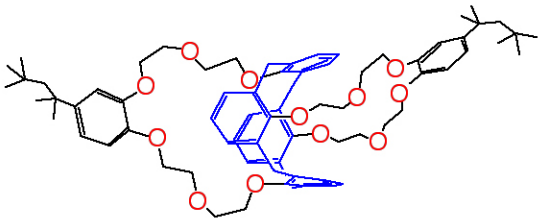
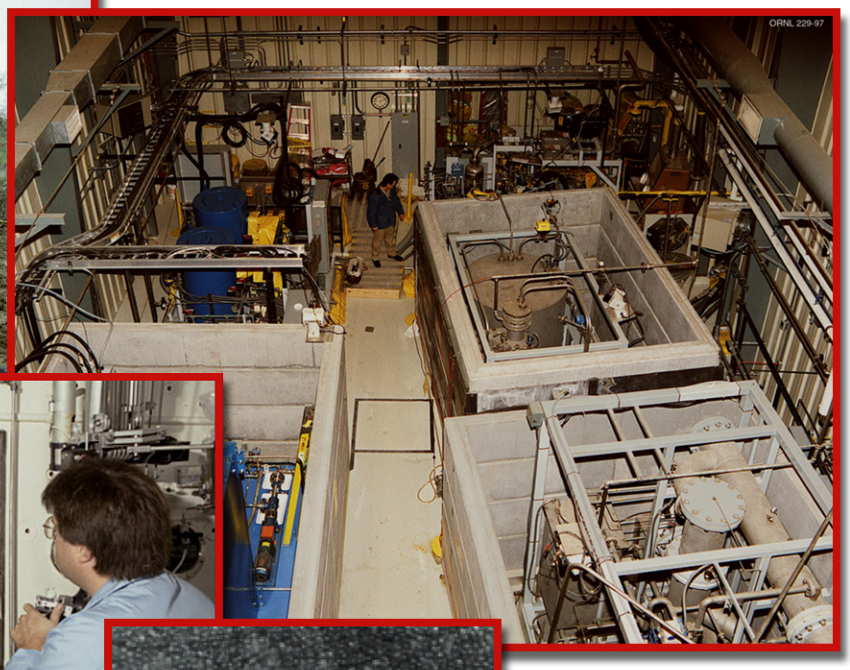
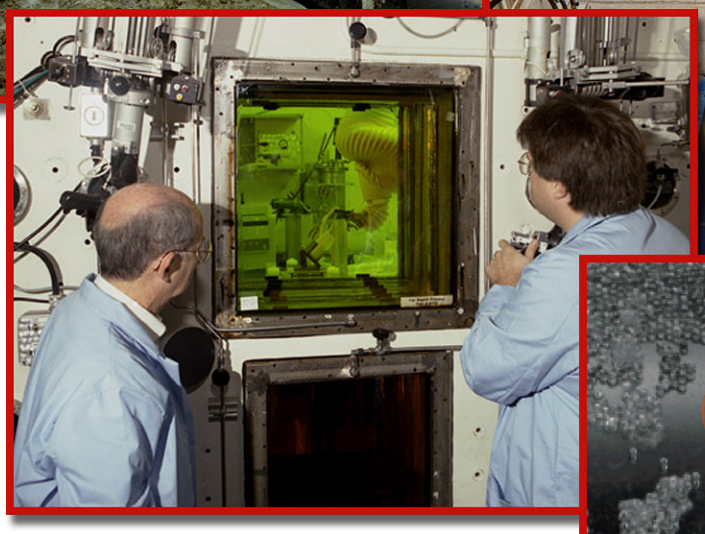
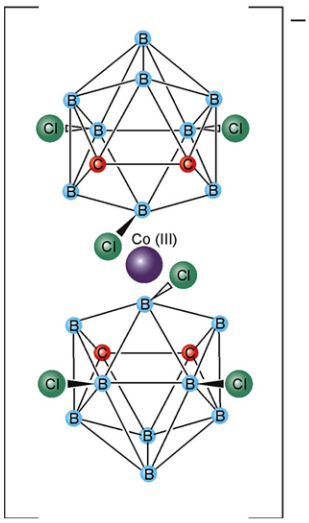
Separations Paths to the Future:

Technology Roadmap for DOE Environmental Management









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Efficient Separations and Processing

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SEPARATIONS PATHS TO THE FUTURE: TECHNOLOGY ROADMAP FOR DOE ENVIRONMENTAL MANAGEMENT

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March 2002

Prepared for
The U.S. Department of Energy's
Environmental Management Program

Prepared by
Oak Ridge National Laboratory
managed by
UT-Battelle, LLC
for the U.S. Department of Energy
under contract DE-AC05-00OR22725

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ACRONYMS

AEA	Atomic Energy Act of 1954, as amended
D&D	deactivation and decommissioning
DOE	U.S. Department of Energy
EM	Office of Environmental Management (DOE)
EMSP	Environmental Management Science Program
EPA	U.S. Environmental Protection Agency
ESP-CP	Efficient Separations and Processing Crosscutting Program
HEPA	high-efficiency particulate air (filter)
HLW	high-level waste
INEEL	Idaho National Engineering and Environmental Laboratory
LLMW	low-level mixed waste
MACT	Maximum Achievable Control Technologies (Rule)
NRC	U.S. Nuclear Regulatory Commission
ORR	Oak Ridge Reservation
PCB	polychlorinated biphenyl
R&D	research and development
RCRA	Resource Conservation and Recovery Act
SRS	Savannah River Site
SVOC	semivolatile organic compound
TCE	trichloroethylene
TFA	Tanks Focus Area
TRU	transuranic
TSCA	Toxic Substances Control Act
VOC	volatile organic compound
WERF	Waste Experiment Reduction Facility
WVDP	West Valley Demonstration Project

FOREWORD

The objective of this technology roadmap is to identify the separations research required to successfully accomplish the goal of the Department of Energy's Environmental Management (EM) Program to clean up and close sites in a cost-effective and timely manner. The roadmap identifies both near-term research (0–5 years) needed to support baseline flow sheets and long-term research (up to 30 years) for developing reasonable alternative flow sheets to reduce risk, lower costs, and/or accelerate the schedule. The scope and timing of the required research and development are also addressed. The roadmap is designed to be a useful strategic planning tool for any program conducting separations research or technology development.

Information for the roadmap was obtained through a variety of sources, including EM planning documents, project roadmaps, the science and technology needs surveys, and the EM Efficient Separations and Processing Crosscutting Program's portfolio analysis. Further input was received through a Separations Technology Roadmapping Workshop held with representatives from the EM Office of Science and Technology's research organizations, technology users, and "outside" technology experts. The workshop brought together over 40 experts to identify requirements for EM separations research. Subsequent conference calls and discussions were conducted with additional parties to gather further information that was used in developing the technology roadmap.

While the roadmap presents a compilation of critical research needs and opportunities, the data-gathering activities for the roadmap were limited by time, scope, degree of participation, and the boundaries that the authors imposed on the subject area. As a result, the emerging roadmap may not fully capture all viewpoints. Although efforts were made to incorporate a broad range of views, some valid ideas may have been excluded because the authors had to exercise judgment in combining and prioritizing information to produce a concise working document. The authors welcome feedback from readers concerning any errors or omissions.

The technology roadmap must be viewed as continually evolving. Based on information gathered in 2001, the document thus represents a "snapshot in time." It is a living document, subject to revision and update as new information becomes available.

EXECUTIVE SUMMARY

Chemical and physical separations are critical to the Department of Energy's (DOE's) long-term efforts to clean up in a cost-effective and timely manner the environmental contamination and accumulated waste in the nation's nuclear weapons complex. The recent document *Adequacy Analysis of the Environmental Quality Research and Development Portfolio* [DOE, September 2000] points to the critical role that separations play in the process:

> Separations are essential to environmental quality for the purpose of isolating toxic substances from non-toxic media to allow the former to be economically managed. For example, managing the large volumes of tank wastes and contaminated soils and groundwater without separation of toxic constituents would not be economically feasible. In theory, all problem areas involve separation of toxic substances from solid media (facilities, equipment, soils), liquids (groundwater), and stored wastes (tank wastes, mixed wastes, spent fuel). Separations technologies are crosscutting because they are used in so many DOE programs and applications. The essence of the cross-cutting problem is economic, efficient separation of very dilute toxic substances from non-toxic media while minimizing the amount of the latter accompanying the former.

Because of their widespread applicability and the economic incentives they offer, separations are often the primary approach to reducing the volume of waste for vitrification or other predisposal treatment options. The importance of separations is also emphasized by the fact that almost one-fifth of the user-identified requirements for technology research and development (R&D) support include separation technologies. In addition, ongoing separations R&D projects within the DOE Environmental Management (EM) Program support management of waste within all classes of media.

Despite widespread current and planned separations science and technology development projects, no unified examination or strategic planning for separations research has been conducted within EM. The purpose of this roadmapping exercise is to provide a cohesive examination of the requirements for near- and long-term separations science and technology research. A comparison of these requirements with the current and planned research and technology development efforts has identified gaps in the existing EM research program that could significantly impact EM's ability to fulfill its mission for site cleanup and closure.

The roadmap identifies the separations research that must be pursued in the near term to support implementation of baseline flow sheets for all sites as well as long-term efforts to develop alternative flow sheets for the high-cost and/or high-risk projects. Opportunities for cost savings and acceleration of cleanup/closure schedules are also addressed.

The roadmap identifies and evaluates the barriers to successful development of the scientific information or technologies and assesses the R&D that must be conducted to overcome these obstacles. The separation processes considered in this roadmap are those needed to accomplish a chemical process, reduce the amount of waste requiring processing or disposal, and/or lower the regulatory category of the waste being considered for final disposal. The impact on costs

associated with treatment and disposal of waste was also a primary factor in selection of separation technologies for consideration. For example, vitrification of high-activity wastes represents one of the major costs for DOE EM. Therefore, success or failure of separation processes designed to reduce the volume of waste requiring vitrification and disposal as high-level waste will have a large effect on future EM costs and budgets.

This documents is designed to be an EM-wide programmatic roadmap and to serve as a useful strategic planning tool for all programs conducting separations research or technology development within EM.

Key Roadmapping Observations

All of the DOE sites have near- to mid-term needs for separations-related scientific data, technology development, and baseline technology performance verification to enable baseline remediation and closure activities to be implemented. Such needs are, for the most part, being addressed by existing EM research programs. However, additional separations R&D could lead to improved flow sheets and thus result in significant savings.

Additional types of separations that can have a particularly large impact on cost and schedule are related to the following types of remediation activities:

- **Reduction or Stabilization of High-Activity Waste.** Removal of sodium salts, organics, and metals from radioactive alkaline sludges to reduce the volume of vitrified high-level waste; treatment of high-aluminum-content acidic calcine to avoid direct vitrification and disposal as high-activity waste; and removal/stabilization of radioactive components in sludge heels, which impact tank closure.
- **Environmental Restoration.** Development of highly selective sorption materials for removing toxic organics and metals from soils and groundwater, methods to fix or remove these contaminants from loaded sorption materials, and fundamental understanding of the effects of separations chemistry on pollutant transport for use in technology design and risk evaluations.
- **Decontamination and Decommissioning.** Separations of radionuclides and metals from metal, debris, and concrete to reduce the volume and/or lower the category of the waste requiring disposal.

Because of the high cost and long schedules associated with remediation of the DOE sites, the potential exists for significant impacts from long-term science and technology developments. The current portfolio of projects is especially deficient in addressing needs at the applied research and exploratory development stages. It presently consists of 57 basic science projects; 4 applied research projects; 13 exploratory and advanced development projects; and 46 engineering development, demonstration, and deployment projects. Scientific research and applied technology activities focused on longer-term, high-risk, and high-cost portions of the flow sheets could lead to significant improvements that could be implemented during future plant upgrades to reduce waste generation, reduce operational risks (or failure modes), and shorten treatment time.

This finding is consistent with that of the *Adequacy Analysis of the Environmental Quality Research and Development Portfolio* [DOE, September 2000], which concluded that applied research and exploratory development research related to separations are the key to achieving substantial cost savings via broader application of improved separations processes, equipment, and technical support and to avoiding costly mistakes by improving the basis for multibillion-dollar decisions. All problem areas in EM could benefit, but the greatest impact will be in the high-cost, long-term areas such as high-level waste, subsurface contamination, decontamination and decommissioning, and nuclear materials.

Lack of backup technology development is a potential barrier to meeting future crucial EM needs. Sites require backups or alternatives to baseline flow sheets in case unforeseen technical or regulatory problems occur. The importance of such a backup technology was illustrated recently when an alternative process to In-Tank Precipitation (ITP) was needed for removal of cesium from tank waste at the Savannah River Site. Before problems with ITP occurred, separations research by the Efficient Separations and Processing Crosscutting Program and the Environmental Management Science Program had already identified two technologies (ion exchange using crystalline silicotitanates and a solvent-extraction process) that were potential alternatives to ITP. A similar need for backup separation technologies exists for other high-profile and high-baseline-cost projects. These include the high-level-waste treatment at Hanford and Idaho. The recent pressure on DOE sites to eliminate incinerators has also created a need for backup technologies, including separation technologies, for treating mixed waste streams planned for incineration.

The development of cost-effective technologies for decontamination of metals and other solids is severely hindered by the lack of federal regulations governing unrestricted release or recycle of these materials. Development of such regulations could significantly impact the amount of waste requiring treatment and the separations research needed to support this technical area.

Although the significant role of separation processes in most processing flow sheets has been identified, some uses of separation technologies have not been fully recognized as such. For example, several needs for aerosol removal and off-gas treatment are incorporated into vitrifier development needs. Although this may be the best approach to off-gas treatment, such technologies are often not recognized as separation processes.

Identified Gaps in Existing Research Program

As a part of the roadmapping exercise, the separations research requirements for DOE EM were identified; prioritized; divided into time frames—near-, mid-, or long-term (i.e., 5–10 years, 10–20 years, and 20–30 years)—in which the research is needed; and categorized into nine waste stream areas. The prioritization was performed by end users and technical experts based on the research's potential impact on reduction of cost, schedule, and/or risk for EM remediation and closure activities.

The highest-priority research requirements are summarized in Figures 1–8 for each waste stream category, with the exception of special/unique waste. The figures show the key research initiatives within the technical area, the time frame for obtaining research results, and the expected outcome if the research is successful. Although the waste stream categories were

selected to describe relatively independent streams, separations are highly crosscutting, and several “links” between categories are noted in the figures. The numbers shown in the figures designate the figure number for the linked waste stream. These linkages fall primarily into two categories: (1) those for which waste stream treatment generates secondary waste streams, which then become feed streams for other waste stream categories, and (2) treatment technologies that can be developed to address needs for multiple waste streams. The linkages for specific waste streams are described in more detail in each section of this roadmap.

The evaluation of the roadmapping information has led to the identification of gaps in the existing EM research program. Although a great deal of separations technology development occurs in EM programs, a significant number of needs remain to be addressed. These needs involve primarily mid- and long-term research associated with process improvements that could lead to significant cost savings and development of alternative technologies associated with backup flow sheets and/or risk reduction.

The areas of high-priority research that have insufficient existing support are shown in bold in Figures 1–8, and research requirements for all nine waste types are summarized below:

I. Dilute Aqueous Solutions. Contaminant-specific natural biotreatment systems, fundamental understanding of how separations chemistry affects pollutant transport and can be incorporated into large-scale geochemical models, treatment methods for reducing secondary waste generation and treatment costs, methods to fix or remove contaminants in loaded sorption material from barriers and natural treatment systems to avoid long-term release of sorbed contaminants from in situ barriers, highly selective separation processes for trace contaminant removal, colloid treatment, and characterization-related separations.

II. Concentrated Aqueous Solutions. New separations of cesium, strontium, and transuranics from alkaline and acidic wastes for alternative flow sheets; sulfate separation/destruction/recycle; improved processes to remove radioactive components to replace high-risk systems and minimize waste generation; development of alternative flow sheets for alkaline and acidic wastes; and improved sequencing and/or combination of processing steps to improve processing efficiency.

III. High-Activity Solids. Separations for radionuclides that impact tank closure (neptunium, etc., from tank heels); removal of metals (chromium, aluminum, and sodium) from vitrifier feed to increase waste-form loading; improved sequencing and/or combination of processing steps to improve processing efficiency; and solids dissolution to produce feeds for radionuclide separation.

IV. Soils and Sediments. Contaminant-specific natural treatment systems, improved treatment methods for transuranic-contaminated sludge, improved soil washing, fundamental understanding of how operating conditions and transport mechanisms impact the effectiveness of treatment processes and incorporation of separations chemistry into large-scale geochemical models, treatment methods for reducing secondary waste generation and treatment costs, methods to fix or remove contaminants in loaded sorption material from barriers and natural treatment systems, and highly selective separation processes for trace contaminant removal.

V. Combustible Solid Waste. Alternative processes to destroy organic components, treatment processes for tri-regulated waste, and processes to separate radioactive and toxic materials from organic waste.

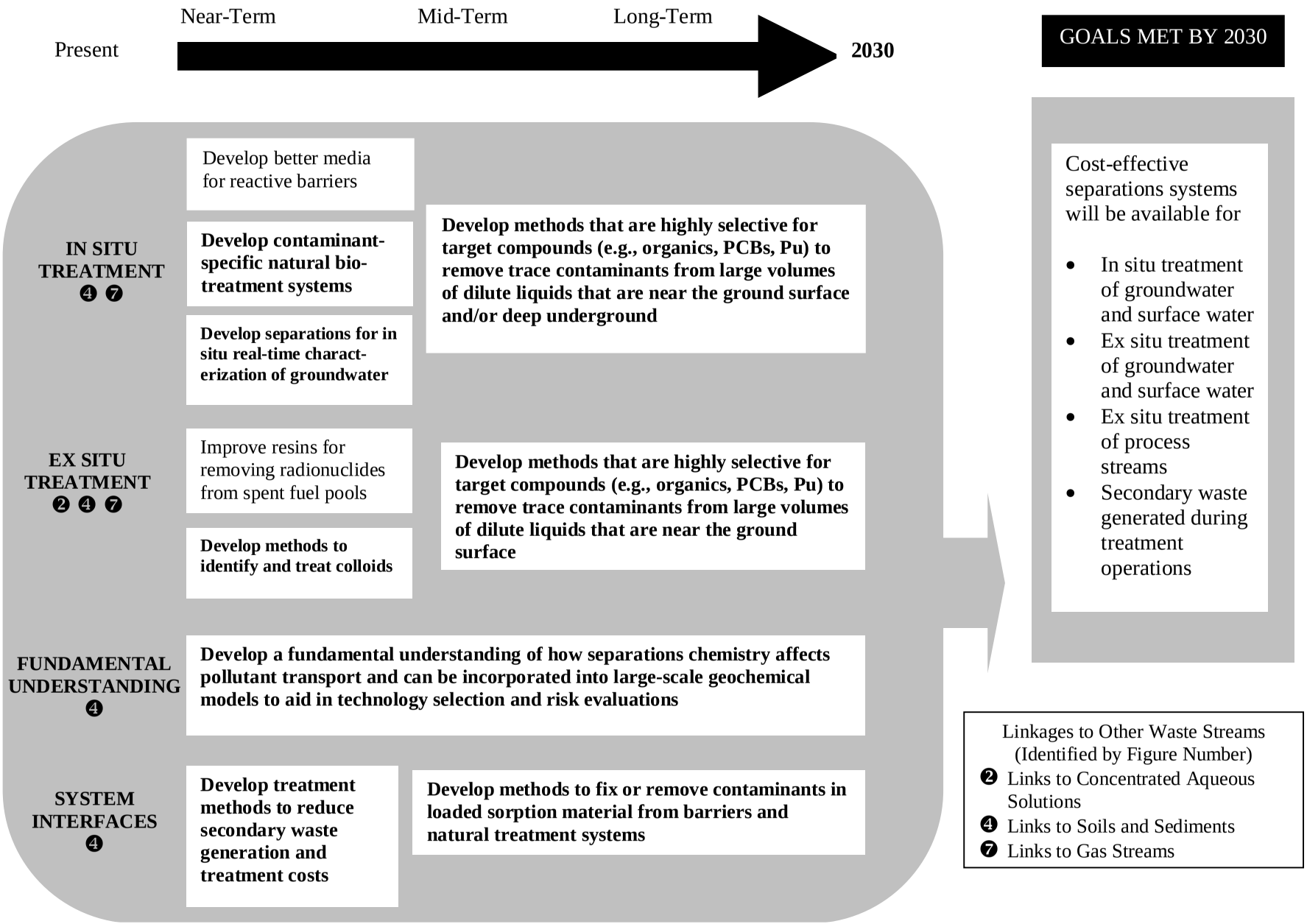
VI. Contaminated Metal, Debris, Concrete, and Other Noncombustible Solids. Separations for nickel recycle, removal of radionuclides from molten metal and classified shapes, treatment processes as alternatives to "chop and dispose," separation/treatment of retrieved buried waste, decontamination of equipment used in high-level-waste processing, and characterization-related separations.

VII. Gas Streams. Improved off-gas treatment systems.

VIII. Tritium. Improved chemical- and rate-based separation processes for tritium.

IX. Special/Unique Waste. Improved processes to manage small quantities of difficult-to-handle waste streams.

Figure 1. High-Priority Research for Dilute Aqueous Solutions



Note: Bold type indicates research with no or significantly insignificant funding

Figure 2. High-Priority Research for Concentrated Aqueous Solutions

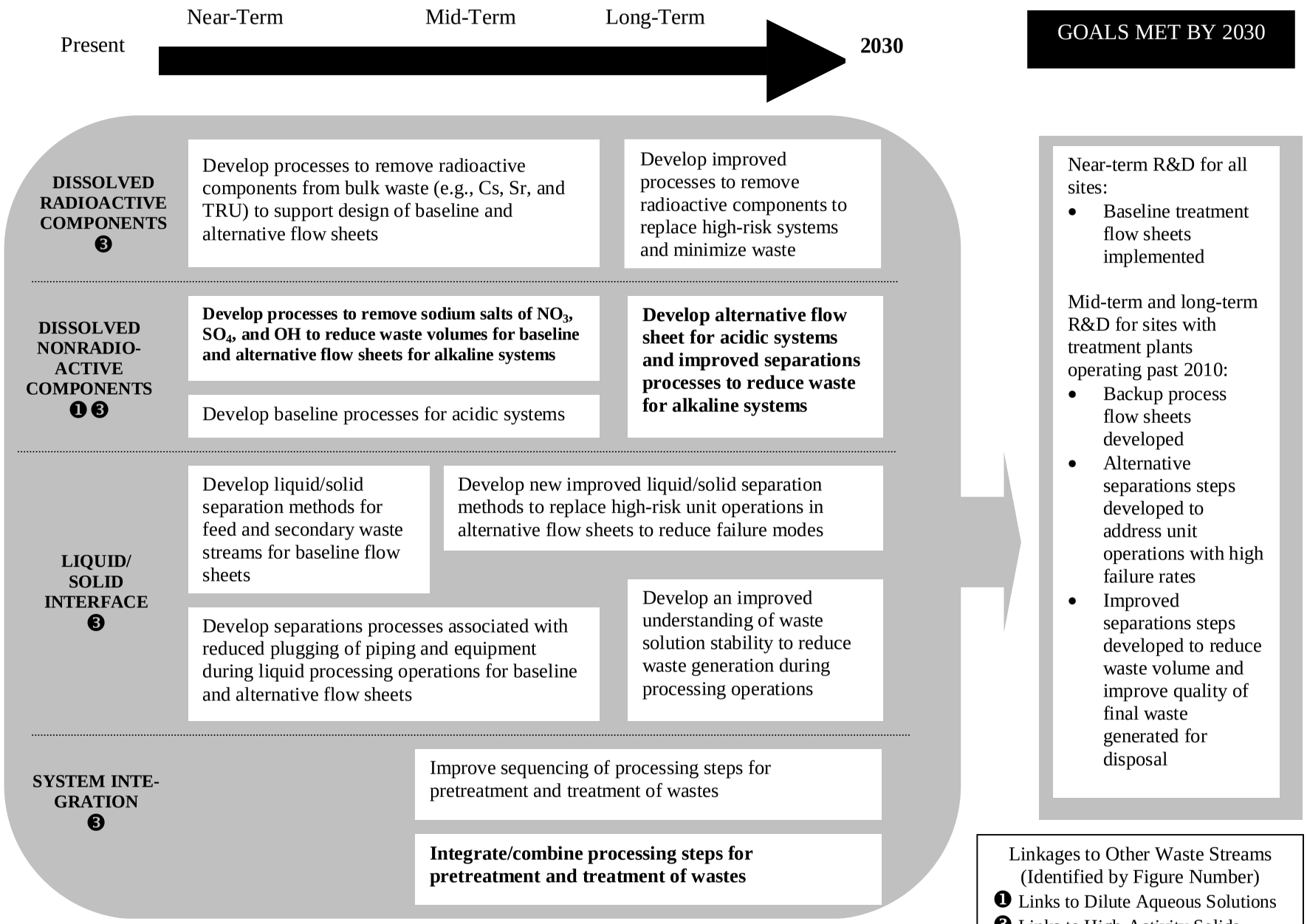


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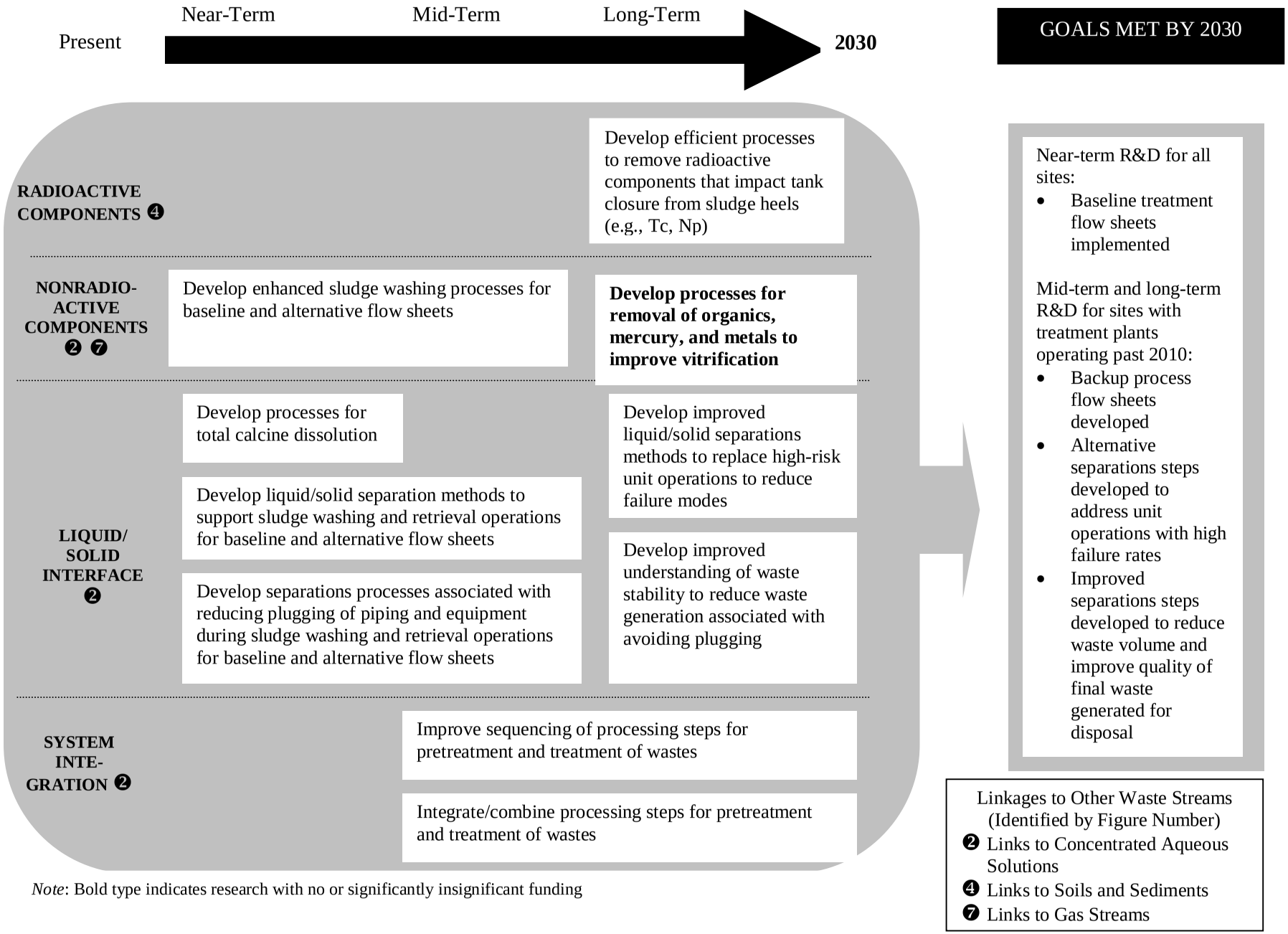
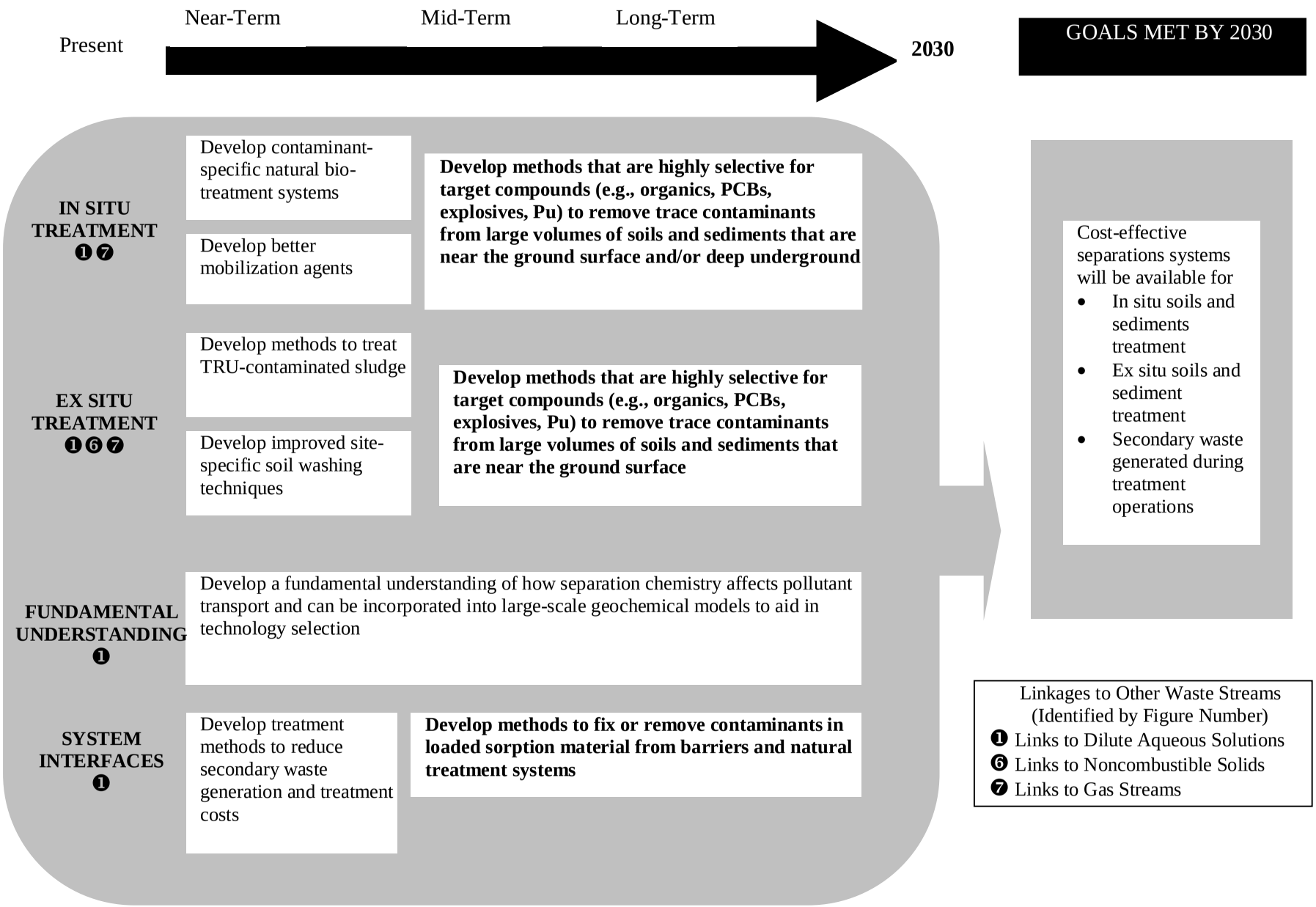
Figure 3. High-Priority Research for High-Activity Solids



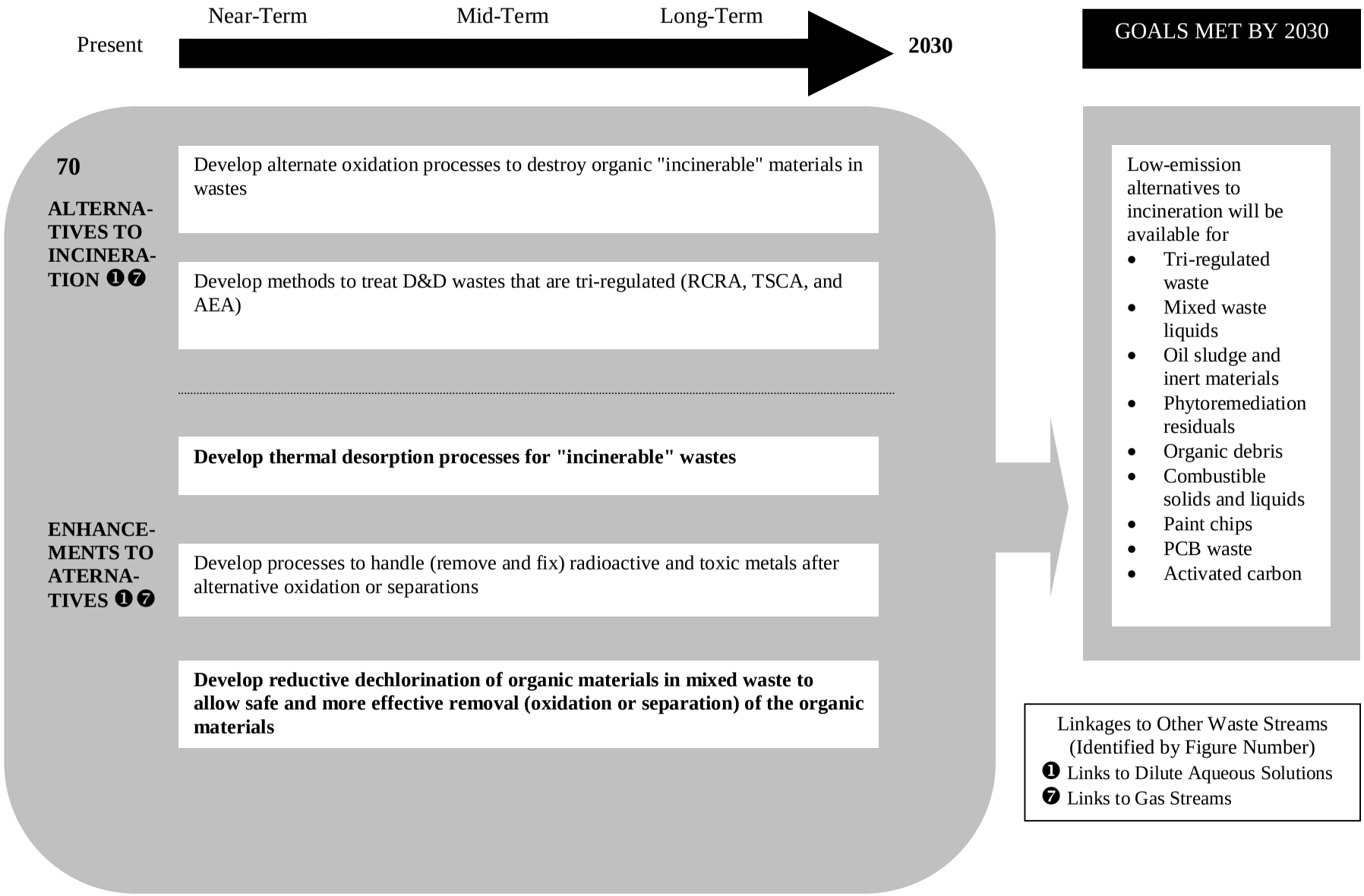
Note: Bold type indicates research with no or significantly insignificant funding

Figure 4. High-Priority Research for Soils and Sediments



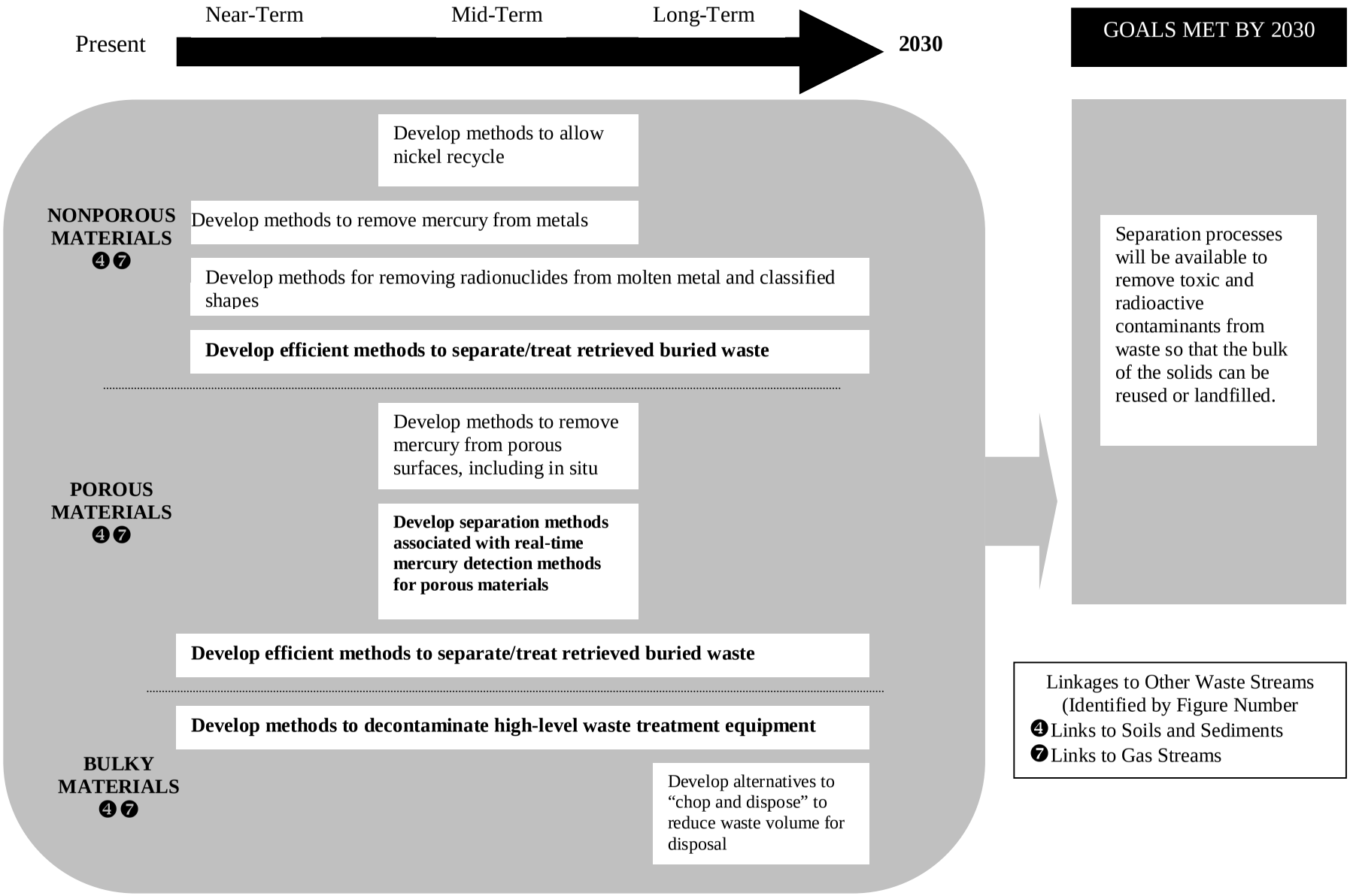
Note: Bold type indicates research with no or significantly insignificant funding

Figure 5. High-Priority Research for Combustible Solid Waste



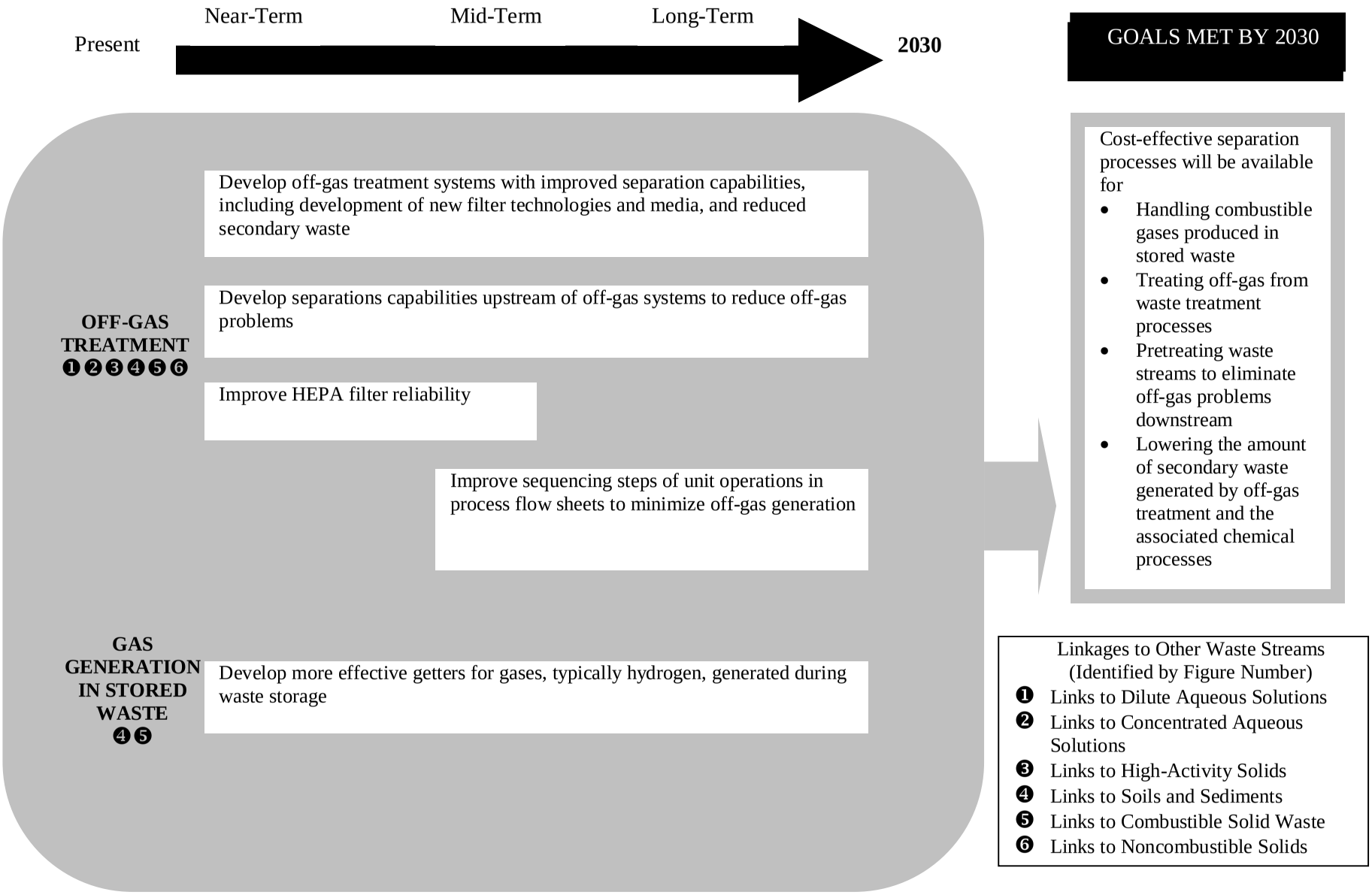
Note: Bold type indicates research with no or significantly insignificant funding

Figure 6. High-Priority Research for Contaminated Metal, Debris, Concrete, and Other Noncombustible Solids



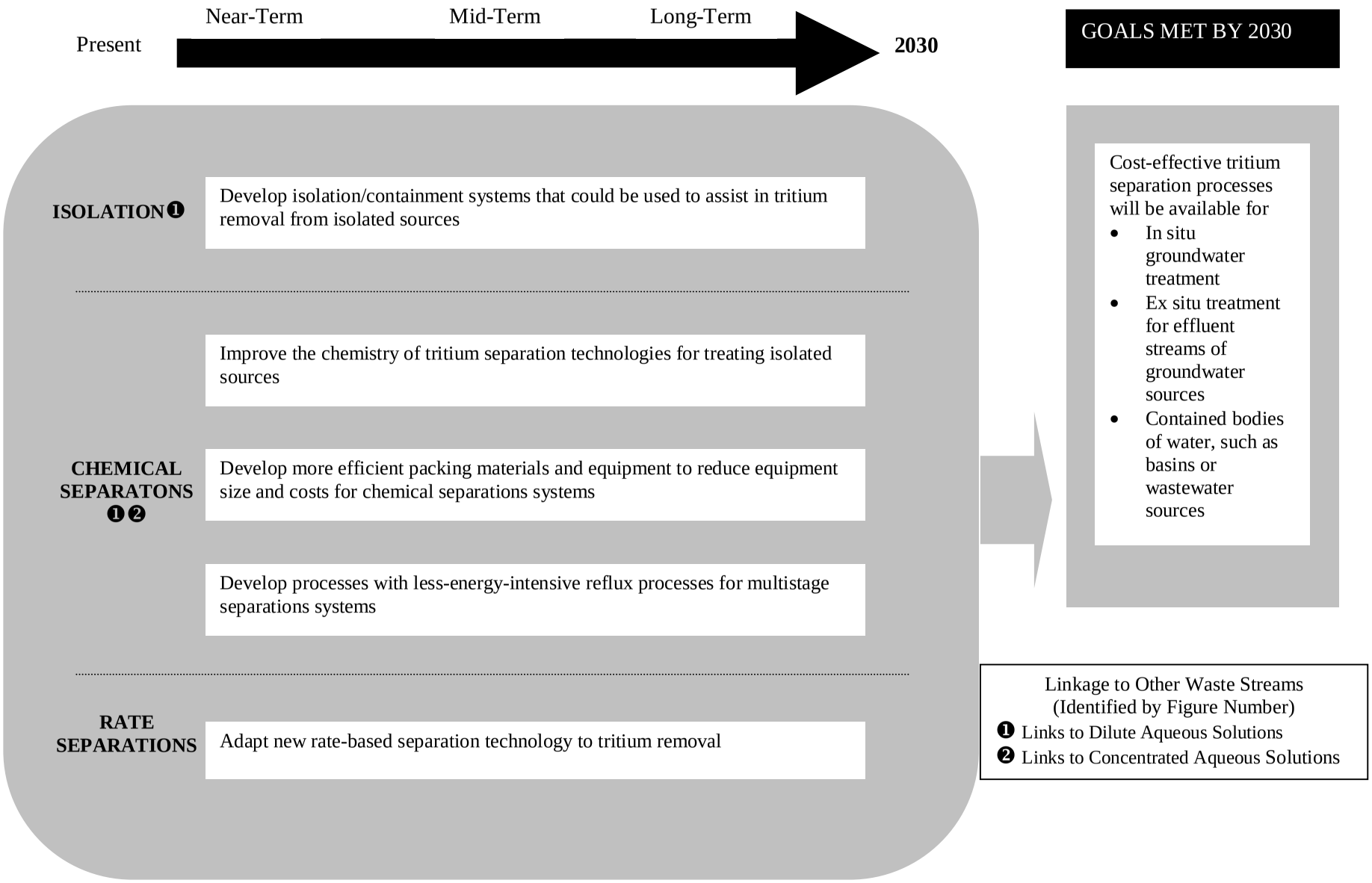
Note: Bold type indicates research with no or significantly insignificant funding

Figure 7. High-Priority Research for Gas Streams



Note: Bold type indicates research with no or significantly insignificant funding

Figure 8. High-Priority Research for Tritium



Note: Bold type indicates research with no or significantly insignificant funding

SEPARATIONS PATHS TO THE FUTURE: TECHNOLOGY ROADMAP FOR DOE ENVIRONMENTAL MANAGEMENT

INTRODUCTION TO ROADMAP

Purpose

This roadmap was developed by the Efficient Separations and Processing Crosscutting Program (ESP-CP), a technology development program in the Department of Energy's (DOE's) Office of Environmental Management (EM). The purpose of this separations roadmap is to obtain a clearer picture of the current state of the separation technologies and future needs for separations to support DOE's environmental and waste cleanup projects. This is a programmatic roadmap, not a project roadmap. It looks at the broad subject of separations over a relatively long time frame. The time frame for the roadmap was set at approximately 30 years. This period covers the expected time to clean up most of the legacy DOE wastes. Long-term projections are particularly important to research and development (R&D) because these are the situations for which major improvements in cost savings and risk reduction can be made.

The Need

There has been a growing awareness within EM of the benefits of management tools such as strategic planning and technology roadmapping. Although ESP-CP has conducted such work for its own portfolio of projects and has maintained awareness of other separation efforts as part of its operating responsibilities, there has been no unified examination or strategic planning for separations within EM. Consequently, ESP-CP undertook a technology roadmapping exercise to examine where near- and long-term separations technology needs occur, to evaluate the barriers to achieving these technologies, and to assess the research that must be conducted to allow the barriers to be overcome. The roadmap should be a useful strategic planning tool for any program conducting separations research or technology development.

The Process

Technology roadmapping is a strategic planning and market analysis tool that was first used in the 1980s by Motorola and has now been widely adopted by other industries and government agencies for allocating resources for technology development. In essence, it uses a team (or teams) of knowledgeable individuals to make predictions of what technologies will be needed and on what schedule. A roadmap also analyzes the technology and knowledge barriers that must be overcome in order to develop the predicted technologies and then lays out the R&D activities that must be conducted to overcome these barriers. For a government agency, technology roadmapping is appropriate when the mission has a high risk of failure or when the consequences of failure are significant, when costs and risks (safety, health, and environmental) are high, and/or when there are multiple organizations working on overlapping aspects of a common problem set. Aspects of all of these characteristics are present in separations for the EM mission.

The separations roadmap followed a four-stage process that is typical of most roadmapping efforts. The first stage is roadmap definition, in which the scope is defined and initial background data are collected. The second stage is the heart of the roadmapping activity. It involves the use of teams to define future technology needs, critical system requirements, risks,

opportunities, alternatives, time lines, and assessments of the currently available technology with respect to the longer-term technology needs. The third stage is the analysis of the workshop results and background information to identify specific R&D activities that are needed to reach the intermediate and final technology goals. The final stage is initial implementation and reiteration of parts of the process to provide ongoing review and update of the roadmap.

Information for the roadmap was obtained through a variety of sources, including EM planning documents, project roadmaps, the science and technology needs surveys, and the ESP-CP's portfolio analysis. Further input was received through a Separations Technology Roadmapping Workshop held in April 2001, with representatives from EM research organizations, technology users, and "outside" technology experts. The workshop brought together over 40 experts to identify requirements for EM separations research. A list of attendees is given in Appendix B. Subsequent conference calls and discussions were conducted to get additional information that was used as the basis for the technology roadmap.

The research requirements were categorized by the time frame in which the information is needed: near-term (5–10 years), the mid-term (10–20 years), long-term (20–30 years), and continuous (or ongoing). The needs were given priority ranking based on impact to cost, schedule, and/or risk reduction: high, medium, and low. They were also categorized into nine waste stream areas. All research needs and opportunities for each waste stream category are provided in individual chapters of this report. The high- and medium-priority research is also summarized in the Executive Summary.

Figures 1–8 of the Executive Summary show the linkages between key research requirements and the time frame for obtaining the results for each waste stream category. Although these categories were selected to describe relatively independent waste streams, separations are highly interrelated and several "links" between categories are noted on the figures. The numbers shown in the figures designate the figure number for the linked waste stream. These linkages fall primarily into two categories: (1) those in which waste stream treatment generates secondary wastes, which then become feed for another waste stream category, and (2) treatment technologies that can be developed to address multiple waste streams. These are also discussed in more detail in the Linkages sections of each chapter of the report.

This roadmap benefited from those produced in other parts of DOE—especially the numerous roadmaps produced in the DOE Office of Industrial Technologies on separation processes for other applications. Efforts were made to link with all of the appropriate roadmaps. This was done by citing the other roadmaps where applicable and by involving as many individuals as possible who participated in other roadmapping activities.

The Authors

The ESP-CP produced this roadmap with the help of several EM programs. As a crosscutting program, the ESP-CP directly supports multiple EM organizations in the development of science and technology to address the major cleanup and closure problems facing EM. The technical objective of ESP-CP is to develop separation and processing technologies that concentrate or immobilize a wide spectrum of radioactive and hazardous wastes or that serve as enabling technologies or subsystems within other waste treatment systems.

I. DILUTE AQUEOUS SOLUTIONS

A. Situational Analysis

Contaminated dilute aqueous solutions are a problem across the DOE complex and include streams such as contaminated groundwater and surface water, spent fuel cooling basin water, currently generated research and process waste, and decontamination waste streams. Contaminants of concern include a wide range of organics such as volatile organic compounds (VOCs), semivolatile organic compounds (SVOCs), chlorinated hydrocarbons and high explosives, Resource and Conservation Recovery Act (RCRA) metals, a wide range of radioactive metal species, and some special contaminants such as tritium (considered in a separate chapter in this roadmap).

While dilute aqueous streams currently arise from environmental restoration, waste management, and waste minimization/pollution prevention activities, it is anticipated that in the future other dilute aqueous streams will arise from decontamination and washing operations and the long-term stewardship program. Site characterization programs are likely to miss some sources of groundwater contamination. Furthermore, as other wastes are landfilled or disposed of on-site, there is a chance the landfills will produce additional groundwater contamination. By comparison, RCRA landfills require monitoring programs because of the chances of barrier failure over an extended time period.

For dilute aqueous solutions, there are probably more treatment alternatives than for most other waste categories due to the large amount of work that has been done outside of DOE. Academic and industrial interest in water purification, taken together with the past efforts by DOE programs such as ESP-CP, have led to a toolbox full of promising new technologies and improved implementations of existing technologies. Most of the contaminants, other than radioactivity, at DOE sites are similar to these found at several industrial facilities. In the industrial arena, the growing demands of the pharmaceutical, biotechnology, and semiconductor industries for ultrapure water have spawned a number of possibilities.

In considering technology development needs for dilute aqueous solutions, the most important point to realize is that the technologies and fundamental understanding gained in pursuing the removal of a target species from a dilute solution may, in some cases, be directly applicable to the removal of the same material from a concentrated solution. For example, the development of a rational design strategy for high-selectivity, high-specificity metal-ion-sequestering agents for use in dilute solution also provides much information, and often the same material, for removing the same target ions from concentrated solutions. The same set of needs—increased capacity, selectivity, affinity, simultaneous removal of multiple species, and robustness—that apply to advances in separation technologies for dilute solutions usually apply to concentrated solutions as well. Of course, the optimum separation agent depends upon the competing components in the solution. Thus, the importance of separation methods for removing materials from dilute solutions may be greater than is evident from individual needs statements.

In terms of current strategy for future research and development, a critical roadmapping linkage for this topic area is the *Vision 2020: 2000 Separations Roadmap*, published by the American Institute of Chemical Engineers' Center for Waste Reduction Technologies

[http://www.aiche.org/cwrt/pdf/sepmap.pdf]. This work includes separations for dilute solutions of three types of feed streams—ionic species from aqueous streams, organic compounds from aqueous streams, and contaminants from organic streams. It addresses the key technical barriers to separations from dilute solutions in terms of fundamental science and data, constraints on current processes, implementation and evolution, and institutional/educational barriers. It also addresses the key research needs in terms of chemistry and data, design and modeling, materials and equipment, and processing.

The major technical barriers cited in *Vision 2020* for all types of dilute waste streams are materials limitations, management of interfacial phenomena, and the cost and time required for pilot-plant testing of new processes. For separation of ionic species from dilute aqueous streams, the key additional barriers are as follows: lack of fundamental property data for modeling (kinetics, thermodynamics, solubilities, organic/inorganic species, mechanical properties), limitations of current selectivity and specificity, low value per gallon combined with high capacity cost to handle dilute streams, long residence times in the contactor, lack of processes to eliminate generation of neutralized solvents, and cost and time of developing technology through pilot-scale testing. For separation of organic species from dilute aqueous streams, the key barriers are as follows: the lack of ability to manage interfacial phenomena; inaccurate predictive tools; inability to design mass separating agents; lack of scaleup methods; lack of on-line analysis; salt buildup; lack of flexible plants; and low value/high processing costs, which reduce incentives to treat dilute solutions.

The goal of separations research is to develop by 2030 separation technologies that will be included in the cost-effective treatment processes for dilute aqueous waste stored in the DOE complex. This will include in situ treatment of groundwater and surface water, ex situ treatment of groundwater and surface water, and ex situ treatment of process streams and secondary waste generated during treatment operations.

B. Current Research and Development

The 2001 EM-funded research on the removal of species from dilute aqueous solution includes 18 basic research projects; 8 applied research projects; and 3 development, demonstration, and deployment projects. Most of these projects involve the design and/or modification of composite inorganic or synthetic organic functionalities to bind target species with high selectivity and affinity.

C. Research Requirements

The main treatment needs expressed by workshop participants were the removal of trace radionuclides from large volumes of aqueous solution, the provision of more and better agents for surface decontamination and contaminant immobilization, the separation and recycle of reagents, improved solid/liquid separations, and colloid removal technologies. The research needs and opportunities are summarized in Table 1, and the linkages between high-priority opportunities are shown in Figure 1 of the Executive Summary. The research needs and opportunities for dilute aqueous solutions are discussed in more detail below.

Table 1. Research for Dilute Aqueous Solutions
(H = High Priority, M = Medium Priority, L = Low Priority)
(NT = Near-Term, MT = Mid-Term, LT = Long-Term, C = Continuous)

In Situ	Ex Situ	Fundamental Understanding	Systems Interfaces
Develop methods to remove trace radionuclides from large volumes of dilute D&D liquids (M) (C) Develop methods (highly selective for targeted compounds) to remove trace contaminants from large volumes of dilute liquids that are near the ground surface, including organics, PCBs, explosives, and Pu (H) (C) Develop methods (highly selective for targeted compounds) to remove low concentrations of contaminants from large volumes of dilute liquids that are deep underground and inaccessible (e.g., under buildings) (H) (C) Develop natural treatment systems that are contaminant specific (H) (NT) Develop separation technologies that are associated with in situ real-time characterization of groundwater (H) (NT) Develop better media for reactive barriers (H) (NT)	Improve efficiency of ion-exchange resins for removing radionuclides from spent fuel pool water (M) (NT) Develop methods (highly selective for targeted compounds) to remove trace contaminants from large volumes of dilute liquids that are near the ground surface, including organics, PCBs, explosives, and Pu (H) (C) Develop methods to remove trace radionuclides from large volumes of dilute D&D liquids (M) (C) Develop methods to identify and treat colloids (M) NT) Develop methods for algae/virus separations from water (L) (LT) Develop methods for liquid metals separation to remove radionuclides from sodium for reuse (L) (C)	Develop an understanding of where technologies can and cannot be successfully applied and why (H) (C) Develop an understanding of how operating conditions (soil chemistry, contaminant species, concentration of contaminants, interference, by-products, and down-gradient migration) impact longevity of barrier (H) (NT) Identify how biota in surface water impact the applicability of separation techniques developed for groundwater treatment (H) (C) Develop an understanding of how sorption, desorption, mixing, and transport mechanisms impact treatment options (H) (NT) Develop methods to determine impact of treatment processes on ecosystem (H) (NT) Integrate separations chemistry into large-scale geochemical/hydrological models to aid in technology selection (M) (C)	Develop methods to remove/fix contaminants in barrier material after they have been removed from groundwater (H) (LT) Develop methods to treat secondary waste generated by natural treatment systems, such as phytoremediation (M) (LT) Develop treatment methods that will reduce the amount of secondary waste and reduce costs of treating (M) (NT)

1. In Situ Treatment. Near-term research opportunities exist to develop better media for use in reactive barriers and to develop contaminant-specific natural treatment systems. There is also a need to develop separation processes associated with in situ real-time characterization methods for groundwater monitoring. All in situ treatment needs are considered to be high priority. High-priority needs also exist to develop separation methods that are highly selective for target compounds [i.e., organics, polychlorinated biphenyls (PCBs), and radionuclides] to remove trace contaminants from large volumes of dilute solutions that are near the ground surface and/or deep underground. High selectivities and high capacities are important for in situ applications where the sorbent needs to function for long periods of time before becoming saturated (loaded) and requiring replacement. For instance, materials for removing strontium can be easily saturated by the higher concentrations of calcium that are present in most groundwater unless the selectivity for strontium over calcium is sufficiently high.

2. Ex Situ Treatment. There are near-term medium-priority research needs to improve ion exchange and sorbent materials for removing radionuclides from spent fuel pool waters and to develop methods to identify and treat colloids. There are high priority long-term needs for developing separations methods that are highly selective for target compounds (i.e., organics, PCBs, and radionuclides) to remove trace contaminants from large volumes of dilute solutions that are near the ground surface or are generated during decontamination and decommissioning operations. With ex situ treatment of groundwater, it is important that all objectionable components be removed to levels acceptable for reinjection of the water into the aquifer. Chemical adjustment of pH may be required prior to reinjection.

3. Fundamental Understanding. The same phenomena of sorption/desorption or ion exchange that are so important in separation processes to remove contaminants also occur in soils and the aquifer. These phenomena govern the transport and spread of contaminants in the underground environment. There are ongoing high- to medium-priority needs to understand how operating conditions, such as soil chemistry, contaminant species, concentration of contaminants, mixing, interference, by-products, and down-gradient migration, as well as sorption, desorption, and transport mechanisms, impact the applicability and life of treatment options. The understanding of separations chemistry should be integrated into improved large-scale geochemical/hydrological models to aid in technology selection and determination of impact on the ecosystem.

4. System Interfaces. Fixation of contaminants in barrier material (particularly in situ) is an ongoing issue, and the need for better fixation methods will remain. However, regulators may also want more assurance that the fixation is permanent or will last for a sufficiently long time. Thus, there is likely to be growing interest in evaluating the long-term effectiveness of the various barriers and fixation methods.

Similar needs are likely to arise from reactive and sorptive barriers. Opportunities will exist for developing new and better barrier materials, but the need to predict the lifetime of the barriers, improve replacement of barrier materials, and address the treatment/ disposal of barrier materials will become more important issues in the future.

Similar issues arise for fixation or treatment of contaminants that have been concentrated by natural treatment systems. This research need is considered to be a medium-priority long-term need.

The development of treatment methods that reduce the amount of secondary waste and reduce costs of treating secondary wastes is a medium-priority near-term need.

D. Linkages

Dilute current waste is usually a secondary waste produced from current operations, equipment and facility washing, etc., and thus is linked to these operations. Groundwater contamination often results from past spills (hopefully, there will be few future spills) and leakage from buried solid wastes. Thus, both the nature and the magnitude of future groundwater contamination will be linked to those operations and occurrences.

The technologies and fundamental understanding gained in pursuing the removal of a target species from a dilute solution are frequently directly applicable to the removal of the same material from a concentrated solution. Therefore, there are direct linkages to the Concentrated Aqueous Solutions section of this report. In situ treatment of soils and sediments is also directly linked to treatment of dilute aqueous streams, as discussed in the Soils and Sediments section. Treatment of volatile organics has a link to the Gas Streams section.

II. CONCENTRATED AQUEOUS SOLUTIONS

A. Situational Analysis

The majority of the concentrated aqueous solutions in the DOE complex are presently associated with the high-activity waste stored in underground tanks. In the future, the volume of solutions generated from decontamination and decommissioning activities will increase and is expected to make up a significant fraction of this waste stream.

The DOE system currently stores about 340 million liters (90 million gallons) of a mixture of high-activity waste solids and liquids containing more than 650 million curies in 280 tanks at five major sites: Hanford, Savannah River Site (SRS), Idaho National Engineering and Environmental Laboratory (INEEL), West Valley Demonstration Project (WVDP), and Oak Ridge Reservation (ORR). These wastes resulted from chemical separations operations required to produce plutonium and/or pilot-plant testing of plutonium recovery processes. Hanford performed additional operations such as recovery of uranium, cesium, and strontium. WVDP wastes were generated from commercial reprocessing of uranium and plutonium from spent nuclear fuel. ORR high-activity, low-level liquid wastes are similar in composition to some of the high-level wastes (HLWs) at Hanford and SRS because they were generated from the development and demonstration of many of the chemical separation processes used at those sites. These wastes were neutralized and concentrated for interim storage. The INEEL wastes were generated from similar processes but were not neutralized for interim storage. INEEL has acidic liquid sodium-bearing wastes. The bulk of the INEEL high-activity waste has been calcined to a dry solid, and these wastes would have to be dissolved with acid if they are to be separated by aqueous-based processes developed for the wastes at the other DOE sites. This would result in a concentrated aqueous solution.

The tanks can contain sludges, saltcake, and supernatant solutions. In this document, the following are considered to be concentrated aqueous solutions: supernatants; dissolved saltcake and calcine; liquids generated during waste retrieval and transfer; and sludge “wash” solutions generated during waste treatment. The remainder of the tank waste is considered under the High-Activity Solids section of this report.

To protect the public, workers, and the environment, radioactive waste must be retrieved from the tanks and converted into an appropriate form for long-term disposal. Liquid wastes retrieved from storage tanks require clarification (i.e., filtration, centrifuging, decanting) to remove suspended solids, such as sludges or precipitates, that may interfere with downstream processing. Radionuclide removal from tank waste supernatant and dissolved wastes is a primary requirement at all the DOE waste tank sites. This is due to the presence of radionuclides that directly impact waste immobilization decisions and the volume and cost of low-level and high-level wastes generated. The primary radionuclides of concern are cesium (Cs), strontium (Sr), technetium (Tc), and transuranic elements (TRUs). Removal processes for these radionuclides include in-tank, at-tank (compact processing), and out-of-tank (processing facility unit operations), all of which separate and concentrate the radionuclides of concern.

The sites have schedules for remediation of wastes and closure of tanks ranging from 2006 for ORR to 2070 for INEEL [*Tanks Focus Area FY 2001–FY 2005 Multiyear Program Plan*, Pacific

Northwest National Laboratory, September 2000]. SRS and WVDP presently have operating waste immobilization facilities, while Hanford, INEEL, and ORR are designing and preparing for future processing to convert tank wastes into final waste forms for disposal. ORR and WVDP have retrieved or consolidated the majority of their bulk wastes for treatment and are focused on residuals removal and tank closure. SRS is processing sludges and developing a flow sheet for supernatant treatment. All baseline flow sheets contain separation processes to segregate solid and liquid wastes associated with retrieval and treatment operations, minimize the amount of high-activity waste for disposal, and cost-effectively handle the large volumes of retrieval and transfer waste generated during processing.

All of the tank sites require near-term separations-related scientific data, technology development, and baseline technology performance verification to improve efficiency, lower costs, reduce risks, and enable the baseline tank waste remediation and closure activities to be implemented. In addition, because HLW remediation represents the most costly and longest-term EM problem, the potential exists for significant impacts from long-term science and technology developments. Scientific research and applied technology activities focused on longer-term, high-risk, and high-cost portions of the HLW processing flow sheets are required to support future decisions on baseline and alternative remediation strategies [National Research Council, *An End State Methodology for Identifying Technology Needs for Environmental Management, with an Example from the Hanford Site Tanks.* National Academy Press, Washington, D.C., 1999]. Hanford, INEEL, and SRS have mid-term and long-term research needs to provide backups to baseline flow sheets in case unforeseen problems arise (as recently occurred at SRS during the removal of cesium from supernatant solutions) and to provide significant improvements to the baseline flow sheets that could be implemented during future plant upgrades to reduce waste generation, operational risks, and life-cycle costs. The mid-term and long-term needs focus on significantly reducing the types and volumes of waste generated and reducing failure modes over the life of these plants. Separation steps with high risk of failure in the baseline flow sheets include solid/liquid separations, piping and equipment plugging, and radionuclide removal steps.

The goal for the EM separations research program for concentrated aqueous solutions is to have baseline flow sheets for all sites and alternative flow sheets developed for Hanford, INEEL, and SRS by 2030. In addition, improved separation processes will be available for implementation in operating plants for unit operations with high failure modes and to further reduce the volume and improve the quality of the final waste forms being generated for disposal.

B. Current Research and Development

Currently supporting, in part, the treatment of high-activity radioactive liquids, as shown in Appendix A, are 33 basic research; 4 exploratory and advanced development; and 18 development, demonstration, and deployment projects. These projects have been implemented to support development of the baseline process flow sheets for Hanford, INEEL, SRS, ORR, and WVDP. The projects primarily focus on R&D to support the design of the following baseline process flow sheets: separation of Cs, Sr, Tc, and actinides from tank supernatant solutions; addressing the caustic and nitrates generated by sludge leaching/washing; solid/liquid separation processes; and understanding the stability of solutions associated with

retrieval and processing of waste to avoid plugging of piping and processing equipment. There is also a limited amount of ongoing research in the DOE Office of Science Small Business Innovative Research Program that is applicable to concentrated aqueous solutions.

C. Research Requirements

Near-term research in separations R&D can improve efficiency, reduce costs, and reduce risks associated with the site's baseline flow sheets. Mid-term and long-term R&D provides opportunities to significantly improve the baseline flow sheets during future plant upgrades to reduce volume and types of waste generated for disposal and to reduce operational risks by addressing unit operations with high failure modes. The research needs and opportunities are summarized in Table 2, and linkages between high-priority opportunities are shown Figure 2 of the Executive Summary and discussed in detail below.

1. Dissolved Radioactive Components. Development of efficient processes to separate radionuclides from the bulk waste is considered a top-priority ongoing research need. Separations of Cs, Sr, Tc, and TRU from alkaline and acidic waste are needed in the near term to mid-term to support design of baseline flow sheets at all the major sites presently storing high-activity-waste liquids. Improved processes are needed to develop backups or alternatives to these baseline flow sheets in the mid-term time frame. Development of contingency flow sheets could avoid the enormous costs associated with potential shutdown of a waste processing facility ($0.5 to 1 billion/year) and, in the case of Hanford, could significantly reduce the life-cycle cost for tank remediation. New processes developed as a result of long-term R&D can also lead to improvements over unit operations in the baseline flow sheets and could be implemented during routine plant upgrades. These improvements could enhance performance by replacing unit operations with high failure rates, increasing processing speeds, minimizing waste quantities, and ensuring that the wastes meet the requirements for appropriate waste-form repositories. In the case of Hanford, alternative processes could be implemented in an annex to the currently designed Waste Treatment Plant. Current technologies being developed include ion exchange, solvent extraction, and precipitation. Future processes should have better selectivity, higher capacity, faster throughputs, and greater robustness. New technologies may include combined resins or extractants. Robustness not only refers to good stability of the separations materials but also implies the ability to handle variations in feeds and the ability to resist fouling or other difficulties. Problems to be avoided include column plugging or blinding of particle surfaces in column ion exchange, crud or emulsion formation in solvent extraction, plugging of filter pores in filtration, foaming in precipitation processes, or unwanted emission of products of degradation or radiolysis in any process. A better fundamental understanding of the chemistry and facilities for hot pilot demonstrations will be required to meet these objectives. The screening technique developed for the SRS alternative salt processing program should be considered for use in design of future large development projects at DOE sites [*Evaluation of Criteria for Selecting a Salt Processing Alternative for High-Level Waste at the Savannah River Site: Interim Report*, the National Academy of Sciences, National Academy Press, Washington, D.C., 2000, http://www.nap.edu/books/NI000344/html/].

Table 2. Research for Concentrated Aqueous Solutions
(H = High Priority, M = Medium Priority, L = Low Priority)
(NT = Near-Term, MT = Mid-Term, LT = Long-Term, C = Continuous)

Dissolved Radioactive Components	Dissolved Nonradioactive Components	Liquid/Solid Interface	System Integration
Develop processes to remove Cs, Sr, and TRU from alkaline waste to support design of baseline and alternative flow sheets (H) (NT, MT) Develop more-efficient processes to remove Cs, Sr, and TRU from acidic waste to support design of baseline and alternative flow sheets (H) (NT, MT) Develop improved processes to remove radionuclides (e.g., Cs, Sr, Tc, and TRU) to replace high-risk systems to reduce failure modes and minimize secondary waste generation (H) (LT) Develop methods to remove radionuclides from decontamination solutions (L) (C)	Develop processes to remove NO_3 and SO_4 to reduce volume of final waste in support of baseline and alternative flow sheets for alkaline systems (H) (NT, MT) Develop processes to remove/recycle caustic to reduce volume of final waste in support of baseline and alternative flow sheets for alkaline systems (H) (NT, MT) Develop processes to remove nonradioactive components that affect volume of waste in acidic systems to support baseline flow sheet development (H) (NT, MT) Develop processes to remove nonradioactive components for acidic systems in support of alternative flow sheet design (H) (MT, LT) Develop improved processes to remove NO_3 and SO_4 to further reduce volume of final waste for alkaline systems (H) (LT) Develop improved processes to remove/recycle caustic to further reduce volume of final waste for alkaline systems (H) (LT)	Develop solid/liquid separation methods to remove fines from feed and secondary waste streams for baseline flow sheet designs (H) (NT) Develop solid/liquid separation methods to remove fines from feed and secondary waste streams for alternative flow sheets to reduce long-term failure modes of high-risk unit operations (H), (MT, LT) Develop separation processes to reduce plugging in piping and equipment during liquid processing for baseline and alternative flow sheets (M) (NT, MT) Develop understanding of solution stability to reduce plugging in piping and equipment during liquid processing to reduce long-term failure modes of high-risk unit operations (M) (LT) Develop improved processes to control foaming in pretreatment, immobilization, and evaporation of waste (L) (NT)	Improve sequencing of processing steps for baseline flow sheets and long-term plant upgrades (M) (MT, LT) Integrate/combine processing steps for baseline flow sheets and long-term plant upgrades (M) (MT, LT) Develop methods to treat newly generated waste as well as legacy waste (L) (C)

2. Dissolved Nonradioactive Components. Development of processes to destroy nitrates, remove/recycle caustic, and remove sulfates generated as a result of sludge washing/leaching are also considered top-priority ongoing research needs. Hanford and SRS schedules require near- and mid-term research to support development of baseline and alternative flow sheets. INEEL's schedule requires more mid- and long-term research to support baseline flow sheet development. Incorporation of these processes in the Hanford flow sheet could reduce the secondary waste generated during retrieval and pretreatment activities at Hanford and reduce the low-activity waste generated for final disposal by 90%. If implemented in the near term, building of new underground storage tanks could be avoided ($80M per tank in savings). Mid-term research results could increase the capacity of existing treatment facilities, reducing the need for second-generation waste treatment facilities at Hanford. Long-term research could enhance plant operating performance by replacing unit operations having high failure rates, increasing processing speeds, and improving the quality/quantity of waste being generated for disposal. Current technologies under development include electrochemical nitrate/nitrite destruction and caustic recycle, solvent extraction for caustic recycle, steam reforming, and sodium nitrate purification. Improvements over existing technologies should reduce the costs, reduce the radionuclide content of the resulting low-activity waste form to contact-handled levels, and stabilize or destroy the nitrate/nitrite. Acceptable waste forms for the resulting low-activity waste form may also need to be developed or negotiated with regulatory agencies. Current technologies being considered are stream reforming with clay additives and grouting.

3. Liquid/Solid Interface. Development of solid/liquid separation methods to remove solid fines from process feed streams and from secondary wastes at large flow/flux rates is a high-priority ongoing research need. Improved processes will reduce the size of processing equipment required and the amount of secondary waste generated and will reduce the potential for failure of downstream processes. Near-term payoffs will occur as a result of reduced size of equipment in the baseline flow sheets, and the mid- and long-term research payoffs will result from reduced failure modes during operations. Current technologies being developed include cross-flow filtration, centrifuges, precoated filtration, settling/decanting, deep-bed filters, and flocculants/filter aids. Improvements over current technologies should include increased flux, enhanced capability to remove low-micron-sized particles, and improved cleaning methods. Potential new technologies for consideration include field-enhanced separations, flotation, and modifications to ion-exchange or solvent-extraction processes to accommodate fines.

Development of separation processes needed to minimize piping and equipment plugging during liquid processing is a medium-priority ongoing research need. The potential cost avoidance for shutdown of transfer lines and process piping and equipment will be high from the startup of operations through the life of the treatment plants. Replacement of two transfer lines at Hanford necessitated by plugging is estimated to be $50M.

4. System Integration. Medium-priority mid- to long-term research needs include improved sequencing of separation steps and combining multiple steps into single unit operations. Improvements in these areas can reduce the initial footprint of the baseline flow sheet, and further technology improvements can be retrofit during routine maintenance or upgrades over the lifetime of the treatment plants.

D. Linkages

Processes developed to destroy NO_3/NO_2 and remove caustic from concentrated aqueous solutions may result in the generation of dilute aqueous waste streams requiring additional treatment and disposal. Most of the separation technologies developed for concentrated aqueous solutions will generate secondary waste requiring treatment as high-activity solids. These are discussed in the Dilute Aqueous Solutions and High-Activity Solids sections of this report.

III. HIGH-ACTIVITY SOLIDS

A. Situational Analysis

The DOE system currently stores about 340 million liters (90 million gallons) of a mixture of high-activity waste solids and liquids containing more than 650 million curies in 280 tanks at five major sites: Hanford, SRS, INEEL, WVDP, and ORR. These wastes resulted from chemical separation operations required to produce plutonium and/or pilot-plant testing of plutonium recovery processes. Hanford performed additional operations such as recovery of uranium, cesium, and strontium. WVDP wastes were generated from commercial reprocessing of uranium and plutonium from spent nuclear fuel. ORR wastes are similar in composition to some of the wastes at Hanford and SRS because they were generated from the development and demonstration of many of the chemical separation processes used at those sites. The wastes from these sites were made strongly alkaline and concentrated for interim storage. The INEEL wastes were maintained in an acidic condition prior to calcining to dry powder.

The DOE radioactive waste tanks can contain sludges, saltcake, soluble calcine, and supernatant solutions. In this document, the sludges, undissolved calcine, and undissolved saltcake are considered to be high-activity solids. The remainder of the tank waste is considered under the Concentrated Aqueous Solutions section of this report. This includes the liquids generated during the retrieval, solids washing/dissolution steps, and secondary waste streams from solids treatment, such as off-gas streams from vitrifiers.

The solid wastes are chemically and physically heterogeneous between sites; between tanks at a given site; and, in some cases, between the phases of waste within a single tank. Tank wastes at Hanford, SRS, ORR, and WVDP are alkaline. Much of the waste at Hanford, SRS, and WVDP is classified as HLW. The majority of INEEL's waste has been calcined. Calcined waste requires further processing to convert it to a more durable long-term waste form, and separations may be selected to minimize the volume of HLW. The State of Idaho wants the calcine removed from the state in a timely manner. However, one U.S. Nuclear Regulatory Commission (NRC) panel recommended leaving the dry calcine in the existing storage bins for up to 300 years to allow time for the bulk of the ^{137}Cs and ^{90}Sr activity to decay. The solid waste at ORR is TRU, not HLW.

To protect the public, workers, and the environment, this radioactive waste must be retrieved from the tanks and converted into an appropriate form for long-term disposal.
Mobilizing bulk and heel wastes within a tank is required for tank waste retrieval and treatment, for ultimate immobilization and disposal of the hazardous waste components, and for tank closure. Mobilizing dense alkaline sludge, saltcake, and dry/hardened materials is particularly challenging and important for retrieval operations. Selective chemical dissolution to enhance heel retrieval may also be necessary. Solid/liquid separations will be required to separate the solid waste from the retrieval liquids for treatment. Sludge waste requires processing to remove entrained radionuclides for downstream separation and processing and to remove salts, organics, and minerals that may impact downstream vitrification.

Sludges at SRS and Hanford will require processing to remove nonradioactive constituents (e.g., aluminum, chromium, or phosphate) that either add to the volume of immobilized HLW or

impact immobilization processing. The baseline sludge processing primarily involves washing/leaching and separations. Sludge dissolution methods will be required for alternative Hanford flow sheets. Calcination is the baseline technology at INEEL for solidifying liquid acidic HLW and storing it as a granular solid in underground stainless steel bins. Development of methods to dissolve currently stored calcine and separate the major radioactive components is an option for waste processing at INEEL.

The sites have schedules for remediation of wastes and closure of tanks ranging from 2006 for ORR to 2070 for INEEL [*Tanks Focus Area FY 2001–FY 2005 Multiyear Program Plan*, Pacific Northwest National Laboratory, September 2000]. SRS and WVDP presently have operating waste immobilization facilities, while Hanford, INEEL, and ORR are designing and preparing for future processing to convert tank wastes into final waste forms for disposal. ORR and WVDP have retrieved or consolidated the majority of their bulk wastes for treatment and are focused on residuals removal and tank closure. SRS is processing sludges and developing a flow sheet for supernatant treatment. All baseline flow sheets contain separation processes to separate solid and liquid wastes associated with retrieval and treatment operations, separation processes to reduce the amount of high-activity waste for disposal, and separations to cost-effectively handle the large volumes of retrieval and transfer waste generated during processing.

All of the sites require near-term separations-related scientific data, technology development, and baseline technology performance verification to improve efficiency, reduce costs, reduce risks, and enable the baseline tank waste remediation and closure activities to be implemented. In addition, because HLW remediation represents the most costly and longest-term EM problem, the potential exists for significant impacts from long-term science and technology developments. Scientific research and applied technology activities focused on longer-term, high-risk, and high-cost portions of the HLW processing flow sheets are required to support future decisions on baseline and alternative remediation strategies [National Research Council, *An End State Methodology for Identifying Technology Needs for Environmental Management, with an Example from the Hanford Site Tanks*, National Academy Press, Washington, D.C., 1999]. Hanford, INEEL, and SRS have mid-term and long-term research needs to provide backups to baseline flow sheets in case unforeseen problems arise (as recently occurred at SRS during the removal of cesium from supernatant solutions) and to provide significant improvements to the baseline flow sheets that could be implemented during future plant upgrades to reduce waste generation, operational risks, and life-cycle costs. The mid-term and long-term needs focus on significantly reducing the types and volumes of waste generated and reducing failure modes over the life of these plants. Separation steps with high risk of failure in the baseline flow sheets are primarily associated with sludge washing, solid/liquid separations, piping, and equipment plugging.

B. Current Research and Development

Currently supporting the treatment of high-activity radioactive solid waste, as shown in Appendix A, are 20 basic research; 6 exploratory and advanced development; and 10 development, demonstration, and deployment projects. These projects have been implemented to support development of the baseline process flow sheets for Hanford, INEEL, SRS, ORR, and WVDP. The projects primarily focus on R&D to support the design of the following baseline process flow sheets: nitrates and technectium from sludge, salt-cake, and

calcine; solid/liquid separation processes; and understanding the stability of solutions associated with retrieval and processing of waste to avoid plugging of piping and processing equipment.

C. Research Requirements

Near-term research in separations R&D can improve efficiency, reduce costs, and reduce risks associated with the site's baseline flow sheets. Mid-term and long-term R&D provides opportunities to significantly improve the baseline flow sheets during future plant upgrades to reduce volume and types of waste generated for disposal and to reduce operational risks by addressing unit operations with high failure modes. The research needs and opportunities are summarized in Table 3, and the linkages between high-priority opportunities are shown in Figure 3 of the Executive Summary and discussed in detail below.

1. Radioactive Components. Needed in the long term is the development of efficient processes to remove from tank heels radionuclides (e.g., ^{99}Tc and ^{237}Np) that could impact tank closure.

2. Nonradioactive Components. Sludge washing/caustic leaching is a high-priority need for the near term and mid-term to reduce the amount of nitrate, sulfate, and other salts that impact the volume of solid waste generated by sludge treatment. Mid- to long-term research needs include separations processes to remove metals [i.e., Cr, Al, Na (high priority)] and organics (medium priority) from the bulk waste to increase waste-form loading and improve vitrification operations. Separating from the vitrifier feed the metals that negatively impact vitrification could reduce the time required for treatment; increase the glass-waste loading, thereby reducing the volume of waste generated for disposal, and avoid macrobatching of feed to the treatment plant. These improvements could result in multibillion-dollar savings over the life of the treatment facilities. Removal of organics and mercury from the vitrifier feed could improve vitrification processing by eliminating foaming, reducing off-gas requirements, and affecting the redox of the melt.

3. Liquid/Solid Interface. Development of solid/liquid separation methods to support retrieval and sludge washing operations is a high-priority ongoing research need. Improved processes will reduce the size of processing equipment required and the amount of secondary waste generated as well as reduce the potential for failure of downstream processes. Near- and mid-term payoffs will occur as a result of reduced size of equipment in the baseline flow sheets, and the mid- and long-term research payoffs will result from reduced failure modes during operations. Current technologies being developed include cross-flow filtration, centrifuges, precoated filtration, settling/ decanting, deep-bed filters, and flocculants/filter aids. Improvements over current technologies should include increased flux, enhanced capability to remove low-micron-sized particles, and improved cleaning methods. Potential new technologies for consideration include field-enhanced separations, flotation, and ion-exchange or solvent-extraction processes to accommodate fines.

Development of separation processes needed to minimize piping and equipment plugging during retrieval and sludge washing is a medium-priority ongoing research need. The potential cost avoidance for shutdown of transfer lines and process piping and equipment will be high from the startup of operations through the life of the treatment plants. The cost of replacing two transfer lines at Hanford, necessitated by plugging, is estimated to be $50M. Recent deposition of

Table 3. Research for High-Activity Solids
(H = High Priority, M = Medium Priority, L = Low Priority)
(NT = Near-Term, MT = Mid-Term, LT = Long-Term, C = Continuous)

Radioactive Components	Nonradioactive Components	Liquid/Solid Interface	System Integration
Develop processes to remove radionuclides that impact closure (e.g., Tc, Np) from tank heels (H) (LT)	Develop enhanced sludge washing processes for baseline and alternative flow sheets (H) (NT, MT) Develop methods for removal of metals (e.g., Cr, Al, Na) to increase loading in waste forms (H) (LT) Develop methods to remove mercury, which impacts off-gas treatment (H) (LT) Develop processes for removing organics to improve vitrification (M) (LT) Develop processes for removal of volatile metals, which impact off-gas treatment for vitrifier (L) (NT, MT) Develop processes for removal of noble metals, which affect life of vitrifier (L) (NT, MT) Develop processes to separate organics and nitrates from waste that will be grouted to reduce waste form failure mode (L) (NT, MT)	Develop solid/liquid separation methods to support sludge washing and retrieval operations for baseline and alternative flow sheets (H) (NT, MT) Develop solid/liquid separation methods to reduce long-term failure modes of high-risk unit operations (H) (LT) Develop processes for dissolving sludge solids (M) (NT) Develop processes for total calcine dissolution to produce feed with optimum composition for treatment (M) (NT) Develop separation processes to reduce plugging in piping and equipment during sludge washing and retrieval operations for baseline and alternative flow sheets (M) (NT, MT) Develop improved understanding of waste solution stability to reduce volume of waste generated to avoid plugging during sludge washing and retrieval operations (M) (LT)	Improve sequencing of processing steps for baseline flow sheets and long-term plant upgrades (M) (MT, LT) Integrate/combine processing steps for baseline flow sheets and long-term plant upgrades (M) (MT, LT) Develop methods to treat newly generated waste as well as legacy waste (L) (C)

aluminosilicate solids in the 2H evaporator vessel and gravity drain line resulted in more than 2 years of inoperation and more than $20M in cleanup and recovery costs.

Present calcine dissolution techniques address approximately 80% of the wastes stored at INEEL. Development of improved techniques to address the remaining 20%, which have a high aluminum content, is considered a medium-priority near-term research need. The objective is to find a process that will dissolve all the calcine and produce a feed stream with the optimal composition for the downstream treatment process. Avoiding direct vitrification of these wastes could possibly save $2 billion, according to some workshop participants. In addition, methods to dissolve Hanford sludge solids are required for developing alternative flow sheets.

4. System Integration. Medium-priority mid- to long-term research needs include improved sequencing of separation steps and combining multiple steps into single unit operations. Improvements in these areas can reduce the initial footprint of the baseline flow sheet, and technology improvements can be achieved over the lifetime of the treatment plants by implementation during routine plant maintenance/upgrades.

D. Linkages

Most the separation technologies developed for high-activity solids will generate secondary wastes that are feed streams for concentrated aqueous solutions treatment. These are discussed in the Concentrated Aqueous Solutions section of this report. Separation processes associated with solidification processes, such as vitrification, will impact the associated secondary gaseous waste streams, which are discussed in the Gas Streams section of the report. Processes developed for sludge washing may have applicability to similar treatment of contaminated soils and sediments (see Soils and Sediments section of the report).

IV. SOILS AND SEDIMENTS

A. Situational Analysis

Contaminated soils and sediments are found throughout the DOE complex and at numerous industrial sites as well. The sediments described here are solids that settle from holding ponds, settling basins, rivers, lakes, etc. Sediments formed in ponds or basins can be transported to other sites during flooding or even during heavy rainfall and heavy water runoff. The contamination in both soils and sediments can result from adsorption of soluble contaminants on clay or other soil-like particles; from direct addition of solutions, oils, or solids during spills; or from slow deposits of contaminated airborne solids from off-gas systems, incinerators, etc.

Separation phenomena such as adsorption/desorption are important to both the removal of contaminants and the transport of solids in the vadose zone and in soil-groundwater systems (aquifers). Data on these processes are important in estimating the migration of contaminants as well as in adsorption or removal of contaminants from groundwater.

Soil treatment can occur in situ or ex situ. Strong preferences exist for in situ processes in the United States. Ex situ treatment of soils or sediments usually involves “soil washing,” the leaching of contaminants from the soil (or sediment) using an acid solution, an alkaline solution, a solvent, a detergent, or other liquid reagent. Ex situ treatment allows the use of a wider range of reagents and permits better control of the “wash” conditions. However, it also involves the cost of excavation, which is often very significant if the contaminated soil is located well below the soil surface. There are also serious issues about the level of contaminant removal and the reintroduction of the treated soils or sediment into the ground. Ex situ soil washing appears to be more readily accepted in Europe than in the United States. The difference in acceptability may be attributed to more extensive experience with the technique in Europe or to differences in regulations that either discourage the less-well-controlled in situ treatment or more easily permit reintroduction of the treated soils into the ground.

In situ treatment methods include the use of bioremediation to destroy organic contaminants or “fix” inorganic contaminants so they will not migrate from the current location. Bioremediation can involve the use of bacteria to destroy organic contaminants or the use of plants destroy contaminants or transfer them safely to the air. Biological or chemical treatment can also lower the valence state of key metal contaminants and make them less soluble.

Volatile contaminants can sometimes be flushed from the soil by air, a process sometimes called soil venting. This can be accomplished by injecting air into the soil (especially when the contaminant is in the vadose zone) or by allowing changes in atmospheric pressure to slowly introduce air into and remove it from the soil (especially applicable to soils near the surface). When the contaminant can be released to the air, no special effort may be needed to contain the contaminant. However, some volatile contaminants may not be released to the air, and special “hoods” may be required to recover the contaminants. Recovery is also likely to require a separation process such as adsorption to treat all the “vented” air prior to release.

Reactive and adsorptive barriers are also considered for some contaminants, but these barriers usually operate on the groundwater to halt contaminant migration. These approaches are discussed in the section of this report on Dilute Aqueous Solutions, including groundwater.

The goal of separations research is to develop by 2030 separation processes that will be included in the cost-effective treatment processes for contaminated soils and sediment (in situ and in ex situ treatment facilities), where the amount of secondary waste is minimized and is adequately disposed of. Treatment of mercury and heavy metals should be leveraged with research programs in other parts of DOE, such as the Office of Industrial Technologies Mining Industry of the Future.

B. Current Research and Development

The Office of Environmental Management has several programs supporting research for separations associated with soils and sediments. As shown in Appendix A, these include 5 basic research; 1 exploratory and advanced development; and 6 development, demonstration, and deployment projects. The projects are primarily associated with removal of radionuclides, mercury, and organics from soils and sediments. Most current research and testing are devoted to in situ treatment methods. Research on in situ treatment of inorganic contaminants focuses largely on methods for fixing the contaminant in the soils and on barriers to retain the contaminant. Biological treatments are being investigated for organic contaminants that are easily degraded.

C. Research Requirements

New methods of soil and sediment treatment are needed to replace present technologies that are inadequate and costly. The research needs and opportunities for separation technologies to treat soils and sediments are likely to become more important in the coming years as estimates for the volume and composition of waste to be generated by environmental remediation and decontamination and decommissioning programs become available. This factor, plus the lack of suitable in situ concepts and the higher priorities in other areas, such as those involving migration of contaminants from site boundaries (by groundwater), results in most of the research needs being focused on ongoing or long-term development needs. More attention must also be given to reduction of secondary wastes in separation operations since there is a common impression that separations increase waste volume rather than reduce it.

The research needs and opportunities are summarized in Table 4, and the linkages between high-priority opportunities are shown in Figure 4 of the Executive Summary. They are discussed in more detail below.

1. In Situ Treatment. Many opportunities for in situ treatment of trace contaminants (organic and inorganic) arise from the present high costs of ex situ treatment. Current research on in situ treatment of inorganic contaminants is focused on methods for fixing the contaminant in the soils and providing barriers to retain the contaminant. These are medium-priority research needs to develop improved isolation methods. The mobility of many toxic (and some radioactive) contaminants can be reduced greatly by redox reduction of the metals (e.g., chromium, technetium, uranium, and TRU) to their lower-valence state. Thus, introduction of proper reductants into the soil can effectively fix these elements in the soil and prevent further migration

Table 4. Research for Soils and Sediments
(H = High Priority, M = Medium Priority, L = Low Priority)
(NT = Near-Term, MT = Mid-Term, LT = Long-Term, C = Continuous)

In Situ	Ex Situ	Fundamental Understanding	System Interfaces
Develop methods (highly selective for targeted compounds) to remove trace contaminants from large volumes of soils that are near the ground surface, including organics, PCBs, explosives, and Pu (H) (C) Develop methods (highly selective for targeted compounds) to remove low concentrations of contaminants from large volumes of soils and sediments that are deep underground and inaccessible (e.g., under buildings) (H) (C) Develop natural treatment systems that are contaminant specific (H) (NT) Develop methods to isolate and/or remove contaminants from sediments (e.g., Pu and Hg) (M) (LT) Develop better agents for mobilization of contaminants (M) (NT)	Develop methods to treat sludges contaminated with TRU (H) (NT) Develop methods (highly selective for targeted compounds) to remove trace contaminants from large volumes of soils that are near the ground surface, including organics, PCBs, explosives, and Pu (H) (C) Develop methods to remove contaminants from sediments (e.g., Pu and Hg) (M) (LT) Develop improved site-specific soil washing techniques (M) (NT)	Develop an understanding of where technologies can and cannot be successfully applied and why (H) (C) Develop an understanding of how operating conditions (soil chemistry, contaminant species, concentration of contaminants, interference, by-products, and down-gradient migration) impact longevity of barrier (H) (C) Develop an understanding of how sorption, desorption, mixing, and transport mechanisms impact treatment options (H) (C) Develop methods to determine impact of treatment processes on ecosystem (H) (C) Integrate separations chemistry into large-scale geochemical/ hydrological models to aid in technology selection (M) (C)	Develop methods to remove/fix contaminants in barrier material after they have been removed from soils and sediments (H) (LT) Develop methods to treat secondary waste generated by natural treatment systems, such as phytoremediation (M) (LT) Develop treatment methods that will reduce the amount of secondary waste and reduce costs of treating (M) (NT)

as long as the reducing environment can be maintained. Studies of such methods will be needed for several years. Both a high-priority ongoing research need to develop in situ separation processes that are highly selective for specific contaminants and a near-term need to develop natural removal systems that are contaminant specific exist at present.

For organic contaminants, the biological treatments presently being studied are for those contaminants that are easily degraded. Some plants can remove organic contaminants from soils and either degrade them or release them to the atmosphere. Some contaminants such as chlorinated solvents [trichloroethylene (TCE), PCBs, etc.] are very difficult to degrade

biologically, and release to the atmosphere may not be allowed in the future by the regulators. Anaerobic dechlorination of these compounds has been studied with some success, but the rates are often slow. Once the chlorine is removed, the resulting hydrocarbons can usually be degraded aerobically more quickly, and the hydrocarbons themselves are not usually as hazardous as the original chlorinated compounds. Dechlorination can also be accomplished chemically by adding a suitable reductant. Reactive barriers with iron metal have been effective in dechlorinating most of these contaminants. However, plugging of the barriers and the ability of groundwater to bypass the barrier are difficulties that have been encountered in these operations.

PCBs present such serious problems that the research needs and opportunities in this technology area will remain important for several years. There are reasons, in addition to economics, for favoring in situ methods for PCBs. Excavation runs the risk of further dispersing the contaminant. The recent decision to dredge the Hudson River to remove PCBs in the sediment (not a DOE responsibility, but a problem potentially similar to some DOE problems) has been challenged because of the near-term hazard of spreading the contamination. However, dredging seems to be the likely method. Similar decisions may be made regarding DOE sites with PCBs and other contaminants that could be spread by dredging or excavation. Comparable problems exist for mercury and other volatile contaminants in DOE soils and sediments.

2. Ex Situ Treatment. Ex situ treatment options are presently very expensive. Research opportunities include development of improved soil and sediment washing processes that are more highly selective for target compounds and are more cost-effective. This approach should be of most interest for the highly contaminated and low-volume soils and sediments that are located near the surface. Of course, the cost of treating extremely large volumes of lightly contaminated soils and the cost for excavating soils from deep formations will always discourage ex situ treatment.

The handling of secondary wastes must be carefully considered in the development of all ex situ treatment processes. Soil washing operations should consider the secondary wastes that can be produced, and attempts should be made to recycle leach solutions or clean the leach solutions to minimize the cost of disposal of these secondary wastes. Soil washing is most likely to be of interest when the contaminant is difficult to remove; when the volume of contaminated soil is not too large; and when disposal of the cleaned soil or sediment is not hindered by “listing” of the waste, which makes costly disposal necessary regardless of the efficiency of the decontamination operations.

3. Fundamental Understanding. There are ongoing high- to medium-priority needs to understand how operating conditions (such as soil chemistry, contaminant species, concentration of contaminants, mixing, interference, by-products, and down-gradient migration), as well as sorption, desorption, and transport mechanisms, impact the applicability and life of treatment options. The understanding of separations chemistry should be integrated into large-scale geochemical/hydrological models to aid in technology selection and determination of impact on the ecosystem.

4. System Interfaces. Fixation of contaminants in barrier material (particularly in situ) is an ongoing issue, and the need for better fixation methods will remain. However, regulators may also want more assurance that the fixation is permanent or will last for a sufficiently long time. Thus, there is likely to be growing interest in evaluating the long-term effectiveness of the various fixation methods.

Similar needs are likely to arise from reactive and sorptive barriers. There will be opportunities for developing new and better barrier materials, but the need to predict the lifetime of the barriers, improve replacement of barrier materials, and improve treatment/disposal of barrier materials will become more important issues in the future. Barriers are discussed in more detail in the Dilute Aqueous Solutions section of this report.

Similar issues arise for fixation or treatment of contaminants that have been concentrated by natural treatment systems. The research need is considered to be of medium priority and long term.

The development of treatment methods that will reduce the amount of secondary waste and reduce costs of treating secondary wastes is a medium-priority near-term need.

D. Linkages

In situ treatment of soils and sediments is directly linked to treatment of dilute aqueous streams, as discussed in the Dilute Aqueous Solutions section of this report. Treatment of volatile organics has a link to the Gas Streams section. Some treatment processes for soils and sediments can be linked to similar treatment processes for noncombustible waste (see the Contaminated Metal, Debris, Concrete, and Other Noncombustible Solids section).

V. COMBUSTIBLE SOLID WASTE

A. Situational Analysis

DOE has successfully incinerated organic-based mixed waste streams and other streams for the past decade. A number of studies have indicated that incineration is the best available technology for appropriate waste streams. However, the issue of emission control, especially dioxin/furan emissions arising from incomplete combustion of waste, and the possibility that excursions from normal operating behavior might lead to the releases of radioactive material have led to greatly increased public concern.

The planned incinerator at INEEL's Advanced Mixed Waste Treatment Facility illustrates the problems faced by incineration. In-depth analysis of a number of treatment alternatives resulted in the selection of incineration with sophisticated off-gas control as the best technology to treat 14,000 cubic meters of low-level, alpha low-level, and TRU wastes containing PCBs and other hazardous components. This stream is part of 65,000 cubic meters of mixed, low-level, and TRU waste that DOE must remove from INEEL by 2018 to comply with a consent decree. A September 1999 lawsuit by environmental groups resulted in an out-of-court settlement that bound DOE to reconsider construction of the new incinerator and to examine other treatment options.

As part of its agreed-to response, DOE formed a Secretarial-level Blue Ribbon Panel on Emerging Technological Alternatives to Incineration. The panel adopted seven evaluation criteria for candidate technologies (environmental, safety, and health risk considerations; stakeholder and regulatory interests; functional and technical performance; operational reliability; pre- and post-treatment requirements; economic viability; and technology maturity) and examined five general categories of technology options [thermal treatment without incineration; aqueous-based chemical oxidation; dehalogenation; separation (soil washing, solvent extraction, and thermal desorption); and biological treatment]. The panel identified four promising near-term technologies (steam reforming, thermal/vacuum desorption, DC arc melter, and plasma torch) and four other potential technologies that required more development (mediated electrochemical oxidation, microwave decomposition, supercritical water oxidation, and solvated electron dehalogenation). During the Panel's deliberations, it was noted that the waste at INEEL was among the most challenging in the DOE complex and that technologies developed for its treatment would likely have applicability to wastes at other sites.

Operational and economic problems related to regulatory changes have also affected DOE incinerators. The Clean Air Act of 1990 mandated that the U.S. Environmental Protection Agency (EPA) promulgate the Maximum Achievable Control Technologies (MACT) Rule for a variety of standard industrial technologies including hazardous waste combustors. In 1999 the final rule specified the emission standards that must met by April 2003 by the three DOE incinerators: the Consolidated Incinerator Facility (CIF) at SRS, the Toxic Substances Control Act (TSCA) Incinerator at Oak Ridge, and the Waste Experimental Reduction Facility (WERF) in Idaho.

Though CIF will meet the MACT emission requirements during normal operation, DOE has announced plans to suspend radioactive and mixed waste incineration at Savannah River for at

least 5 years. The other two DOE incinerators did not meet the new standards. The Oak Ridge TSCA incinerator could have met the standards by reducing its waste throughput, and WERF could have met them by the expenditure of capital funds.

The Oak Ridge TSCA Incinerator is the only incinerator in the DOE complex permitted to treat TSCA-regulated, radioactively contaminated PCB waste. An August 1999 DOE Inspector General audit determined that DOE did not operate the incinerator at the capacity permitted by the State of Tennessee or at the "attainable" capacity as determined by Bechtel Jacobs LLC, the contractor operating the incinerator. Several factors contributed to the shortfall in actual operations relative to the capacity of the incinerator, the most important being that the facility was designed to incinerate more waste than Oak Ridge planned to treat. The audit also showed that the waste could be treated more economically at commercial facilities that were soon to become available. As a result, the decision was made to increase the burn rate to incinerate all Oak Ridge waste and close the facility by 2003.

In the case of the WERF incinerator, a cost-benefit analysis examining the size of potential waste streams against the capital costs of modifications to meet the MACT rule indicated that upgrading was not economically sound. The incinerator has subsequently been shut down.

As a consequence, DOE's incineration capacity is now severely restricted and may disappear altogether. Thus, new and low-emission alternative methods are needed for the regulatory-compliant treatment of the legacy and future mixed waste streams that were to be addressed via incineration. The potential volumes of waste involved are large, with one current estimate [http://www.ntw-mixedwaste.org/background/archive/pdf/3-1hulet.pdf] at over 100,000 tons.

The objective of separations research in this area is to develop low-emission alternatives for all waste streams that had previously been treated by incineration. The streams include the following: septage higher than Land Disposal Restriction Limits, mixed-low-level-waste (MLLW)-suspect liquids, waste oil sludge, phytoremediation residuals, organic debris, combustible solids, combustible organic liquids, oil-contaminated inert material, paint chips, PCB wastes, and activated carbon. Some of the waste streams, though superficially amenable to incineration, have not been incinerated due to their high content of explosives or mercury (which is subject to very strict emissions controls). For other streams, characterization data are not yet available and may ultimately be very difficult to obtain. This adds more urgency to the need for alternative technologies.

B. Current Research and Development

There are two active research projects for developing alternatives to incineration, both of which address the treatment of radioactively contaminated organics (see Appendix A). The major future research effort planned for addressing this category of wastes is the TRU and Mixed Waste Focus Area Work Package MW-07 (Alternatives to Incineration to Reduce Emission Hazards). At the present time, the individual technologies to be examined have not yet been determined. The strategy is to conduct a broad range of efforts over the various stages of development, including basic science research and full-scale demonstrations. The latter will involve side-by-side comparison at the Western Environmental Technology Office in Butte, Montana, to collect performance, design, scaleup, and permitting data on three to five primary alternative treatment

processes. These processes will be chosen by competitive solicitation to represent the three general classes of alternatives: thermal, aqueous-based chemical oxidation, and separations. Concurrent alternative approaches will be examined at other sites. These may be thermal methods (e.g., steam reforming), chemical and aqueous-based methods (e.g., direct chemical oxidation), and/or methods involving organic separation steps (e.g., thermal desorption).

C. Research Requirements

Although the EM program for Alternatives to Incineration to Reduce Emission Hazards is broad and well planned, the magnitude of the problem provides strong incentives to develop more alternatives. The window of opportunity in the case of the INEEL waste, at a minimum, is long enough to allow innovative approaches to be developed and demonstrated if a promising candidate from the suite of technologies chosen by EM does not emerge. The separations research needs are summarized in Table 5, and linkages are shown in Figure 5 of the Executive Summery. They include alternatives to incineration and enhancements to these alternatives. All research needs are considered to be ongoing and high priority.

Table 5. Research for Combustible Solid Waste
(H = High Priority, M = Medium Priority, L = Low Priority)
(NT = Near-Term, MT = Mid-Term, LT = Long-Term, C = Continuous)

Alternatives to Incineration	Enhancements to Alternatives
Develop alternate oxidation processes to destroy organic) materials in wastes (H) (C) Develop methods to treat D&D wastes that are tri-regulated (RCRA, TSCA, and AEA) (H) (C)	Develop thermal desorption processes for combustible wastes (H) (C) Develop processes to handle (remove and fix) radioactive and toxic metals after alternative oxidation or separation (M) (C) Develop reductive dechlorination of organic materials in mixed waste to allow safe and more effective removal (oxidation or separation) of the organic materials (M) (C)

Separation processes such as soil washing and thermal desorption may play major roles in the alternatives to incineration. One of the attractive features of incineration is its apparent applicability to a wide variety of wastes. When alternatives to incineration are adopted, it may not be possible to treat such a wide range of wastes in a single facility. Thus, there may be no one facility available for all wastes. This could create an increased need for more separation facilities to treat the numerous waste types.

Potential separation technologies might focus on either organic components (PCBs) or hazardous components (radionuclides or RCRA metals such as mercury) and could include approaches used for treatment of bulk materials such as those considered in the section on noncombustible waste. Novel approaches such as supercritical fluid extraction or innovative material leaching/washing may offer possible solutions to this problem. Even if a separation process does not offer a

complete solution, it may work synergistically with another treatment to yield a candidate system.

D. Linkages

Treatment options for combustible waste are likely to generate gaseous waste streams and secondary dilute aqueous solutions, which will require additional treatment (see Dilute Aqueous Solutions and Gas Streams sections of this report).

VI. CONTAMINATED METAL, DEBRIS, CONCRETE, AND OTHER NONCOMBUSTIBLE SOLIDS

A. Situational Analysis

Future DOE cleanup activities, particularly deactivation and decommissioning (D&D) operations, are anticipated to generate massive solid waste streams. DOE and its predecessor organizations constructed over 20,000 facilities to conduct the wide range of activities necessary for the production of nuclear weapons, and many of these facilities became contaminated with radioactive and hazardous materials. The end of the Cold War resulted in about 5000 facilities that were no longer needed. Of these, about 3300 were involved in nuclear weapons production and therefore likely to have radioactive contamination in addition to hazardous material contamination.

Surveillance, monitoring, and maintenance costs for these facilities threaten to become a major drain on the DOE budget. Moreover, their continued existence gives rise to risks of further contamination and of accidents as the physical infrastructure deteriorates. Thus, there are strong driving forces to remove these facilities and decontamination is a prerequisite. Some of the facilities, such as the 14 surplus production reactors, must be cleaned up prior to being placed in interim safe storage. Others, such as the fuel reprocessing facilities and the various weapon component fabrication, assembly, dismantling, modification, and maintenance facilities, will be cleaned up prior to or during dismantling. In addition to the physical structure of the buildings, there are large quantities of equipment and internal fittings to be removed. For example, over 1800 contaminated glove boxes are in use or in storage in the DOE complex and miles of piping and ductwork with various levels of contamination exist.

Metals (particularly steel) and concrete are the major categories of solid waste that will arise from the decommissioning activities. DOE has accumulated over 500,000 tons of scrap metal at various facilities, and the total is likely to grow larger. The three gaseous-diffusion plants at Oak Ridge alone could generate another 500,000 tons of scrap metal. In addition to steel, there are large amounts of copper, brass, aluminum, lead, and nickel. It is also estimated that there are over 400 million cubic feet of concrete in the DOE complex, distributed such that over 400 million square feet are in need of decontamination.

Much of the contaminated metal, debris, concrete, and other noncombustible solids are stored or buried mixed wastes. DOE facilities currently contain massive volumes of buried wastes in landfills. It is anticipated that the vast majority of these wastes can be left “in place,” perhaps after suitable barriers are installed to prevent rainwater from entering the burial ground (or to restrict the quantity) in order to reduce movement of contaminants from the landfill. Nevertheless, it is likely that some fraction of these wastes will have to be removed and repackaged for disposal. This type of operation was planned for Pit 9 at INEEL, but the vendor’s plans proved to be impractical. This should not be considered proof that such retrieval and repackaging will never be necessary, and plans for eventually removing materials from Pit 9 are continuing.

There are a number of common aspects in the management of DOE-contaminated steel and concrete. For example, the ability to recycle either of these materials would have significant

beneficial impacts: the considerable costs of direct disposal could be avoided; risks arising from breach of the landfills would be eliminated; and the economic values of the recycled material would be realized. However, significantly different issues pertain to the ultimate use of the recycled materials and have impact on the technologies that might be developed to achieve the decontamination.

In the case of steel decontamination, technologies do exist and have been used for the removal of major surface contaminants. Even so, implementation of these technologies to enable recycle, and thus examination of the need for better technologies, has been hindered by the fact that no federal regulations exist for the unrestricted release of either surface or volumetrically contaminated metal. The NRC has a suggested guideline for surface contamination known as the "1.86 Rule," and although EPA has the authority to create a radiation standard for recycled material, it has suspended attempts to do so. After spending years trying to develop national standards, both agencies were unable to do so because they were not able to develop consensus within the scientific community. State environmental agencies are left as the only organizations with any supervisory power. Through consultation with these agencies and using the NRC-suggested surface contamination guideline, some material has been released from DOE for recycle. However, most attempts have met with strong public opposition, and this, in turn, has led to growing industry concern. In January 2000, DOE issued a moratorium on the release of volumetrically contaminated metals pending a decision by NRC on whether to establish national standards. In July 2000, DOE halted the unrestricted release of scrap pending improvements in DOE release criteria and information management.

Though this leads to an uncertain situation at present, it is likely that standards will eventually be established as a result of international trade pressures. The major European countries and Taiwan have developed national guidance for release of radioactive materials and have active recycling industries. Some of this recycled material already enters the United States as imported steel. As a result of an existing international trade in radioactively contaminated metals, including oil-field piping contaminated with naturally occurring radioactive materials, the International Atomic Energy Agency and the Commission of European Communities have developed draft regulatory limits for individual radionuclides. Starting points for standards addressing volumetric contamination are also available, such as the concept of a "pseudo-surface-contamination level." In this approach, it is assumed that all internal and external contamination is uniformly distributed on the exterior surface of the material, and the result is then compared with surface contamination release criteria.

The main contribution from separation technologies would be to achieve the highest degree of surface decontamination both to assist in the development of clear release criteria and in the ability to achieve those criteria. Separations that address volumetric contamination will necessarily involve some change in the state of the metal, and metal recycling clearly indicates that melting is the most effective overall process. Since DOE is exploring the possibility of a dedicated melter for the recycle of metals within the DOE complex, there may be technologies based on a better understanding of the partitioning behavior that occurs in the melting process.

Recycled concrete can be used as excavated fill material, road-base material, and concrete aggregate for construction. Economically, it is a far less-attractive material than recycled steel

and has not been subject to any large-scale recycling efforts. Any recycle uses would have to be located near the source of the waste materials, because the low value of the material would make long-distance shipping impractical. Consequently, although there have been fewer contentious issues surrounding it, the enormous projected volume of the waste stream, combined with the disposal costs of even mildly contaminated material, creates a strong impetus for seeking better decontamination methods that will enable release for recycle and yield major cost avoidances. The porous nature of concrete means that "surface contamination" extends far deeper than in the case of metal. Scabbling technologies to remove the top 1 inch of contaminated concrete surface are available, but most such technologies either produce contaminated airborne particles or become extremely expensive as the depth of contamination increases. The airborne particles also pose a health risk, and the filter technologies used to control the particles can produce further large secondary waste streams. Furthermore, since contamination can involve both radioactive species and hazardous species such as chromium, scabbling can generate mixed waste streams that cause further waste management problems.

Separation processes that eliminate, or greatly reduce the need for, scabbling or other physical abrasion techniques and allow the concrete to be recycled or disposed of in a less restrictive waste category would make a significant contribution to decommissioning operations. Though an ideal separation technology would work on the contaminated concrete while it is in place, methods such as leaching of dismantled or scabbled concrete may also be useful. The current understanding of decontamination indicates that most contaminants exist as either precipitates within the concrete matrix or as strongly bound species. Aqueous-based approaches must therefore possess both solubilization or desorption features and some means of transporting the solubilized species out of the matrix.

The role of separations in buried mixed waste operations is in the preparation of the materials for repackaging and disposal. Any excavation activity will increase the volume of solids to be handled since additional soils and any packaging materials will also be retrieved. There may even be both toxic and radioactive materials in the landfills that will be classified as mixed waste, thus making it impossible to return them directly to a similar landfill. Separations will be helpful to reduce the volume of the higher-activity wastes so the bulk of the solids retrieved can be sent to less expensive disposal facilities. It would be desirable to return the bulk of the material in a sufficiently clean form to landfills that would require no restrictions and/or reuse some of the materials. For separations to play a potential role in treatment of wastes retrieved from landfills, it will be necessary for the cost of disposal to be related to the toxic and radioactive content of the waste: that is, use of separations to concentrate the contaminants within a small portion of the waste would have to "free" the remaining waste for less costly disposal. If all of the retrieved material has to be handled and disposed of in the same manner, there may be little incentive for using separations.

The largest technical barrier to treatment of buried waste is the lack of knowledge of the contents of landfills. The location of specific buried wastes may not be known accurately enough to prevent excavation of excessive quantities of uncontaminated soil and rock.

There are economic and technical barriers to excavation and treatment of buried waste. Therefore, retrieval of these wastes is not likely to occur in many cases for several years.

However, the threat of leakage of contaminants from landfills will remain a serious risk for DOE. The problem could become more severe because of increases in the leak rate or because the regulations become more restrictive for such leakage.

B. Current Research and Development

DOE EM has several programs supporting research for separations associated with noncombustible soil waste. As shown in Appendix A, these include six development, demonstration, and deployment projects and eight basic research projects. The majority of the projects focus on removing radioactive contaminants from metals and construction materials.

Most research into decontamination involves exploration of alternatives, such as plasma streams or electromechanical shock to replace scabbling or other physical abrasion processes. Though comparatively little work has been performed on the fundamentals of decontamination as a separation process per se, there are many areas of research that have direct relevance and application. Much of the recent interest has been on physical decontamination methods such as the use of high-velocity dry ice pellets for metal surfaces and scabbling of concrete surfaces. In general, much of the work on development of improved sequestering ligands for use in treating aqueous solutions has a direct bearing on the desorption or solubilization of the contaminant in either the concrete matrix or on a metal surface. Lessons from rational ligand design will also be of use here in the design of solubilizing agents. Some current specific approaches include the use of water-soluble chelating polymers and aqueous biopolymer solutions to achieve complexation and removal of the contaminant.

Electrochemical methods have been investigated for both metal and concrete decontamination. Electrolytic removal of contaminants from a metal surface (where the bulk metal is used as one of the electrodes) is currently under investigation. An important aspect of this work appears to be in the understanding of how the electrolyte solution in contact with the metal surface affects contaminant removal. Electrokinetic processes have been investigated for decontaminating concrete by drawing on the direct parallel between the effectiveness of electrokinetics in low-porosity soils and the fact that concrete may be considered a quasi-mineral. In a similar fashion, the parallels between concrete and rock will make much of the current work on advanced leaching processes in the mining and minerals industry directly relevant to the possible use of leaching as a means of decontaminating concrete. Work on contaminant removal from various subsurface environments, including sludges, will be of benefit to an improved understanding of contaminant behavior in concrete.

Some work has also been performed on the use of supercritical fluids containing metal-binding ligands as a decontamination technology not only for (primarily) porous solids such as concrete but also for roughened metal surfaces. The ability of the supercritical fluid to penetrate the solid, together with its liquid-like solubilizing capacity, makes the use of the supercritical regime very attractive, though this would work only in a closed system and could not easily apply to large surface decontamination problems. Ionic liquids have also been used rather than ligands (at supercritical and normal conditions) because of their unique solvation properties.

C. Research Requirements

The research needs and opportunities are summarized in Table 6, and the linkages between high-priority opportunities are shown in Figure 6 of the Executive Summary. They are discussed in more detail below.

Table 6. Research for Contaminated Metal, Debris, Concrete, and Other Noncombustible Solids
(H = High Priority, M = Medium Priority, L = Low Priority)
(N T = Near-Term, MT = Mid-Term, LT = Long-Term, C = Continuous)

Nonporous Materials	Porous Materials	Bulky Materials
Develop methods to remove mercury from metals (H) (MT) Develop methods to separate/treat retrieved buried waste (M) (C) Develop improvements to baseline treatment options for removing radionuclides from molten metals and classified shapes (M) (C) Develop methods to allow nickel recycle (M) (C) Develop improvements to baseline treatment options for treating debris; remove radioactive contaminants from large volumes of construction debris, including metals (L) (C)	Develop methods to remove mercury from porous surfaces, including in situ methods to address contaminated slabs and foundations (H) (MT) Develop real-time mercury detection methods for porous media (H) (MT) Develop methods to separate/treat retrieved buried waste (M) (C) Develop alternative to baseline treatment options for treating debris; remove radioactive contaminants from large volumes of construction debris, including metals (L) (C)	Develop improved decontamination methods as alternatives to baseline process of "chop and dispose" to reduce waste volume to reduce regulatory risk (H) (LT) Develop methods to decontaminate equipment used in high-level waste processing (H) (C)

1. Nonporous Materials. A high-priority mid-term research need is to develop methods to remove mercury from metals. Alternative technologies for consideration include leaching with polymers and biological methods. Medium-priority ongoing research needs include separation methods that will allow metal recycle and development of improvements to baseline treatment options for removing radionuclides from molten metals and classified shapes. Options include melting and separating, removing contaminants from the solid material, chopping and leaching, and treating surfaces electrochemically. Treatment of retrieved buried waste is also a medium-priority issue.

A low-priority ongoing need is to develop improvements to baseline treatment options for treating debris and removing radioactive contaminants from large volumes of construction debris, including metals. There is a need for better chemical separations, magnetic separations, methods for immobilizing contaminants, and reuse.

For metal surfaces, the main need is for improved decontamination technologies that achieve or surpass the performance of current baseline methods (such as nitric acid rinse) but do not generate the problematic secondary wastes. In general, a better understanding of the

fundamentals of chemical decontamination is required. The Idaho Site Technology Coordinating Group has succinctly stated the needs. Fundamental studies are needed on the physical/chemical binding of radionuclides to bare and weathered concrete and painted concrete surfaces. Mesoscale modeling and experiments are needed to characterize flow and percolation of fluids through porous and fractured concrete surfaces. The influence of chemical, mechanical, and biological processes on the physical properties and fracture of concrete requires characterization. These data will lead to the development of more efficient chemical and biological processes for decontamination.

For metals, the fundamental chemistry of adsorption and binding of radioactive isotopes to alloys needs to be studied. The development of recyclable chelating agents to minimize secondary waste represents an opportunity. Reagents developed to extract radionuclides from solution can be modified to act on surface-bonded contaminants. Interaction of contamination with corrosion and oxidation products and organics (e.g., paint and oil) requires characterization through surface science studies (secondary ion mass spectrometry, electron microprobe, electron spectroscopy for chemical analysis, Auger, surface Raman, etc.) and solid-state chemical modeling. Segregation and trapping of radioactive species at defects (e.g., pores, weldments, or cracks) would also benefit from surface science studies and modeling.

It should also be noted that there are special cases where the robustness and flexibility of separation technologies are important. For example, there are many situations in which piping or ductwork is known to be contaminated but where the pipes are embedded in concrete or are located beneath concrete slabs. The costs associated with removing the pipes and disposing of them as radioactive waste can be as high as $1200 per linear foot.

2. Porous Materials. There is a high-priority mid-term need to develop methods to remove mercury from porous surfaces, including in situ methods to address contaminated slabs and foundations. Alternatives for consideration include leaching with polymers, electrokinetics, selective stabilization, grouting, and biological methods. Another high-priority mid-term need is to develop real-time mercury detection methods for porous media. Treatment of retrieved buried waste is a medium-priority issue. A low-priority ongoing need is to develop improvements to baseline treatment options for treating debris and removing radioactive contaminants from large volumes of construction debris, including metals. A need also exists for better chemical separations, magnetic separations, immobilizing methods, and reuse.

Decontamination studies must also investigate the entire decontamination operation, including disposition of the decontamination medium. For supercritical fluid decontamination and the use of dry ice pellets, the fluid may be vaporized, leaving only a small volume of contaminant-loaded residue (assuming that the vapor/gas is clean and suitable for release or recycle). When aqueous solutions are used, it may be necessary, or at least more economical, to concentrate the contaminant. In some cases, it may be possible to reuse the solution (or at least the water) once the contaminants are removed. In all cases, efforts will be needed to minimize the production of secondary wastes.

3. Bulky Materials. A high-priority long-term research need is to develop improved decontamination methods as alternatives to the baseline process of “chop and dispose” in order to reduce the waste volume and to reduce regulatory risk (i.e., disposal sites may not be available or may be too expensive). Decontamination of equipment used in high-level waste processing is also an issue. The equipment itself is presently being considered high-level waste and being disposed of accordingly. This approach will not be technically or economically viable as high-level waste processing activities increase. Of particular concern is high-level waste melter equipment.

D. Linkages

Some treatment processes for noncombustible waste can be linked to similar treatment processes for soils and sediments. Also, some of these processes will generate secondary gaseous waste that will need to be treated. See the sections on Soils and Sediments and Gas Streams for more detail.

VII. GAS STREAMS

A. Situational Analysis

There are currently two serious problems associated with gases in DOE EM facilities: (1) off-gas or emission control and (2) generation of combustible gases (principally hydrogen) in stored waste. Separation processes can be important for separating constituents upstream to eliminate off-gas problems or for removing the gases during off-gas treatment in storage containers.

Off-gases and other gaseous effluents are important to most EM treatment and pretreatment systems because all operations dealing with toxic or radioactive contaminants must be isolated from the environment. Therefore, any ventilation from the equipment must be treated before it is released to the environment. Other streams, such as the off-gas from vitrifiers, incinerators, soil venting operations, etc., could carry significant quantities of contaminants; therefore, high removal efficiencies may be needed. In some cases, filtration to remove particulates is required since escaping contaminants may be adsorbed on the particles. In other cases, the contaminant could be the gas itself such as mercury, VOCs, etc.

Off-gas treatment is a widely used high-cost operation at many DOE facilities. However, it is usually not identified specifically as a separations need. Off-gas treatment is usually incorporated into the vitrifier, the incinerator, or the other piece of equipment being studied. This approach may be appropriate, since off-gas systems may be supplied by the vendor of the equipment. Furthermore, off-gas problems are common in other industries and many industrial firms have developed and marketed off-gas equipment. Nevertheless, one should remember that the off-gas systems (i.e., separation systems) may make up a substantial portion of the cost of a facility such as a vitrifier. Furthermore, the off-gas system is crucial to successful operation of the facility.

The perceived potential for the off-gas system to allow unacceptable releases of contaminants is the principal reason that incinerators and other “thermal” processes have been under attack. In addition, treatment of off-gas scrubber solutions can be a significant problem. Treatment facilities for dilute aqueous solutions often limit the amount of specific constituents in scrubber solutions that can be accepted into the facilities. Recycle of off-gas scrubber solutions could reduce waste volume. However, feeding off-gas scrub solutions to facilities that treat concentrated aqueous solutions and/or to solid treatment facilities could result in an increase in solid waste generation and/or problems in treatment. In any case, it is necessary to handle and dispose of the scrubber solutions properly. At SRS, the scrubber solutions are returned to the tanks but carry considerable silica from the frit used in the vitrifier. This results in an undesirable buildup of silica in the tanks, which may have caused or contributed to the formation of precipitates in the evaporator used to concentrate the waste for interim storage.

Removal of aerosols from air is necessary in a number of applications. The ventilation air above the HLW tank liquids requires effective aerosol removal because of the high activity in the wastes. Similar problems are likely to result from a variety of D&D operations using liquids or solutions.

Another major current problem is the handling of combustible gases, especially hydrogen, produced in stored waste. Although combustible vapors can be released from wastes that contain

organic materials, radiolytic hydrogen can be released from essentially any waste with sufficient radioactivity and water or organic compounds, even if the water is in hydrates or another solid form.

The goal of separations research is to develop treatment solutions for problematic constituents in off-gas streams by removing them upstream or by treatment of the off-gas stream itself by 2030. Solutions will also be developed for handling combustible gases produced in stored waste.

B. Current Research and Development

Despite its importance, relatively little separations research is specifically dedicated to off-gas treatment. Some research is done as part of vitrifier development projects at Hanford, INEEL, and SRS. Several projects for separating the waste constituents feeding treatment units are related to reducing off-gas generation downstream. These are covered in the Linkages section below.

Current filters [usually high-efficiency particulate air (HEPA) filters] use disposable cartridges. Frequent changing of these filters can contribute significantly to personnel exposure and to the waste volume generated at many sites. There is a strongly recognized need for filters that exhibit longer service life and that can be cleaned or changed more easily to reduce waste volumes and/or personnel exposure. Several approaches have been suggested and explored in recent years. EM has one active project to develop washable HEPA filters and one project to reduce aerosols (see Appendix A).

The four active EM projects associated with off-gas filtration are included in vitrification studies under immobilization tasks (see Appendix A). There may be additional studies in ongoing programs that have not yet been identified. Nevertheless, the off-gas work is believed to be no more than a small portion of the existing budget going to vitrification. The manufacturers of vitrification equipment and the commercial suppliers of off-gas equipment may be doing significant development in this area outside of DOE-funded work. Four research projects are also under way in EM that support treatment of off-gas in waste containers (see Appendix A).

C. Research Requirements

The research needs and opportunities are summarized in Table 7, and the linkages between high-priority areas are shown in Figure 7 of the Executive Summary. They are discussed in more detail below.

1. Off-Gas Treatment. Although there is no strongly recognized need for improvements in off-gas treatment other than for improved HEPA filters, other needs likely exist. The more serious question is whether commercial firms are filling the need. As long as DOE needs are not significantly different from those of similar commercial facilities, it is likely that the commercial sector will provide the needed technologies. If DOE needs are significantly different, it may be necessary to support additional R&D to meet DOE-specific requirements. Again, the firms that are developing equipment for the commercial sector could still be the most appropriate groups to do such development if they can gain from their commercial experience and expertise. The unique DOE problems are likely to include the need for extremely high decontamination of off-

Table 7. Research for Gas Streams
(H = High Priority, M = Medium Priority, L = Low Priority)
(NT = Near-Term, MT = Mid-Term, LT = Long-Term, C = Continuous)

Off-Gas Treatment	Gas Generation in Stored Waste
Improve off-gas treatment systems (H) (MT, LT) Improve processing operations to reduce off-gas problems (H) (MT, LT) Improve HEPA filter reliability (H) (LT) Develop methods to improve aerosol separations—potentially include development of new filter technologies and media (membranes, electrostatic precipitators) (H) (C) Develop methods to treat particulates generated during excavation and D&D (H) (C) Develop economic separation processes to minimize off-gas treatment of high-activity waste (M) (MT, LT) Develop economic separation processes to minimize off-gas treatment of concentrated aqueous solutions (M) (MT, LT) Improve sequencing steps of unit operations in process flow sheets to minimize off-gas generation (M) (LT)	Develop more-effective hydrogen getters (i.e., those poisoned less easily) (H) (LT)

gas streams and the need to decontaminate any filters or scrub streams to minimize wastes. There are also difficulties in maintenance and operation of equipment in high-radiation fields.

Development of improved HEPA filters should continue for a few years, and incremental improvements could continue for several years. Because HEPA filters are replaced frequently and can be housed in standard sized and shaped equipment, it is likely that incremental improvements can be implemented quickly and effectively. The lack of barriers for implementation makes it more attractive to continue improvements as long as such improvements can be made.

2. Gas Generation in Stored Waste. Hydrogen capture offers considerable research opportunities for the coming few years. Improvements can be made in developing new, innovative getter materials; better ways to install getter materials in waste storage containers; and periodic regeneration of getter materials to minimize exposures and costs of long-term waste storage.

DOE EM is completing its evaluation of processing and treatment for the bulk of its wastes. In the coming years, more attention could be devoted to small waste sources that cannot be treated with any bulk waste treatment systems. Handling these special or difficult wastes may generate special or difficult off-gas problems. It is hard to predict either the treatment method to be used for these wastes or the off-gas problems with the treatment because these wastes are still to be

identified and are likely to consist of numerous types. It is unlikely that generalizations can be made to describe either the treatment of or the off-gas problems arising from these wastes.

D. Linkages

Gas streams are generated as a result of treating essentially all the streams discussed in other chapters of this report. Therefore, there are linkages to all other waste streams from the perspective of generation. Treatment of off-gas streams generates additional waste that must be treated as dilute or concentrated aqueous wastes or as solid sediments. The total volume and individual components of these waste streams often cause problems for the waste treatment systems, as discussed in the individual chapters of this report. Many of the off-gas treatment processes are covered in the design and procurement of thermal solid waste treatment systems. Therefore, there are direct links to those chapters of this report from the waste generation perceptive. Process flow sheets often contain separation processes upstream of thermal processes to reduce or eliminate components in the feed stream that will cause off-gas problems. These have traditionally been the focus of separations R&D to support gaseous streams, and they are also covered in the aqueous and solid waste chapters of this report.

VIII. TRITIUM

A. Situational Analysis

Tritium contamination occurs in numerous waste waters, spent fuel storage basins, and groundwater throughout the DOE complex. Although the concentrations of tritium are often very low, further reduction of the tritium concentrations is very difficult and costly. Because tritium is an isotope of hydrogen, a major component of water, removal of tritium from the bulk water is an “isotope” separation and not a simpler chemical separation. Isotopes of individual elements are so similar that no extraction agent shows strong affinity for one isotope over the others. Because of the light weight of hydrogen isotopes, the differences in affinity (usually expressed in terms of a “separation factor”) are somewhat larger than one finds for isotopes of heavier elements. However, the difference in the affinities are always small. There are also theoretical reasons for not expecting to find large differences in the affinities, and this gives very little hope that a “magic” adsorbent will be found that can remove traces of tritium from dilute waste streams cheaply.

Since some tritium-containing streams (especially groundwaters) are extremely dilute, with concentrations only a small factor greater than the allowable concentrations, removal of only a modest fraction of the tritium would be very inexpensive. Unfortunately, with the small differences in the affinities among the isotopes, it is unlikely that any isotope separation process will be as economical as the sorption processes used to remove other dilute contaminants.

All separation operations must produce two streams: in this case, a dilute (purified) product and a concentrated product. Besides removing the tritium from the dilute stream, the process must also produce a product sufficiently concentrated that the waste volume will be acceptable. This means that a great many “stages” of separations will be needed to raise the concentration to sufficient levels so that cost-effective storage/disposal is possible. (The short half-life of tritium, approximately 12 years, makes long-term storage akin to disposal.)

As noted above, because of its relatively short half-life, tritium contamination is removed naturally with time. That means that successful storage can compete with separation, if regulators accept storage or containment as an option. Approximately one-half of the tritium decays every 12 years. One or two hundred years of storage or containment would eliminate essentially any tritium contamination problem, and much shorter times would be needed for some dilute problems. With the cost of large tritium removal equipment being so high and delays in treatment necessary, the effects of decay and storage can be important and probably should be utilized or at least taken into account in planning.

The objective of separations research for tritium is to develop cost-effective separation processes by 2030 to adequately provide treatment for contaminated wastewaters (in situ and in ex situ treatment facilities).

B. Current Research and Development

Despite the low differences in affinities (or separation factors), effective separation methods have been developed and deployed to produce heavy water (deuterium) and to remove and concentrate tritium from tritium production streams. A recent study was completed by the

Savannah River Site and the University of South Carolina [H. H. Fulbright et al. *Status and Practicality of Detritiation and Tritium Reduction Strategies for Environmental Remediation*, WSRC-TR-96-0075] that summarizes and compares the different tritium separation technologies that have been developed and used. The report's focus is on large-scale separation and the recovery of deuterium or tritium, and it analyzes specific examples of problems and plant sizes. The optimum process could obviously vary somewhat depending upon the size of the facility, the feed composition, and the desired product(s). The hydrogen sulfide–exchange process was identified as the most economical for the large-scale operations evaluated. Nevertheless, this is a very complex and expensive facility that involves toxic materials (hydrogen sulfide) as well as radioactivity (tritium). Deployment of very large facilities of this type would be costly for many large DOE problems.

Current DOE EM–funded research for tritium removal is limited to a project studying a kinetic isotopic effect that could provide an improved tritium separation approach (see Appendix A). This project explores the differences in exchange rates with an organic compound. The potential advantages of this technique include the avoidance of toxic materials (like hydrogen sulfide). Furthermore, the approach may prove to be attractive for smaller applications, even if it does not prove to be the most economical for large-scale facilities. Other organizations are also actively studying tritium separations. Research in Russia includes H_2S-H_2–based separations [*Sep. Sci. Technol*. 36, 1949 (2001)] and metal hydrate–based separations [*Sep. Sci. Technol*. 36, 2027 (2001)].

C. Research Requirements

The separation of tritium is considered to be an extremely difficult problem for the reasons described above. All research opportunities in this area are considered to be long-term ones, and each area of research is considered to be of equally high priority. Because of the cost of tritium removal operations, it will likely always be desirable to remove the tritium from the highest concentration possible, that is from the source of the contamination rather than after the tritium has been diluted with much large volumes of groundwaters or surface waters. Used in this way, tritium removal can become practical, even when it is not practical to treat large groundwater plumes. These research needs and opportunities are summarized in Table 8, and linkages between high-priority opportunities are shown in Figure 8 of the Executive Summary and are discussed in detail below:

1. Isolation. Isolation is expected to play an important role in tritium control. In some cases, isolation alone may be sufficient. Since tritium has a relatively short half-life of approximately 12 years, isolation of tritium for approximately 100 years will remove most of the hazard. In other cases, it may be desirable to isolate the tritium source but speed the cleanup by removing tritium from the isolated source. This could include cases where regulators will not approve isolation for 100 years or when there are practical problems with maintaining isolation for that long.

Because the chemistry of the hydrogen isotopes is very similar, one should not expect a simple material such as an in situ barrier, like those proposed for several other trace contaminants, to provide good tritium removal. However, there is no reason to think that substantial improvements over the current tritium removal techniques cannot be achieved. Although

Table 8. Research for Tritium
(H = High Priority, M = Medium Priority, L = Low Priority)
(NT = Near-Term, MT = Mid-Term, LT = Long-Term, C = Continuous)

Isolation	Chemical Separations	Rate Separations
Develop isolation/ containment systems that could be used to assist in tritium removal systems (H) (C)	Improve chemistry of tritium separation technologies to improve separation efficiencies (H) (C) Develop more-efficient packing materials and equipment to reduce equipment size and costs (H) (C) Develop processes with less-energy-intensive reflux processes for multistage separation systems (H) (C)	Adapt new rate-based methods, similar to those used in hydrogen isotope separations technology, for tritium removal (H) (C)

practical tritium removal systems may not be built to solve all tritium contamination problems, any substantial improvements should be able to extend the practical applications of tritium to more problems and improve performance wherever it is used.

2. Chemical Separations. The differences in chemical affinities between hydrogen isotopes may be relatively small compared with those in chemical separation systems, but different approaches give different results. Thus, there is room for improvement in the chemistry used in the separation step even if a breakthrough cannot be achieved on the scale of orders of magnitude. Fortunately, there are also additional ways to improve performance and reduce cost. The size of the equipment can also be reduced if the separations can be carried out in smaller and less costly equipment. Developments of more-compact (more-effective) packing materials in other processes could also enhance similar tritium separation approaches. Most of the costs of stage operations, such as those required for isotope separations, involve energy consumed in the "reflux" of internal streams. This reflux is necessary for such multistage operations, but its importance is better left explained in textbooks on separation methods. If a system is chosen that uses less energy in the reflux, the cost of the recycle is reduced. (For instance, electrolysis of water gives a relatively high separation of tritium from hydrogen in a single stage, compared with most other options. However, the amount of energy used and the cost of reflux are too high for electrolysis to be attractive.)

3. Rate Separations. Most isotope separation processes are based upon differences in chemical affinities; however, it is also possible to utilize differences in rate process for the different isotopes. Although the chemistry does not suggest that one should expect very large differences in the rated processes, this area has received less attention and should now be addressed. As mentioned above, one Environmental Management Science Program (EMSP) project is currently studying a kinetic isotopic effect that could provide an improved tritium separation approach.

Several new hydrogen isotope separation approaches have been suggested in recent years, but not all have resulted in published tests. Several new concepts may arise in the coming years, as this is still an area of active thought and research.

4. Applications Issues. The opportunities for new tritium separation technologies are also related to the way in which they are applied. Needs statements are not likely to specify details about how the tritium removal systems would be used, and this implies that a facility would be built to treat an effluent stream of a groundwater source and discharge the decontaminated product. (Although a specification on the degree to which the tritium would be concentrated in the "reject" stream for storage/disposal should probably be provided as well, that level of detail is not always given.) If regulations permit, tritium separation from contaminated bodies of water (basins, isolated plumes, wastewater tanks, etc.) can be combined with isolation/containment to make up the tritium removal system. If the system is allowed to continuously remove only a fraction of the tritium from such a waste source, the concentration of tritium could be lowered, perhaps somewhat more slowly, with a much smaller and less costly separation system.

D. Linkages

Chemical separation processes developed for tritium may also have cross-links to treatment processes developed for applications in which relatively low concentrations of a contaminant will be removed from aqueous solutions. These are discussed in the Dilute Aqueous Solutions and Concentrated Aqueous Solutions section of the report.

IX. SPECIAL/UNIQUE WASTES

A. Situational Analysis

The phrase "unique wastes" is an umbrella term covering three main types of mixed waste: (1) a sizable and increasing number of small-quantity, difficult-to-treat wastes; (2) mercury-bearing wastes that can not be incinerated; and (3) salt- and ash-bearing wastes. Because mixed waste was recognized as a special waste category long after waste collection and consolidation activities had begun, it encompasses a very broad range of contaminants, constituents, and matrices. As a consequence of the variety of streams inherent in the mixed waste category, there is a large and growing group of small-quantity wastes. This unique category is broad and includes water-reactive wastes, pyrophoric wastes, high-explosive and miscellaneous highly energetic wastes, wastes barred from available disposal facilities due to specific aspects of their radioactive nature, batteries, uranium chips, compressed gas cylinders, tritium-contaminated material, and nonincinerable organics. Some of these wastes possess very specific features that make them difficult to treat. Examples include contaminated classified shapes that cannot be easily handled for security reasons and wastes that are too radioactive to be treated with most other low-level waste and yet are not classed as HLW.

Often the major problem faced in dealing with special or unique wastes is the fact that the streams are small in size. Resources budgeted for the development of technologies to manage wastes tend to be directed toward large-volume waste types where the development of a single technology can have a large impact on inventory reduction. As a result, small streams tend to be overlooked in prioritization schemes. Since the EM complex is so large and RCRA and radioactive contaminants frequently occur together, the number of these small "orphan" waste streams will grow. In the case of mercury-bearing wastes (and similarly for tritium-containing wastes), public concerns and a tightening regulatory environment make the incineration option no longer feasible. In the case of salt- and ash-bearing wastes, the problem is the difficulty that these components pose in achieving a satisfactory waste form.

Unique wastes comprise about 10% of the total mixed waste inventory. In the absence of suitable treatments, the cost of disposal for these materials could be much higher than 10% of the cost of managing the entire DOE EM inventory, perhaps several-fold higher. The present strategy for unique waste is to move away from developing new technologies for these streams and instead to emphasize the implementation of existing, demonstrated technologies together with attempting to synergistically integrate multiple-site waste streams. Though this approach has merits, it faces vulnerabilities in that barriers to waste transportation between sites may make widespread integration excessively expensive. Differing site schedules may also make integration unattainable. These factors tend to weigh heavily in favor of technologies that are flexible and transportable between sites.

Separations can play a part in two main areas. First, it is likely that a significant portion of the waste streams will remain "orphaned" after existing technologies have been reevaluated in the light of the new strategy. The cost implications posed by these remaining streams give a strong impetus to examine other approaches such as innovative separations technologies. The second avenue for separations is to provide enabling technologies for treatment of integrated waste streams that allow existing treatments to perform effectively.

A final issue in analyzing the situation pertaining to unique waste is that regulatory developments may open up new possibilities for management of these wastes. For example, EPA is considering an innovative approach for the treatment of certain low-level mixed waste (LLMW). The new proposal is narrowly targeted to one facility in the pharmaceutical industry but has the potential to be more widely applied. In this rule making, EPA is proposing site-specific regulatory relief from RCRA so that small volumes of mixed waste may be treated on-site using thermal treatment, with the residues disposed of as low-level radioactive waste. In this specific pilot project, EPA is testing its belief that in certain scenarios such as small volumes of pharmaceutical R&D-generated LLMW being treated by a bench-scale high-temperature catalytic oxidation unit in an NRC-licensed laboratory, NRC regulatory oversight provides sufficient safeguards to ensure protection of human health and the environment without additional RCRA Subtitle C oversight. If the project is a success, EPA will move to adopt this site-specific exclusion as a nationwide generic exclusion. Certain of the unique wastes may fall directly into this category while others may be encompassed in the future if the approach is broadened to allow treatments other than catalytic oxidation. These possibilities reinforce a view long held among some that the value of separations to mixed waste treatment is to show that the RCRA and/or radioactive components can be effectively separated into streams that are more manageable under alternative regulatory classifications if such a revision is permitted.

B. Current Research and Development

Little research is being conducted on technologies for unique wastes. EM has five projects associated with mercury removal. There is also a project for measuring and modeling mixed wastes and a project on tri-contaminated wastes.

Two factors operate against these wastes receiving research funds: the priority received by the wastes within the DOE system and the fact that their small volume—coupled with the heterogeneity of the waste grouping—does not offer profit margins large enough to entice private industry. As mentioned above, the strategy for unique waste is to move away from developing new technologies for these streams and instead to emphasize implementation of existing, demonstrated technologies together with attempting to synergistically integrate multiple-site waste streams.

C. Research Requirements

The varied nature of these waste streams makes a planned approach very difficult. No single technology or group of technologies is likely to address all of the site needs. A true roadmap for this group is inappropriate and would, in any case, be extremely unwieldy. Moreover, the cost of managing these wastes could be out of proportion to their volume. The issue of unique wastes is raised here because separation technologies developed for some other purposes could find applications within this category.

D. Linkages

Many of the anticipated unique wastes and their potential treatment methods have not been identified and described, so the linkages are uncertain. One can anticipate some linkages to other waste problems, but there are likely to be fewer linkages than for the more common waste problems.

Appendix A. DOE Environmental Management Separations Projects for 2001

Project Title	TTP	DOE Program[a]	Dilute Aqueous Sol'ns	Concentrated Aqueous Sol'ns	High-Activity Solids	Soils & Sediments	Incinerable Solids	Non-incinerable Solids	Gases	Tritium	Special/ Unique Wastes
Deployment of Highly Selective Nuclide Removal System (NURES) and 3M Selective Membrane Cartridges (ASTD)	SR09DD61	D&DFA	X								
Optimal Plutonium Precipitation for Stabilization Feed Preparation	RL31NM11	NMFA	X								
Specialized Separation Utilizing 3M Membrane	FT06IP01	SCFA	X								
In situ Chemical Stabilization of Metals and Radionuclides Through Enhanced Anaerobic Reduction Precipitation	FT01AR01	AR	X								
Development of In situ Chelation/Reduction Process for Remediation of Subsurface Metals and Radionuclides	FT01AR01	AR	X								
In situ Stabilization of Subsurface Contaminants Using Microbial Polymers	FT01AR01	AR	X								
Use of Apatite for Chemical Stabilization of Subsurface Contaminants	FT01AR01	AR	X								
Mercury Removal from Mixed Matrices Using Polymer Filtration	AL10C321	ESP	X			X					X
Removal of Radioactive Cations and Anions from Polluted Water Using Ligand-Modified Colloid-Enhanced Ultrafiltration	60041	EMSP	X								
Synthesis of New Water-Soluble Metal-Binding Polymers: Combinatorial Chemistry Approach	54724	EMSP	X	X							
Contaminant-Organic Complexes, Their Structure and Energetics in Surface Decontamination Processes	64947	EMSP	X	X				X			
"Green" Biopolymers for Improved Decontamination of Metals from Surfaces: Sorptive Characterization and Coating Properties	64907	EMSP	X	X				X			
Actinide-Specific Interfacial Chemistry of Monolayer Coated Mesoporous Ceramics	65370	EMSP	X	X							
Complexants for Actinide Element Coordination and Immobilization	65378	EMSP	X	X							
Electroactive Materials for Anion Separation—Technetium from Nitrate	65409	EMSP	X	X							

Project Title	TTP	DOE Program[a]	Dilute Aqueous Sol'ns	Concen-trated Aqueous Sol'ns	High-Activity Solids	Soils & Sedi-ments	Inciner-able Solids	Non-incincer-able Solids	Gases	Tri-tium	Special/ Unique Wastes
New Metal Niobate and Silicotitanate Ion Exchangers: Development and Characterization	73748	EMSP	X	X							
Computational Design of Metal Ion Sequestering Agents	73759	EMSP	X	X							
Speciation, Mobility and Fate of Actinides in the Groundwater at the Hanford Site	70132	EMSP	X			X					
Fixations Mechanism and Desorption Rates of Sorbed Cs in HLW Contaminated Subsurface Sediments: Implications to Future Behavior and in-Ground Stability	73758	EMSP	X			X					
New Anion-Exchange Resins for Improved Separations of Nuclear Materials	54770	EMSP	X	X							
Rational Synthesis of Imprinted Organofunctional Sol-Gel Materials for Toxic Metal Separation	60096	EMSP	X								
Managing Tight-Binding Receptors for New Separation Technologies (?)	73850	EMSP	X								
Adsorption/Membrane Filtration as a Contaminant Concentration and Separation Process for Mixed Wastes and Tank Wastes	55146	EMSP	X	X							
Potential-Modulated Intercalation of Alkali Cations into Metal Hexacyanoferrate Coated Electrodes	60123	EMSP	X	X							
Supramolecular Chemistry of Selective Anion Recognition for Anions of Environmental Relevance	54864	EMSP	X	X							
Managing Tight-binding Receptors for New Separations Technologies	54791	EMSP	X								
Corrosion-Resistant Honeycomb Ceramic for Economical Membrane Separation of Individual Wastewater		SBIR	X								
Removal of Chlorinated VOCs for Groundwater and Other Wastewater Streams		SBIR	X								
Corrosion-Resistant Honeycomb Ceramic for Economical Membrane Separation of Individual Wastewater		SBIR	X								
Removal of Chlorinated VOCs for Groundwater and Other Wastewater Streams		SBIR	X								
Prevention of the Precipitation of Unwanted Solids during Canyon Dissolution	SR11NM12	NMFA		X							

Project Title	TTP	DOE Program[a]	Dilute Aqueous Sol'ns	Concentrated Aqueous Sol'ns	High-Activity Solids	Soils & Sediments	Incinerable Solids	Non-incinerable Solids	Gases	Tritium	Special/ Unique Wastes
Dissolution and Stabilization of Plutonium Using Thermally Unstable Complexants	CH21NM11	NMFA		X				X			
SRS Salt Processing Project (PNNL)	RL31WT21	TFA		X							
SRS Salt Processing Project (PNNL)	RL31WT32	TFA		X							
SRS Salt Processing Project (ORNL)	OR01WT21	TFA		X							
SRS Salt Processing Project (ORNL)	OR01WT22	TFA		X							
SRS Salt Processing Project (SRS)	SR01WT21	TFA		X							
SRS Salt Processing Project (ANL)	CH21WT21	TFA		X							
SRS Salt Processing Project (SNL)	AL21WT21	TFA		X							
Decon and Filter Leach Processes Waste Volume Reduction (INEEL)	ID70WT32	TFA		X							
Tank Waste Chemistry Pretreatment Studies (RL)	RL09WT32	TFA		X							
Tank Waste Chemistry Pretreatment Studies (CHG)	RL08WT41	TFA		X							
Tank Waste Chemistry Pretreatment Studies (PNNL)	RL36WT41	TFA		X							
Tank Waste Chemistry Pretreatment Studies (ORNL)	OR16WT41	TFA		X							
Tank Waste Chemistry Pretreatment Studies (SRS)	SR19WT31	TFA		X							
Tank Waste Chemistry Pretreatment Studies (Industry Programs)	FT02WT21	TFA		X							
Tank Waste Chemistry Pretreatment Studies (AEA)	HQ06PS11	TFA		X							
Cross-Flow Filtration	ID70WT32	TFA		X	X						
INEEL Integrated Radionuclide Separations Process (INEEL)	ID70WT32	ESP		X							
INEEL Integrated Radionuclide Separations Process (International Programs)	HQ06T222	ESP		X							
Removal of Chloride from Waste Solutions	TBD	ESP		X							
Solubility/Stability after Sludge Washing (MSU Pretreatment)	FT07IPP02	ESP		X							
Chemical Speciation of Strontium, Americium, and Curium in High Level Waste: Predictive Modeling of Phase Partitioning During Tank Processing	54621	EMSP		X	X						

Project Title	TTP	DOE Pro-gram[a]	Dilute Aqueous Sol'ns	Concen-trated Aqueous Sol'ns	High-Activity Solids	Soils & Sedi-ments	Incinerable Solids	Non-incincer-able Solids	Gases	Tri-tium	Special/ Unique Wastes
Reactivity of Peroxynitrite: Implications for Hanford Waste Management and Remediation	59982	EMSP		X	X						
Chemical Speciation of Inorganic Compounds under Hydrothermal Conditions	60050	EMSP		X							
Actinide-Aluminate Speciation in Alkaline Radioactive Waste	65318	EMSP		X	X						
Chemical Speciation of Strontium, Americium, and Curium in High Level Waste: Predictive Modeling of Phase Partitioning During Tank Processing	73749	EMSP		X	X						
Ion Recognition Approach to Volume Reduction of Alkaline Tank Waste by Separation and Recycle of Sodium Hydroxide and Sodium Nitrate	65339	EMSP		X							
Solution Effects on Cesium Complexation with Calixarene Crown Ethers from Liquid to Supercritical Fluids	65351	EMSP		X	X		X	X			
Developing a Fundamental Basis for the Characterization, Separation, and Disposal of Plutonium and Other Actinides in High Level Radioactive Waste: The Effect of Temperature and Electrolyte Concentrations on Actinide Speciation	65352	EMSP		X	X						
Next Generation Extractants for Cesium Separation from High-Level Waste: From Fundamental Concepts to Site Implementation	73803	EMSP		X							
Reactivity of Peroxynitrite: Implications for Hanford Waste Management and Remediation	73824	EMSP		X							
Supramolecular Chemistry of Selective Anion Recognition for Anions of Environmental Relevance	74019	EMSP		X							
Understanding the Chemistry of the Actinides in HLW Tank Systems	81962	EMSP		X	X						
Electroactive Materials for Anion Separation—Technetium from Nitrate	81912	EMSP		X							
Ion Recognition Approach to Volume Reduction of Alkaline Tank Waste by Separation of Sodium Salt	81935	EMSP		X							

Project Title	TTP	DOE Program[a]	Dilute Aqueous Sol'ns	Concentrated Aqueous Sol'ns	High-Activity Solids	Soils & Sediments	Incinerable Solids	Non-incinerable Solids	Gases	Tritium	Special/ Unique Wastes
Mechanisms and Kinetics of Organic Aging and Characterization of Intermediates in High-Level Waste	81883	EMSP		X	X						
Characterization of Actinides in Simulated Alkaline Tank Waste Sludges and Leach	81940	EMSP		X	X						
Precipitation and Deposition of Aluminum-Containing Phases in Tank Wastes	81887	EMSP		X	X						
Foaming and Antifoaming in Radioactive Waste Pretreatment and Immobilization	81867	EMSP		X	X						
A New Class of Solvents for TRU Dissolution and Separation: Ionic Liquids	81891	EMSP		X							
Fundamental Chemistry of the Universal Extractant (UNEX) for the Simultaneous Separation of Fission Products and Transuranics from High Level Waste Streams	81895	EMSP		X							
Novel Fission-Product Separation Based on Room-Temperature Ionic Liquid	81929	EMSP		X							
Technetium Chemistry in HLW: Role of Organic Complexants	81921	EMSP			X						
Physiochemical Processes Controlling the Source Term from Tank Residuals	81893	EMSP			X						
Speciation, Dissolution, and Redox Reactions of Chromium Relevant to Pretreatment and Separations of High-Level Tank Wastes	18896	EMSP			X						
Decontamination of HEU and Conversion of Classified Shapes	AL02New	NMFA			X			X			
Sludge Washing Pretreatment Studies (RL)	RL09WT32	TFA			X						
Sludge Washing Pretreatment Studies (ORNL)	OR16WT41	TFA			X						
Sludge Washing Pretreatment Studies (CHG)	RL08WT41	TFA			X						
Sludge Washing Pretreatment Studies (PNNL)	RL36WT41	TFA			X						
Sludge Washing Pretreatment Studies (SRS)	SR19WT31	TFA			X						
Baseline Dissolution Testing with Actual Idaho Calcine (AEA)	HQ06PS11	TFA			X						
Baseline Dissolution Testing with Actual Idaho Calcine (INEEL)	ID70WT32	TFA			X						
Removal of Key Non-Radioactive Elements from Radioactive Tank Sludge	RL01C321	ESP			X						

Project Title	TTP	DOE Pro-gram[a]	Dilute Aqueous Sol'ns	Concen-trated Aqueous Sol'ns	High-Activity Solids	Soils & Sedi-ments	Incinerable Solids	Non-incincer-able Solids	Gases	Tri-tium	Special/ Unique Wastes
Selective Chemical Dissolution of Tank Heels to Improve Retrieval (ANL)	AL01C311	ESP			X						
Selective Chemical Dissolution of Tank Heels to Improve Retrieval (SRS)	SR01C321	ESP			X						
Sludge Washing and Dissolution (Hanford Sludge)	OR01C322	ESP			X						
Sludge Washing and Dissolution (SRS Sludge)	OR01C321	ESP			X						
Leaching and Treatment of Technetium for Tank Closure	RL00C321	ESP			X						
Physical, Chemical and Structural Evolution of Zeolite-Containing Waste Forms Produced From Metakaolinite and Calcined HLW	65366	EMSP			X						
Dynamic Effects of Tank Waste Aging on Radionuclide-Complexant Interactions	59993	EMSP			X						
New Silicotitanate Waste Forms: Development and Characterization	60345	EMSP			X						
Speciation, Dissolution, and Redox Reactions of Chromium Relevant to Pretreatment and Separation of High-Level Tank Wastes	65368	EMSP			X						
Precipitation and Deposition of Aluminum-Containing Phases in Tank Wastes	65411	EMSP			X						
Fuel Pool Sludge Treatment (FY 2002 Start)	ID02NEW	D&DFA				X					
Demo/Deploy of Thermal Desorption	OH01MW21	TMFA				X					
UNDEERC Technology Assessment—Task—Remediation of Organically Contaminated Soil Using Hot/Liquid Subcritical Water	FT06IP01	TMFA				X					
Alternative Field Methods to Treat Mercury in Soil	FT06IP01	Ind				X					X
Effective Remediation Technologies in Difficult Vadose and Saturated Zone Conditions	FT06IP01	Ind				X					
Technical Evaluation of Remediation Technologies for Pu-Contaminated Soils at NTS	FT06IP01	Ind				X					
Collaboration: Interfacial Soil Chemistry of Radionuclides in the Unsaturated Zone	70126	EMSP				X					

Project Title	TTP	DOE Program[a]	Dilute Aqueous Sol'ns	Concentrated Aqueous Sol'ns	High-Activity Solids	Soils & Sediments	Incinerable Solids	Non-incinerable Solids	Gases	Tritium	Special/ Unique Wastes
Immobilization of Radionuclides in the Hanford Vadose Zone by Incorporation in Solid Phases	70081	EMSP				X					
Radiation Effects on Sorption and Mobilization of Radionuclides during Transport through the Geosphere	73762	EMSP				X					
Decontamination/Destruction Technology Demonstration for Organics in Transuranic Waste	TBD	TMFA					X	X			
Mercury Removal from Metal and Porous Surfaces (FY 2002 Start)	OR02NEW	D&DFA						X			X
Removal and Treatment of Mobile Contaminants (FY 2002 Start)	OR02NEW	D&DFA						X			
Decontamination of Uranium Parts by Laser Ablation (new title)	AL11NM11	NMFA						X			
Removal of Plutonium Contamination	SF21NM13	NMFA						X			
Micelle Formation and Surface Interactions in Supercritical CO_2—Fundamental Studies for the Extraction of Actinides from Contaminated Surfaces	64865	EMSP						X			
Improved Decontamination: Interfacial, Transport, and Chemical Properties of Aqueous Surfactant Cleaners	64912	EMSP						X			
Supercritical Carbon Dioxide–Soluble Ligands for Extracting Actinide Metal Ions from Porous Solids	64965	EMSP						X			
Radiolytic and Thermal Process Relevant to Dry Storage of Spent Nuclear Fuels	60392	EMSP						X			
Thermodynamics of the Volatilization of Actinide Metals in the High-Temperature Treatment of Radioactive Wastes	60319	EMSP						X			
Characterization and Safety (SRS)	SR18WT21	TFA							X		
Immobilization (SRS)	SR16WT31	TFA							X		
Immobilization (INEEL)	ID77WT31	TFA							X		
Immobilization (RL)	RL09WT31	TFA							X		
Hydrogen Gas Getters for TRU Waste	AL16MW43	TMFA							X		
Polymer Getters for TRUPACT II	AL21MW11	TMFA							X		
Pressure Reduction Technology for TRUPACT II	SR19MW45	TMFA							X		
Improved Hydrogen Gas Getters for TRU Wastes	ID00MW14	TMFA							X		
Electrically Driven Technologies for Radioactive Aerosol Abatement	65328	EMSP							X		

Project Title	TTP	DOE Program[a]	Dilute Aqueous Sol'ns	Concentrated Aqueous Sol'ns	High-Activity Solids	Soils & Sediments	Incinerable Solids	Non-incinerable Solids	Gases	Tritium	Special/ Unique Wastes
Utilization of Kinetic Isotope Effect for the Concentration of Tritium	ID02NEW	TMFA								X	
TRU Waste–Contaminated Oil Solidification (NoChar) - ASTD	OH21MW21	TMFA									X
Mercury Removal from DOE Waste Organics	OR00C321	ESP									X
PNNL Support for Removal of Mercury from DOE Organic Liquids	RL30C321	ESP									X
Measurements and Models for Hazardous Chemical and Mixed Wastes	60155	EMSP									X

[a]DOE Programs Funding Environmental Management Separations Research in 2001

AR = Applied Research Program
D&DFA = Deactivation and Decommissioning Focus Area
EMSP - Environmental Management Science Program
ESP = Efficient Separations and Processing Crosscutting Program
Ind = Industry Program
NMFA = Nuclear Materials Focus Area
SBIR = Small Business Innovative Research Program (DOE Office of Science)
SCFA = Subsurface Contaminants Focus Area
TFA = Tanks Focus Area
TMFA = Transuranic and Mixed Waste Focus Area

Appendix B. Separations Technology Roadmapping Workshop Attendees

Last Name	First Name	Organization
Andres	Tina	University of North Dakota
Bonner	Bill	Pacific Northwest National Laboratory
Browne	Alan	Energetics
Charoglu	Emily	EnviroIssues
Corey	Jack	Westinghouse Savannah River Corporation
Dressen	Louise	EnviroIssues
DuTeau	Jeff	SAIC
Fink	Samuel D.	Westinghouse Savannah River Corporation
Harness	Jerry	Department of Energy
Hiller	Deb	EnviroIssues
Hobbs	David	Westinghouse Savannah River Corporation
Imrich	Janice	EnviroIssues
Janecky	David	Los Alamos National Laboratory
Josephson	Gary	Pacific Northwest National Laboratory
Kauffman	Jennifer	EnviroIssues
Kelsh	Dennis	Gonzaga University
Kirk	Paula	Bechtel Jacobs Corporation
Lumetta	Gregg	Pacific Northwest National Laboratory
Miles	Maxcine	Department of Energy
McGinnis	Phil	Oak Ridge National Laboratory
Moyer	Bruce	Oak Ridge National Laboratory
Murphy	James	Idaho National Engineering and Environmental Laboratory
Murphy	John	Department of Energy
Robinson	Sharon	Oak Ridge National Laboratory
Rose	Rob	Florida International University
Tasker	Ian	Concurrent Technologies Corporation
Tavlarides	Larry	Syracuse University
Tedder	Dan	Georgia Technological University
Thompson	Major	Westinghouse Savannah River Corporation
Todd	Terry A.	Idaho National Engineering and Environmental Laboratory
Voos	Gerard	Waste Policy Institute
Washer	Phil	Department of Energy
Watson	Jack	Oak Ridge National Laboratory
Wilburn	Dianne	Los Alamos National Laboratory