil, or are suspected to have leaked. Sixty-three have been interim stabilized (i.e., supernatant and interstitial liquid has been pumped from the tank solids), and the remaining four have had most of the supernate removed to limit further leakage. It is estimated that a total of about 3,800 m^3 (1 million gallons) of tank waste has leaked to the surrounding soil. No waste has been added to the single-shell tanks since 1980 (Hanlon, 1998).

The 28 double-shell tanks were constructed between 1968 and 1986, with the first being placed in service in 1971. Double-shell tanks consist of a carbon steel primary inner tank, an annular space, and a secondary steel outer tank encased in reinforced concrete. These tanks have a capacity of 3,800 m^3 to 4,400 m^3 (1 to 1.16 million gallons). The double-shell tanks currently contain about 69,000 m^3 (18 million gallons) of waste, mostly in liquid (slurry) form, although there are some sludges and saltcakes. There is no evidence that any of the double-shell tanks have leaked from the primary inner tank.

The total radioactivity content of the Hanford tanks is approximately 198 million curies, of which two-thirds are in the tank solids. The main sources of radioactivity of the waste are cesium-137 and strontium-90 and their decay products. The chemical constituents of the solids are mostly precipitated hydrated oxides of iron, aluminum, and other metals. Saltcake is primarily sodium nitrate and nitrite, and the supernatant liquid contains large amounts of dissolved sodium salts, especially nitrates, nitrites and hydroxides.

TANK WASTE REMEDIATION TECHNOLOGY DEVELOPMENT PROGRAM

Beginning in fiscal year 1994, EM reorganized its program on technology development for the remediation of tank waste. This reorganization was to provide enhanced coordination of technology development under the EM Office of Science and Technology (EM-OST) and to be relevant to all DOE sites (Hanford, ORNL, Savannah River, and INEEL) that are charged with remediation of tank waste. The new program management system involved the Richland Operations Office as the lead field office to coordinate activities at the sites through the Tank Focus Area (TFA) management team and the Site Technology Coordination Groups (STCG). Representatives from several national laboratories, academia, and industry participate in TFA technology development activities. The thrust of the technology development program is to

[3] For example, at Hanford in the 1960s and 1970s, cesium and strontium were recovered from the tank waste using organic compounds (e.g., salts of citric acid); the waste was then returned to the tanks (Gephart and Lundgren, 1997).

provide needed technologies to overcome the technical obstacles that jeopardize tank waste remediation performance and compliance and to reduce costs.

Briefly, the TFA program development process is initiated by formulation of technology needs and local priorities at each of the four sites through their STCGs. The technology needs are screened, justified, evaluated, reviewed, and cast into a problem element structure similar to a work breakdown structure commonly used for large projects. The problem element structure has been applied to a generic tank waste remediation flowsheet (Pacific Northwest National Laboratory, 1997b) that is broadly applicable to the four sites. The relevance of proposed site-specific technology development to the problem element structure allows coordination of technology development among the DOE sites and with participating programs from industry and universities, along with EM cross-cutting programs and other user programs. The committee did not see evidence of a focus on end states as the EM technology development programs were constructed or justified. In particular, while the technology development program has led to such projects as the Hanford Tank Initiative (HTI) that involve some coordination of technology development, there is still little evidence that the technology needs assessment is based on a transparent systems approach.

The TFA has also enlisted other parts of the DOE EM organization in its program development activities. At the behest of Congress (Public Law 104-46, 1995), DOE established a basic science program, called the Environmental Management Science Program (EMSP), to support the technology development activities. The program was initiated to provide basic information needed to reduce the cost of implementing waste remediation. For example, EMSP is supporting research to understand the movement of contaminants in the vadose zone.

LAYOUT OF THE REPORT

The report layout generally conforms to the end state based approach for identifying technology development needs. The end state based approach, a principal product of the committee's study, is presented in Chapter 2. This is followed in Chapter 3 by consideration of the Hanford Site tank waste remediation in terms of developing illustrative end states and functional flowsheets. These functional flowsheets and end states become the basis for assessing technology development needs of important function process steps selected by the committee. In Chapter 4, technology needs for selected functions of the chosen scenarios are briefly assessed, using the Hanford tanks as an example. Conclusions and recommendations are provided in Chapter 5.

2

Conceptual Approach to Defining Technology Development Requirements Based on End State Criteria

A conceptual approach to deriving a technology development program is based on end state criteria. This chapter discusses end states for wastes, the justification for using end states as a basis for defining a technology development program, and a conceptual approach to defining a technology development program based on end state considerations.

DEFINITION, PURPOSE, AND MEANING OF AN END STATE BASED APPROACH

The establishment of fully defined program objectives and of clear program priorities for technology development investments have become increasingly important to the Office of Environmental Management (EM) for meeting schedules, cost constraints, and other requirements. A systematic planning process should provide the framework for identification of technology development needs. The use of a systematic process is imperative for efficient and effective completion of EM's mission to manage the environmental problems at its sites. The end state approach recommended by this committee is such a systematic and disciplined process.

The committee notes that the end state based approach is similar in principal to the widely used systems engineering process to define technology development needs.[1] Top-level requirements defined as a part of the systems engineering process include end state specifications, and the flowdown therefrom provides specific requirements for each process step. The functional flowsheets defined as a part of the end state approach are the same as the architectures that are part of the systems engineering process. Both approaches call for explicit consideration of alternatives. The primary distinction between these two approaches is that the portions of the systems engineering process related to definition of a technology development program have been elaborated in the end state based approach to fulfill the purposes of this report.

In an earlier report, the National Research Council (1996a) concluded that end state specification of the products resulting from remediation activities are an appropriate and necessary basis for planning and conducting a waste-related technology development program. In this context, an end state can be expressed as the desired composition, configuration, performance, and location of a particular waste product at the completion of remediation activities, frequently wastes emplaced in a disposal facility. If the phased-decision approach

[1] See, for example, Sage, 1992.

previously recommended by the National Research Council (1996a) were to be used, the end state may be that associated with the end of one of the phases.

The process of using end state specifications to derive technology development requirements is shown in Figure 3. The committee proposes a seven-step approach for identifying technology development needs for remediation of the waste in tanks and the tank sites:

1) characterize the initial state or condition of the wastes and sites to be remediated,
2) identify reference and alternative scenarios to accomplish the general remediation objective,
3) specify the waste forms and environmental conditions as the desired end states,
4) define the functional flowsheets required to transform the initial waste or waste site into the desired end states,
5) combine essentially identical functions in the flowsheets into a unique set of functions,
6) allocate end state specifications to each processing function as functional requirements, and
7) assess the respective development or deployment status of the technology required for each function to yield technology needs.

In the final analysis, the approach for identifying the technology development needs noted in this study was driven by end states that are believed to be reasonable in terms of regulatory, budgetary, and technical acceptability. Critical to managing the end state based approach is the level of detail associated with the definition of scenarios and functional flowsheets. Consideration of functional operations rather than specific processes is required. The framework of scenarios in which technologies are discussed in this report is defined at a relatively high level to avoid having the study consumed in the details of flowsheet process engineering and chemistry.

The development of the end state approach begins by *characterizing the initial state* of the subject waste to provide the data for subsequent processes and evaluations. The initial state represents the existing condition of the waste being managed and is often thought to be only the compositional and physical characteristics of the stored waste. In systems as complex as those at Department of Energy (DOE) sites, many other aspects, such as the contaminated environment surrounding the tanks, must be included in the definition of the initial state. These are discussed in a following section on characterization of the initial state.

Based on knowledge of the initial state, a few plausible approaches are developed that will result in the transition of the waste from its initial state to an end state. These approaches, called *scenarios,* are qualitative descriptions of the transition path of waste from its initial state to an end state. Examples of scenario descriptions are 'exhume all waste to yield a site suitable for unrestricted use' or 'stabilize waste in place with long-term institutional controls.' Scenario development would focus on a *reference scenario* that is based on the best current judgment of the most desired processes for remediation. In general, scenario definition should also include a few plausible *alternative scenarios* that incorporate reasonable changes in circumstances.

Then, *end state specifications* are developed for each scenario. Selection of the scenario and its associated end state(s) is based on such considerations as risk reduction, cost minimization, environmental regulations, and stakeholder values. A complete specification of an end state will include not only compositional and physical requirements that meet product

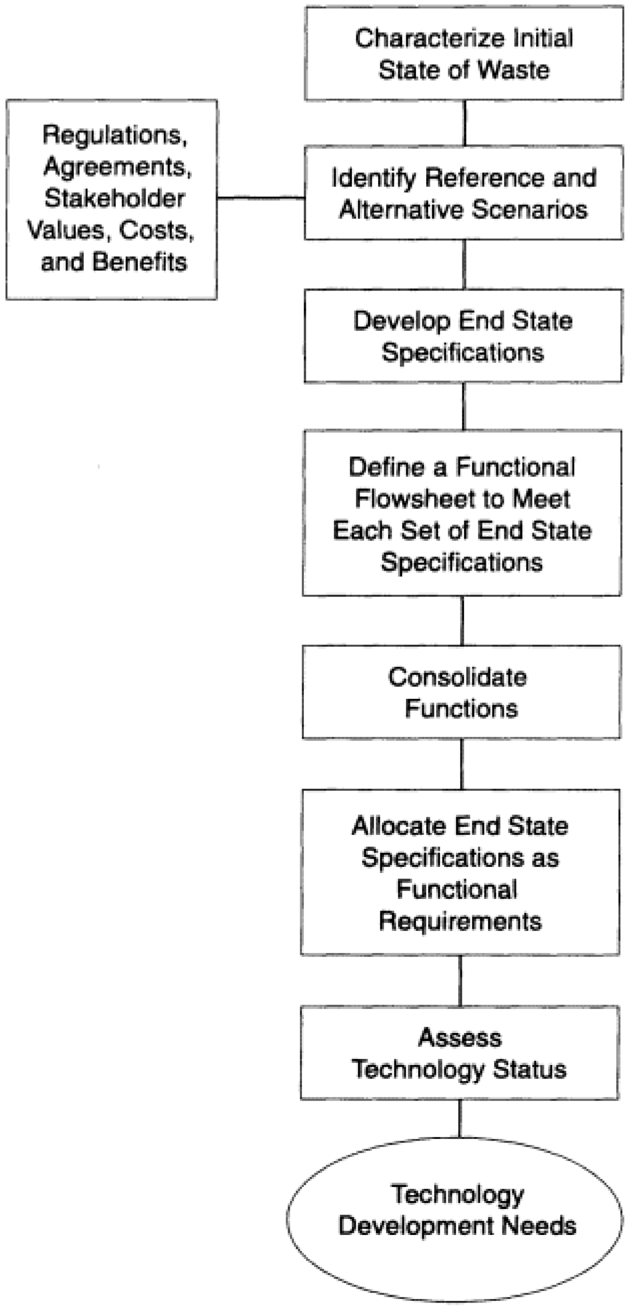

Figure 3.
Process for Using End State Criteria to Derive Technology Development Requirements

acceptance or other criteria but also the location, legal, societal, and institutional requirements for the products. The list of products for which end state specifications are to be developed should be shortened by eliminating those for which technology development is unlikely to be needed.

Given the initial state and end state specifications, a relatively simple *functional flowsheet* is then developed for each scenario to achieve its associated end states. These flowsheets identify the steps needed to accomplish a waste treatment scenario, expressed in terms of the function to be performed instead of the specific processes to be employed. These steps define the actions and the intermediate products required to translate the initial state of the waste into one that meets its end state specifications. When the list of functions and associated requirements is defined for the selected range of plausible scenarios, the duplicate functions are *consolidated.* This yields a unique set of functions and their associated performance requirements that provides the basis for deriving the technology development requirements.

The performance requirements inferred from the resulting end state specifications are then allocated to each function *as functional requirements,* which define how well the function must perform. Then, for each function a *technology assessment* is performed to compare technology requirements for each function to the state of existing technology capabilities. If existing technology or science is inadequate, a gap is identified that should be pursued as part of a technology development program.

The following section discusses the justification for using an end state based approach. Each step is discussed in more detail from the vantage point of the technology developer.

BENEFITS AND LIMITATIONS OF THE APPROACH

The primary benefits of an end state based approach as a basis for a technology development program are (1) the technology development needs are specifically tied to a plausible set of end states for the initial wastes by an explicit decision logic, (2) the technology development program is designed to support multiple plausible sets of end states until a final decision on the preferred end state or end states is made, and (3) the technology development program that uses this process properly has the integrity to withstand scrutiny from the research community at large, Congress, stakeholders, and various DOE review committees.

The explicit connection of the technology development program to the desired end states of the initial wastes is intended to impose discipline and efficiency on the technology development program. The need for each technology development project may be derived from a specification of the end state to be achieved and a technology assessment to determine whether additional development is required. A proposed technology development project that cannot lead to achieving a plausible end state should not be funded unless it addresses other technical needs related to implementation of new technology. If technology to achieve the end state already exists, then justification of additional technology development would require that such development lead to increased benefits, such as reduction of implementation cost or risk, that would compensate for the projected cost of the development. In the absence of an end state based approach, there is the risk that some research projects would address inconsequential needs.

Because technology development typically requires years to produce deployable results, whereas knowledge concerning remediation problems and decisions on how to best manage them are changing much more frequently, a technology development program must proceed in the face of considerable uncertainty. As technology development nears completion, its results, when combined with an analysis of relevant externally imposed constraints, will provide decision makers with reliable information to make informed decisions on technology implementation. If technology development supporting only a reference scenario is pursued, changes in externally imposed constraints (such as resource limitations or changes in allowable risks) may inhibit or prevent implementation of the reference approach due to inadequate technology. Without pursuing technology development for the alternative scenarios, the information needed to select the best course of action will not be available and, if the reference approach is even partially deficient, there will be costly delays stemming from the time required to develop additional technology.

The issue of how to allocate technology development resources among reference and alternative scenarios is a policy decision that should be explicitly addressed by DOE. Investing a significant fraction of technology development resources in functions supporting alternative scenarios and their associated end states is a useful form of technology portfolio management.

Not all remediation problems require technology development or consideration of alternative scenarios. If remediation can be completed in the near term with an acceptable[2] demonstrated technology, then technology development is not required. If remediation is to be completed in the near term, but technology is inadequate, it is likely that only a reference scenario and its associated set of end states need to be addressed. However, the remediation problems in which EM is investing most of its technology development resources involve complex, long-term projects [e.g., high-level waste (HLW) tank remediation, subsurface contamination, facility decontamination and decommissioning] where changes in such external factors as budget, regulations, and stakeholder values are likely to occur. In these cases, an end state based approach that includes reference and alternative scenarios should be used.

The consideration of reference and alternative scenarios and their associated end states as described here is not intended to address the issue of whether redundant technology development should be supported to meet the end state specifications of a specific scenario. That is, the scope of alternatives does not address whether two or more different technology development projects should be pursued to meet a specific functional requirement. Such redundancy is justifiable when the need is critical or the probability for success of a single technology is judged to be low.

Another benefit of using the end state based approach to define an appropriate technology development program is its clarity (i.e., it can be readily understood). When properly documented, there is a clear path from the problem to the solution through specification of the initial problem, definition of a reference scenario and alternatives to accommodate uncertainty, identification of functional approaches to move from the initial problem to the solution, assessment of the adequacy of existing technology, and support for technology development only in those areas where technology is inadequate. The existence of this traceable path provides clear linkage of the proposed technology development projects to the ultimate desired end state of the waste, which, after appropriate independent reviews, should provide adequate justification to decision makers to support the technology development program. Achieving this linkage requires documentation of the various steps taken to implement the end state based approach. Detailed documentation should be provided to those directly involved in the process (i.e., problem owners, technology providers, reviewers). The committee notes that this documentation tends to be voluminous and frequently incomprehensible to decision makers, who need summary formats that focus on the relationship of technology development projects to bridging the gap between the initial and end states.

[2] In this context, 'acceptable' means that the technology meets risk goals and is cost effective in a risk-cost-benefit analysis.

CHARACTERIZING THE INITIAL STATE

The first step in defining a technology development program based on end state considerations is to characterize the initial state of the waste (e.g., contaminated liquid, solid wastes, buried wastes) to the extent necessary to evaluate process performance needs and compliance with regulations. Common waste characterization parameters are location, age, volume, and chemical and physical characteristics, including their variability and uncertainty. Characterization parameters that are less commonly considered should include the regulatory status of the target waste, the nature of nearby contaminated sites, and proposed future land uses. Also important are compliance agreements and applicable regulations.

Typically, the technology development organization is not in a position to characterize the waste or associated waste management approaches. If the initial state cannot be satisfactorily defined, a definitive and timely plan for characterizing the initial state should be established and implemented by the problem owner. In the interim, the technology development organization must rely on provisional information, including that which it develops internally. In many cases this information is likely to be uncertain or incomplete, and defining an end state based technology development program may require the technology development organization to use speculative calculations or assumptions subject to future validation. In all cases the data, analyses, and assumptions used as a basis for defining technology development requirements should be clearly documented at the outset.

Using the Hanford tanks as an example, characterization of the initial state could include the amount, chemical and physical properties and radioactive content of waste in the tanks, condition of the tanks, characteristics of contamination in the immediately surrounding soil and ground water, classification of the waste (i.e., mostly HLW with constituents regulated under the Resource, Conservation, and Recovery Act of 1976, as amended, or RCRA), features of existing compliance agreements, and changes that may take place during subsequent processing steps. Uncertainties in the preceding should be explicitly addressed, but only the characterization information necessary to support initial decision making, regulatory compliance, safety and environmental risk assessments, and the design of functional flowsheets should be obtained.

REFERENCE AND ALTERNATIVE SCENARIOS

A scenario defines the qualitative transition path of waste from an initial state to a specified end state. For example, one Hanford tank scenario might be cleanup of the tank farms to levels acceptable for unrestricted future use (i.e., a 'greenfield'), and retrieved tank contents processed to yield HLW sent to off-site disposal and low-activity waste (LAW) for on-site disposal. Another Hanford tank scenario might be stabilization of tanks and their contents to the point that the site is acceptable only for certain types of restricted industrial use with continuing institutional control (i.e., a 'brownfield').

Definition of plausible scenarios for products should be based on consideration of the specific situation, including any legal precedents, applicable regulations and compliance agreements, stakeholder values, and foreseeable budgetary constraints, as well as the technical state of the art. Any of these factors may ultimately constrain the viability of the scenarios. For example, limitations on any future budget may render certain scenarios essentially unachievable. Similarly, stakeholder concerns may favor a particular scenario as being the preferred remediation path. While scenarios should be plausible, it is important to recognize that the range of alternative scenarios need not be limited solely to those that are now considered to be optimal or that meet current compliance agreements and regulations. Instead, the alternatives should represent outcomes that have a reasonable chance of being considered for accomplishment in the future, given the potential for changes in both technology and public values between the present time and the time when final remediation decisions will be made.

Admittedly, determining which scenarios have a reasonable chance of being considered for deployment is a subjective decision, since it is essentially a prediction of a highly uncertain future state of affairs in an institutionally driven process. It is nonetheless possible to identify outcomes with differing degrees of plausibility. For example, while a 'greenfield' solution (i.e., removal of all wastes and tanks, and decontamination of all soil) may be financially and technically impractical at many sites, it is relatively easy to imagine situations in which stakeholders and regulators may eventually require a higher degree of cleanup than specified by current regulations and agreements. Similarly, while it may be societally unacceptable simply to walk away from unremediated tanks, it is plausible that situations will occur in which taxpayer concerns and Congressional action result in cleanup budgets that are significantly lower than current projections. This could lead to the need to remediate lower-risk tanks in place. Since final disposal sites have not yet been established for many product wastes, factors such as acceptable waste forms, the volume of wastes that can be accommodated, and the cost of disposal could change from current plans, again leading to possible alternative scenarios. Finally, it is likely that a case-by-case combination of remediation scenarios may be beneficial in many cases. The end state based approach provides the basis for this option.

The committee notes that the number of scenarios carried forward into subsequent steps must be limited to remain tractable. Although each case will vary, a minimum preferred outcome is for one scenario and associated end state set to represent the current baseline approach (the approach currently preferred and planned by the problem owner); a second scenario to represent a plausible scenario based on a highly risk-averse, resource-available environment; and a third scenario to represent a risk-tolerant, resource-constrained environment.

Other issues arise from privatization of cleanup activities. At present, privatization is the planned approach for some cleanup activities, which would suggest that the private sector (rather than DOE) is responsible for any needed technology development in support of these activities. As noted in "Harnessing the Market: The Opportunities and Challenges of Privatization" (U.S. Department of Energy, 1997a), several factors may cause privatization to be less than fully successful. These include DOE's lack of experience in overseeing privatized activities and the absence of firm end state specifications, as well as some contractors' lack of experience with the kinds of complex, multi-regulator environments that characterize many DOE sites. It may be reasonable in some situations to postulate failure or limited use of privatization as one scenario to be evaluated, resulting in a need for DOE to develop technologies as a backup in case suitable technologies are not forthcoming from the private sector.

The breadth of scenarios beyond the current baseline that need to be considered may depend in part on the level of the organization performing the evaluation. In particular, individual sites are subject to strong and immediate operational and stakeholder pressures, and hence site managers may not be able to do much more than plan for their current baseline activities. By contrast, central organizations, such as those in DOE headquarters, are at least to some degree insulated from these pressures and potentially able to take a longer and broader view. Thus, a function of a central environmental management organization may be to specify a broader range of potential future scenarios and ensure that technologies are developed to meet the needs of those scenarios that are considered plausible, as well as avoiding duplication of technology development efforts.

The committee recognizes that stakeholder concerns and compliance agreements are important factors that could limit DOE's ability to implement an end state based approach to defining an appropriate technology development program. Some stakeholders do apparently recognize that readjustments to the baseline may become necessary if a particular approach proves to be infeasible, for whatever reason (technical, programmatic, or political). At present, many public stakeholders apparently desire that DOE follow the existing baseline approach. They view the investment of significant resources in technology development for alternative scenarios as a diversion from that effort. This is unfortunate in the committee's view, because more explicit consideration of alternatives as proposed herein could make the overall DOE program more robust with respect to unexpected developments, as well as provide a more transparent rationale for adoption of a particular approach from among the candidate approaches.

END STATE SPECIFICATIONS

One set of end state specifications is developed for each scenario. The end state specification set defines an objective of remediation for a scenario and should be quantified to the extent possible. To determine end state specifications for use in establishing an appropriate technology development program, the specifications can be grouped into those related to human health and ecological risk (e.g., safety, hazard, land and resource use) and those related to cost (e.g., process reliability, performance, efficiency). These groups are not always separable, as in the case where the cost of remediation must be reduced to affordable levels to allow it to occur while still reducing risk to acceptable limits; moreover, any of the end state specifications may be dictated by technical, institutional, or societal factors.

Risk-related end state specifications are normally fixed limits that must be shown to be met, with due consideration for uncertainties, for a remediation activity to be acceptable under regulations, but where further risk reductions are not required except in the case of some occupational or public health and safety situations (e.g., as low as reasonably achievable, or ALARA, requirements). Risk-related specifications are translated into usable end state specifications for products using a modified risk assessment. Normally, the risk assessment process begins with a specific initial state for a hazardous material, postulates mechanisms by which the material can be released, and then estimates the likelihood of releases and the resulting doses to humans. To define the scenario and the end state set of specifications, the allowable impact is specified (the risk specification) and this, in combination with postulated release mechanisms, is used to determine the acceptable pre-release state of the hazardous material, which is the end state specification of the product. The end state specification frequently consists of information on the allowable inventory or concentration of hazardous species in a product, the allowable release rate of the species under various conditions, and the packaging of the product.

Conceptually, translating a risk-related end state specification into a useful end state specification for waste products from a scenario is straightforward. In reality, there are numerous factors that can yield different results or results with large uncertainties. Some of the most common factors are use of different measures of risk (e.g., different affected populations, different locations, population vs. individual impacts), inadequate knowledge of ground water movement, and imperfect knowledge of the interaction of hazardous species with water, soil, and air. To achieve the best results, all of these need to be consistently and accurately specified in an appropriate way (National Research Council, 1983, 1994a, 1996a, and 1996b) in the context of the problem. This should include explicit characterization of uncertainties that are expressed quantitatively to the maximum extent possible.

In contrast to regulated risk, cost-related specifications have no fixed limits, and there is presumably always the desire to invest in technology development to reduce the cost of operations more than the amount of the investment. In many cases risk limits can be met and the primary driving force for technology development is to reduce the cost of achieving the same risk-related end state specification. Using a process similar to a risk assessment, the costs of producing and dispositioning the products are estimated, the largest cost contributors identified, and the most important factors that might be altered to reduce the cost are determined.

To continue the Hanford tank example, end state specifications could contain a limit on dose to an individual from LAW in an on-site, near-surface disposal facility, and a requirement to reduce the number of very costly HLW glass logs. This, when coupled with a modified risk assessment, could result in an end state specification to lower the maximum allowable release rates of important radionuclides in the LAW (e.g., technetium-99, cesium-137). A cost analysis could result in an analysis to reduce the volume of the HLW.

As in the case of specifying the initial state of the waste, if the end states of the products are not completely specified, a plan leading to the timely resolution of the open items should be prepared and executed. The clearly preferred option is for end state specifications to come from the DOE site problem owners. If these are not forthcoming, the next preferred option is for them to be provided by relevant EM headquarters' remediation programs. Finally, if they are not forthcoming from either of these sources, DOE technology development organizations should develop and clearly state enabling assumptions. The committee expects that it will frequently be the case that end states and related technology development requirements will require provisional specifications from technology development organizations in the face of major uncertainties in costs, benefits, public acceptability, and many other factors. Regardless of who develops the scenarios and end state specifications, the uncertainties are likely to be so large that only a modest analytical effort, coupled with a substantial amount of judgment, will be useful—that is, it will be necessary to avoid the trap of over-analysis in the absence of reliable data.

DEFINING FUNCTIONAL FLOWSHEETS AND REQUIREMENTS

Given a set of end state specifications for the products from each scenario, the next step is to create for each set a conceptual flowsheet composed of functions that will take the waste from its initial state into products that meet the end state specifications. This is called a *functional flowsheet.* It is functional because it does not state the means (i.e., specific process) by which the goal is accomplished. Instead, this flowsheet states only the functions that must be performed. For example, one function related to the previously mentioned brownfield scenario could be to *stabilize buried waste.* The flowsheet is stated in this form so that any technology that might perform the required function (e.g., in situ vitrification, grouting) is not precluded from consideration during technology evaluation. The functional flowsheets developed for each scenario could include activities that meet the general requirements of the scenario's end state specifications for each product.

The committee notes that, in many cases, knowledge of available and projected technology can define or limit the functions that can be considered. As a consequence, the end state based approach in general, and development of functional flowsheets in particular, often requires iteration to achieve closure.

FUNCTIONAL FLOWSHEETS CONSOLIDATION

In many cases different scenarios and associated functional flowsheets will have a number of functions in common. These must be consolidated into a unique list of functions, listing each function only once to avoid possible subsequent duplication. This needs to be performed with recognition that functions having the same general description may have different functional requirements. For example, flowsheets for two scenarios could both contain the function *tank stabilization.* However, in one flowsheet the stabilization function could need to meet more stringent end state specifications than in another because waste may not be postulated to be retrieved in the first. Thus, the second flowsheet could need to have only the function *tank stabilization,* while the first flowsheet could be modified to have this same function followed by an *enhanced tank stabilization* function to elicit better stabilization technologies.

FUNCTIONAL REQUIREMENT ALLOCATION

The consolidated functions in each flowsheet must be accompanied by the performance requirements (called functional requirements) that are derived from and will achieve the specifications of the associated end state set. For example, the function *exhume buried waste* would be accompanied by specification of the maximum allowable residual contamination levels. This, in effect, defines what is waste to be exhumed and what is the residual and soil contamination that can remain.

The process of allocating functional requirements to meet end state specifications requires some attention. An end state specification on the allowable release rate of radionuclides from LAW could result in the requirement that the *radionuclide removal* function remove a certain fraction of each radionuclide from the LAW stream. Alternatively, it could be equally possible to achieve the same release rate with an improved waste form or a combination of removal and waste form, thereby meeting the specification. While noting that the allocation of the end state specifications to yield functional requirements could be necessary in many cases, the committee suggests that the requirements always be accompanied by the ultimate end state specification, with some explanation of their relationship.

Continuing the Hanford tank example, two of the consolidated functions could be removal of radiocesium from the supernatant liquid and solidification of the supernatant liquid to yield immobilized LAW. The end state specification for the LAW is postulated to limit the release rate of radiocesium from the immobilized LAW. The requirement for meeting this specification could be allocated entirely to the cesium removal function as a very high removal fraction, to the solidification function in the form of a very low release rate limit for cesium, or intermediate combinations of these.

TECHNOLOGY ASSESSMENT

Given the consolidated list of functions and associated requirements for the scenarios, the next step in the end state based methodology is to ascertain whether acceptable technology already exists to perform each of the functions identified above and meet the functional requirements. If so, no further technology development is required. If not, the function becomes a candidate for technology development. The process of determining the adequacy of available technology to perform a specific function is called *technology assessment,* and should be performed and explicitly documented for each function.

A typical approach to technology assessment would be to consult with experts in a particular field to survey similar activities and experience. For example, in the brownfield scenario, experts in site stabilization would be consulted and a survey of burial site stabilization projects would be conducted. The objective is to provide a database to assess the applicability of the technologies to each function. Inquiries concerning the technology status must be undertaken very carefully, because situation-specific differences can render useless a technology proven to work in an ostensibly similar situation.

The technology status related to a particular function, when compared to the requirements of that function, provides the basis to decide whether technology development is required through answers to a few key questions:

1) Is demonstrated (including deployed) technology available? If there is no technology that has addressed problems sufficiently similar to the case at hand (i.e., there is a technology gap), then further technology development is required. The technology assessment will have defined the status of the technology (e.g., still at the bench scale), which, in turn, defines the next logical step in the technology development process (e.g., engineering development).
2) If demonstrated technology exists (i.e., existing technology meets the functional requirements), is additional technology development (i.e., technology improvement) desired and justified? The need for technology improvement is often driven by considerations of cost or risk. For example, in the brownfield scenario it may be determined that exhumation using conventional techniques (e.g., backhoes and people in protective clothing) is demonstrated technology, but is expensive because of the labor-intensive nature of the work under difficult conditions that exposes many workers to radiation and hazardous substances. Thus, a determination may be made that additional technology development is needed to develop cost-effective robotic technologies to exhume buried waste sites. This decision typically requires balancing the investment in technology development plus the higher capital cost of a more sophisticated technology against the operational cost and risk of existing methods. This decision often must be based on highly uncertain information, especially concerning the performance and cost of a yet-to-be-demonstrated technology. Such decisions often must be made subjectively based on the information at hand, and then periodically reevaluated.
3) If neither technology gaps exist nor improvements are required, does the technology developer need to provide technical support to the implementing organizations? This activity is normally required of newly demonstrated technologies, but not those that have been in routine use.

When demonstrated technology is not available, several developing technologies that might eventually be adapted to perform the required function will exist. In this case, it is often necessary to select among the candidate developing technologies because limited technology development resources are available. This decision is typically based on subjective evaluation of such considerations as projected costs, the potential for successful completion of technology development, and the likely performance of the process. Approaches for selecting, prioritizing, and decision making for technology development projects to meet EM needs are currently the subject of a National Research Council study in support of DOE's Office of Science and Technology (OST) program.[3]

[3] This study is being conducted by the National Research Council Committee on Prioritization and Decision Making in the DOE-OST.

PERFORMING TECHNOLOGY DEVELOPMENT

Completion of the entire process described above results in a portfolio of technology development activities that, if successfully completed, would allow the scenarios, or combinations thereof, to be implemented and their associated end state specifications to be achieved. That is, upon completion of the technology development, decision makers would have the information necessary to confidently select the best scenario or scenarios to achieve the preferred end state(s), and the information necessary to proceed to implementation would be available. The key elements of this process are (1) the functional requirements that the new technology must meet, because the requirements were derived from consideration of alternative end states of the waste that specify this performance, and (2) the selection of the best candidate technology for meeting these requirements based on formal technology assessment and selection process.

There is the need for active feedback in the end state based approach. As technology development proceeds, the potential for successfully completing development and the performance of the new technology will become increasingly clear. As it does, the desirability of continuing technology development should be periodically reviewed, probably on an annual basis. If new information indicates that a technology development project will have higher costs or lower performance than previously estimated, it should again be subjected to the decision making sequence described earlier in this chapter to determine whether it should continue.

SUMMARY

The establishment of fully defined program objectives and the setting of clear program priorities for technology development investments have become increasingly important to meeting schedules, cost constraints, and other requirements. A systematic technical planning process is needed to provide the framework for identification of technology development needs. The end state based approach is such a systematic and disciplined process.

It is possible to specify a generic approach to determine waste-related technology development needs based primarily on consideration of the end state to be achieved for the waste. This approach consists of (1) characterizing the initial state or condition of the wastes or waste site to be remediated, (2) identifying reference and alternative scenarios to accomplish a general remediation objective, (3) specifying the product forms and requirements of the desired end states of such scenarios, (4) defining the functional flowsheets required to transform the initial waste or waste site into the desired end states, (5) combining essentially identical functions in the flowsheets into a unique set of functions, (6) allocation of end state specifications to each processing function as functional requirements, and (7) comparatively assessing the respective development or deployment status of the technology required for each function to yield technology development needs. The end state based approach incorporates key elements of the widely used systems engineering process. A difference between the traditional systems engineering approach and the end state based approach is that the portions of the systems engineering process related to definition of a technology development program, such as the use of alternative scenarios, are specifically focused for explication in the end state approach.

Technology development typically requires years to produce deployable results, whereas regulations and stakeholder values concerning remediation problems and decisions on how to best manage them change more frequently. This uncertainty requires that an appropriate technology development program be based on a range of plausible scenarios. The committee believes that the end state based approach should encompass (1) a *reference scenario* that is essentially the current site baseline or most likely approach, plus (2) at least one *plausible alternative scenario* to efficiently accommodate uncertainty. An end state based approach that considers a range of plausible scenarios will identify technology gaps associated with the site baseline flow sheet and technology development needs associated with credible alternative functional flowsheets. Furthermore, it will identify uncertainties and potential improvements to the existing site baseline process technology that often lead to additional development needs. Allocation of technology development resources among a reference approach and alternatives is a policy decision requiring explicit attention by EM, with the aid of cost and risk assessment results.

The committee notes that not all remediation problems require technology development or consideration of alternative sets of end states. In particular, short-term problems with well-defined solutions should not require the end state based approach. Consideration of reference and alternative end states does not address the issue of whether multiple technology development projects should be supported to meet a specific processing functional requirement. That is, the scope of *alternatives* does not address whether two or more different technology development projects should be pursued to meet a specific technology development need. Development of multiple processes is justifiable when the need is critical to implementing the scenario and the probability of success of a single technology development project is judged to be low.

End State Specifications

End state specifications can be grouped into those related to human health risk (e.g., safety, hazard) and those related to cost (e.g., process reliability, performance, efficiency) for use in establishing an appropriate technology development program. These specifications must provide sufficient information to allow technology development to achieve processes that will produce acceptable waste products.

Performance assessment (whether described as risk assessment, decision analysis, or scenario analysis), cost assessment, and trade-off studies are necessary to translate risk and cost specifications into usable end state specifications. However, the risk- and cost-related information necessary to establish end state specifications is often not available. For this reason, plans leading to the timely resolution of the open items must be prepared and executed, and in the interim enabling assumptions may be developed by problem owners or, if necessary, technology providers. It will always be the case that end states and related functional requirements will have to be identified in the face of uncertainties in costs, benefits, public acceptability, and many other relevant factors. The uncertainties are likely to be so large that only a modest analytical effort, coupled with substantial expert judgment, will be useful to avoid over-analysis in the absence of reliable data.

Tank waste remediation activities yield primary and secondary products resulting from waste processing and site remediation. It is necessary to identify both of these groups of products as a basis for developing end state specifications. In the case of Hanford tank remediation, products might include HLW, LAW, the tanks and tank farms themselves, secondary solid wastes (radioactive, mixed, or chemically hazardous), processed gaseous and liquid effluents, sanitary wastes, uncontaminated construction wastes, materials suitable for recycling, and the byproducts of facility decontamination and decommissioning. For many of the products the end state specifications and technology for achieving them are well-known and commercially available, and their explicit inclusion in the functional flowsheet would serve no useful purpose related to technology development. Thus, in the case of technology development for the current baseline approach to Hanford tanks remediation, the list of products might be reduced to HLW, LAW, and the tanks and tank farms.

Benefits of the End State Based Approach

The primary benefits of the end state based approach to determining a technology development program are that (1) requirements are explicitly tied to a plausible set of end states for the wastes, (2) the program is designed to efficiently support multiple sets of plausible end states for the wastes until a final decision on the preferred end state is made, and (3) the program evolved using this process has the integrity to withstand external scrutiny. This results from the presence of a clear path from the problem to the solution through specifying the initial problem, defining a reference goal and alternatives to accommodate uncertainty, identifying functional approaches to transition from the initial problem to the solution, assessing the adequacy of existing technology, and supporting technology development only in those areas where technology is inadequate.

3

Example of an End State Based Analysis of Technology Development Needs for the Hanford Tanks

The committee's reference scenario, emphasized in this report, is essentially the same as the scenario identified in the recent Hanford Tank Waste Remediation System (TWRS) Record of Decision [U.S. Department of Energy (DOE), 1997b] except for transportation to and internment in a national repository. This scenario calls for retrieving most (99 percent of the volume) of the waste from each of the tanks, separation of the waste into high-level waste (HLW) and low-activity waste (LAW) streams, closing the tanks subject to occasional surveillance, and leaving the tank farm area unsuitable for future unrestricted use. After separation, the HLW is vitrified for interim on-site storage, and the LAW is immobilized for permanent on-site disposal.

Two alternative scenarios were also defined by the committee. One, an *in situ disposal* scenario is defined to suggest a remediation approach that stabilizes tanks without waste retrieval. This scenario reflects the possibility that some of the tanks and their contents represent a relatively low risk and their contents might not require retrieval, or that budgets may alter the cost-risk-benefit balance to allow for retrieval of waste from only the higher-risk tanks. A second alternative scenario may be referred to as the *extensive separations* scenario to cover the case that could be driven by the need to reduce the HLW volume because of the cost of immobilizing and disposing of the waste in a repository. This scenario could also reduce the radionuclide content of the immobilized LAW should that be deemed necessary in the future.

Detailed information underpinning the example was obtained from the Hanford Site TWRS Environmental Impact Statement, previous reports of the National Research Council, and the DOE Environmental Management Office of Science and Technology (EM-OST) and its Tank Focus Area (TFA). In addition, as a framework for the identification, discussion, and recommendation of technologies, the committee reviewed selected risk studies (Colson et al., 1997; Franklin et al., 1996; Harper et al., 1996; Hesser et al., 1995; Johnson et al., 1993; MacFarlane et al., 1994, 1995 a, b) associated with the tanks to determine the role of risk assessment in identifying technology development needs. All these studies addressed the Hanford Site, but they were performed too recently for the committee to be able to judge conclusively the effects they may have had on actual decisions on the tank remediation or technology development programs. Although no impacts were observed up to this time, the committee, nevertheless, believed the studies to be important in understanding the overall risk presented by the tanks and has included a review of these risk studies in Appendix A.

SCOPE

The Hanford HLW tanks example will focus on remediation of buried tanks containing wastes in the form of alkaline nitrate supernatant, sludge, and saltcake, and the associated tank farms at the Hanford Site. This includes the tanks and their contents as well as the immediately surrounding soil and ground water contaminated with radionuclides or hazardous chemicals. The example does not consider remediation of other sites at Hanford [e.g., miscellaneous underground storage tanks (MUSTs), cesium/strontium capsules, reactors, canyons, cribs, low-level waste (LLW) burial grounds] or larger ground-water contamination issues.

CONDITIONS AFFECTING SCENARIO SPECIFICATION

Initial Conditions

The Hanford Site was established in 1943 as part of the Manhattan Project for the production of weapons-grade plutonium. The site (also known as the Hanford Reservation) occupies approximately 1,450 km^2 (560 square mi.) along the Columbia River in south-central Washington, north of the city of Richland. The site's primary mission remained production of weapons-grade plutonium until 1989. Its current mission is the management of waste generated by the weapons production program and the remediation of the site environment contaminated by that waste.

To produce plutonium, uranium metal was irradiated in graphite-moderated reactors. The irradiated uranium metal was allowed to partially decay, and plutonium was separated from the uranium and other radioactive waste by-products by chemical processing. Large amounts of uranium metal were processed to recover plutonium to make nuclear weapons, and the chemical separations processes resulted in large volumes of radioactive wastes that were ultimately stored in tanks.

From 1943 to 1989, the Hanford Site processed approximately 100,000 metric tons (110,000 short tons) of uranium metal and generated approximately 250,000 metric tons (280,000 short tons) of HLW. The waste was managed in compliance with the laws and regulations applicable at the time, but major changes in laws and regulations governing waste management and disposal have over time become more stringent and have resulted in changes in the waste management program.

Beginning in the 1940s and extending through the early 1960s, 149 single-shell carbon steel tanks with capacities of 210 m^3 (55,000 gallons) to 3,800 m^3 (1 million gallons) were built to store the HLW near the center of the Hanford Site in a region known as the 200 Areas. Management of the acidic HLW generated by the chemical separations plants consisted of neutralization by the addition of sodium hydroxide or calcium carbonate and storage in the large underground tanks until a long-term disposal solution could be found.

During the 1960s, uranium was extracted from some of the HLW stored in the single-shell tanks. This action introduced additional chemicals into the stored waste. To provide more tank space for plutonium production, efforts were made to concentrate the tank waste by separating radioactive solids from liquids. Chemicals (e.g., ferrocyanide) were added to the tanks to precipitate cesium-137, which had dissolved in the liquid phase, to the bottom of the tanks, thereby reducing the radioactivity of the liquid layer. Also, overflow piping connections built between several of the single-shell tanks allowed liquid waste to flow from one tank to another and radioactive solids to settle. The liquid waste resulting from these efforts was siphoned off and sent to shallow subsurface drainfields, known as cribs, for disposal into the ground. These actions, while providing tank space for additional waste from plutonium production, resulted in higher concentrations of heat-generating radionuclides in the waste, which threatened the integrity of the tanks.

This heat generation problem was addressed during the 1960s and 1970s when much of the cesium and strontium was removed from the then-existing tank waste. The cesium and strontium were converted to salts, encapsulated in metal cylinders, and stored in a separate facility as waste by-product for commercial use, which never developed to any significant level.

Leakage of waste from single-shell tanks was first suspected in 1956 and confirmed in 1961. By the late 1980s, 67 of the single-shell tanks were known or suspected leakers (Hanlon, 1998). To address the issue of single-shell tank leakage, the Hanford Site adopted a new double-shell tank design that included an outer shell to contain any leakage from the liquid-containing inner shell. The double-shell tank design provided for leak detection and liquid recovery before any waste could reach the surrounding soil.

Between 1968 and 1986, 28 double-shell tanks with capacities ranging from 3,800 m^3 (1 million gallons) to 4,400 m^3 (1.16 million gallons) were constructed in the 200 Areas. Much of the free-standing liquid contained in the single-shell tanks was pumped into the double-shell tanks. However, the solids remaining in the single-shell tanks still contain some liquids in the interstitial void spaces. No leaks are known to have occurred from the inner shells of the double-shell tanks.

At the Hanford Site there are currently approximately 203,000 m^3 (54 million gallons) of waste stored in 177 large tanks. Because the wastes were neutralized to permit storage in carbon steel tanks, most of the chemicals present in the waste precipitated or crystallized. In the liquid remaining in the tanks, the primary dissolved chemicals are non-radioactive sodium nitrate, nitrite, and hydroxide, with much smaller amounts of other chemicals.

To limit leakage and conserve tank space, as much liquid as possible, given other safety considerations, was evaporated from or pumped out of all single-shell tanks. This resulted in the precipitation of many soluble salts from the supersaturated liquid. There are now four distinct types of material—liquid, saltcake, sludge, and slurry—in most of the Hanford tanks (U.S. Department of Energy and Washington State Department of Ecology, 1996). All these materials contain radioactive components.

- *Liquid* includes the supernatant and drainable interstitial liquid in the tanks. It contains substantial amounts of dissolved chemicals, especially sodium salts such as hydroxide and nitrate/nitrite, often near or at their respective solubility limits. Major radionuclides include cesium-137, technetium-99, and a fraction of the strontium-90.
- *Saltcake* is a crystalline mixture of chemical salts that precipitated when neutralized liquids were concentrated to reduce storage volume or potential waste mobility. In general, it is composed of the same mix of chemicals and radionuclides as is in the liquid.
- *Sludge* is a generally viscous, amorphous mixture of relatively insoluble chemicals that precipitated in the tanks as a result of neutralization. Iron and aluminum hydrous oxide compounds are typically important components, but sludges are usually heterogeneous and contain a wide variety of cations and anions as well as interstitial saltcake or liquid. Phosphate ion forms a gelatinous precipitate in the sludge with a variety of cations. The sludge contains most of the radionuclides, with strontium-90 being a major constituent.
- *Slurry* is a tank waste comprising solid, generally crystalline particles suspended in a liquid. Most of the solids are alkaline nitrate salts that crystallized in the tanks when liquid wastes were concentrated, but some materials similar to sludges are also present. Slurry is found

only in double-shell tanks at Hanford. Radionuclide constituents are similar to those in the liquid and saltcake.

The volumes of the various waste types for single-shell and double-shell tanks are summarized in Table 2. The estimated amount of non-radioactive chemical components of the tank wastes and the estimated amount of radioactive constituents are found in the Hanford TWRS Final Environmental Impact Statement (U.S. Department of Energy and Washington State Department of Ecology, 1996, Tables A.2.1.2 and A.2.1.3).

In addition to the chemicals and radionuclides contained within the tanks, an estimated one million curies of radionuclides and associated chemicals were released or leaked to the soil beneath the tanks due to an estimated 3,800 m^3 (1 million gallons) of leaked liquid (U.S. Department of Energy and Washington State Department of Ecology, 1996, pp. 1-5 and 1-8; Hanlon, 1998) plus an estimated 3 million m^3 (800 million gallons) of liquid effluents discharged to surface and subsurface drain fields (U.S. Department of Energy, 1996a, p. 2A-13). The close proximity to the tanks of a portion of the released contamination requires that it be considered as part of the tank closure problem (National Research Council, 1996a).

Management Strategies

Plans and strategies for the long-term management and disposal of Hanford high-level tank waste have been developed and modified over the last 25 years as national policy and regulations have evolved. A comprehensive discussion of these management strategies and their evolution during the past years is given in Appendix B.

The current DOE strategy for remediation of the Hanford HLW tanks is reliant on phased implementation of privatization. DOE's basic objective in implementing privatization is the significant cost and technology benefits that would accrue to the government. DOE expects privatization to result in reduced life cycle costs, access to innovative state-of-the-art technology, and reduced financial risk to the government. However, considerable skepticism exists that such benefits will actually be achieved (Weida, 1997). DOE's own alternative cost comparison in the TWRS environmental impact statement shows the phased implementation alternative to be potentially more costly than most other alternatives. In addition, privatization contractors are not likely to take large financial risks in implementing new untried technology without substantial risk premiums that would increase costs. Thus, the likelihood of accessing truly innovative state-of-the-art technology appears low. In May 1998, DOE down-selected from two privatization contractors to one. This action would appear to put successful implementation of privatization even more at risk and to make the need for DOE to conduct technology development on the privatized processing functions even greater. If the selected private contractor is unsuccessful in deploying its selected technology or is unsuccessful for any other reason, the responsibility for performing tank remediation will rest solely with DOE.

Since the potential for failure of the privatization approach exists and the impact on the schedule and cost is high, the committee concludes that it is important that OST maintain an orderly and comprehensive technology development program regardless of the status of the privatization program. The current DOE policy with regard to technology development diverts attention from critical needs (e.g., vitrification offgas cleanup) and rather focuses attention on only those items that support providing a waste feed to the contractors; that is, addressing DOE commitments from the privatization contract. This in turn causes considerable confusion in the technology development prioritization process. Identified technology needs that directly support providing a waste feed to the contractors receive preference over those needs that are associated with a processing function belonging to the privatization contractors. The greater need may, in fact, be the latter.

Table 2 Waste Volumes for the Hanford Tanks, as of May 31, 1998a

Waste Form	Single-Shell Tanks, m^3 (1000 gal)	Double-Shell Tanks, m^3 (1000 gal)	Total, m^3 (1000 gal)
Liquid			
Supernatant	2,112 (558)	54,305 (14,346)	56,417 (14,904)
Solids[b]			
Slurry	0	1,552 (410)	1,552 (410)
Sludge	44,914 (11,865)	13,317 (3,518)	58,231 (15,383)
Saltcake	86,784 (22,926)	299 (79)	87,083 (23,005)
Total Waste	133,810 (35,349)	69,473 (18,353)	203,283 (53,702)

NOTES:
[a] The accuracy of the data (reported in 1000 gal) is limited to two or three significant figures.
[b] Solids contain interstitial liquid within the interstitial spaces of the sludge and saltcake that is not added to the total waste volume. For single-shell tanks the volume of interstitial liquid is 8,438 m^3 (2,229,000 gal), for double-shell tanks the volume of interstitial liquid is 17,600 m^3 (4,650,000 gal). The single-shell tanks' interstitial liquid remains in the tanks following interim stabilization.
SOURCE: Hanlon (1998), Tables E-5 and E-6.

END STATE ANALYSIS

This chapter has, so far, provided the scope of the Hanford tanks example and background on the initial state of the waste. The next step in the end state based approach is to define possible end states for the waste products. Three potential end states for the committee's reference and alternative scenarios are identified for the example:

- *Closed Tank Farms*—the general end state for a closed tank farm will be remediation to the point that it is acceptable for stewardship (long-term institutional control), defined as not being acceptable for public use and requiring periodic surveillance to prevent intrusion. The definition of acceptable will vary with the scenario being considered.
- *Immobilized HLW*—the general end state for the retrieved HLW is standard borosilicate glass logs that are certified for transport and acceptance in a deep geologic repository but that are temporarily residing in a passively cooled on-site storage facility. Beyond this, it is assumed that there are no limits on radionuclide and chemical contents.
- *Disposed LAW*—the general end state for the LAW stream is an immobilized form containing most of the chemicals in the tanks and a very limited amount of radionuclides. The

waste is assumed to be emplaced in on-site near-surface disposal facilities that meet long-term performance requirements imposed by regulations as demonstrated by a performance assessment.

The remediation operations could also produce a number of processed liquid and gaseous effluents and solid waste that must be managed in accordance with applicable regulations. There are end states for each of these streams that must also be considered in an actual implementation of the end state based approach. In general, existing technology is adequate to achieve these end states. However, the committee finds that one stream, the vitrifier offgas, may be particularly troublesome, and the technology needs for this stream are addressed later in this report.

In addition to a qualitative description, complete definition of an end state will involve specifications related to the physical and chemical characteristics of the waste products. Initially, the characteristics of a product such as a waste form in its disposal environment may be stated in terms of maximum allowable cost or impacts on a population. Through the process of cost and performance assessment and interactions with stakeholders, these are translated into specifications more directly relevant to the design of a tank remediation system. Examples are the maximum allowable cost per unit of waste, concentration of radionuclides in wastes, and the allowable release rate of radionuclides from wastes.

In the case of the Hanford TWRS program, the translation and allocation of general risk and cost requirements into end state specifications appropriate for use in tank remediation have been partially accomplished and documented (Acree, 1998). Although many aspects of this might be viewed as incomplete and interim, the committee believes that sufficient information on the end states is available to plan and conduct a prudently contingent technology development program for the Hanford baseline flowsheet.

For other site applications of the end state based process, it may be necessary for a group organized by the technology development program to specify the plausible range of end state characteristics without a substantial base of information such as that available on the Hanford tanks and the potential disposal and storage environment. This should generally be possible in a straightforward manner using existing information and experience.

The Hanford tank remediation scenario example has been specifically designed to accommodate uncertainties by requiring the technology development program to address a plausible range of end states, not a single set of end states. It is highly likely that the ultimate approach will fall within the plausible range if the alternatives are properly defined.

High-Level Waste

The present criteria that the vitrified HLW from Hanford tanks are found in several documents; TRW Environmental Safety Systems Inc. (1997) and U.S. Department of Energy (1996d, 1998b). This document is a primary source that consolidates engineering limits and requirements from other sources established as a part of the repository design and licensing process. Criteria resulting from the repository design establish limits on the physical dimensions, shape, weight, heat generation, criticality, etc., to ensure that the HLW canister can be handled within the anticipated design envelope of the repository. In the case of Hanford tank remediation, accommodating the physical (e.g., package size and shape) requirements for repository design is relatively straightforward, having negligible implications for technology needs.

However, the requirements from the yet-to-be-completed licensing process could have significant technology development implications. In particular, the HLW product is a major component of a system that maintains the hazard from the disposal facility within acceptable limits. The composition and resilience of the HLW package and contents are major factors in meeting these limits. The heterogeneous nature of the Hanford tank wastes could pose significant challenges to producing a waste form such as glass that consistently meets repository licensing requirements concerning composition and homogeneity. There are two interrelated primary documents containing criteria that have significant technology development implications, Title 40 of the Code of Federal Regulations (CFR) Part 191 and 10 CFR 60. Neither in its present form is applicable to HLW destined for a repository, currently being studied for siting at Yucca Mountain, Nevada. Following a complex series of legal, institutional, and legislative events (see National Research Council, 1995, pp. 15-18 for more details), 40 CFR 191 as it applies to the disposal of HLW has been remanded to the U.S. Environmental Protection Agency (USEPA) for revision and repromulgation. The USEPA is promulgating new standards, and as of this writing, the new draft standard that would be applicable to Hanford HLW has not been released. When the new USEPA standard is finally in place, the U.S. Nuclear Regulatory Commission (USNRC) draft regulation 10 CFR 63 [entitled "Disposal of High-Level Radioactive Wastes in a Proposed Geological Repository at Yucca Mountain, Nevada" (A. Campbell, USNRC, personal communication, February 1999)] will be revised to reflect the USEPA dose limits standard.

Low-Activity Waste

Most of the Hanford tank waste is classified as HLW because its source is the first solvent extraction cycle of the fuel processing that was conducted at Hanford. Reclassifying a portion of the separated and chemically treated waste so that it can be managed using the same approach as LLW (i.e., near-surface disposal) avoids having to meet much more demanding and costly requirements. Thus, the first step is to meet the criteria necessary to reclassify and manage this waste as non-HLW (i.e., LAW).

The framework used to reclassify the separated and treated material as LAW is to show that the radioactive constituent concentration in the waste is low enough so that the waste is *incidental* to the production of the HLW and, thus, is no longer HLW. After extensive discussion and analysis by the DOE and USNRC, the USNRC determined (Bernero, 1993) that the large volume of LAW separated from the tank contents would not be HLW if the following specifications were met:

1) the wastes have been or will be processed to remove key radionuclides to the maximum extent that is technically and economically practical,
2) the wastes will be incorporated in a solid physical form at a concentration that does not exceed the applicable concentration limits for Class C waste as set out in 10 CFR 61, and
3) the wastes are to be managed, pursuant to the Atomic Energy Act, so that safety requirements comparable to the performance objective set out in 10 CFR 61 Subpart C are satisfied.

An analysis of the Hanford LAW, including a preliminary risk assessment of on-site LAW disposal (Westinghouse Hanford Company, 1996), has been performed by the DOE and its contractors (Petersen, 1996). The analysis has been evaluated by the USNRC and its contractors (Mackin, et al., 1997). The USNRC's ". . . preliminary finding is a provisional agreement that the LAW portion of the Hanford tank waste planned for removal from the tanks and disposal on site is incidental waste and is, therefore, not subject to NRC [USNRC] licensing authority" (Paperiello, 1997) if the tank waste is appropriately managed.

In quantitative terms relevant to identification of technology development needs, the requirements for removal of radionuclides are (Petersen, 1996):

- less than 3 percent solids carryover into the final waste product,
- greater than 97 percent removal of radiocesium from the LAW stream, and
- greater than 75 percent removal of transuranic nuclides from those tanks with chemical constituents that render these nuclides significantly soluble.

Determination of the extent of radionuclide removal is first based on meeting the less-than-Class-C waste criterion, but also reflects the maximum extent to which radionuclide removal is technically feasible and economically practical. Removal of other mobile radionuclides such as technetium-99, selenium-79, and uranium may be required, depending on the results of future site/design-specific performance assessments for the LAW. The need to have a solid form in specification (2) above would be met by using a waste form such as calcine, grout, or glass.

The final specification (3) is met by showing that the LAW meets other applicable acceptance criteria like any similar LLW from DOE operations. Primary among these criteria is the USEPA standard for dose from drinking water of less than 0.04mSv/y (4mrem/y), which has been adopted by DOE. After the waste is reclassified as non-HLW, it is subject to the LLW disposal requirements in DOE Order 5820.2A (U.S. Department of Energy, 1988b), although this does not appear to add any requirements that would define additional technology development needs. Finally, the material in the Hanford tanks is a chemically hazardous waste because of its characteristics and some USEPA-listed constituents that it contains. As a result, the waste is subject to the provisions of RCRA and the State of Washington Administrative Code Dangerous Waste Regulations 172-303, both of which require that the waste be processed to remove its hazardous characteristics (e.g., toxicity, corrosivity). This will impose certain requirements on the LAW form, such as being able to reduce the leachability of the toxic constituents to acceptable levels as defined by the standard Toxicity Characteristic Leaching Procedure.

Tank Farm Closure

After tank waste retrieval is completed, the committee assumed that the tanks and associated external contamination will not be physically removed. Consequently, it will be necessary to take actions to leave the tank farms in a suitable long-term disposal condition. As described above for the LAW, any residual waste heel in the tanks is initially classified as HLW. Thus, the first step is to reclassify the waste as being incidental to facilitate appropriate disposition. The approach would presumably be similar to that employed for the LAW. The tanks and their residual contents are assumed to be remediated to meet requirements that may include, but may not be limited to, the USNRC's incidental waste determination, DOE's regulations for near-surface disposal of radioactive waste, and the hazardous waste regulations in the state of Washington's Dangerous Waste regulations, Federal RCRA regulations, and the Federal Comprehensive Environmental Response, Compensation, and Liability Act of 1980, as amended (CERCLA).

In contrast to the relatively advanced state of criteria development for HLW and LAW, similar efforts for tank farm closure are just beginning. Closure considerations were specifically excluded from the recent Hanford tank waste remediation environmental impact statement (U.S. Department of Energy and Washington State Department of Ecology, 1996). A plan to work through the many issues associated with closure of Hanford tank farms has been prepared (U.S. Department of Energy, 1996a). This leaves those attempting to define technology development needs to support Hanford tank closure in the uncertain position of having to establish provisional requirements in order to proceed. The committee believes that explicitly establishing provisional requirements with the operating organizations responsible for the tanks is the preferred course, as compared to doing nothing or allowing technology development to proceed with no consistent objectives. Since the process of retrieval of the residual heel will likely open leaks in the tanks and cause additional contamination of the surrounding environment (vadose zone), end state criteria for tank closure could include the requirement of no further significant vadose zone contamination.

Cross-Cutting Factors

There are a number of factors, termed cross-cutting factors by the committee, that can affect all end states of Hanford tank waste remediation and most other remediation programs. The first is *technology limitations.* Specifically, there are fundamental limits to what can be achieved by technology. Most noteworthy among these is that complete separation of two intermixed substances in waste is not possible. This means for example that waste retrieval cannot be absolutely complete, cesium separations from LAW streams cannot be absolutely complete. In addition, there are practical limits on what technology can achieve. These are most often expressed in economic terms, which are considered below.

A second cross-cutting factor that has had, and probably will continue to have, a major effect on end state criteria is *stakeholder values.* Stakeholder input can occur in a variety of forums, including public meetings, comments on draft documents, the legislative process, and through a variety of oversight committees. This input is highly variable and sometimes contradictory, and generally does not provide a suitable basis for defining end state criteria. When fully considered, integrated with other aspects of the issues, and transformed into a coherent result, information based on stakeholder values is an important part of establishing end state specifications. Such specifications are typically set forth in binding legal agreements, such as the Tri-Party Agreement (TPA) among the Washington State Department of Ecology, U.S. Environmental Protection Agency, and the U.S. Department of Energy (1996) and records of decision such as the recent environmental impact statement concerning remediation of Hanford tanks (U.S. Department of Energy and Washington State Department of Ecology, 1996). Of particular note in this regard are commitments to preclude grout as the LAW immobilization matrix and to establish a goal of retrieving 99 percent of the waste volume from each Hanford tank. Both commitments strongly reflect stakeholder values.

A third cross-cutting factor that has a major effect on the need for technology development is *cost.* One aspect of cost is the adequacy of remediation and waste cleanup budgets, both near- and long-term. Inadequate near-term budgets can restrict the amount of technology development that can be performed irrespective of need and, as a consequence, can render certain otherwise desirable remediation scenarios infeasible. For example, if needed technology development for removal of radiocesium from LAW were not supported, the LAW might be too hazardous for near-surface disposal, thus requiring the LAW to remain with the HLW and be managed at significantly greater cost. Inadequate long-term budgets for remediation operations can have a feedback effect on the need for technology development. For example, if budgets are substantially inadequate to support waste retrieval and processing from all tanks, as currently required by the TPA, this could lead to some of the low-risk tanks being closed without waste retrieval, resulting in a need for technology development to stabilize waste in place.

A second aspect of cost is its use as a driving force for optimization. As a standard practice, design engineers work to achieve the minimum life-cycle cost for a process, given constraints such as those mentioned in previous sections. This consideration frequently results in the need for technology development to lower the cost of performing a specific process or remediation function. For example, the cost and other problems resulting from the use of large volumes of water to sluice sludges from tanks resulted in the development of a new generation of sludge retrieval tools that send much less water to subsequent processes.

A very important use of cost in relation to Hanford tank remediation is to determine how much processing is enough. On one hand, it is possible to do very little processing, resulting in no separation of LAW from the HLW, and then to vitrify the entire composite waste stream. This approach would entail the need for technology development on high-throughput vitrifiers for HLW. While conceptually straightforward, the cost of disposing the HLW would be very high. On the other hand, it is possible to process extensively the tank waste to result in an extremely small volume of HLW, and the same or a modestly larger amount of LAW for less expensive onsite disposal. This approach would entail the need for technology development on a variety of tank waste processing techniques to separate more of the non-radioactive chemicals from the radioactive constituents that must be in the HLW. This would greatly reduce the disposal cost, but would result in higher processing costs. Technical staff at Hanford conducted such an evaluation (Westinghouse Hanford Company, 1993) and concluded that a middle course (what is now essentially the Hanford baseline tank remediation process) was probably the most cost-effective, but recommended further development of the alternative bounding scenarios. The committee also notes that optimizing cost may necessitate consideration of costs that are beyond the postulated end state (e.g., transportation and repository costs in optimizing HLW volumes).

DEVELOPMENT OF FUNCTIONAL FLOWSHEETS

It is conceivable and likely desirable that not all the Hanford tanks and tank waste will be remediated using a single scenario. Instead, as recommended in an earlier study by the National Research Council (1996a), a phased decision-analysis approach based primarily on risk and cost should be considered. In this approach, some of the highest risk tanks would be subjected to extensive remediation, tanks involving moderate risks and costs could be addressed using current reference techniques, and lower risk tanks could be remediated using in situ techniques. Elements of this approach were recognized in the recent Hanford TWRS environmental impact statement (U.S. Department of Energy and Washington State Department of Ecology, 1996) in which two ex situ/in situ alternatives involving combinations of the in situ fill and cap and ex situ intermediate separations alternatives were considered (see Table 3), but not adopted.

The development and use of end state based scenarios for technology development supports a phased decision-making approach by identifying technology needs to support a reference and plausible alternative scenarios. If end state based scenarios and technology identification are pursued to completion, the result would be demonstrated technology that could then be used to implement a reference scenario, either of the plausible alternative scenarios, or a decision-based combination of these using risk, cost, or any other considerations.

Table 3 Selected Impacts of Hanford Tank Waste Remediation Alternatives

Environmental Impact Statement Alternative	Operational Impacts[a] (fatalities)	Long-term (10,000-year) Impacts (fatalities)		
		On-Site Farmer	Recreational User	Cost ($ B)
No action	19	600	40	13 to 16
Long-term management	19	600	40	19 to 23
In situ fill and cap	3	300	20	7 to 9
In situ vitrification	5	1	0	16 to 27
Ex situ/in situ combination 1	6	60	0	22 to 27
Ex situ/in situ combination 2	6	60	3	17 to 20
Ex situ no separations	6	10	0	59 to 75
Ex situ intermediate separations	7	10	0	29 to 35
Ex situ extensive separations	7	10	0	27 to 38
Phased implementation[b] (preferred alternative)	9	10	0	30 to 38

[a] Industrial accidents (including transportation) and radiological impacts, primarily occupational.
[b] Essentially the ex situ intermediate separations alternative.
SOURCE: U.S. Department of Energy and Washington State Department of Ecology (1996), Tables 5.7.1, 5.7.3, and 5.7.6.

The risk studies summarized in Appendix A demonstrate that end state based approaches, including some consideration of alternative scenarios, have been pursued by EM. Moreover, the interest in risk-based analyses seems to have been increasing through at least 1994 (National Research Council, 1994b). However, the committee was unable to find any evidence that such risk studies had an effect on the choice of baseline or alternative remediation scenarios or strategies for the Hanford Site tank wastes. In particular, the only scenario currently being pursued for the Hanford tank remediation is a phased implementation, the estimated cost and risk of which are both higher than some other alternatives. The committee believes that such risk-based analyses could be advantageous to technology development decision making, and that the apparent trend toward decision making with the aid of end state based analyses should be continued.

Development of plausible alternative end state scenarios at Hanford should begin with the current Hanford baseline scenario (the most recent baseline available to the committee is defined in U.S. Department of Energy, 1997b). The committee's reference scenario embodies all the relevant factors in the present Hanford baseline. In the following section, the committee's reference and two alternative scenarios are identified and associated with the end states specified, based on the impacts of a range of plausible future events.

In the case of the Hanford tanks a useful perspective and basis for specifying the committee's reference scenario and plausible alternative scenarios is the wide spectrum of tank waste remediation alternatives in the recent TWRS environmental impact statement (U.S.

Department of Energy and Washington State Department of Ecology, 1996). A summary of the health and economic impacts of these alternatives is given in Table 3.

Committee's Reference Scenario

The committee's reference scenario is an adaptation of the Hanford tank remediation baseline scenario that was identified in the recent Record of Decision (U.S. Department of Energy, 1997b) and in Table 3 as the ex situ intermediate separations alternative. It is one of the more costly alternatives evaluated in the environmental impact statement and it entails a moderate level of operational impacts, but it results in one of the lowest levels of long-term impacts. The essence of this scenario is to retrieve most of the waste from all the tanks. The tanks would then be filled, closed, and subjected to occasional surveillance, resulting in the tank farm area being perpetually unsuitable for unrestricted use. The waste would be processed into a vitrified HLW fraction suitable for storage in a passively cooled on-site temporary storage facility and certified for transport to and acceptance in a deep geological repository, and a vitrified LAW fraction that is suitable for on-site near-surface disposal. The relative amounts of HLW and LAW to be produced appear to be consistent with the currently accepted balance of life-cycle cost and risk reduction. This scenario, shown as a schematic flowchart in the middle portion of Figure 4, is summarized below in terms of the operations (functions) in the committee's reference flowsheet.

Characterization. In this step, the wastes in the tanks, the tanks themselves, and the immediately surrounding soil and water are characterized to an extent adequate to resolve safety issues and to allow retrieval and treatment operations, including consideration of leakage during retrieval. This characterization may include measurement of the concentration of various waste constituents (chemicals or radionuclides), the physical properties, particularly rheological properties, of the heterogeneous waste, the integrity of the tanks, and the extent of soil and ground water contamination surrounding the tanks (for determining risk of residual waste left at the tank farms).

It is important to note that characterization will likely occur throughout the scenario. For example, retrieved waste liquids and solids may be characterized to obtain more precise information on the separate streams, the feed to a vitrifier would have to be characterized to determine feed adjustments, and tanks for which waste retrieval operations have been completed would have to be characterized with respect to their residual contents. For clarity, characterization is shown only once in Figure 4.

Mobilization and Retrieval. If substantial amounts of supernatant liquids remain in the tanks, these would first be retrieved by simple pumping. Then a dilute sodium hydroxide solution would be introduced to sluice the soft solids in the tank bottom into a pumpable slurry. This would simultaneously dissolve some of the highly soluble species, such as sodium nitrate and nitrite, that constitute a significant fraction of some of the solids. After the liquids and soft sludges are removed to the extent possible, more aggressive methods would be employed to recover residual soft solids and hard heels. These would include high-pressure water jets deployed on robotic arms or small in-tank vehicles to break up the hard heels, and small sluicer/vacuums to recover pockets of soft sludge and hard-heel fragments. Concrete removal technologies appear to be relevant to these tasks. The extent and type of application of such aggressive methods are strongly influenced by the end state requirements for the tanks.

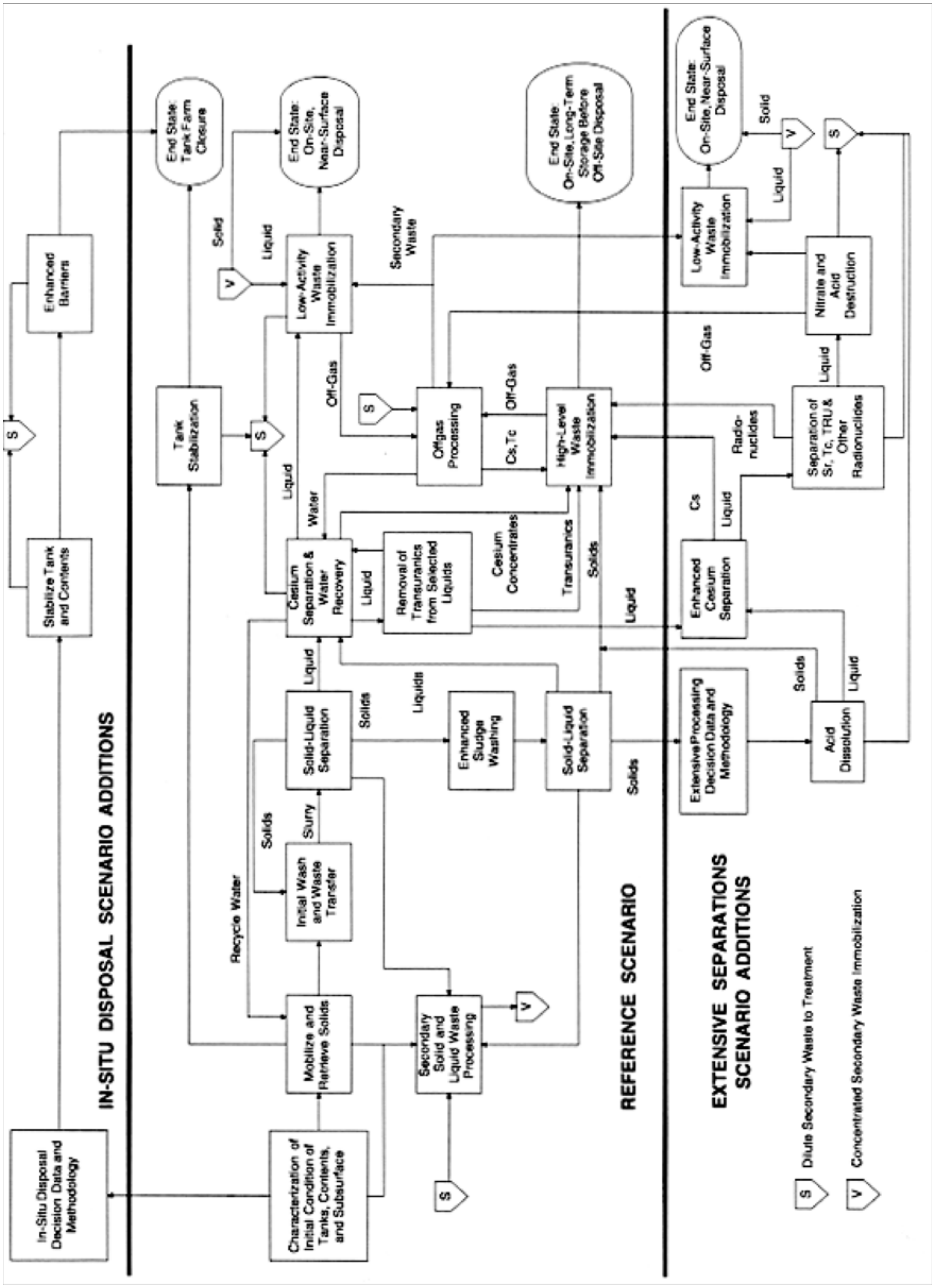

Figure 4.
Committee's Reference and Plausible Bounding Scenarios and Functional Flowsheets for Hanford Site Tanks and Associated Wastes.

The extent to which the removal of tank contents will be required is defined by an acceptable end state for the tank, which will be comprised of interrelated specifications on the allowable amount of residual tank contents, the methods used to stabilize the tanks, and ultimate stewardship requirements. Decisions on these specifications will be based on multi-attribute trade-offs involving stakeholders that include local and regional governments, Native Americans, the Department of Energy and its contractors, regulatory organizations, and the U.S. Congress. These deliberations are not yet complete and, as a result, finalized end state specifications are not available. However, an interim goal has been established in the TPA by the Washington State Department of Ecology, USEPA, and DOE (1996) to retrieve about 99 percent of the waste volume from each tank. The committee believes this is an appropriate scenario goal for planning and conducting a technology development program related to tank waste retrieval. The products of this operation are a solution with high concentrations of sodium salts in which solids are suspended, and almost-empty tanks. The former is transferred to a processing facility and the latter is subjected to stabilization, closure, and long-term institutional control (stewardship).

Initial Washes and Waste Transfers. Initial solids washing actually begins during mobilization and retrieval operations, as insoluble solids are mobilized and salts are dissolved and dispersed in the slurry. This washing action continues as the waste slurry is transferred through pipelines to a collection tank, where the output from several retrieval operations is accumulated and blended. The waste slurry is transferred through a double-walled pipeline (a primary pipe within a secondary pipe) that allows for detection of leaks in the primary pipe. These transfer pipes can extend for several miles to reach the processing facility, and careful operation is necessary to avoid conditions that result in plugging.

The retrieval of tank waste is not likely to proceed on a strictly sequential tank-by-tank basis. Instead, at some point, wastes from various tanks will be blended, to the extent possible within operational constraints such as available tank space and transfer lines and their integrity, to eliminate extremes in composition and adverse chemical reactions. Some of the tanks contain large amounts of particular species (radionuclides and chemicals) that, if not blended, could result in increased HLW volumes or the need for highly flexible (and therefore uneconomical) processes downstream. While this blending operation is likely and desirable, it is not shown in Figure 4 in the interests of keeping the diagram simple. Since processing of both blended and unblended wastes can be expected, subsequent steps and their technologies must be capable of handling both waste forms. The product of this operation is a slurry of cesium-contaminated salt-laden water containing insoluble solids, all of which proceed to solid-liquid separation operations.

Solid-Liquid Separation. In this operation the solids are separated from most of the water used for retrieval and initial solids washing operations using such techniques as decanting, filtration, and centrifugation. The operation is necessary because waste retrieval and transfer operations normally require much more water than is necessary or desirable in downstream operations, and the subsequent processing is different for the solid and liquid streams. The liquid stream proceeds to cesium separation and water recovery operations, and the solids to enhanced sludge washing.

The liquids do not have to be totally separated from the solids at this step because subsequent solids processing (i.e., enhanced sludge washing) will involve introducing additional liquids that will be separated and routed to cesium separations. However, the separation of solids from the liquid stream must be essentially complete for two reasons. First, solids can compromise the cesium removal operation that immediately follows. The extent of the separation required to avoid this problem depends on the specific nature of the solids and the cesium removal process selected. Consequently, the extent of separation cannot be specified at the outset, but it must be taken into account during its execution by communication among various representatives of the technology development program. The second reason for the importance of the degree of solid-liquid separation is that, after cesium removal, this stream becomes LAW in near-surface disposal. The allowable concentration of a number of intermediate- to long-lived radionuclides (e.g., strontium and transuranic nuclides) in the LAW will be determined during preparation of the performance assessment, and may be further limited by waste classification requirements. Since many of the intermediate- to long-lived radionuclides occur in the solid phase, efficient solid-liquid separation is an important function. For this scenario, an appropriate basis for planning and conducting a technology development program would be that the solids in the liquid stream would result in the LAW having concentrations of radionuclides less than Class B concentrations for intermediate-lived radionuclides, such as radiocesium and radiostrontium, and less than Class C concentrations for long-lived radionuclides specified in 10 CFR 61 (U.S. Nuclear Regulatory Commission, 1982a) or the more detailed final environmental impact statement on 10 CFR 61 (U.S. Nuclear Regulatory Commission, 1982b). The resulting allowable concentrations of key radionuclides are listed in Table 4 and, where appropriate, are subject to reductions according to the sum of the fractions rule used by the USNRC as specified in 10 CFR 61.55(a)(7).

Cesium Removal and Water Recovery. In this operation the cesium dissolved in salt-laden water is removed by use of technologies such as ion exchange or solvent extraction to yield a liquid LAW. This step is required because cesium salts are generally very soluble and there is more radioactive cesium-135 and -137 in the waste than is tolerable in the LAW. For this scenario, it is assumed that the cesium must be removed so that its concentration in the immobilized LAW is less than the Class B level specified in 10 CFR 61 (see Table 4).

After the cesium has been removed, the resulting liquid stream contains mostly water with substantial amounts of dissolved soluble chemicals and traces of radionuclides. It is desirable to greatly reduce the amount of water in this stream that must be subsequently evaporated during vitrification and to provide essentially chemical-free water for reuse in tank retrieval operations. This is accomplished using techniques such as evaporation prior to transfer to vitrification.

The products of the cesium removal and water recovery are threefold: a concentrated cesium product (e.g., a liquid containing dissolved cesium, or a solid containing sorbed cesium) that will become part of the vitrified HLW; a concentrated, salt-laden liquid (evaporator bottoms) that will become part of the vitrified LAW; and a relatively pure water stream (evaporator overheads) that is recycled to retrieval operations.

Removal of Transuranics from Selected Liquids. With the exception of compounds of cesium and technetium, most chemicals are quite insoluble under the highly alkaline conditions in the Hanford tanks. Some of the Hanford tanks contain chemical complexants that solubilize these ordinarily insoluble compounds to the extent that the resulting LAW will not meet the end state concentration goals shown in Table 4. This is particularly the case for the transuranics in at least three Hanford tanks containing organic chemicals such as ethylene diamine tetraacetic acid (EDTA). For these tanks it will be necessary either to destroy the remaining organic complexants and remove (e.g., extract, precipitate) the transuranic elements, or to scavenge a sufficient quantity from the liquid phase that will meet the concentration goals of the resulting LAW, estimated to require removal of about 75 percent of the transuranic elements (Petersen, 1996). The output of this operation is a solution of chemicals and trace radionuclides having a significantly reduced concentration of transuranic elements that proceeds to LAW immobilization, and a small stream of transuranic elements that goes to HLW vitrification.

Table 4 Committee's Reference Hanford Tank Remediation Scenario—Concentration Goals for Key Radionuclides in Low-Activity Waste (LAW) for the Purposes of Planning Technology Development

Radionuclide	Concentration Goals In LAW (Ci/m^3)
^{14}C	• 8
^{90}Sr	• 150
^{99}Tc	• 3
^{137}Cs	• 44
^{129}I	• 0.08
Transuranic elements	• 100 nCi/g [<TRU (by definition)]

SOURCE: U.S. Nuclear Regulatory Commission (1982a,b).

Low-Activity Waste Immobilization. Although other immobilization processes are candidates for this function, only vitrification is discussed since it is the process currently accepted by the Hanford TPA signatories and stakeholders. In this operation the concentrated liquid product from cesium separation and water recovery is mixed with glass-making chemicals and heated to a temperature above 1000 °C. The result is first the evaporation of the residual water, then water of hydration, and then the decomposition of species such as nitrates, nitrites, carbonates, and sulfates to yield gaseous nitrogen oxides, carbon dioxide, and sulfur dioxide. What remains in the vitrifier is mostly oxides of various cations, which are incorporated into a glass matrix and poured into containers. The products of LAW vitrification are packages of LAW glass and a significant offgas stream discussed below. The end state of the vitrified LAW is on-site near-surface disposal. The performance requirement of the LAW disposal unit may dictate the maximum acceptable dissolution rate of certain radionuclides and limited concentrations of troublesome elements in the LAW glass.

On-Site Near-Surface Disposal. This type of disposal represents the physical end state for the vitrified, containerized LAW and secondary solid low-level wastes. As noted earlier in this chapter, the end state also imposes additional requirements on the long-term performance of the disposal site, very likely requiring the use of additional barriers beyond the waste form. For the purposes of the committee's reference scenario, an appropriate basis for planning and conducting a technology development program is to assume that the LAW disposal site will require a means to fill any void spaces in the waste emplacement horizon, a multicomponent cap designed to last for centuries, barriers to intruder access, monitoring wells, and occasional surveillance to detect and limit any intrusion.

Enhanced Sludge Washing. The solids from the solid-liquid separation operation still contain large amounts of non-radioactive process chemicals that are not highly soluble in near-neutral solutions. Examples of these are aluminum, chromium, and iron compounds. It is cost effective to remove some of these chemicals to reduce the volume of the HLW, which has much higher processing and disposal costs than the LAW. This is accomplished by enhanced sludge washing, which involves contacting the solids with a concentrated aqueous solution of caustic soda. Under these conditions it is thought that many of the HLW glass volume-limiting constituents other than iron will be dissolved, leaving most of the radionuclides in the solid phase. The remaining solids are separated from the liquid by solid-liquid separation techniques similar to those described below.

The extent to which the solids should be solubilized is bounded by two competing goals. First, the extent and nature of enhanced sludge washing must not be such that too many radionuclides (except for cesium, which will be removed later) are dissolved or suspended in the liquid stream. If this occurs, the allowable concentration of radionuclides in the LAW would likely be exceeded. For planning and conducting a technology development program, the goals in Table 4 are again applicable. This consideration would indicate less solubilization. On the other hand, greater solubilization will result in fewer solids proceeding to the HLW vitrifier which, in turn, will reduce the volume of expensive HLW. Many uncertainties remain before a precise cost-effective balance can be specified. However, an appropriate goal for planning and conducting a technology development program would appear to be a vitrified HLW volume of about 15,000 m^3, a value suggested in the TWRS final environmental impact statement (U.S. Department of Energy and Washington State Department of Ecology, 1996). The major product of enhanced sludge washing is a slurry composed of dissolved chemicals and insoluble suspended solids that are routed to the solid-liquid separators.

Solid-Liquid Separations. In this operation the solids are separated from most of the liquid used for enhanced sludge washing operations. The techniques and considerations involved in this are essentially the same as those described above for solid-liquid separation following the initial solids washing operation, and they are not repeated here. The liquid stream from this operation proceeds to cesium separation and water recovery operations, and the solids to HLW vitrification.

High-Level Waste Vitrifier. The HLW vitrifier will convert the insoluble solids to a glass product, essentially the same operation as the vitrification of LAW described above. The primary difference is the throughput of the HLW vitrifier, which is about 10 percent of that for the LAW vitrifier. However, HLW vitrification involves much greater radionuclide concentrations.

The general requirement placed on the HLW product is that it must meet specifications for sustained temporary on-site storage, transportation to a repository site, and emplacement at that site. As discussed earlier in this chapter under end state criteria, many of the regulations that might provide specifications for this product have not been finalized. However the previous requirements specified in 40 CFR 191, 10 CFR 60, and supporting documents from the DOE Office of Civilian Radioactive Waste Management (U.S. Department of Energy, 1993) provide an appropriate basis for planning and conducting a technology development program. In effect, this requires that careful attention be given to the formulation and manufacture of a substantially homogeneous glass to achieve a suitably low dissolution rate, to the type of package in which it is contained, and to the quality assurance of its production. In addition, for the purposes of this report, the vitrified HLW packages are required to withstand about 50 years of on-site dry storage without significant degradation. The products of this operation are vitrified HLW glass logs and a significant offgas stream discussed below.

On-Site Temporary Storage. This operation involves placing each HLW package in a separate cylindrical hole in a storage facility and sealing the hole with a shielding plug. The facility is typically of concrete construction and designed to remove through conduction and convection the relatively low levels of decay heat (i.e., no water cooling is used). Such a facility is in operation at the Savannah River Site.

This is the physical end state of the HLW for technology development planning purposes. Requirements for transportation and the repository are assumed to be outside the scope of the present effort. The design requirements for a facility of this type are straightforward, especially in an arid climate such as that at Hanford. The single exception is the design life. It is the view of the committee that a 50-year design life is an appropriate basis for planning and conducting a technology development program because of the uncertain schedules for approval, construction, and operation of a deep geologic repository.

Offgas Processing. Managing the offgases from the LAW and HLW vitrifiers is a complex and challenging undertaking because of the simultaneous presence of relatively large volumes of gas (air, steam, volatile oxides), corrosive species (nitric and sulfuric acids resulting from the volatilization of nitrates and sulfur oxides), semivolatile radionuclides (cesium, technetium, and ruthenium), and semivolatile chemicals (boron, sodium compounds), all at the very high temperatures typical of vitrifiers. The function of the offgas system is to remove the hazardous constituents to acceptable levels and recycle what is recovered. Processes used could include condensation, filtration, and liquid scrubbing.

The end state of the offgas stream is that it is cleaned sufficiently to be acceptable for release to the atmosphere. Regulations on 'how clean is clean' are presently available for Hanford and are an appropriate basis for planning and conducting a technology development program. The applicable regulatory requirements for effluent discharges are in the TWRS Mission Analysis Report (Acree, 1998). Typically, products of offgas processing that lead to meeting the qualitative end state for the offgas are cleaned gases released to the environment, condensed steam (water) for recycle to retrieval operations or secondary waste treatment, recovered radionuclides recycled to the HLW vitrifier, LAW recycled to the LAW vitrifier, and other secondary LAW (e.g., contaminated nitric and sulfuric acids) sent to secondary waste processing.

Tank Stabilization. It is assumed that the tanks from which waste has been retrieved will not be exhumed because of the extensive cost and risk to workers. Tank stabilization is assumed to involve filling the tank with a material such as gravel or rocks that, at a minimum, prevents tank collapse and surface subsidence. Stabilization could be extended to involve the use of a grout matrix poured into the tank to completely fill it with a resulting strong monolith, eliminating voids and thus reducing subsequent water collection in the tank.

Establishment of end state requirements for the purpose of a tank stabilization and closure technology development program is in its fledgling stages. The committee believes that a prudent planning basis for its reference scenario is that the tank be filled with a pourable agent such as grout to eliminate voids completely where water might collect and leach the residual heel. The grout stabilizing agent could also be designed to retard leaching and to retain potentially troublesome waste products such as technetium.

Tank Farm Closure. This operation is essentially the same as the closure of the on-site, near-surface LAW disposal site discussed above, although additional characterization of the tank contents and adjacent contaminated soil before and after stabilization is likely to be required. The end state and attendant requirements are assumed to be the same for the committee's reference scenario.

Secondary Waste Processing. Many of the operations described above produce secondary wastes. These could be solid wastes ranging from failed equipment, protective clothing, filters, etc., to a variety of liquids from the various processing operations. These wastes would be processed to yield a releasable liquid effluent, solid wastes suitably treated for on-site near-surface disposal, and a concentrated liquid that would be sent to the LAW vitrifier. Such treatment usually involves existing technology, although there can be exceptions such as disposition of used vitrifiers. The end state requirements for most of these have already been discussed. For the liquid effluent, the Hanford Site has already established criteria for release of liquid effluents (see Acree, 1998), which are an appropriate basis for planning and conducting a technology development program.

In Situ Disposal Scenario

It is the view of the committee that in situ disposal (i.e., tank waste left in place) constitutes another plausible scenario for planning and conducting a technology development program. This scenario could be driven by a combination of factors such as the need to accomplish remediation with a significantly reduced budget, or the recognition that many of the tanks represent a relatively low risk that may not warrant waste retrieval and treatment. As shown in Table 3, alternatives involving in situ techniques reduce the total cost of remediating the tanks by several billion dollars while somewhat decreasing operational impacts. The functions required to implement this scenario, which would replace essentially all of the functions in the committee's reference scenario, are shown in the upper portion of Figure 4 and are described below.

Decision Data and Methodology. The first step in proceeding with in situ tank remediation is to decide which tanks are acceptable for such disposition. A preliminary study (Nelson, 1995) to determine how many tanks could potentially be disposed in situ has been completed and is discussed in Appendix A. While such decisions have many non-technical aspects related to stakeholder values and risk management, there are also technical implications. It will first be necessary to know the contents and characteristics of the tanks to a greater precision than what might be required for retrieval, thus requiring additional characterization and potentially additional technology development. It will be necessary to use knowledge of the tank contents to design the stabilization process and thereby predict both the post-remediation performance of the waste-bearing tanks as an immobilization medium and the relevant geohydrology, both current and predictable future, to provide information on the potential future risks from in situ disposal. This then provides a partial basis for decisions on which tanks are suitable for in situ disposal.

Stabilize Tank and Contents. This operation is conceptually similar to the tank stabilization operation under the committee's reference scenario. However, there are two important differences. First, the tank would contain a significant amount of waste. Some of the waste is likely to be 'soft' and partially mixable with stabilization agents, while other portions are likely to be hard and not readily mixable. Further, many tanks are likely to have holes that would leak if substantial amounts of liquids were introduced. Achieving adequate in situ stabilization under these conditions will be a major challenge. Second, the stabilization agent, which should be appropriately reactive to retain selected waste components, must also be compatible with the waste, which is highly alkaline-again, a major technology challenge.

The performance requirements for this scenario have not been established. Potential performance of yet-to-be-developed stabilization and engineered barrier system technologies (discussed below) have not been demonstrated. This fact, in turn, precludes determining the range of wastes that might be acceptable for in situ disposal and the trade-offs among cost, risk, and technical performance. The committee notes that the relationship between general performance requirements and the allowable concentration of radionuclides in LAW in on-site near-surface disposal has been established. The committee believes a prudent interim basis for planning and conducting technology development for an alternative scenario such as in situ disposal would be to assume that the impacts from radionuclides released from an in situ disposal site would be the same as those from the LAW disposal site, and to establish targets for site release limits for in situ disposal accordingly. After technology development has proceeded, the feasibility of the goal can be examined, and the technology development results will establish an initial basis for review of end state requirements with regulators.

The result of this operation is a tank with the contents mixed and immobilized to the extent practical and the tank completely filled with a solid material to prevent tank collapse.

Enhanced Barriers. Because of the increased inventory of radionuclides and toxic chemicals that would remain in the tanks in this scenario, it is assumed that enhanced barriers to water ingress and outward migration of toxic species would be employed. The most commonly identified forms of these barriers are impermeable surface caps and subsurface vertical and subhorizontal walls to reduce further the amount of water contacting the stabilized tank and the rate at which contaminated water can move into the biosphere. More advanced technologies involve barriers that chemically react with hazardous constituents (e.g., sorb radionuclides, precipitate toxic metals).

As with tank stabilization, the requirements for these barriers have not been established, but overall criteria for health risks exist. The approach to technology development is the same as that described for tank stabilization and, in fact, chemical adjustment, tank stabilization, and barrier technology must be developed in concert. The result of this operation is a tank farm in which the tank contents have been chemically adjusted and stabilized, and around which enhanced barriers have been installed. The tank farm is then capped as discussed earlier in this chapter under "Tank Farm Closure." At present it is not clear that permanent barriers can be established that will not require some long-term institutional control and maintenance over some of the more highly contaminated areas, including residual waste in remediated tanks and tank farms.

Extensive Separations Scenario

It is the opinion of the committee that an extensive separations scenario is another plausible alternative scenario for planning and conducting a technology development program for Hanford Site tank remediation. This scenario could be driven either by the need to further reduce radionuclide contents in LAW because of increased calculated risks or risk adversity, or the need to reduce vitrified HLW volume because of increases in the cost of disposing of waste in the repository, or both. As indicated in Table 3, the presently estimated operational and long-term impacts and total cost of this scenario may be about the same as for the committee's reference scenario. The drive to reduce the radionuclide contents of the LAW and the volume of HLW results in the need for significantly more intensive processing of the tank waste to remove additional radionuclides and volume-increasing chemicals. The additions to the reference scenario that would be required to implement this scenario are shown in the lower portion of Figure 4. Changes in the amount and nature of the HLW may be sufficiently large such that the requirements on downstream operations involving HLW (e.g., vitrification, storage) could be altered.

Decision Data and Methodology. The first step in proceeding with this scenario is to decide which tank contents should be subjected to extensive processing. If the driving force is risk reduction, the information required would be related to the tank contents and potential releases of hazardous materials. If the driving force is HLW volume and cost, the information required would relate to chemicals (e.g., chromium) that significantly increase glass volume. In either case, there would be a need for more information on the contents of the tank wastes that will be treated using the extensive separations scenario, which has implications for characterization technology development requirements. These were described earlier in this chapter under the "In Situ Disposal Scenario" section on "Decision Data and Methodology."

Dissolution. The chemicals remaining in the radionuclide-laden solids resulting from enhanced sludge washing in the committee's reference scenario need to be removed if HLW volume reduction is desired. Instead of going to the HLW vitrifier, as in the committee's reference scenario, the solids selected for extensive separations would be dissolved. This is likely to require the use of one or more strong mineral acids and possibly alternative reagents. Since the solids and the radionuclides therein were already destined for the vitrifier in the committee's reference scenario, no additional risk reduction for the waste stream is achieved by dissolution and additional separations processing. The extent of dissolution required is a function of the degree to which cost analyses indicate volume reduction of the HLW is justified.

The output from this operation is an acid solution of radionuclides and chemicals for subsequent processing and the undissolved solids that are sent to the HLW vitrifier as in the committee's reference scenario.

Enhanced Cesium Removal. The solids from enhanced sludge washing may contain significant amounts of cesium. The cesium will be released during dissolution and may require removal to assure adequate risk reduction before the liquid can proceed to LAW vitrification. Additionally, the cesium concentrations in the liquid stream in the committee's reference scenario may be sufficiently high to require enhanced cesium recovery using highly selective techniques such as specialized ion exchange media or solvent extraction. The output from this operation is recovered cesium, routed to the HLW vitrifier in the committee's reference scenario, and an acidic liquid stream, which is routed to additional separations.

The committee recommends that as a basis for planning and conducting a technology development program, the resulting LAW should contain no more than Class A concentrations of radionuclides (U.S. Nuclear Regulatory Commission, 1982a). The values for a few key radionuclides are given in Table 5.

Separation of Strontium, Technetium, Transuranic Elements, and Other Radionuclides. The acidic product from enhanced cesium recovery contains significant amounts of dissolved elements such as strontium, technetium, and transuranics. These will be recovered using such techniques as ion exchange and solvent extraction. As with cesium, the committee recommends that the basis for planning and conducting a technology development program for extensive separations should be that the resulting LAW contain Class A concentrations of strontium, technetium, transuranic elements, and any other radionuclides that might limit achieving equivalent levels of risk. The radionuclide concentrations for Class A waste are given in Table 5.

Table 5 Extensive Separations Hanford Tank Remediation Scenario—Concentration Goals for Key Radionuclides in Low-Activity Waste (LAW) for the Purposes of Planning Technology Development

Radionuclide	Concentration Goals In LAW (Ci/m^3)
^{14}C	• 0.8
^{90}Sr	• 0.04
^{99}Tc	• 0.3
^{137}Cs	• 1
^{129}I	• 0.008
Transuranic elements	• 10 nCi/g

SOURCE: Based on Class A low-level waste radionuclide concentrations as found in U.S. Nuclear Regulatory Commission (1982a); 10 CFR 61.55, Table 1; and 10 CFR 61.55(a)(3)(i).

The outputs from this operation are recovered radionuclides, which are routed to the HLW vitrifier, and an acidic liquid waste stream having smaller amounts of radionuclides than in the committee's reference scenario.

Nitrate and Acid Destruction. To make the acidic stream compatible with subsequent immobilization operations, the nitric acid must be destroyed. This is accomplished by adding non-volume-increasing chemicals such as formic acid or sugar, resulting in the evolution of nitrogen oxides and carbon dioxide gases, which may be scrubbed out. The extent to which the acid needs to be destroyed is defined by LAW operational considerations. The output from this operation is a near-neutral liquid waste stream which is routed to LAW immobilization operations.

LAW Immobilization. The lower radionuclide concentration in the LAW resulting from this scenario (as compared to the committee's reference scenario) should allow the use of less-expensive technology such as grout for the purposes of LAW immobilization. There is some debate about whether the life-cycle cost of technology such as grout is indeed less than that of vitrification. Some argue that the lower costs of grouting are outweighed by its larger volume, and thus the need for more costly disposal facilities. If this were the case, then the LAW might more properly be routed to the same type of LAW vitrification facility as that used in the committee's reference scenario. If grout were to be used, the LAW would be thoroughly mixed with grouting chemicals and formed into monoliths in retrievable containers (e.g., metal drums) or large near-surface vaults.

The performance of the engineered barriers should be such that, when in combination with the reduced radionuclide levels, the resulting risks are commensurate with Class A low-level wastes. The result of this operation is immobilized LAW for on-site disposal.

On-Site Near-Surface Disposal. This is the physical end state for the containerized LAW and secondary solid LLW. The considerations for this operation are essentially the same as for the committee's reference scenario and will not be repeated here.

Extreme Scenarios

It is possible to consider other scenarios that broaden the coverage of end states even further. For example, it is conceivable that the tank contents could be removed and processed approximately as indicated in the committee's reference or extensive separations scenarios, and the tanks would be exhumed, sectioned, and sent for disposal elsewhere, leaving a *greenfield* site suitable for unrestricted access and use. On the other hand, one of the obligatory environmental impact statement alternatives is *no action.* In the committee's view both scenarios are too extreme and unlikely to constitute a plausible planning basis for a technology development program for Hanford tanks. Consequently, the technology development needs of these scenarios are not included in this analysis, and extreme scenarios should not be the basis of analyses in defining a technology development program.

FUNCTIONAL FLOWSHEET CONSOLIDATION

The functional flowsheets for the three scenarios described earlier in this chapter are diagrammed in Figure 4 to demonstrate the commonalties with the current Hanford baseline flowsheet. The purpose in doing so is to highlight the very important point that only a few additional processing functions over those required for the committee's reference flowsheet are necessary to implement any of the three scenarios. Specifically, by being able to immobilize tank waste in situ, install subsurface barriers, perform enhanced cesium recovery, dissolve residual sludge, and separate strontium, technetium, and transuranic elements in addition to the committee's reference scenario functions, it would be possible to remediate tanks and tank waste under a wide range of end state requirements. This provides a contingency in case less extensive technologies can or must be used, as well as more extensive separations technologies in case of HLW disposal cost considerations. It is beyond the scope of this study to estimate the cost of undertaking the incremental technology development to support all three scenarios, but such cost may be a fraction of the potential savings achieved by selectively deploying all three scenarios as opposed to pursuing only the committee's reference scenario. The following chapter will provide a summary technology assessment for selected functions of the flowsheets shown in Figure 4. The assessment identifies areas that could require technology development, and compares these requirements against ongoing technology development activities.

SUMMARY

An examination of the alternatives proposed in the TWRS environmental impact statement (see Table 3) demonstrates that remediation of Hanford tanks using a combination of disposal end states associated with the committee's reference and alternative scenarios (i.e., in situ and ex situ, with varying degrees of radionuclide separations depending on the specific characteristics of the waste) offers the potential for substantial cost savings with little or no adverse impact on risks. The processing functions required to implement the alternative scenarios and reach the alternative end states, and the required performance of each function, can be determined by specifying a reference and two plausible bounding alternative scenarios. This can be done with modest effort even though uncertainty may exist in the completeness and formality of the specifications of all of the required end states.

The number of processing functions required to implement three scenarios (the committee's reference and two plausible alternatives) is substantially less than triple the number of operations for the committee's reference scenario alone. Thus, the committee believes that the incremental cost for a comprehensive and robust technology program would be reasonable when compared to the potential cost savings that would be experienced from employing an in situ disposal scenario for some tank waste, and to the potential schedule and cost penalties that would be experienced if a more extensive separations scenario is needed in the future.

An end state based approach employing a reference scenario and plausible alternatives should be used in identifying technology needs for all DOE waste disposal and environmental remediation programs that do not have firmly defined short-term end states that can be achieved using demonstrated technology. Further, the greater the program uncertainties (technical, regulatory, institutional), the greater is the need for applying this approach to provide information and contingency options to decision makers.

Finally, the committee notes that, in some cases, critical TWRS program policy or requirements specification documents, which might provide the basis for the end state based approach, remain under review or in draft form for long periods of time. In many instances the Hanford program direction has changed before an applicable report could be completed, implying that major decisions and changes in program direction are sometimes undertaken by decision makers without the benefit of all pertinent information. While the committee does not recommend that documents be completed if they are already irrelevant, it is important that the relevant documents be completed promptly and made accessible so that all data and information, including risk-based decision analyses, are available to DOE decision makers in time to provide visible support for key decisions, especially those related to a sound technology development program.

4

Results of an End State Based Analysis of Technology Development Needs for the Hanford Tanks

A limited application of the end state approach, exemplified by the three scenarios for Hanford tanks remediation described in Chapter 3, can bring into focus the technology development needs to meet functional requirements. It is not the intent of this report to discuss the technology needs of each processing function shown or implied in the scenarios. Rather, four important functions have been selected, and these will be discussed in some detail to illustrate the type of review and analysis for evaluating technology development needs to support deployment of remediation systems. This illustrates the final steps of the end state approach shown in Figure 3.

The Hanford tanks end state remains to be negotiated with the state, its citizens, tribal nations, and the U.S. Environmental Protection Agency (USEPA). At present, the Tank Waste Remediation System (TWRS) has adopted some target end states to provide a focus for work. The committee was unable to determine whether those end states had been formally adopted by the Department of Energy (DOE). Although a recent Hanford report (Acree, 1998) discusses end states, the committee found little indication that the Office of Environmental Management (EM) program plans to explicitly address end state issues in the near term (i.e., before fiscal year 2000), even though some of the issues (e.g., chemically active barriers to migration of radioactive species) will require innovative technologies for their solution. Comprehensive performance and cost assessments would identify the nature and priority of technology development needs, or, in the case of the DOE Environmental Management Science Program (EMSP), the need for more basic research.

The committee found the lack of well defined end states a potential EM remediation program deficiency that increases the risk of failure to meet schedules, budgets, and technical requirements. Hence, end state definitions and associated technology development needs are not completely defined and integrated in the Office of Science and Technology (OST) programs. As noted above, there are tentative criteria for some of the end states for the Hanford remediation system. However, to thoroughly identify waste remediation process technology needs, the end states must be completely defined and pertinent attributes of the end states must be described in terms that can be related to process steps.

The committee recognizes that its reference scenario, while very similar to the Hanford baseline (U.S. Department of Energy, 1997b), may not be adequate to uncover all technology development needs for remediation of all the Hanford tanks. Nevertheless, the approach described herein identifies gaps and needs for improvements in planned remediation processes, as well as technology needs to address and alleviate those deficiencies. Also, it is likely to uncover deficiencies and needs in the Hanford baseline scenario, even when remediation activities are well under way. The committee believes that the analysis presented below for the four processing functions selected for review demonstrates the process that DOE should use to identify waste remediation technology needs.

By comparing scenarios such as the three presented in this report, it is possible to identify common functions for the scenarios, as well as those that are relevant to only one or two of the scenarios. In this way, a comprehensive set of technology gaps and improvement needs can be readily identified without duplication of effort, and once the results of performance and cost assessments are in hand, a judgment can be made about the relative priorities of the technology needs.

Various technologies required for tank waste remediation have been developed by TWRS program elements, DOE national laboratories, industry, and university laboratories. This development work was carried out over a period of many years, and some of the work was done before the tank contents were adequately characterized and the complexity of the remediation task fully appreciated. Therefore, the evaluation of technology deficiencies and needs should include a review of previously developed technologies to determine if they are still relevant and adequate.

Technology needs refers to the actions required to obtain specified information or to carry out specified functions. As used in this report, it does not refer to the acquisition of data or information through the use of well-defined or established practices or techniques. Technology needs arise when existing processes are inadequate for one or more reasons, such as safety and health risk, inability to perform the functions required to meet end state criteria, economics, and limitations on applicability or scale-up to the required levels.

TECHNOLOGY DEVELOPMENT PROGRAM FOR HANFORD TANK WASTES

The Site Technology Coordinating Group (STCG) for Hanford, which includes TWRS program representatives, identifies technology development needs for tank remediation. The EM technology development programs that directly address or have some potential relevance to address these needs consist of three major components, listed in order of decreasing funding: (1) a significant portion of the Tank Focus Area portfolio (Pacific Northwest National Laboratory, 1997a), (2) the Hanford Tank Initiative (HTI) (Root, 1997), and (3) a number of miscellaneous technology development and technical support activities funded directly by Hanford TWRS (D. Wodrich, DOE Richland, personal communication, 1997). Needs being addressed by these three components are summarized as follows:

- *Storage*—monitoring tank integrity, in situ waste characterization, reduction of waste streams designated for tank storage.
- *Retrieval*—mobilization and retrieval of bulk waste, retrieval of heels, saltcake dissolution, blending of wastes, transfer of slurries in pipelines, leak detection and mitigation, establishing the technical basis for retrieval performance criteria.
- *Processing*—radionuclide removal, solids washing, enhanced sludge washing, behavior of wash solutions, solid-liquid separation, maintaining water balances.
- *Immobilization*—testing of low-activity waste (LAW) waste forms performance in support of risk assessment and development of waste acceptance criteria, optimization of high-level waste (HLW) glass formulations.

- *Closure*—measuring the quantity of radioactive waste residue in a tank, sampling the plume of contaminants in soil, establishing the technical basis for closure criteria.

The Hanford privatization contractors are also presumably performing technology development activities, especially in the areas related to radionuclide separations and immobilization.

TECHNOLOGY ASSESSMENT FOR SELECTED FUNCTIONS OF THE SCENARIOS

The three example Hanford waste tank remediation scenarios presented in Figure 4 in Chapter 3 were used to select four functions to illustrate the definition of requirements and technology development needs. The four functional process steps selected for further analysis are (see bold outlined boxes in Figure 5) (1) enhanced sludge washing, (2) offgas processing, (3) stabilization of tanks and unretrieved contents, and (4) enhanced barriers for tanks from which the contents have not been removed. They were selected partly for their process importance and partly to provide an example of technology development needs not currently in DOE's program.

Enhanced Sludge Washing

Some of the chemicals that can have a negative effect on costs or processing operations, especially on vitrification, will certainly not be removed when tank sludges are washed with water or dilute caustic solution. Therefore, an enhanced washing step is included in Hanford's baseline and the committee's reference scenario. Compounds of particular interest are those containing chromium, phosphate, aluminum, and sodium, because they will either remain in large quantities in washed sludges or have a disproportionately large impact on HLW volume (Beahm et al., 1997). The diverse nature of the tank solids suggests that no single enhanced sludge washing procedure will be effective for all of the tank waste.

Enhanced sludge washing is described in Chapter 3 and shown in Figure 5. The general functional requirement of enhanced sludge washing is to reduce the total volume of the vitrified HLW product by solubilizing non-radioactive chemicals that are not soluble in near-neutral water and routing the remaining insoluble solids, which contain most of the radionuclides, to the HLW vitrifier. A product of the enhanced washing step is a solution containing primarily non-radioactive, amphoteric, bulk chemicals. This solution is routed to a cesium removal step. The technology development needs relate to removing potentially deleterious and voluminous bulk chemicals from the waste solids going to the HLW vitrifier while retaining important radionuclides, such as transuranic elements and strontium, in the HLW stream.

Specific functional requirements for the removal of key species (i.e., aluminum, chromium, sodium, phosphates) to achieve a HLW end state volume target of about 15,000 m^3 (4 million gallons) are given by Boston (1997) and are used for this example. There is also a requirement that transuranic elements not be solubilized to an extent that would result in the immobilized LAW being a transuranic waste (i.e., greater than 100 nCi/g of long-lived alpha radioactivity). More desirably, the waste should meet the U.S. Nuclear Regulatory Commission's criteria for Class A waste of ¬ 10 nCi/g. Based on values given in the TWRS Environmental

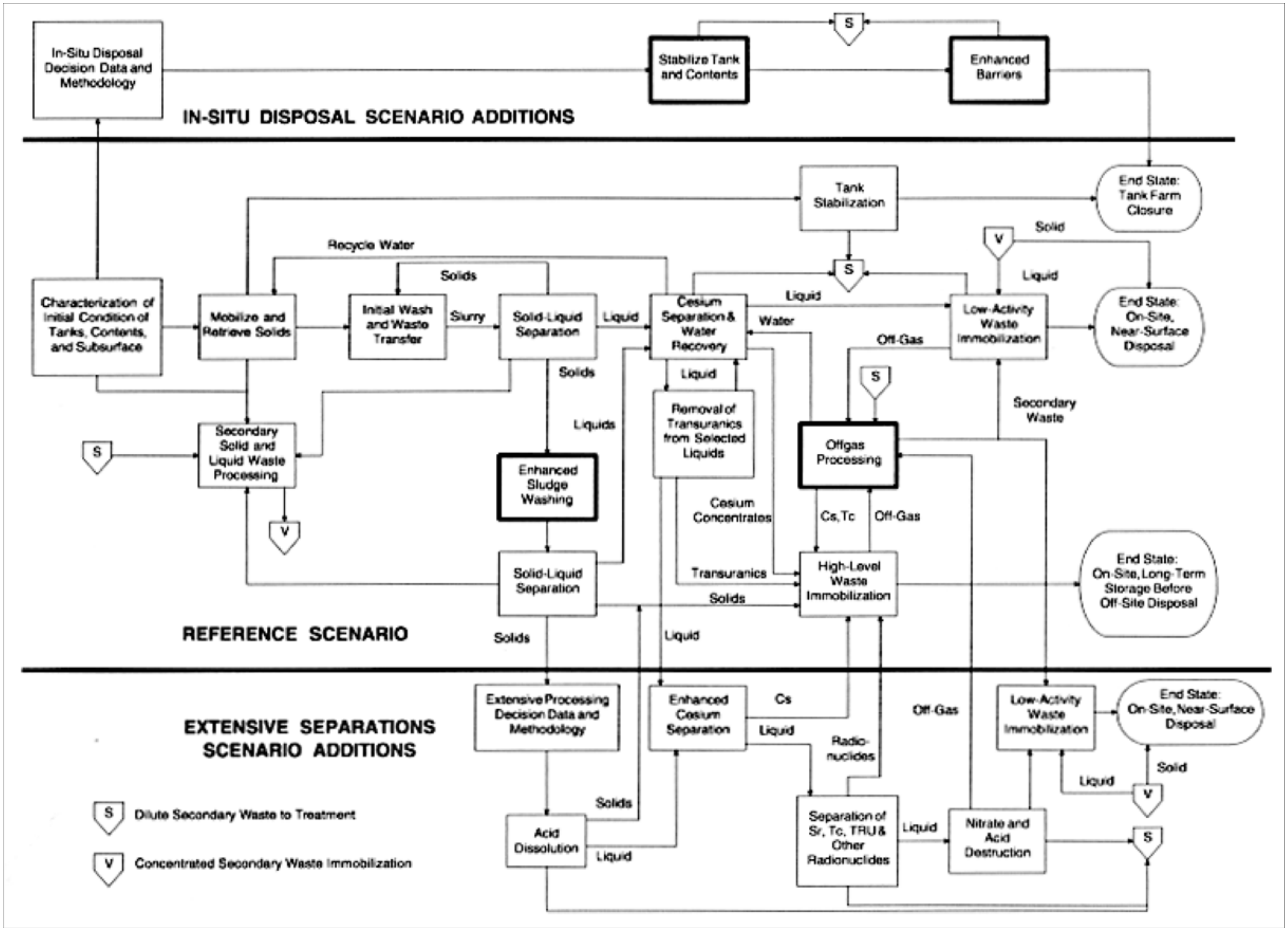

Figure 5.
Committee's Reference and Plausible Bounding Scenarios and Functional Flowsheets for Hanford Site Tanks and Associated Wastes (same as Figure 4), with Functions Selected for Discussion in This Report Shown in Bold Outlined Boxes

Impact Statement (EIS) (U.S. Department of Energy and Washington State Department of Ecology, 1996), the average concentration of transuranics in the immobilized LAW if the entire inventory is solubilized is about 144 nCi/g. Thus, on average, in order to meet a limit of 10 nCi/g in the immobilized LAW, at most 10/144 or about 7 percent of the important transuranic elements (americium and plutonium) could be solubilized.

The ultimate determinant of permissible technetium content of the LAW is the dose from technetium to the critical group in the vicinity of the Hanford Site. The actual dose has yet to be determined by confirmed modeling studies for technetium release from LAW and transport to the geographical point where the dose must meet the standard, especially that for ground water contamination. In the absence of a regulatory dose standard and an accepted modeling study for technetium release, prudence dictates that methods for technetium removal from the LAW stream be developed to ensure a capability for meeting eventual regulatory requirements. Technology needs relate to removing technetium to levels that meet these requirements.

Use of caustic solutions to leach sludges can lead to formation of colloids, gels, and precipitates that can plug pipelines or interfere with subsequent processes. Even though there appears to be little evidence to date of problems from colloid, gel, and precipitate formation caused by enhanced sludge washing, the potential for such formation remains a concern. Colloidal forms of the actinides such as plutonium and americium could remain with the LAW stream, potentially changing the waste classification of some wastes. Gels and precipitates from combinations of the many chemicals in the wastes could easily form, especially as the wastes cool in pipelines. As a result, a qualitative functional requirement is to sufficiently understand this operation so that these undesirable species are not formed in unacceptable amounts.

Enhanced sludge washing has received a great deal of attention at Hanford because of its cost benefits and the avoidance of process complications (McConville, Johnson, and Derby, 1995; Orme, 1995). Study of chromium chemistry and caustic recovery was identified as being important by the Hanford STCG (Pacific Northwest National Laboratory, 1997a, b). Chemical solubility data in the highly caustic wash solutions expected to be used for enhanced sludge washing are available on some existing Hanford tank waste (Peretrukhin, Shilov, and Pikaev, 1995; Peretrukhin et al., 1996), and on some compounds that are expected to be formed during processing. There appear to be little data available on the rates at which compounds will be formed or dissolved, although there is some information on the kinetics of valence changes and their effects on solubility (Shilov et al., 1996). This may cause some unsuspected effects, such as the formation of insoluble compounds that may cause problems in transfer lines. In addition, there is evidence that some of these processes will be quite slow, occurring over days or weeks (Beahm, et al., 1998). Slow reaction rates could have a large effect on flowsheet design, process efficiency, plant throughput, and production scheduling. Also, there appear to be few systematic and relevant studies on the effects of temperature on formation and solubility of compounds such as aluminum hydroxide and various oxides of aluminum, phosphates and fluorophosphates, and carbonates. All of these could cause problems with formulation and consistent production of an acceptably homogeneous glass, and with the feasibility of achieving the desired volume reductions, both of which are important aspects of the HLW end state. It is important to continue the work on adverse consequences of precipitation reactions to the waste treatment process.

Changing valence states of the ions of concern to improve their removal by enhanced sludge washing is another important issue. For example, it is possible to dramatically change chromium chemistry (and enhance its removal) through valence state adjustments using oxidizing chemicals such as permanganate or ozone. This process is being studied for tanks in which the chromium has proven difficult to remove by enhanced sludge washing (Rapko, Delegard, and Wagner, 1997; Lumetta and Rapko, in press). Other elements in the tank wastes (e.g., plutonium and neptunium) are also subject to valence changes under redox conditions similar to those being considered for chromium valence adjustment. However, recent evidence (Rapko, 1998) indicates that while the highest potential concentration of transuranics in LAW glass observed in laboratory scale experiments is about 10 nCi/g, more typical concentrations would be on the order of 1 nCi/g, both of which are probably low enough to be acceptable.

In light of the diverse chemistry of the wastes and the need to mix wastes from various tanks to partially homogenize the feed to the vitrifier, the sludge washing chemistry and accompanying physical and chemical changes must be predictable. Enhanced sludge washing is identified by the DOE Tank Focus Area (TFA) (Pacific Northwest National Laboratory, 1997b) to be at the engineering development stage, and only parametric tests are planned. Table 6 summarizes the OST technology development projects needed for this process step. Enhanced sludge washing has also been studied by TWRS, and presumably by the Hanford tank privatization contractors.

As shown in the table, OST is or has been pursuing several projects related to enhanced sludge washing. The committee was unable to determine from information received from OST whether enhanced sludge washing needs are being identified and pursued systematically at a level required for basic understanding, and whether the projects selected will contribute to meeting the processing function's requirements.

Vitrifier Offgas Processing

Offgas processing will be required at various process steps throughout the Hanford baseline scenario, and also in the committee's reference scenario shown in Figure 5. Offgases from the HLW and LAW vitrifiers present formidable cleanup problems because of the high temperatures and the resultant decomposition and vaporization of a variety of chemicals (International Atomic Energy Agency, 1988). These chemicals include radionuclides (such as cesium and technetium) in the form of hydroxides or oxides, as well as other volatile metallic compounds, oxides of nitrogen, and organic compounds. In addition to these chemicals, there will also be large quantities of vaporized water and entrained materials to be treated at many points in the process. Ruthenium, which contributes little to the total radioactivity in tank wastes but is present in appreciable quantities, will likely appear in the offgas stream and must also be managed.

The qualitative functional requirement for offgas processing is a stream that is acceptable for release to the atmosphere, plus internal streams (usually aqueous) suitable either for the secondary waste processing system or, if suitable, for recycling to the vitrifier. The offgas streams contain the chemical compounds of ruthenium, sodium, and boron, which could clog the offgas processing system. In particular, the functional requirements for offgas processing are not driven by a scenario end state criteria, but rather they are largely defined by acceptance requirements for other functions in the flowsheet. Qualitative functional requirements are the following:

- removal of a variety of semivolatile compounds of radionuclides such as cesium, iodine, and technetium,
- destruction or removal of nitrogen oxides resulting from decomposition of nitrate and nitrite salts in the vitrifier, and
- removal of sulfur oxides resulting from decomposition of sulfates in the vitrifier.

Table 6 Department of Energy Office of Science and Technology Projects on Enhanced Sludge Washing

Technology Needed	Technical Task Plan	Title
Removal of troublesome chemicals	AL16WT41-A	Parametric studies of Hanford sludge
	OR16WT41-C	Prevention of solids formation
Solubility data for selected compounds	RL08WT41-A	Saltcake dissolution
	OR16WT41-B	Saltcake dissolution
Kinetic data for compound formation	OR16WT3 1-C	Control of leachate solids formation
Colloid, gel, and precipitate formation		
Temperature coefficient of solubility for hydroxides of aluminum, iron, and zirconium, phosphates and fluorophosphates		No specific projects identified

SOURCE: Pacific Northwest National Laboratory (1997b).

In addition, problems may be caused by the presence of mercury and similar chemicals. The technology development needs relate to retaining radioactive and toxic wastes in the vitrified product and preventing deleterious buildups of solids and radioactivity in the offgas system.

Recovery and recycling of cesium and technetium will be required because the volatilities of their oxides are such that it may be difficult to retain them completely in the glass melt. This may result in a relatively large inventory of these elements in the offgas stream, either in gaseous form or as aerosols formed in the gas stream leaving the vitrifier. Buildup of radioactivity from cesium could lead to high radiation levels in parts of the offgas system. Contamination by technetium is a concern because of the volatility of its oxides (Vida, 1994) and its very long half-life. This contamination could become, for example, an important problem during equipment decontamination for repair or maintenance. Since the French vitrification experience suggests that the volatility of both technetium and ruthenium can be reduced during vitrification of HLW (Jouan, Moncouyoux, and Halaszovich, 1985), a similar reduction in the volatilities of technetium and ruthenium compounds could occur during vitrification of Hanford waste, although this needs to be validated for the vitrifier and unique waste compositions at Hanford. The committee notes that the Hanford vitrifier is not likely to operate under the more desirable reducing conditions that would inhibit chemical volatility because of the presence of nitrates, air, and other oxidizing substances.

Entrained particles or aerosols of compounds of cesium, technetium, and ruthenium, as well as volatilized compounds, can adhere to pipes and eventually obstruct gas flow (Yonega et al., 1985). This is also a problem in the LAW vitrifier, where volatilization of boric acid and alkali borates is likely to occur. Deposited particles can also lead to maintenance problems. The extent of the volatilization problems depends to a large extent on the design and operating conditions of the vitrifier (Wilson, 1996; Whyatt et al., 1996).

In general, condensers and scrubbers are used to remove vaporized and entrained materials from offgas streams (International Atomic Energy Agency, 1988, p. 31-39). Catalytic destruction of nitrogen oxides is also an option for the LAW vitrifier offgas, but catalyst poisoning may be a problem and must be addressed by technology development. The water produced in the reaction will also need to be treated to remove contaminants.

Chloride and fluoride, which can be present in the vitrifier offgas from some of the tank wastes, can cause corrosion problems, as can oxides of sulfur in the presence of water. Sulfur oxides can be removed by sorption on reactive sorber beds. More generally, corrosive components of the offgas stream will need to be considered either in equipment design or removed and stabilized in the vitrified wastes.

Processing of secondary wastes from the offgas system will be required. Some work on this is being supported at the Savannah River Site with its small experimental vitrifiers (Pacific Northwest National Laboratory, 1997b), but its relevance to the Hanford wastes for the privatization work is unknown to the committee. Tests of the LAW vitrifier with attention to offgas cleanup to meet regulatory and internal recycling criteria will need to be completed to verify performance.

The application of large vitrifiers that function reliably in a radioactive environment will require offgas treatment systems capable of performing their required functions over a sustained period with a variety of feed compositions. A generalized flowsheet for the functions of various components of an offgas system has been issued (U.S. Department of Energy and Washington State Department of Ecology, 1996, p. B-96) based largely on conventional hot-gas quenching by aqueous spray treatments and with a focus on the bulk of the offgas chemicals (e.g., nitrogen oxides, sulfur dioxide).

The committee found no Hanford-designated technology needs identified by the STCG for this function, nor are there relevant projects on these offgas topics evident in the TFA program or elsewhere in OST. The privatization contractors responsible for the vitrification may complete technology development necessary to deploy a reliable offgas system, but information on privatization contractor activities in this regard were not available to the committee. However, the committee found no documentation that specifies or ensures any role for DOE in this matter. Treatment of some offgas from highly radioactive operations is a mature engineering practice, and it is only in the cases of unusual materials in the offgas or of extraordinary throughputs where special attention may be needed. Both unusual materials and exceptional throughputs may be expected from the Hanford vitrifiers. The Savannah River Site vitrifier has an offgas system that required special attention because of (1) its unique design, (2) the unusual components of the feed that could reach the offgas system and require management, (3) issues of scaling up from small experiments, and (4) unusual (high or low) throughput. Accordingly, there is reason to believe that special attention will also be needed at Hanford.

Stabilize Tanks Containing Unretrieved Waste

In the in situ scenario, tanks and their contents are presumed to be disposed of in place. Stabilizing tanks containing waste is a necessary function in the committee's in situ disposal scenario. Stabilizing the entire contents of tanks from which all pumpable liquid has been removed is an alternative considered in the recent Hanford TRWS EIS (U.S. Department of Energy and Washington State Department of Ecology, 1996), but it was not adopted in the Record of Decision (U.S. Department of Energy, 1997b).

This function will require filling the tanks containing a mixture of soft and hard materials with stabilizing agents. Unless changes to the waste are made, the stabilization agents must be compatible with highly alkaline waste, retain radionuclides, prevent tank collapse, and allow stabilized tanks to meet applicable performance criteria. Specific functional requirements have not yet been developed or postulated. In principle, the end state criterion (such as dose limits for the immobilized LAW in near-surface disposal as defined in the committee's reference scenario in Chapter 3 and set by the U.S. Nuclear Regulatory Commission and DOE Orders) should suffice for planning purposes. Translating dose limits into quantitative requirements (e.g., maximum radionuclide release rates for the stabilization agents, required degree of homogenization) requires a detailed performance assessment. Therefore, the discussion of technology needs and status here is based on generic functional requirements.

Technology development needs relate to the retention of waste components in the tanks. An additional need is the development of stabilization agents that have the ability to resist degradation by ground water while immobilizing radionuclides. Immobilization of such radionuclides as technetium may be particularly challenging. Achieving this may require that the stabilization agent be impermeable and insoluble, as well as capable of maintaining an environment that reduces the mobility of important radionuclides. Some technologies, such as reducing grouts used in nearly empty tanks at the Savannah River Site, have been developed and might meet this need, but more development and demonstration would be needed for the Hanford application.

Stabilizing agents such as grout must also adequately mix with substantial amounts of waste in the tanks. This involves mixing large amounts of material, some of which may not be readily mobile, and working through relatively small tank penetrations without further degrading the integrity of the tank. Technology development to meet this need is not now underway nor planned by OST. Technology is also needed to characterize the stabilized tank to assure that the functional requirements have been met without adversely impacting the stabilization function. Technology development to meet this need is neither underway nor planned.

In summary, the technology required to implement in situ stabilization does not appear to exist in OST, and there is essentially no ongoing technology development in this arena. This finding is not unexpected because DOE and local public stakeholders do not currently support consideration of the in situ disposal scenario.

Enhanced Barriers for Unretrieved Tanks and Waste

The provision of enhanced barriers for unretrieved tanks containing stabilized waste is a necessary function of the committee's in situ disposal scenario. Use of barriers on stabilized unretrieved tanks was considered in the in situ alternative in the recent Hanford TRWS EIS (U.S. Department of Energy and Washington State Department of Ecology, 1996), although the exact nature of the barriers was not described.

This function will require placing physical barriers around a stabilized tank to prevent intrusion of water, humans, and biota, as well as reactive barriers to inhibit migration of radioactive and toxic constituents. Because of the greater inventory of radioactive toxic materials in the in situ disposal scenario than in the nearly empty tanks of the committee's reference scenario, we expect the functional requirements for the enhanced barrier system to be much more stringent than for the barrier system in the committee's reference scenario. As with stabilization of unretrieved tanks, translating this into specific quantitative functional requirements (e.g., maximum allowable water ingress and radionuclide release rates as a function of time) requires a detailed performance assessment. Therefore, the discussion of the technology needs and status here is based on generic functional requirements. The utility of barriers, both on and beneath the surface of the ground, in diminishing the effects of tank leakage and retarding subsequent transport of radionuclides has been discussed in a number of publications and reports, including a report of a recent workshop by the National Research Council (1997).

A large amount of design (Myers and Duranceau, 1994), engineering study (Skelly et al., 1996), and experimental work (Gee et al., 1994) has been done on surface barriers to prevent ingress of water. Follow-up studies on the performance of existing surface barriers are continuing.

A study of the use of subsurface barriers to mitigate leakage from Hanford tanks has been prepared (Treat et al., 1995). However, subsurface barriers are considered by DOE and the Hanford TWRS to provide only marginal reduction with regard to radionuclide release and transport at relatively high cost (J. Honeyman, personal communication, November 12, 1997). Consequently, the Tri-Party Agreement milestones for development of subsurface barriers have been deleted from the tank waste remediation program.

Barriers may be physical, chemical, or a combination of the two. Achieving highly effective chemical barriers depends on finding chemical substances that remain effective over long periods of time to incorporate into the soil or other materials surrounding tanks or tank farms and that will react with the radionuclides of concern to stop or greatly retard their movement (Balsley et al., 1997). Effective and economically acceptable barrier materials could substantially diminish the risk from tank leakage. The OST program for this process step is summarized in Table 7.

Leak mitigation for single-shell tanks was identified as a technology need, but was assigned a low priority. Hanford had identified a technical need for getter materials (especially for technetium and selenium) for LAW storage and disposal. The TFA combined this issue with evaluation and modeling of moisture flow for performance assessment and assigned the combined project a low priority. It is important to note that, even if the needs in Table 7 are funded, they relate to barriers for the tanks that are nearly empty. No programs relevant to enhanced barriers for closed tanks from which waste has not been removed were identified.

The committee believes that enhanced barriers could contribute significantly to retention of important mobile radionuclides on site and to making cost effective alternatives to the Hanford baseline flowsheet feasible. Enhanced barriers have been considered for use in the Hanford baseline, but apparently only research and development on the standard Hanford cap has been funded.

TABLE 7 Department of Energy Office of Science and Technology Projects on Enhanced Barriers

Problem Area	Technical Task Title	Status
Inhibit further leakage	Tank leak detection and mitigation	Low priority and not funded
	Tank leak mitigation/repair	Low priority and not funded
Surface barriers	Several projects completed, especially standard Hanford cap	No work on enhanced barriers.
Subsurface barriers		No activity or plans
Technetium engineered barriers	Getter material for technetium and selenium, related to LAW disposal	Low priority and not funded

SOURCE: Pacific Northwest National Laboratory (1997b).

SUMMARY AND CONCLUSIONS

Four important functions were selected from the three example scenarios developed in Chapter 3. Realistic but hypothetical functional requirements were then developed for each of the example functions. The current status of technology in each of the four areas was compared to the requirements, yielding technology development needs. The needs were then compared to the present DOE EM technology development program to evaluate the adequacy of the program to support the four selected functions.

Based on this example, the committee finds that the end state based approach to specifying an appropriate technology development program can systematically and efficiently identify technology needs and necessary changes in ongoing technology development efforts. The committee inferred, from the absence of programs on some technologies needed for the baseline remediation system, that DOE's technology development program appears to have been substantially limited by the potential for privatization of some tank remediation functions. This is an appropriate approach in cases where applicable technologies are known, or where similar problems have been successfully addressed by the private sector under competitive circumstances. In the case of the unique Hanford situation, where only one private sector contractor remains, this approach should be reassessed with a view toward providing incentives for private sector efficiency, improved technology for potential use by the private sector, and maintaining DOE expertise for the purpose of being able to better manage the privatization work and to provide a contingency option in case privatization fails.

The committee also notes that technology development to meet the requirements of alternative scenarios is essentially non-existent. Such development is highly desirable to facilitate a more flexible approach to tank remediation that likely could also balance risk and cost.

5

Conclusions and Recommendations

The primary objective of this study was to provide recommendations on an approach for identifying technology development needs for managing environmental contamination, especially the high-level waste (HLW) in large underground tanks at Department of Energy (DOE) sites. The recommended approach is based primarily on the systems engineering process with emphasis on end state requirements for remediation products. Consideration was given to alternatives for achieving different end states for a given initial remediation problem. The committee believes that the recommended approach can be applied to DOE waste remediation in general, not just to waste in tanks. While the proposed method is considered generic, the waste in the large underground Hanford tanks was used as an example to illustrate the approach. The example is not exhaustive, is for illustrative purposes only, and considers only selected steps in the Hanford functional flowsheets devised by the committee.

Since the focus of the committee's effort was on the method for identifying technology requirements, not on their application, the conclusions and recommendations are organized accordingly. In particular, priority is given to end state methodology, followed by insights obtained through application of the Hanford example. The committee also briefly comments on the Office of Environmental Management (EM) tank technology development program and the impact on this program of such external factors as privatization.

THE END STATE METHODOLOGY

Conclusions

A systematic process for identifying technology development needs to support the cleanup of waste stored in large buried tanks is essential to economical and effective solutions to site remediation. The end state approach is a systematic and disciplined framework, based on the principles of systems engineering, for the identification of technology development needs.

The committee concludes that it is possible to specify a generic approach to determine waste-related technology needs that is based primarily on consideration of the end state of the waste. The approach is as follows:

- Characterize the initial state or condition of the wastes and sites to be remediated (e.g., waste volume and constituents, applicable regulations).

- Identify reference and alternative remediation scenarios that each accomplish a general remediation objective of providing for the health and safety of the public and the environment.
- Specify waste forms and environmental and other required conditions of the desired end states for each of the relevant remediation products. The end state is often characterized by a complete set of product acceptance criteria or site closure specifications from each scenario or alternative scenario.
- Define the flowsheets for each alternative scenario in terms of the functions to be performed (but not a specific technology to be used) in transforming the initial waste into the desired end states.
- Combine essentially identical functions in the flowsheets into a unique set of functions. Significantly different functions in different flowsheets (e.g., substantially differing degrees of decontamination) should be represented separately.
- Allocate the end state specifications to each processing function as functional requirements.
- Assess the technology required to perform each function or operation. The lack of correspondence between the functional requirement and the current status of the technology yields technology development needs.

When implementing the end state methodology, it is important to note that technology development typically requires several years to produce deployable results, depending on the initial state of knowledge and the technology status. In contrast, regulations, knowledge, and stakeholder values concerning remediation issues and decisions often change much more rapidly. An appropriate technology development program should be based on a range of plausible scenarios that is likely to include those finally selected for implementation.

In particular, an end state based approach that considers a range of plausible scenarios will identify technology gaps and technology development needs associated with credible alternative flowsheets. Implementing such an approach will also identify uncertainties and potential improvements to the existing baseline flowsheet, if it exists, that can lead to more desirable scenarios.

Other findings and conclusions of the committee regarding the end state based approach are as follows:

- The lack of a range of firmly defined, plausible end states increases the probability of failure to meet schedules, budgets, and technical requirements. This range of end states is also necessary to meet contingencies, externalities, and other factors.
- The lack of provisional end states, which could provide a basis for proceeding with an end state based approach in the absence of firmly defined end states to technology development, also hinders the rational identification and prioritization of technology development activities.

- It is not always necessary to consider alternative end states, as there may be circumstances where the end state is unlikely to change. This is not the situation at the Hanford Site or at many of the DOE defense nuclear weapons complex remediation sites.
- In establishing an appropriate technology development program, end state specifications can be grouped into those related to human health and ecological risk (e.g., safety, hazard), those related to cost and schedules (e.g., process reliability, performance, efficiency), and societal externalities (e.g., policy on allowable risks, desirable end state specifications, the role of privatization). To form the basis for a technology development program, these must be translated into specific requirements for each function. Some type of performance assessment (whether it is described as risk analysis, decision analysis, or systems analysis) for necessary in translating health and environmental risk-related end state requirements into quantitative specifications. Similarly, cost assessments and trade studies are necessary for translating cost-related end state requirements into quantitative specifications. However, the risk- and cost-related information necessary to establish specific end state specifications is often not available, so contingency approaches to establishing such information should be developed.
- Several risk studies have been conducted on possible remediation strategies at Hanford. From the information provided to the committee, any effect that such quantitative risk studies have had on the choice of these strategies was not apparent.

Recommendations

- An end state based approach to establishing an appropriate technology development programing support of DOE's environmental management program should be adopted. In particular, this approach should encompass reference end states for each waste stream, plus plausible alternative end states for each waste stream to accommodate uncertainty and potential future programmatic changes.
- Sufficient technology development resources should be invested in scenarios involving alternative end states to provide reasonable assurance that a solution will be available in case unforeseen but all too frequent technical surprises or externally imposed changes make it impossible to implement the preferred baseline approach. DOE should consider alternative end states unless the remediation process is short-term and proven cost-effective technology exists.
- Detailed documentation of the various steps taken in implementing the end state based approach should be developed for use by the custodians of the waste, those engaged in technology development, and oversight groups. Circumstances where alternative end states are not considered should be well documented as part of the evidence base justifying the decision made. In addition, executive level documentation appropriate for decision makers, such as DOE senior management and the Congress, should be developed.
- If initial conditions or end states cannot be adequately specified, a plan leading to the timely resolution of the open items should be prepared and executed. In the interim, enabling assumptions regarding the initial conditions and desired end states of the waste should be developed and clearly stated, preferably by problem owners, but by technology providers if necessary. End states and related technology requirements will frequently have to be identified in

the face of major uncertainties about costs, benefits, public acceptability, and other relevant factors.

- Cost-risk studies should be more widely used in remediation decision making that forms the basis for technology development in an end state based approach. In particular, such studies should be used both to determine what must be done to protect human health and the environment at reasonable costs and to identify activities that yield only minimal risk reduction and hence should be considered as candidates for possible elimination.

THE HANFORD EXAMPLE

This illustrative application of the end state based methodology to the Hanford high-level radioactive waste tanks identifies potential technology needs in four functional areas. The functions considered in the technology assessment were enhanced sludge washing and vitrification offgas processing in the committee's reference scenario, and enhanced barriers and stabilization of the tank contents in an in situ remediation scenario. The committee recognizes that unaddressed technology needs for some of the functional areas are due to the decision by DOE to focus resources largely on the Hanford baseline flowsheet.

Conclusions

- The functions required to reliably remediate Hanford tank wastes in the face of technical and institutional uncertainties and the required performance of each function can be determined by specifying a reference scenario corresponding to the Hanford baseline and two plausible bounding scenarios, and the associated end states of the products from each. This can be done despite substantial uncertainties in the end states, since Hanford has not fully defined the end state for its baseline flowsheet.
- Many of the technology needs for the committee's reference flowsheet for remediating the wastes in the Hanford tanks, which corresponds closely to the Hanford baseline flowsheet (subject to the unknown contents of the private sector flowsheet), have been identified by the DOE and its contractors. The committee has two concerns: (1) the apparent lack (i.e., the inability of the committee to find any objective evidence) of a systematic end state based process for ferreting out technology development needs and creating a basis for decision making, and (2) the lack of technology development for end states other than those for the Hanford baseline flowsheet.

Enhanced Sludge Washing

- The diverse nature of the tank wastes suggests that no single enhanced sludge washing procedure will be effective for all of the tank wastes.
- In the course of its review, the committee found little information on the rates at which reactions will proceed, solids will be dissolved, or products will be formed as a result of enhanced sludge washing of actual waste. Some of these processes presently appear to be quite slow, occurring over days or weeks. Excessively long reaction times could have a large impact on process flowsheets and on the specific sequence of process steps. The formation of colloids

(especially with respect to the actinides), gels, and precipitates, and the treatment of the full range of solids to be encountered and formed are also important issues not adequately addressed.

- Changing the valences of such elements as chromium to enhance their removal from sludges may result in deleterious changes of the valences of other elements, such as the actinides.

Vitrifier Offgas Processing

- The committee found no Hanford-designated technology needs identified by the Site Technology Coordination Groups for vitrification offgas processing, nor are there relevant projects evident in the Tank Focus Area program or elsewhere in DOE EM.
- The primary technology development needs relate to preventing radioactive and toxic wastes from leaving the vitrifier offgas and to preventing deleterious buildup of both radioactive and non-radioactive solids in the offgas system. Technology needs include information on (1) a number of potentially troublesome phenomena (e.g., condensation, decomposition, reaction) related to the species and quantities that evolve from the vitrifier, (2) the processing of secondary wastes, (3) remote operations of offgas systems handling large volumes of gas from large vitrifiers, and (4) offgas cleanup processes.

Enhanced Barriers for In Situ Disposal of Tanks Containing Unretrieved Wastes

- Barrier technology development is necessary to adequately mitigate the transport of specific radionuclides such as the long-lived technetium-99.
- There is no apparent technology development currently underway on enhanced barriers for closure of tanks from which waste has not been retrieved.

Stabilization of Tanks and Their Contents In Situ

- There are no apparent technology development projects currently underway for stabilization of Hanford tanks from which the wastes have not been removed.

Recommendation

- The end state based approach should be applied on a broad scale to comprehensively identify technology development needs. The need for such an assessment based on alternative end states is highlighted by the extensive uncertainty surrounding the entire tank closure program.

DOE TANK WASTE REMEDIATION TECHNOLOGY DEVELOPMENT PROGRAM

Conclusions

- The committee finds that the scope and extent of the DOE tank waste remediation technology development program is large and varied, and that specifications for some of the final product forms (end states) are available. However, progress in providing technology necessary for remediation is impeded by the lack of complete definition of the requirements for both baseline and alternative end states of remediation scenarios. Technology development needs cannot be fully defined until these requirements are specified in adequate detail by the responsible programs in DOE EM.

- Some of the technology needs important to closure of tanks containing substantial amounts of waste may not have practical solutions immediately available and may require prolonged development efforts and contributions from carefully formulated programs. More basic research may be required in these cases to identify suitable technologies.

Recommendations

- The DOE EM technology development program should make an end state based approach a functional part of the process for defining its work.
- Alternative scenarios including defined end states should be formulated and evaluated, and technology development unique to these scenarios should be pursued on a basis that is prioritized with the help of performance assessment results and additional knowledge from relevant scientific research.

GENERAL FACTORS

Conclusions

- Decision making related to technology needed for the remediation of high-level radioactive wastes in tanks must consider factors other than purely scientific and technical. These other considerations, referred to in this report as *external factors,* include the constraints on decision making that come from organizational changes, regulations, stakeholder agreements, congressional actions, etc. While external factors were not a focus of the committee's review, such issues as privatization and the DOE organization have a major influence on technical decisions.
- The privatization initiative diverts DOE attention from addressing some tank waste remediation technology development needs (e.g., vitrification offgas treatment). There is a lack of explicit strategy and policy statements by DOE on what its role in the technology development is in light of privatization.

Recommendations

- The committee urges DOE's Office of Science and Technology to adopt broadly the end state based method of identifying technology requirements to reduce sensitivity to future uncertainties such as changes in regulations, budgets, policies, and program participants. Technology development activities with long lead times should be designed to transcend the effects of these inevitable changes.

- An end state based framework for making decisions about technology needs should be used to provide much needed visibility of the relationship of the various activities (including risk studies) to the final objectives.
- Given DOE's lack of experience in privatization of such major functions as research, development, and cleanup operations, the committee recommends parallel pursuit of technology development for an alternative to the current privatization strategy for the Hanford Tank Waste Remediation System. It is not considered prudent to rely totally on privatization to develop the required technologies for systems with the history and complexity of high-level radioactive waste in tanks. The uncertainties are great, and the chances for failure are too high not to pursue alternatives.

Abbreviations and Acronyms

ALARA	as low as reasonably achievable
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980, as amended
CFR	Code of Federal Regulations
DOE	U.S. Department of Energy
EDTA	ethylene diamine tetraacetic acid
EIS	environmental impact statement
EM	Office of Environmental Management
EMSP	Environmental Management Science Program
FR	Federal Regulation
HTI	Hanford Tank Initiative
HLW	high-level waste
INEEL	Idaho National Engineering and Environmental Laboratory
LAW	low-activity waste
LLW	low-level waste
MUST	miscellaneous underground storage tanks (at Hanford Site)
ORNL	Oak Ridge National Laboratory
OST	Office of Science and Technology (EM-50)
PRA	probabilistic risk assessment
RCRA	Resource, Conservation, and Recovery Act of 1976, as amended
ROD	record of decision
STCG	Site Technology Coordination Group
TFA	Tank Focus Area
TPA	Tri-Party Agreement (at Hanford Site)
TRU	transuranic
TWRS	Tank Waste Remediation System (at Hanford Site)
USAEC	U.S. Atomic Energy Commission
USEPA	U.S. Environmental Protection Agency
USNRC	U.S. Nuclear Regulatory Commission

Glossary

amphoteric— capable of reacting chemically either as an acid or as a base.

brownfield— remediation of a contaminated site or facility to a level acceptable only for certain types of restricted industrial use with continuing institutional control and maintenance.

committee's reference scenario (committee's reference flowsheet)— the remediation baseline developed by the committee which is somewhat analogous to the Hanford baseline scenario (flowsheet).

end state— the final product of a waste processing, remediation, or management scenario characterized well enough in terms of chemical, physical, and radioactive attributes to allow details of scenarios to be specified.

flowsheet— an outline that identifies the process step sequences at various levels of detail that are incorporated in a scenario leading to end states.

function— a generalized description of an activity that effects the desired changes leading to end states (e.g., chemical engineering unit operations).

functional flowsheet— a generalized description of processing operations (functions) used to demonstrate the transformation of initial radioactive wastes to end states.

greenfield— remediation of a contaminated site or facility to a level acceptable for unrestricted future use.

Hanford baseline scenario (Hanford baseline flowsheet) — the DOE Hanford baseline for remediation of the HLW tanks.

high-level waste (HLW)— radioactive waste material derived from the first cycle of solvent extraction from processing of irradiated fuel, or equivalent material from other parts of the processing operations, and spent nuclear fuel (from 10 CFR 50).

low activity waste (LAW)— incidental radioactive waste derived from removal of radionuclides from HLW and having properties similar to those described by the U.S. Nuclear Regulatory Commission (USNRC) in 10 CFR 61, but not under the jurisdiction of the USNRC.

low-level waste (LLW)— radioactive waste not classified as high-level radioactive waste, transuranic waste, spent nuclear fuel, or byproduct material described by the U.S. Nuclear Regulatory Commission (USNRC) in 10 CFR 61.

process step— description of the details of functions (processing operations) sufficient to identify applicable and required technologies.

risk— the answer to three questions, "What can go wrong?", "How likely is it?", and "What are the consequences?".

scenario— a qualitative description of the transition path of waste from its initial state to a specified end state.

solid— a material present in a liquid in excess of its solubility limit.

sludge— a semi-solid, viscous, amorphous material that is substantially insoluble.

slurry— a suspension of solids in a liquid.

technology needs — new information on chemical, physical, and engineering processes required to successfully carry out a function or process step.

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Appendix A

Summary of Scenario-Based Studies of the Remediation of High-Level Waste in Tanks

This committee is by no means the first group to adopt a scenario-based approach to the cleanup of wastes in the Department of Energy (DOE) complex in general, or Hanford tank wastes in particular. Therefore, to provide some historical perspective, in this appendix we review several reports dealing with the Hanford tank wastes from a risk-based or scenario-based approach. These reports were chosen for their direct or indirect relevance to the issue of identifying technology needs. The reports discussed here use methods that are similar to the end state approach that we propose, and could be used (or adapted) to identify technology development needs; moreover, some studies contain explicit recommendations for needed technology development. The bibliography at the end of this appendix lists all risk-based reports that were provided to this committee by DOE and its contractors. Note that this list may not be comprehensive, as there may well be additional risk-based applications of which the committee has not yet become aware.

EVALUATING ALTERNATIVE STRATEGIES FOR TANK WASTE TREATMENT

Two studies apply a decision analysis or risk-based approach to evaluating alternative strategies for tank waste treatment. In particular, Johnson et al., (1993) deals with the decision of whether to pursue extensive separations, in order to reduce the volume of the ultimate high-level waste (HLW) form or whether to pursue high-capacity vitrification. The motivation for this study was the growing concern in the early 1990s about the ability of the then-planned Hanford Waste Vitrification Plant to successfully vitrify all single- and double-shelled tank waste. Therefore, this study adopted a decision analysis approach to evaluate the performance of various alternative strategies for processing the tank wastes.

As a result of technical uncertainties at the time of that study, Johnson et al., (1993) recommended that plans and technology development for two alternative bounding technologies for the Hanford tanks waste disposal program be carried forward in parallel:

- extensive separations followed by vitrification at a relatively small plant (possibly even at another DOE site); and
- high-capacity vitrification with minimal pretreatment.

Even though the option of minimal pretreatment followed by high-capacity vitrification was desirable from the point of view of several criteria (e.g., the use of relatively simple and mature technologies), it was recommended that the final selection between these two technology paths be deferred to preserve the flexibility to choose the best technology in the future, once the uncertainties of each were more fully understood.

The flexible or contingent nature of this recommendation is in keeping with decision analysis theory about the value of information. In situations where the cost of pursuing two strategies in parallel is not exorbitant and a final decision is not absolutely necessary, deferring the final decision until key uncertainties have been resolved can facilitate a better result.

The two-track strategy recommended by Johnson et al., (1993) was never fully implemented at Hanford. In particular, an integrated technology development program focused on extensive separations was never funded. More recently, following completion of the March 1996 Tri-Party Agreement milestone to evaluate enhanced sludge washing, it was determined that enhanced sludge washing was likely to lead to an acceptably small volume of high-level waste, and advanced separations were not required. Moreover, high-capacity vitrification sufficient to permit "minimal pretreatment" is also not being seriously pursued at this time. Thus, Hanford seems to be pursuing a middle course, rather than the two bounding approaches recommended by this study.

The report by Hesser et al., (1995), undertaken in response to a request by the then DOE Assistant Secretary for Environmental Management, is somewhat more far-reaching. In particular, it lays out risk-based cleanup strategies consistent with an expected annual Hanford site funding profile of $1.05 billion and addresses not only tank waste but also nuclear materials, solid waste, environmental contamination to groundwater and soils, and major facilities. The report notes that at the hypothesized funding level, "Cost reduction efforts alone cannot achieve the necessary savings. Changes in schedules and/or scope of cleanup are necessary."

The report considers four general strategies: the existing baseline strategy; an extended version of the baseline strategy; a risk-based strategy; and a composite strategy that addresses land use and mortgage reduction in addition to risk reduction. With regard to tank waste, both the risk-based strategy and the composite strategy involve in situ disposal of liquid waste. In particular, the report states that under a risk-based strategy, "In situ disposal of tank waste would be the preferred option. Technology for in situ disposal should be developed." Hesser et al., (1995) note that this approach would be less acceptable to local stakeholders than the existing baseline strategy, but would reduce worker risk (by nearly an order of magnitude), expected cost (by more than $10 billion), and the time required to complete the cleanup (by more than 10 years); there were no significant differences between the baseline and risk-based strategies with regard to public risk.

SCENARIO-BASED APPROACHES TO CHARACTERIZATION OF HANFORD TANKS WASTE AND TECHNOLOGY DEVELOPMENT

The next two reports discussed are concerned primarily with developing rather than applying scenario-based methodologies. In particular, Colson et al., (1997) develop a risk-based approach specifically intended to help in making decisions regarding the characterization of tank wastes. This effort was undertaken in response to a request by the DOE Assistant Secretary for Environmental Management, who noted:

> "The potential impact of a technically flawed strategy [for waste characterization] is significant. Underestimated risks can result in unnecessary exposure of workers or the public to hazardous materials. Overestimated or ill-defined risks can unnecessarily constrain processing actions and greatly increase the costs of tank waste remediation.

Delays and increased costs from improperly structured efforts can erode public confidence as well as support."

A variant of the methodology developed and applied in this report may well be usable to aid in determining technology development needs instead of waste characterization needs, since both types of activities are aimed at uncertainty reduction. However, the report in some places adopts fairly sophisticated terminology and mathematical methods. More illustrations of how the method can be adapted to situations of varying degrees of complexity might help to ensure that the method is readily applicable in practice.

It is worth noting, by the way, that this report specifically addresses methods of managing potential conflicts of interest, and also recommends "early and open sharing of information and ideas among the project teams, DOE, regulators, stakeholders, tribes, and the public." These issues are clearly critical in today's stakeholder environment.

The draft report by Franklin et al., (1996) lays out a possible method specifically intended for prioritizing some technology development efforts-particularly those efforts undertaken for contingency planning purposes. As such, it is perhaps more directly related to the charge of this committee than the other reports reviewed in this appendix.

The report considers a number of discrete scenarios (ranging from the existing baseline scenario to in situ remediation) based on externalities such as the possible lack of a repository, significant budget reductions, or regulatory changes. Therefore, the methodology described in the report, or a similar approach for addressing the same issues, could be one way of implementing the process described in Chapter 2 of this report. In particular, the report considers a much broader range of scenarios than many of the other studies we have reviewed (including in situ disposal), which is appropriate since the proposed method is intended as a contingency planning tool. To be fully useful and defensible, applications of this method must be based on models that are technically as sound as possible and on parameter estimates that reflect the best available data.

SUPPORTING ANALYSES OF SAFETY AND ENVIRONMENTAL RISK

The reports reviewed in this appendix provide information that can be useful in future risk-based decisions among alternative remediation scenarios, potentially providing a basis for achieving reduced risk at reasonable cost. Several probabilistic safety assessments of the Hanford tanks (MacFarlane et al., 1994, 1995a, and 1995b) are described below. The work described in these reports constitutes a comprehensive risk analysis of all 18 tank farms at the Hanford Site.

The effort involved in this analysis was extensive, and hence could not be reviewed in detail by this committee. However, the information they provide can be useful in a number of technology development decisions using a scenario-based approach. For example, MacFarlane et al., (1995a) conclude that only 35 of the 177 waste tanks contribute more than 1 percent each to the total risk prior to waste retrieval. This information can be helpful in identifying plausible scenarios for use in an end state approach. For example, the indication that many tanks pose a relatively low risk could lead to the inclusion of the apparently less-expensive in situ disposal scenario as one of the alternatives to be considered in identifying technology development needs. Similarly, MacFarlane et al., (1995b) conclude that sluicing is associated with substantially lower risks than mechanical or pneumatic retrieval of tank wastes, even in tanks that are known to be leaking. This again can be useful input in focusing further technology development activities, either by encouraging greater emphasis on technologies for sluicing or by ensuring that future development activities in support of mechanical and pneumatic retrieval technologies focus on minimizing retrieval risks.

The committee also recognizes that these reports were intentionally limited in scope. In particular, the extent to which they consider the effects of human error is unclear, and they cover only retrieval, not such post-retrieval processing steps as vitrification. Therefore, it may well be worthwhile to perform additional risk analyses in the future to address these issues.

Finally, the letter report by Jacobs Engineering (Nelson, 1995) determines how many tanks would need to be retrieved (and how many could be handled by in situ disposal) to meet a 10-4 risk criterion on site. The report does not make any recommendations or assumptions about whether in situ disposal is reasonable or desirable, but rather it examines what the implication would be for disposal requirements.

Based on the criterion of 10-4 or less risk of contracting cancer by a hypothesized future farmer on the site (presumably per lifetime), the report concludes that this criterion could be achieved by retrieving 99 percent of the waste from roughly 40 percent of the tanks and remediating the remainder of the tanks on-site with a cap-and-fill strategy. The report also estimates that this approach would yield substantial cost savings over the current baseline. The cost savings are anticipated to be less than proportional to the reduction in the number of tanks to be retrieved, largely because the cost of the melter needed to vitrify the retrieved wastes would probably not scale linearly with the required throughput.

The report does not discuss the political acceptability of the proposed risk-based approach. Since the tanks assumed to be remediated in situ generally contain only a small fraction of the high-risk radionuclides, capping and filling is assumed to be an acceptable method of stabilizing the nonretrieved wastes. Therefore, the report does not discuss the technology development that would be necessary for more substantial forms of in situ stabilization, such as in situ vitrification.

SUMMARY

The studies summarized here (on average about three years old) all use end state approaches, including at least some consideration of alternative scenarios. The committee believes that these studies contribute significantly to our overall understanding of the health, environmental, and programmatic risk from the Hanford tanks, and that the general approach adopted therein can be a useful way of identifying technology development needs. However, any effect these studies may have had on actual decisions regarding either tank waste remediation in general or technology development programs in particular was not evident from the documentation and other information available to the committee.

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Appendix B

Management Strategies for Remediation of High-Level Waste at the Hanford Site

In 1972, the U. S. Atomic Energy Commission (USAEC) [a predecessor agency of the Department of Energy (DOE)] issued a report (U.S. Atomic Energy Commission, 1972) defining policies, criteria, and strategies for the management of Hanford high-level tank waste. Most of the heat-producing fission products (strontium-90 and cesium-137) were to be removed, solidified, encapsulated, and stored in cooling basins. The remaining liquids were to be evaporated to saltcake for interim storage. Three alternatives under consideration for the long-term storage of the Hanford high-level tank waste in a suitable chemical and physical form were (1) on site storage in near-surface engineered facilities, (2) on site storage in caverns mined in the deep basalt underlying the Hanford site, and (3) off site disposal in a federal repository. Studies and evaluations were underway at that time to provide the information and data necessary to make the needed decisions. This plan was never implemented, but the studies formed the starting point for subsequent disposal evaluations.

In 1977, the Energy Research and Development Administration (another predecessor agency, following the USAEC, of DOE) issued an evaluation of 27 alternative plans (U.S. Energy Research and Development Administration, 1977) for the processing and disposal of Hanford high-level tank waste. These 27 alternatives were further studied and developed, and the environmental aspects of four of the alternatives were issued in 1980 (Rockwell Hanford Operations, 1980). Still further studies and evaluations led to the issuance of the Hanford Defense Waste Environmental Impact Statement in 1987 (U.S. Department of Energy, 1987) and its associated 1988 Record of Decision (U.S. Department of Energy, 1988a). The Record of Decision converted to policy and into implementation the results of the many previous engineering studies relating to the disposal of Hanford tank waste.

The implementation strategy for the 1988 Record of Decision called for a phased approach for the processing of only double-shell tank waste for disposal. Single-shell tank waste was to be the subject of further studies and a subsequent environmental impact statement. Initially, the supernatant that qualified as low-level waste would be recovered and made into grout for on-site near-surface disposal. This was to be followed by retrieval of sludge, which would be washed using water to separate soluble solids. These solids would be pretreated to provide a low-activity liquid waste stream that could also be made into grout and disposed on site in near-surface vaults. These two separation approaches had been used during the prior cesium and strontium removal campaigns to free up much needed double-shell tank space for ongoing plutonium separations processing and to demonstrate early disposal of tank waste in a grout form. According to the 1988 Record of Decision, further separations of the low-activity portion from the high-level portion of the remaining sludge were to be undertaken at a later date as more advanced separations technology became available. The objective of this phased approach was to start disposing of tank waste as soon as possible while minimizing the volume of HLW to be vitrified and sent to a geologic repository.

The advanced separations technologies were to be developed in the laboratory and subsequently tested on a pilot scale in B Plant (one of the three original chemical separations facilities in the Hanford Site 200 Areas, built in 1944). Upon successful demonstration on a pilot-scale basis, full-scale production capability would be installed in the B Plant canyon for the processing of the remaining double-shell tank waste.

Design of the Hanford low-level grout facility and the Hanford Waste Vitrification Plant was initiated in the late 1980s. Construction of the grout facility was completed in 1987 and 500,000 gallons (2,000 m^3) of low-level supernatant were processed into grout in 1988.

In 1986, DOE agreed that all mixed waste (i.e., those wastes containing both radioactive and hazardous chemicals) at its sites were subject to the provisions of the Resource Conservation and Recovery Act of 1976 (RCRA). In 1987, officials of Region 10 of the U.S. Environmental Protection Agency delegated regulatory authority for all mixed waste at the Hanford Site to the Washington State Department of Ecology. The Hanford tank wastes are deemed to contain hazardous substances under RCRA provisions and, as a consequence of the new regulations, the tank wastes also become subject to State of Washington regulation.

In February 1988 negotiations were initiated among the DOE, the U.S. Environmental Protection Agency, and the Washington State Department of Ecology on a compliance agreement for cleanup of the Hanford Site. In May 1989, the three parties signed the Hanford Federal Facility Agreement and Consent Order (also called the Tri-Party Agreement, or TPA) (Washington State Department of Ecology, U.S. Environmental Protection Agency, and U.S. Department of Energy, 1996 - current amendment) which established milestones enforceable by law for specific cleanup actions. The strategy for cleanup of tank waste incorporated in the TPA was that implemented for the 1988 Record of Decision (U.S. Department of Energy, 1988a).

Several safety issues concerning day-to-day operations were identified in early 1990. These safety issues were deemed to pose unacceptable risks for continued operations without corrective actions. Originally, 54 tanks (48 single-shell tanks and 6 double-shell tanks) were identified as having potential for release of highly radioactive material in the event of an uncontrolled temperature or pressure excursion. These 54 tanks were designated as Watch List Tanks in response to Public Law 101-510, Section 3137, "Safety Measures for Waste Tanks at Hanford Nuclear Reservation," of the National Defense Authorization Act for Fiscal 1991. Sixteen tanks have subsequently been removed from the Watch List.

The immediate concern for resolution of the safety issues resulted in major changes in programmatic needs that preempted the previously established disposal program strategy promulgated by the 1988 Record of Decision and the 1989 TPA. The redirection of technical and financial resources to resolve or mitigate the safety issues and the imposition of operating restrictions caused slippage in the schedules of activities supporting the disposal program outlined in the TPA. Additionally, tank safety issue resolution was expected to require double-shell tank space that was dedicated to supporting the disposal program. In some cases, the Hanford baseline schedules could not be recovered, and, consequently, the 1989 TPA provisions regarding tank waste could not be met.

Following the issuance of the 1988 Record of Decision and the 1989 TPA, knowledge of conditions of the single-shell tank waste evolved considerably, resulting in some changes in thinking that previously had favored in situ disposal. Also, RCRA and the Nuclear Waste Policy Act of 1982, as amended, requirements ran counter to the in situ disposal approach. As a result, in December 1991 DOE made a decision that retrieval of all single-shell tank waste would be used in subsequent tank waste remediation program planning. This meant a four-fold increase in the amount of tank waste to be processed, much more than could be handled by the planned vitrification and grout facilities.

Also, in this same time period B Plant was determined to be unacceptable as a pretreatment facility because it did not comply with current environmental regulations. Upgrades to reach compliance were not cost effective. A decision was made not to use B Plant for radionuclide separations processing, a decision that increased the cost and time duration for the disposal program.

Another issue developed when concerns about the performance of grout over the long term (i.e., leachability) were identified. This concern seriously challenged the acceptability of grout as a waste disposal form for low-level waste, even though it was being used at the Savannah River Site. In addition, other factors such as high radionuclide content, lack of retrievability, and the large number of vaults required raised further questions about the merit of grout as a low-level waste form.

To accommodate these major programmatic changes and impacts, in December 1991 the Secretary of Energy directed that an integrated single-shell and double-shell Tank Waste Remediation System (TWRS) program be established to plan and implement the disposal of all Hanford tank waste. A systems engineering approach was used to identify requirements, develop a program architecture, and study various disposal alternatives. By March 1993, DOE proposed a rebaselined TWRS program to the other two parties of the Tri-Party Agreement. The three parties immediately commenced negotiations on an amendment to the TPA.

Central to the DOE proposed program was the issue of dealing with the four-fold increase in waste volume resulting from the need to retrieve and dispose of all the single-shell tank waste. As noted previously, the capacity of the vitrification plant under design at that time was inadequate for the mission. Either a reduction of HLW volume using extensive separations technology or an increase in capacity of the vitrification facility, or a combination of both, would be required to process all the HLW in a reasonable time. The DOE proposed the cessation of design on the vitrification facility until extensive separations technology and a large-capacity melter could be developed. When this development work was completed, the proper sizing for the facilities would be established, and a definitive disposal strategy would be issued.

Another negotiation issue of major significance was the acceptance of grout as a low-activity waste (LAW) form. The disposal strategy presented by DOE for renegotiation of the 1988 TPA included development of separations technology that would reduce environmental risk from near-surface disposal by removing more of the radionuclides and hazardous chemicals of concern. During six months of negotiations among the three parties, input was sought from several stakeholders groups (e.g., regulators, special interest groups, the public at large, local governmental agencies, Native Americans). Two major benefits resulted from this public involvement effort and changed the proposed March 1993 strategy.

First, there was considerable opposition on the part of the stakeholders to the use of grout as a LAW form. This opposition stemmed primarily from concerns about the long-term performance of grout regardless of the radionuclide content and from the large amount of site acreage required for near-surface vaults. There was considerable interest in using vitrification as the technology for immobilizing LAW. As a result, the use of grout was abandoned and glass was adopted as the preferred form for LAW.

Second, because of the great uncertainty surrounding the construction of a federal repository to receive the immobilized HLW, the concept of minimizing glass volume was viewed by the stakeholders as less important than getting on with the task of cleanup. As a result, it was believed that sufficient HLW glass volume reduction could be obtained by enhanced sludge washing, and large-capacity melters could process the expected volume of LAW in a reasonable time period. Although both enhanced sludge washing and large-capacity melters required development, it was believed this was a lower risk than the extensive separations technology and would result in an earlier commencement of disposal operations (J. Roecker, personal communication, 1998). If new cost-effective advanced separations technology were to become available at a later date, it would be incorporated to enhance the overall process.

The negotiations were completed by September 1993 and a revised TPA change package was issued for public review and comment. On January 25, 1994, Amendment 4 to the Hanford Federal Facility Agreement and Consent Order was signed, defining a new technical strategy for the disposal of Hanford tank waste. Although Amendment 4 defined a new technical strategy, many of the technologies to be employed were identical to those contemplated in the original TPA issued in 1989. The TPA Amendment 4 planning base envisioned immediate implementation of the full disposal program by the on-site Management and Operations contractor.

In the early 1990s the idea of *reinventing government* was introduced by the federal government. This idea was in turn conceptualized by DOE to mean that new and innovative approaches would be undertaken to accomplish normal government functions. The Secretary of Energy determined that *privatization* of some of DOE's waste site cleanup and environmental remediation would result in new and innovative approaches to accomplishing government functions. Privatization was defined by DOE as including the following:

- divestiture of functions,
- contracting out, and
- asset transfers.

A report defining DOE's approach to privatizing government functions was issued by the Privatization Working Group in January 1997 (U.S. Department of Energy, 1997a).

As a result, almost immediately upon issuance of Amendment 4 of the TPA, DOE began changing its disposal strategy planning to incorporate a phased implementation approach using commercial contractors competing on a fixed price basis; this was commonly know as the TWRS Privatization Initiative. With this approach the disposal of Hanford tank waste would be divided into two phases (U.S. Department of Energy, 1997b). During Phase I approximately 10 to 15 percent of the waste volume would be processed by two commercial firms on a fixed price basis. Phase I was further subdivided into 'A' and 'B' phases, Phase IA being a conceptual design phase leading to establishment of firm fixed prices for processing waste during Phase IB. The contractors would be paid a firm fixed price for deliverables at the end of Phase IA and for the delivery of immobilized waste during Phase IB. Upon successful completion of Phase I, each of the competing contractors would be invited to submit proposals for Phase II. One or two contractors could potentially be selected for Phase II processing.

On January 28, 1994, in a Notice of Intent published in the Federal Register (59 FR 4052), DOE announced its intent to prepare two environmental impact statements; (1) an interim action statement to resolve urgent tank safety issues, and (2) a TWRS statement addressing the long-term disposition of Hanford tank waste. The interim action Final Environmental Impact Statement was issued in October 1995, along with its corresponding Record of Decision (60 FR 61687) in November 1995. The TWRS Final Environmental Impact Statement (U.S. Department of Energy and Washington State Department of Ecology, 1996) addressing long term disposal of Hanford tank waste was issued in August 1996. The related Record of Decision (62 FR 8693) was issued in February 1997 (U.S. Department of Energy, 1997b).

In the 1997 Record of Decision DOE decided to implement the Phased Implementation alternative (the Preferred Alternative) for the management and disposition of the Hanford tank waste. Under the Phased Implementation alternative, the tank waste would continue to be stored in existing single- and double-shell tanks until the waste is retrieved for treatment, immobilization, and disposal. Initially a small quantity of waste would be treated and immobilized by implementing a demonstration phase (Phase I) to verify that the processes will function effectively and that the operations can be carried out in a cost effective manner using a *privatized contract* approach. Following successful completion of the demonstration phase, a full-scale production phase (Phase II) would be implemented. During both Phases I and II continued operation of the tank farm system and actions to address safety and regulatory compliance issues would be performed. The DOE would also continue to characterize the tank waste and perform technology development activities to reduce uncertainties and evaluate emerging technologies.

A TPA modification defining milestones implementing the phased TWRS Privatization Initiative was issued by DOE in December 1995, and was approved July 24, 1996. In February 1996 DOE issued a request for proposals (U.S. Department of Energy, 1996b) for the TWRS Privatization Initiative. Proposals were received in May 1996 (Briggs, 1996) and contracts with two commercial firms were signed in September 1996. Work has been completed on Phase IA deliverables and the results were delivered to DOE in January 1998.

In the DOE privatization approach, cleanup and environmental remediation facilities are developed, financed, constructed, owned, operated, and deactivated by the contractor(s). The technology development for those processing functions that fall under the privatization contractors is generally the responsibility of the contractors. In the privatization case, the technology development requirements for DOE are generally limited to those actions required of DOE to provide waste characterization data and waste delivery to the contractors, and to develop basic information for preparation of subsequent contract negotiations.

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Appendix C

Statement of Task

The objective of the Committee on Technologies for Cleanup of High-Level Waste in Tanks in the DOE Weapons Complex is to provide recommendations on an approach for identifying technology requirements for remediating the high-level waste tanks across the DOE weapons complex. To this end, the study group will adopt an end state and scenario-based framework to expose technology needs for different alternatives of remediation. To illustrate the approach, consideration will be given to a select number of site specific remediation scenarios. Technology needs will be identified and reviewed for selected process steps within each of the scenarios. The scenarios selected will include a reference base case as well as alternatives that represent plausible bounding cases. Finally, the study group will review technologies being developed by DOE that support remediation of high-level waste tanks to determine that the right needs are being addressed and the right technologies are being pursued.

Appendix D

Biographical Sketches of Committee Members

B. John Garrick, *Chair,* was a founder of PLG, Inc., and retired as President and Chief Executive Officer in 1997. Currently he has an active consulting practice in the development and application of the risk sciences to systems in the nuclear, space, chemical, and marine fields. He received the Society for Risk Analysis Distinguished Achievement Award and was appointed to the U.S. Nuclear Regulatory Commission's Advisory Committee on Nuclear Waste in 1994, for which he is now Chairman. Dr. Garrick was elected to the National Academy of Engineering in 1993, serves in various capacities for the National Research Council. He holds a Ph.D. in engineering and applied science from the University of California, Los Angeles.

Vicki M. Bier earned her B.S. from Stanford in 1976 and her Ph.D. from MIT in 1983. Her specialties include operations research and risk assessment. Dr. Bier is an associate professor in the Department of Industrial Engineering and the Department of Engineering Physics at the University of Wisconsin-Madison, where she has been on the faculty since 1989. From 1982 to 1989 she worked in risk assessment of nuclear power plants for Pickard, Lowe and Garrick, Inc. Dr. Bier's memberships include the Institute for Operations Research and the Management Sciences and the Society for Risk Analysis. Her research interests focus on the treatment of uncertainty in estimation and decision making.

Allen G. Croff is associate director of the Chemical Technology Division at Oak Ridge National Laboratory (ORNL). His areas of focus include initiation and technical management of research and development involving waste management, nuclear fuel cycles, transportation, conservation, and renewable energy. Since joining ORNL in 1974, he has been involved in numerous technical studies that have focused on waste management and nuclear fuel cycles, including: (1) supervising and participating in the updating, maintenance, and implementation of the ORIGEN-2 computer code; (2) developing a risk-based, generally applicable radioactive waste classification system; (3) multidisciplinary development and assessment of actinide partitioning and transmutation; and (4) leading and participating on multidisciplinary national and international technical committees. He is a member of the National Council on Radiation Protection and Management and the DOE Nuclear Research Advisory Committee. He has a B.S. in chemical engineering from Michigan State University, a Nuclear Engineering degree from the Massachusetts Institute of Technology, and an M.B.A. from the University of Tennessee.

Marshall E. Drummond was President and Chief Executive of Eastern Washington University from 1990 to 1998. He has published numerous articles on information systems, management, and personnel training. He has served on numerous boards and committees including Spokane Chamber of Commerce and Executive Committee, Spokane Symphony Board, United Way Board, Seattle Chamber of Commerce, Commonwealth Club of California, and the San Francisco Symphony. He chaired both the Hanford Future Uses Commission and the Hanford Tank Waste Commission. Dr. Drummond was a member of the National Research Council Sub Committee on Emerging Technologies for Radioactive Waste Management and Disposal. He received his B.S. in Economics and Management and his M.B.A. from San Jose University and his Ed.D. in Organizational Management and Leadership from the University of San Francisco.

John Roecker has more than 40 years of experience in engineering, nuclear operations, and program management, including radioactive and hazardous waste management, nuclear chemical processing, space nuclear auxiliary power systems, breeder reactors, and commercial nuclear systems. He is currently an active consultant in the Tank Waste Remediation Systems (TWRS) privatization program at Hanford. Mr. Roecker has been employed by various companies at the Hanford Site since 1977. He served as manager of the TWRS Program Integration, deputy manager of defense waste remediation, and assistant to the vice president of environmental and waste management at the Westinghouse Hanford Company. Prior to working at Westinghouse Hanford, Mr. Roecker was employed by Rockwell International and Rockwell Hanford Operations where he served as Director of Research and Engineering and as Director of Waste Management Programs. He received a B.S. in engineering physics from the University of Illinois. He is a Registered Professional Nuclear Engineer and a member of the American Nuclear Society.

Claude Sombret was born and educated in Paris. He holds a Ph.D. in ceramics. Dr. Sombret joined the Commissariat à l'Energie Atomique (CEA) in 1957, where he held several positions until his retirement in 1994. Currently, Dr. Sombret is working as a consultant and resides in Villeneuve-Lès-Avignon, France. He has been involved in R&D in the field of waste management and has conducted research on the specification of the French nuclear waste classes, as well as on processes of industrial interest dealing with high-level vitrification. One of these processes is now implemented in the French vitrification facilities at Marcoule (AVM) and at La Hague (R7 and T7) and at Sellafield, UK (WVP). He played a major role in the design of AVM and participated in the design of R7 and T7. Dr. Sombret has published articles in French, American, and British journals and has presented over fifty papers at various symposia. He is a member of many societies and associations, including the American Nuclear Society, the American Ceramic Society, and the Materials Research Society.

Martin J. Steindler worked at Argonne National Laboratory until his retirement in 1993. His last position at Argonne was as Director of the Chemical Technology Division. Dr. Steindler's expertise is in the fields of the nuclear fuel cycle and associated chemistry, engineering, and safety. In addition, he has experience in the structure and management of RD&D organizations and activities. He has published more than 125 papers, patents, and reports on topics in these areas. He received a B.S. degree in 1948, an M.S. degree in 1949, and a Ph.D. degree in 1952, all in chemistry from the University of Chicago. During his career, Dr. Steindler has been a consultant to the Atomic Energy Commission, the Energy Research and Development Agency, and various Department of Energy Laboratories. He chaired both the Materials Review

Board for the DOE Office of Civilian Radioactive Waste Management and the USNRC's Advisory Committee on Nuclear Waste. Dr. Steindler has served on several NRC committees, and currently serves on the Board of Radioactive Waste.

Raymond G. Wymer is a retired director of the Chemical Technology Division of Oak Ridge National Laboratory. He is a specialist in radiochemical separations technology for radioactive waste management and nuclear fuel reprocessing. He is a consultant for the Oak Ridge National Laboratory and for the U.S. Department of Energy in the area of chemical separations technology. He consults for the U.S. Department of State and the U.S. Department of Energy on matters of nuclear nonproliferation. He is currently a member of the U.S. Nuclear Regulatory Commission Advisory Committee on Nuclear Waste. He is a fellow of the American Nuclear Society and the American Institute of Chemists, and has received the American Institute of Chemical Engineers Robert E. Wilson Award in Nuclear Chemical Engineering and the American Nuclear Society's Special Award for Outstanding Work on the Nuclear Fuel Cycle. He received a B.A. from Memphis State University and an M.A. and Ph.D. from Vanderbilt University.