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# Affordable Cleanup? Opportunities for Cost Reduction in the Decontamination and Decommissioning of the Nation's Uranium Enrichment Facilities

Committee on Decontamination and Decommissioning of Uranium Enrichment Facilities, National Research Council

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# Affordable Cleanup?

## Opportunities for cost reduction in the decontamination and decommissioning of the nation's uranium enrichment facilities

Committee on Decontamination
and Decommissioning
of Uranium Enrichment Facilities
Board on Energy and Environmental Systems
Commission on Engineering and Technical Systems
National Research Council

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# Preface

This report was prepared in response to a request by the U.S. Department of Energy (DOE) following on the Energy Policy Act of 1992, which calls for the National Academy of Sciences to conduct a study and provide recommendations for reducing costs associated with the decontamination and decommissioning (D&D) of the nation's uranium enrichment facilities located at Oak Ridge, Tennessee; Paducah, Kentucky; and Portsmouth, Ohio. The committee was also asked to assess options for the disposition of the large inventory of depleted uranium hexafluoride that is stored in steel cylinders at these three sites (see Appendix A for the committee's full statement of task).

The D&D of these large facilities will occur following the closure of the plants. The Oak Ridge plant has already been shut down; the Paducah and Portsmouth plants are being leased by the United States Enrichment Corporation from the federal government to produce enriched uranium for the electric utility sector. Cost estimates have been made for the D&D of the three plants, and DOE is currently engaged in planning for the effort. This large effort, with a projected cost of billions of dollars, will entail cleanup of radioactive and hazardous materials within a complex regulatory environment and will face numerous uncertainties before it is complete.

Given the multifaceted nature of the subject, the committee at its first meeting in February 1994, divided itself into three panels: the Cost Analysis Panel, which analyzed existing cost estimates and the costs of previous D&D experiences; the Decision and Process Analysis Panel, which focused on such issues as risk, end states of the sites, stakeholder involvement, and the management approach; and, finally, the Technology Panel, which considered the host of technologies needed for D&D (see Appendix B for more on the committee's panel structure). In addition to participating in full committee meetings, the panels met separately through January 1995, producing analyses that were used by the committee in its report (see Appendix C for a description of all the committee and panel meetings and activities).

The committee was large, with widely varying backgrounds and expertise (see Appendix D for biographies), yet the members worked effectively and harmoniously to find ways to substantially reduce the cost of the D&D safely and securely. I express my appreciation to the committee members for their time, dedication, and above all, frank and professional discussion. This group of highly able people devoted themselves to an important national problem and worked together to achieve an objective. It was a privilege to work with them.

The interdisciplinary nature of the study required a cooperative effort by several boards at the National Research Council (NRC). The Board on Energy and Environmental Systems (BEES), Commission on Engineering and Technical Systems, led the effort with staff in support of the committee as follows: Dev Mani, Director, BEES; James Zucchetto, Study Director; Jill Wilson, who worked with the Technology Panel and on the problem of options for disposition of uranium hexafluoride; and Tracy Wilson, who worked with the Decision and Process Analysis Panel. Susanna Clarendon, Administrative and Project Assistant, provided invaluable assistance in the logistical arrangements for the meetings and site visits and in preparing the many drafts of the committee's report. The BEES staff worked with the committee throughout the study effort, including the completion of the committee's report. NRC staff Douglas Raber, Director, Chemical Sciences and Technology Board (BCST), Commission on Physical Sciences, Mathematics, and Applications, and Scott Weidman, BCST, with the assistance of Maria Jones, Senior Project Assistant, worked with the Technology Panel from February 1994 to January 1995; and NRC staff K. T. (Karyanil) Thomas, Board on Radioactive Waste Management, Commission on Geosciences, Environment and Resources, with the assistance of Verna Bowen, Administrative Assistant, provided support to the Cost Analysis Panel from March 1994 to January 1995. My compliments to the NRC cooperative staff effort in this study.

I also appreciate contributions by Roger Shaw, GPU Nuclear Corporation, who worked with committee member Philip R. Clark, Sr., on the committee's behalf, and Keith Compton, graduate student at Clemson University, who worked with committee member Robert Fjeld and other committee members in collecting information and addressing selected tasks.

I wish to express my sincere thanks to the many people at DOE/EM-40, the Oak Ridge Operations Office, Lockheed Martin Energy Systems (formerly Martin Marietta Energy Systems), and Lockheed Martin Utility Systems who arranged the informative visits to the three plant sites. I would also like to thank the numerous people from government, the private sector, universities, local groups at the sites, the Oil, Chemical and Atomic Workers International Union, and others for the time they contributed to presentations and discussions at the committee meetings, as well as at the committee's June 1994 workshop. These were all important inputs to the committee's work.

DALE F. STEIN, *chair*

Committee on Decontamination and Decommissioning of Uranium Enrichment Facilities

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# Executive Summary

The Energy Policy Act of 1992 (EPACT) called on the National Academy of Sciences to conduct a study and provide recommendations for reducing costs associated with the decontamination and decommissioning (D&D) of the nation's gaseous diffusion uranium enrichment facilities located at Oak Ridge, Tennessee; Paducah, Kentucky; and Portsmouth, Ohio. Following on this act and a request from the U.S. Department of Energy (DOE), the National Research Council (principal operating arm of the National Academy of Sciences) established the Committee on Decontamination and Decommissioning of Uranium Enrichment Facilities in November 1993. Beyond recommending general ways to reduce D&D costs, the committee was also charged with assessing options for the disposition of the large inventory of depleted uranium hexafluoride ($DUF_6$) stored at the three sites. The committee was not asked to make a specific cost estimate for the D&D of the three gaseous diffusion plants (GDPs).

The committee determined the following:

- D&D of the GDPs is essentially a large deconstruction and demolition project that can effectively be undertaken in the near term.
- Based on the experience with other D&D projects, previously estimated costs to carry out the D&D of the three GDPs are high, and there are opportunities for major cost reductions.
- Proven technologies are available for cost-effective D&D of the GDPs. However, selection of the most effective process for some activities will benefit from a few focused demonstration projects (or programs). A large research and development program is not needed.
- Risks to public health and safety from the currently nonoperating GDP at Oak Ridge are small and do not require urgent action; the situation will be the same for the other two GDPs once they cease operations. However, until the D&D is complete, preventing the release or spread of the hazardous and radioactive materials inside the GDP buildings requires significant expenditures for surveillance, maintenance, and monitoring, and the risks will increase with time.
- D&D of the GDPs is a formidable task, but it can be completed successfully if able leaders on site are given sufficient freedom and authority. This will require

- some changes in current management practices applied to D&D and definition and implementation of a coordinated set of regulatory requirements.
- The use of an incremental, prioritized cost- and risk-reduction approach for the D&D program would permit D&D to begin soon, even though major uncertainties hamper planning and the complete D&D of the GDPs. For example, given the uncertainties and assumptions about the end states for the sites, a plan can be developed that entails a progressive D&D of the facilities in a stepwise fashion based on analysis of costs, risks, and social values. The most likely end states should be used in the first planning effort with the plan updated as the uncertainties become resolved and end states change.
- Consistent with the prioritized cost- and risk-reduction process, the $DUF_6$ should be converted to a more stable chemical form for long-term storage.
- The scope of the committee charter was D&D of the facilities but did not include environmental restoration of the property under and around the buildings. However, the committee believes that the cleanup of the sites requires integrating the D&D of buildings and equipment, environmental restoration (such as for soil and groundwater contamination), and management of $DUF_6$. The committee considered this integration in its deliberations and in this report.

## THE GDPS

The Oak Ridge GDP is a closed facility: some parts of the plant were closed in 1964; the remainder of the plant ceased operations in 1985, and permanent closure occurred in 1987. The Paducah and Portsmouth GDPs are operating plants, currently leased by the United States Enrichment Corporation (USEC) from DOE for the production of enriched uranium for the electric utility industry.

D&D requires the removal of radioactive and hazardous materials from buildings and equipment. The GDPs are complexes of large buildings, with hundreds of acres of floor area and thousands of large pieces of equipment. In addition to the process buildings that contain the enrichment cascades, there are auxiliary buildings, electrical switchyards, and connecting piping and electrical systems. The Oak Ridge and Portsmouth facilities were once used to produce highly enriched uranium (greater than 20 percent enrichment) for military purposes. The Portsmouth highly enriched uranium section was shut down in 1992.

Upon shutdown of an operating GDP, a significant amount of uranium deposits in the equipment can be removed by treatment with gaseous chlorine trifluoride ($ClF_3$), which is heated by the compressors. The highly enriched uranium section of the Portsmouth plant has undergone such treatment to remove a significant part of the highly enriched uranium deposits representing a criticality concern. The USEC is obligated to remove uranium deposits representing a criticality risk before returning the facilities to DOE. It will likely subject the low enriched uranium sections of the Paducah and Portsmouth plants to such gaseous treatment to remove deposits representing a nuclear criticality risk before returning the facilities to DOE.[1] Quantities of highly enriched uranium remain in some of the process buildings at the Oak Ridge plant, the result of a cessation of operations without the benefit of a systematic removal of uranium deposits, such as with gaseous treatment. Because Oak Ridge is not a functioning plant, heated gaseous $ClF_3$ cannot be passed, post facto, through the process equipment for uranium deposit removal. A deposit removal program is under way (using mechanical means, avoiding contact with water; and testing gaseous $ClF_3$ at low [room] temperatures) to remove deposits from the Oak Ridge equipment that represent a nuclear criticality risk. Decontamination and removal of enriched uranium in the cascade equipment must occur in a carefully controlled manner to avoid nuclear criticality accidents and to conform to safeguards and security requirements for special nuclear materials. Preventing criticality is a distinguishing feature of the D&D of the GDPs, especially for the Oak Ridge site. Preventing criticality can be expensive, and a cost-effective D&D requires a clear understanding of where criticality will be a major concern, where it will be a relatively minor concern and easily handled, and where it is of no concern. In addition, large quantities of hazardous substances such as asbestos and polychlorinated biphenyls (PCBs) will have to be dealt with safely at all three sites.

Currently, there is no quantitative analysis of risk for a nonoperating plant, such as the Oak Ridge GDP. Although uranium is radioactive, its primary risk to human health is its chemical toxicity upon ingestion or inhalation. The uranium in the buildings is contained, for the most part, inside process equipment and does not present a hazard to human health. Other hazardous substances, such as asbestos and PCBs, are also contained within the buildings. Because potential exposure of the public to contaminants near a nonoperating plant is low to nonexistent, the committee believes that the near-term risk to the public from closed facilities is low. Although the risk is low, it will increase with time if the buildings and process equipment are allowed to deteriorate; for example, water could leak into the buildings and carry contaminants into the surrounding environment or, at the Oak Ridge GDP, possibly initiate small nuclear criticality events. The current program to remove uranium deposits at the Oak Ridge site is directed toward eliminating such a possibility; namely, removing the deposits that have the potential for a criticality incident.

The vast bulk of the uranium at the GDP sites is in the form of $DUF_6$ stored outdoors in steel cylinders. If $DUF_6$ were to escape into the atmosphere, it would react with moisture in the air to form hydrogen fluoride (HF), a very toxic substance. Breaches that have occurred in some storage cylinders have been self-sealing, not allowing much $DUF_6$ to escape. Although the committee has not conducted risk assessments or atmospheric dispersion modeling, it believes that if leaks are small, HF is unlikely to reach site boundaries in dangerous concentrations. For large releases, concentrations at the site boundaries would depend on atmospheric conditions. It seems to the committee that a major release of $DUF_6$ from the large inventory contained in the steel cylinders in the storage yards is a very low probability event, provided that the cylinders are adequately maintained and monitored.

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[1] In a nuclear criticality event, an assemblage of enriched uranium results in a short-duration (millisecond) burst of heat and radiation. Such an event is usually self-limiting because the energy release disrupts the geometric configuration of the enriched material that caused the criticality. Nonetheless, a criticality event is better avoided. The addition of water, a neutron moderator, increases the possibility of criticality occurring. For most of the deposits in the plants, uranium deposits do not represent a criticality risk in the absence of water.

The committee believes that the primary risks will probably be to on-site workers performing surveillance, maintenance, and D&D activities. Potential risks will arise not only from possible chemical or radioactive contamination, but also from industrial accidents. Minimizing such risks will require strict adherence to applicable worker health and safety protection rules. To minimize risks during D&D operations, procedures will need to be designed to meet standards required for preventing criticality.

## D&D COST ESTIMATES

Two D&D cost estimates were commissioned by DOE in 1991 to support the transition of the management of the enrichment facilities from the federal government to the USEC. Ebasco Environmental (Ebasco) assumed that the facilities would be cleaned of radioactive and hazardous materials and the sites restored to a condition such that a future occupant would not be exposed to harmful levels of substances. An initial estimate by Ebasco amounted to about $46 billion, but a successive set of reevaluations resulted in a final D&D cost estimate of $16.1 billion. The decrease in estimated cost from $46 billion to $16.1 billion reflected changes in scope and assumptions including reductions in overhead rates, fewer newly constructed facilities, greatly reduced program integration costs, and reductions in waste management costs. Disposal of the low-level radioactive waste generated was assumed to be at the sites. TLG Engineering (TLG) made an estimate for D&D of $13.9 billion, using different assumptions. For example, TLG assumed that the major cascade components would be removed, sealed, and transported to the Nevada Test Site for low-level radioactive waste disposal without prior decontamination. The committee believes that insufficient time was spent on the development of these cost estimates to conduct a thorough evaluation of alternative D&D technologies and waste disposal options or to optimize D&D operation sequence and schedule.

The DOE's D&D program is incorporating the Ebasco $16.1 billion estimate in its *D&D Program Life Cycle Baseline Summary*. Both operating plants are assumed to close by 2005. The Ebasco estimate assumed a sequential cleanup—Oak Ridge, followed by Paducah, and then Portsmouth—extending over three decades to the year 2030.

A 1991 Martin Marietta Energy Systems (MMES) study estimated that converting the $DUF_6$ into uranium oxide ($U_3O_8$) would cost between $1.3 billion and $4 billion (in 1992 dollars). These costs are in addition to the Ebasco and TLG cost estimates for the D&D of enrichment buildings, equipment, and materials.

## THE UNCERTAIN CONTEXT

A number of uncertainties make D&D planning, cost estimation, and execution difficult. These are discussed briefly below.

### Final State of the Sites

Although the scope of the study was limited to the D&D of the buildings and equipment, D&D must be considered within the context of the total site. The existing D&D cost estimates assumed that the equipment and radioactive and hazardous materials would be removed from the buildings, which could subsequently be reused. Even if reuse of the buildings is not a desirable alternative, removal of the equipment and buildings may be the preferred approach, since the very long period of radioactive decay of uranium, as well as the large quantities of stable hazardous materials, makes entombment in place an unattractive alternative. However, a combination of end states could exist at each site: some buildings might be reused, some demolished, and some undergo continued surveillance and maintenance. End states should be determined with stakeholder involvement.

### Disposal of Waste

The D&D of the facilities will generate low-level radioactive, mixed, and hazardous wastes. For low-level radioactive wastes rapidly rising disposal costs, closure of disposal sites, and potential public opposition to transport and licensing of new disposal sites make such waste management, siting, and transport uncertain and increasingly expensive. There are regulatory uncertainties about mixed wastes and, to a lesser degree, also about hazardous wastes.

### Criteria for Release of Decontaminated Materials

Significant economic benefits may be realized if the large quantities of valuable metals in the plants can be decontaminated and reused. Surface-contaminated metals could be cleaned to whatever surface release criteria are established. Much of the nickel is in the diffusion barriers,[2] for which it would be impractical to determine compliance with surface release criteria. Evaluation of such materials for release may be achieved with volumetric contamination standards, which do not exist at present in the United States. The U.S. Environmental Protection Agency and the U.S. Nuclear Regulatory Commission have begun preliminary work on criteria for release of radioactively contaminated materials. These criteria, which are uncertain at this time, will affect D&D costs. The availability of such standards is necessary for any recycling program.

### The D&D Fund and Budgetary Uncertainties

The EPACT established a D&D Fund that would accumulate a total of $7.2 billion dollars over 15 years. However, the D&D Fund is being used for other than D&D activities. For example, in fiscal years 1993 and 1994, $165 million from this fund was spent on remedial actions, such as soil and groundwater cleanup. If the current profile of spending from the fund continues, there may not be sufficient funds to meet future GDP D&D needs. In addition, the federal government did not contribute as much as the 1992 act prescribed, and a recent court action makes the expected contributions from the electric utility industry uncertain.

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[2] The diffusion barriers, or membranes, are contained in the diffuser units in the cascade and accomplish the separation of $^{235}UF_6$ by diffusion. Thousands of diffuser units are required to achieve significant separation (see Chapter 2).

### Sequence of Plant Cleanup

The competitive economics of the U.S. enrichment plants in the world market for enriched uranium and the total demand for enrichment services are uncertain but could lead to early closure of either the Paducah or Portsmouth plant. If so, it might be preferable for a recently closed plant to undergo D&D first rather than, as currently planned, starting with the Oak Ridge plant. The sequence of plant cleanup should be reviewed for its cost implications.

### Management of $DUF_6$

It is uncertain what the plan will be for the management and funding for possible disposition of the $DUF_6$. Possible options include refurbishment or replacement of the deteriorated cylinders with subsequent continued surveillance and maintenance; conversion of $DUF_6$ to a useful product; or conversion of the $DUF_6$ to the more stable oxide form for storage on site or at another location or for disposal. Each option has different implications for cost and future end states of the sites and can affect resources available for D&D.

## RECOMMENDATIONS

The following sections summarize the committee's principal recommendations.

### Previous D&D Experience

The committee reviewed the Ebasco and TLG cost estimates, other cost analyses of the D&D of the GDPs, and experience from the D&D of nuclear power reactors, such as the Shippingport Atomic Power Station. It also had the benefit of actual reported data from the D&D of the British Nuclear Fuels Ltd. (BNFL) Capenhurst GDP in the United Kingdom, which was smaller but of design similar to that of the U.S. plants.

The cost of the Capenhurst D&D effort was about $160 million (in 1994 dollars). The operating plant, before completely ceasing of operations, was treated with gaseous $ClF_3$ to remove significant amounts of the uranium deposited on the surface of the equipment in the plant cascades. The Capenhurst equipment was then removed, cut up into pieces, and dry mechanical removal of uranium was used to minimize criticality concerns. The metal pieces were then decontaminated using a series of aqueous (chemical) decontamination baths. British surface-release standards were achieved for most of the metal, allowing recycling to the commercial market. Concrete was surface decontaminated, and the clean material was used for road fill. Approximately 99 percent of the material in the plant, excluding the diffusion barrier material, had been recycled as of early 1995. Experience with melt refining in 1995 gives BNFL optimism that they can effectively decontaminate parts that are otherwise difficult to decontaminate. The Capenhurst D&D experience, as well as other D&D efforts, demonstrates that technology exists to accomplish the D&D of the GDPs in a cost-effective manner.

Although the Capenhurst plant was much smaller than the U.S. GDPs and used some different materials of construction, these differences are not sufficient to account for the hundredfold difference between the actual D&D cost of the Capenhurst facility and the estimates for the U.S. GDPs. The review of previous D&D experiences and of the cost estimates leads the committee to believe that there are significant opportunities to reduce the costs for the D&D of the GDPs. While the potential cost savings are uncertain, they could exceed 50 percent of the current Ebasco estimate of $16.1 billion. Most of the cost reduction opportunities are not based on advances in technology but could come about from taking a different technical and management approach to the D&D than was assumed in the cost estimates.

> **Recommendation.** The committee recommends that the technical and management approaches used successfully for the D&D of the Capenhurst gaseous diffusion plant and for recently completed D&D projects with U.S. nuclear power reactors be carefully considered by DOE to reduce costs for D&D of U.S. GDPs.

Major areas of potential cost reduction are identified below (see Chapter 6 for other detailed examples and approaches).

### Contracting and Management

Large reductions in D&D project cost are unlikely to be achieved under the currently proposed project management approach using multiple prime contractors. Experience with other DOE projects demonstrates conclusively that this concept results in much higher costs than those of comparable projects managed by other government agencies and the private sector. DOE has traditionally managed its sites and the projects on its sites using a management and operations contractor, an approach assumed in the Ebasco cost estimate. This management approach uses multiple layers of management and results in a high ratio of the costs of management and professional services to the costs of actual D&D.

A more cost-effective approach would be a management structure employing a single prime contractor, as was done for the Shippingport D&D, who would assume total responsibility and accountability for all aspects of the D&D of the GDPs. This decommissioning operations contractor would be selected through an open, competitive bidding process based on demonstrated experience in successful management of D&D projects of comparable complexity. Improvements in the cost-effectiveness of projects could be achieved by incorporating financial incentives in the prime contract and all subcontracts. As part of the process of reducing costs, every aspect of the D&D effort needs to be examined closely to identify the most cost-effective alternatives and to eliminate redundant and excessive management oversight, while complying with health, safety, and environmental protection requirements.

> **Recommendation.** Once adequate planning is in place to permit work to proceed, the committee recommends that a single contractor for carrying out D&D operations be selected through open competition and assigned total responsibility and accountability for all aspects of the assigned work.

### Need for New Facilities

The Ebasco and TLG cost estimates assume the construction of two, new generalized multi-purpose facilities: a high-assay decontamination facility for equipment contaminated with highly enriched uranium; and a low-assay decontamination facility for equipment contaminated with low-enriched uranium. This plan is quite different from the D&D experience at Capenhurst, where existing buildings were used to house a single, simple decontamination facility and limited-purpose shops were used to handle highly enriched uranium. The variety of technologies and capabilities and the large size of these decontamination facilities led to very high estimated capital and operating costs. The estimated direct capital and operating costs of the postulated low- and high-assay decontamination facilities, along with the certification facilities, is close to $3.5 billion.

> **Recommendation.** The committee recommends that the high-assay decontamination facility be eliminated and the low-assay decontamination facility be simplified to focus primarily on aqueous decontamination and be housed in existing buildings.

The cost estimates also assumed construction of a new administration building at the Oak Ridge GDP site for several thousand people, the large staff resulting from the assumed management and contracting approach. Such construction is not warranted, especially if the committee's recommended management and contracting approaches are implemented, which should reduce the size of the management and professional staff to levels that can adequately be housed in existing administrative buildings.

> **Recommendation.** The committee recommends that existing facilities be used to house the management and professional D&D staff rather than constructing a new administration building.

## Waste Management

Management of hazardous, radioactive, and mixed wastes presents significant opportunities for cost reduction. The quantity of waste from D&D will be substantial and its disposal expensive. This quantity could be reduced by reusing decontaminated materials. The value of decontaminating materials for reuse will be strongly affected by the cost of decontamination, the market value of the material, and the savings from reducing the amount of waste requiring disposal. The uncertainties associated with low-level radioactive and mixed waste disposal and the potential large cost favor a strategy of waste minimization. Waste minimization strategies should incorporate several general rules:

- Materials should be cleaned and reused, if economically feasible.
- Generation of mixed waste, which contain both hazardous and radioactive wastes, should be avoided, because its processing and disposal entails a costly and complex regulatory regime.
- Approaches, such as reuse, should be taken that minimize the creation of secondary waste streams, such as contaminated water from cleaning operations.

The committee is also concerned about the practice of temporarily storing radioactive, hazardous, and mixed wastes from other activities on the Oak Ridge Reservation within the GDP process buildings. This will complicate and could delay D&D efforts and will engender costs during D&D that should not be ascribed to the D&D program.

> **Recommendation.** The committee recommends that an integrated, optimized waste management plan be developed that encompasses material reuse, recycling, packaging, transport, and waste disposal. Consistent with cost reduction and public health and environmental protection, materials should be cleaned to free-release standards and released to the commercial sector for recycling. Material that cannot be cleaned to free-release standards should be considered for recycling within the DOE or Department of Defense complexes in applications where slightly contaminated materials are acceptable, such as for shield blocks or waste containers.

## Regulatory Coordination

There are numerous laws, regulations, and regulatory bodies at federal, state, and local levels, that will affect D&D. The large number of regulators with jurisdiction over the enrichment plants and their decontamination, and the large number of applicable laws and regulations, virtually ensure an overlapping and conflicting regulatory regime. This very complex regulatory environment can result in costly and labor-intensive site practices and may be counterproductive to protecting public health and safety. The regulatory environment could also result in delays, extending annual surveillance and maintenance expenditures.

Guidelines for decommissioning have been published by the Nuclear Regulatory Commission and by DOE. Cooperative efforts are under way by DOE, the Environmental Protection Agency, and the Nuclear Regulatory Commission to develop release standards based on current radiation protection concepts. The draft guidelines include a proposed annual dose equivalent of 15 mrem/yr, based on generic exposure scenarios, for the release of sites and materials. The agencies recommend that each exposure scenario be evaluated for a specific site.

The committee believes that regulatory coordination should proceed expeditiously; avoiding conflicting, redundant, or unnecessary regulations is essential to reduce costs and streamline site practices. DOE should capitalize upon recent congressional interest in regulatory coordination, particularly in the area of radiation standards.

> **Recommendation.** The committee recommends that DOE seek coordination of all regulatory aspects of D&D with the appropriate state and federal agencies early in planning to provide consistency during D&D planning and execution.

## Coordinated Planning

Coordinated planning—at the DOE headquarters level, across the complex of the three GDPs, and at each site—will be required to ensure that D&D is integrated effectively with other operating or cleanup activities at the sites and that resources, including disbursements from the D&D Fund, are used effectively. DOE-level planning would outline decisions on D&D financing, on integration of D&D with other DOE programs, and on the broad contracting, regulatory, and stakeholder involvement approaches for D&D.

A complex-level master plan would coordinate such decisions as the sequence of plant cleanup, the priority actions to be taken, allocation of funds among the sites, and cleanup strategies, including approaches to waste management and recycling. Setting priorities would be based on analysis of risks, costs, and social values.

Site-specific plans are also needed to coordinate D&D, environmental remediation efforts, and management of the $DUF_6$ inventory at each of the three sites. For example, it would be costly if previously cleaned areas of soil and the groundwater were recontaminated during D&D operations. For Oak Ridge, the site plan should be coordinated with the plan for the whole Oak Ridge Reservation. It was not clear to the committee that the idea of cleaning the areas that the buildings occupy to greenfield status is reasonable, especially if other parts of the sites remain contaminated or if $DUF_6$ continues to be stored on site.

Detailed site-level D&D plans, which the committee believes should not take more than 18 to 24 months to prepare, should be developed, delineating the sequence of activities necessary to incrementally achieve the D&D of the facilities. The sequence of tasks should be based on considerations of cost and risk. Uncertainty regarding the final end states should not delay the development of this D&D plan, which would be expected to change as the situation evolves. The D&D plan should incorporate all major assumptions (technical, cost, and institutional), a proposed management organizational structure for both DOE and the decommissioning operations contractor, tradeoff studies for determining an optimized decommissioning sequence, a detailed work breakdown structure, and a detailed cost estimate and schedule. The detailed sequence document with a work breakdown structure would specify, for example, the sequence of steps required to dismantle and remove the equipment, decontaminate the equipment and buildings, tear down any indicated buildings, recycle material, and dispose of wastes. These plans would be used by the decommissioning contractor for soliciting competitive bids for execution of the work.

> **Recommendation.** The committee recommends that DOE develop three plans, namely, headquarters-level, GDP complex-level, and GDP site-level, that address and integrate the D&D of the facilities, environmental remediation activities, and management of the $DUF_6$.

## Stakeholder Involvement

Site planning and the associated planning for D&D of the GDPs should be undertaken in consultation with the stakeholders, such as public groups, regulators, workers, DOE, and any future potential users of the sites. This process of communication among various interested parties should start at the beginning of planning. For example, a consensus-building process would elicit public advice on the incremental cost- and risk-reduction approach and on the desired end states of the sites, taking into account costs, risks, and social values. It is essential that a credible and meaningful stakeholder and public involvement process be implemented that ensures smooth planning and implementation of D&D. Increased attention to stakeholders and the public concerning D&D at the three GDP sites can contribute to decisions that enjoy wide public acceptance and could avoid lengthy delays and additional costs arising from court challenges to the planned actions. Effective efforts to integrate the multiplicity of citizen and stakeholder interests are needed to provide meaningful inputs to decision making on such issues as health and safety, budgets, employment, and end states.

> **Recommendation.** The committee recommends that a stakeholder involvement program be pursued to obtain timely and substantive public participation and input to ensure that social values are reflected in policy decisions.

### Prioritized Cost and Risk Reduction

Proceeding expeditiously with D&D planning and execution is important because delays will lead to substantial expenditures for surveillance and maintenance, deterioration of the facilities will exacerbate these costs, risks to individuals will increase, and the costs for an expensive safeguards and security regime for highly enriched uranium will continue. Because the D&D of the three sites could very well occur over a period of several decades, political priorities, budget commitments, and regulatory standards could change. The uncertain context within which D&D will be planned and executed could also result in serious delays.

A prioritized, incremental cost- and risk-reduction approach would identify conditions at the sites that, if not quickly remediated, could lead to increased risks or costs as a result of delay. This approach would allow initiating D&D operations during the planning process. For example, regardless of the end states of the sites, removal of highly enriched uranium deposits from the Oak Ridge process equipment should be a first priority because this would reduce safeguards and security costs, reduce the risk of criticality accidents, and reduce costs of subsequent D&D efforts because nuclear criticality would be of much less concern. A prioritized cost- and risk-reduction approach would identify the best sequence of D&D actions to be included in a detailed D&D plan and cost estimate. This approach would schedule projects within the detailed D&D work plan to minimize risks to workers and the public, minimize total costs of surveillance and maintenance and D&D activities, be flexible, and not preclude alternative end states.

> **Recommendation.** The committee recommends that a prioritized costand risk-reduction approach be used as a basis for developing the D&D plan. This approach should be used to accomplish D&D activities prior to completion of the entire plan.

### D&D Technology Issues

Proven technologies are available for the D&D of the GDPs. These include technologies for characterization, disassembly, removal of uranium deposits from the process equipment, decontamination of the process equipment and buildings, melt refining and recycling of metals, and treatment of wastes. A major research and development program is not needed. However, there are some uncertainties about technical effectiveness, such as the degree to which certain technologies can remove technetium-99 ($^{99}$Tc, which is present from using recycled reactor feed) or decontaminate to the required levels, and about what degree of cost savings can be achieved. The large areas in the plants that need to be characterized and the repetitive nature of the equipment design encourage the use of robotics and automation. Determining answers to performance and cost-effectiveness questions would require a few focused demonstrations, not major research and development programs. With regard to decontamination technologies, the committee believes that while gaseous decontamination using $ClF_3$ is appropriate for removing bulk uranium deposits representing a criticality risk, for example, in the high-assay section at Portsmouth, subsequent decontamination should use aqueous techniques rather than gaseous $ClF_3$. Aqueous technology has proven to be very effective, and the committee envisions laboratory-scale efforts of a sufficient size to ascertain performance at full-scale operation. Automation and robotics demonstrations may have to occur in the plants. Such focused demonstration efforts on currently available technologies would help D&D planners select the most appropriate technologies based on considerations of cost, environmental protection, performance, and safety.

> **Recommendation.** The committee recommends that a few highly focused D&D demonstrations be undertaken to verify the cost and effectiveness of specific technologies, including the following two:

- Optimization of aqueous decontamination to remove radioactive surface contamination from materials and process equipment, with special attention to $^{99}$Tc.
- Support of current DOE robotics programs, with highly focused demonstrations to verify potential cost savings and safety benefits.

The committee recommends that a modest research program be established to develop methods to effectively decontaminate the diffusion barrier material.

## Safeguards and Security

The assumption was made in the Ebasco cost estimate that the diffusion barrier, or membrane, and compressor seals would be declassified prior to D&D. Costs will be higher if these components remain classified and the D&D has to be carried out in a “secure" environment. Furthermore, the D&D of the GDPs will require the handling of special nuclear materials. The regulatory requirements to safeguard these materials entail significant costs that could be reduced if less stringent requirements could be applied. For example, special nuclear material should be removed from the high-enrichment sections of the cascade prior to the start of large-scale D&D operations so that safeguards and security requirements can be relaxed.

> **Recommendation.** The committee recommends that to reduce costs without compromising information security for the gaseous diffusion technology DOE should try to define physical security requirements that allow uncleared workers under adequate supervision to conduct D&D operations. In addition, DOE should conduct an in-depth evaluation of the safeguards and security requirements during D&D to determine how their impact on D&D cost could be reduced.

## $DUF_6$

A DOE study has found that past practices for storage of $DUF_6$ have been inadequate in several respects. There have been no serious consequences, however, and there is a vigorous program to correct past deficiencies.

There is general agreement, however, that $DUF_6$ is an unsuitable chemical form for long-term storage; it is too reactive and too volatile. Eventually it needs to be converted to the more suitable form uranium oxide ($U_3O_8$). No large-scale uses for the $DUF_6$ have been identified, and the most promising potential uses do not preclude conversion to oxide.

Estimates prepared for DOE indicate that costs for the conversion of $DUF_6$ to $U_3O_8$ will be high, over $2 billion. It should be possible to realize cost savings by optimizing a number of factors, such as plant size and the conversion schedule. Conversion processes are conventionally used in the nuclear fuel industry, and several alternatives are known. The processes are rather simple, so that large cost reductions through new technology do not appear likely. Considering cost, risk, and social values, the most attractive of the known processes can be chosen.

Significant savings in the cost of long-term storage should be possible by improving the physical properties of the $U_3O_8$; in particular, increased particle size and much higher packing density should be possible, which would reduce storage costs based on volumetric fees. This area promises benefits from a limited research and development program.

> **Recommendation.** The committee recommends that, if consistent with the prioritized cost- and risk-reduction process, the $DUF_6$ should be converted to the more stable chemical form, $U_3O_8$, for storage or disposal.

# 1

# Introduction

This chapter presents a brief introduction to the study, identifying important aspects of the decontamination and decommissioning (D&D) of the gaseous diffusion plants (GDPs) that comprise the nation's uranium enrichment facilities.[1] The discussion covers the objectives of the study, a brief history and description of the gaseous diffusion facilities, the establishment of the United States Enrichment Corporation (USEC) and the D&D cost estimates developed to support the transfer of management of the enrichment facilities from the federal government to the corporation, the implications the Energy Policy Act of 1992 (EPACT) for D&D, and a brief overview of the committee's report.

## STUDY BACKGROUND AND OBJECTIVES

EPACT, signed into law on October 24, 1992, calls for the National Academy of Sciences to conduct a study and provide recommendations for reducing costs associated with the D&D of the nation's uranium enrichment facilities located at Oak Ridge, Tennessee; Paducah, Kentucky; and Portsmouth, Ohio (U.S. Congress, 1992).[2] Following EPACT, the U.S. Department of Energy (DOE) Assistant Secretary for Environmental Restoration and Waste Management requested that the National Research Council (NRC), principal operating arm of the National Academy of Sciences, undertake such a study. In response, in November 1993, the NRC established the Committee on Decontamination and Decommissioning of Uranium Enrichment Facilities to study opportunities for cost reduction in the D&D of the nation's GDPs. The committee was also charged with assessing options for the disposition of a large inventory of depleted uranium hexafluoride ($DUF_6$) stored outdoors in steel cylinders at each of the sites.[3] As part of this effort, the committee reviewed previous cost studies for the D&D of the GDPs and for the disposition of the $DUF_6$ inventory. The committee was not asked to develop specific D&D cost estimates. (Appendix A contains the committee's complete statement of task.)

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[1] D&D activities include characterization, decontamination, dismantling, and disposition of a facility's equipment and structures, as well as waste treatment. Decontamination consists of those activities that reduce levels of radioactive and/or hazardous contamination in or on materials, structures, and equipment (DOE, 1994).

[2] The Ohio plant is actually located in Piketon, Ohio, about 20 miles north of Portsmouth, but it is generally referred to as the Portsmouth site.

[3] Depleted uranium has a $^{235}U$ isotopic content less than the 0.71 percent by weight in natural uranium.

The committee's study identifies opportunities for cost reduction vis-à-vis existing cost estimates. The study also considers practices and approaches that would likely reduce D&D costs in a broader context. The only gaseous diffusion plant that has undergone D&D for which cost information is available is a British Nuclear Fuels (BNFL) plant at Capenhurst in the United Kingdom. This experience and its reported cost data served as an important benchmark in addressing the costs of D&D of the U.S. plants.

The present study is restricted to the D&D of the buildings and equipment comprising the GDPs. As defined by the statement of task, the study excludes consideration of environmental restoration activities, such as cleanup of soils and groundwater at the three enrichment facility sites. Also excluded are the gaseous centrifuge facilities at the Oak Ridge and Portsmouth sites that were never used for commercial production. These facilities do not represent a major part of the D&D costs at these sites, but some of this study's recommendations are pertinent to their D&D as well. The committee has considered the coordination and integration of D&D, environmental restoration, and management options for the $DUF_6$ for cost-effective management of the cleanup program.

## THE U.S. URANIUM ENRICHMENT ENTERPRISE

Natural uranium found in ore deposits consists of the three isotopes uranium-234, uranium-235, and uranium-238 ($^{234}U$, $^{235}U$, and $^{238}U$). $^{234}U$ is found in trace amounts; $^{235}U$ and $^{238}U$ occur in abundances of about 0.71 and 99.28 percent, respectively. The percent by weight of $^{235}U$ to all uranium atoms is termed the percent enrichment of $^{235}U$ in uranium; thus, for natural uranium the enrichment level is 0.71 percent. Many applications require enrichment levels above 0.71 percent, typically from 2 to 5 percent for light-water power reactors and 20 percent and greater for such applications as research reactors, compact reactors for naval use, and nuclear weapons.

The U.S. uranium enrichment program was created in the 1940s to produce enriched uranium for military applications, such as nuclear weapons. The three GDPs were used primarily for this mission through the 1960s, but in 1964 Congress authorized the private ownership of enriched uranium for commercial uses. After this time, the amount of enriched material delivered to the commercial sector grew rapidly, making up 90 percent of all the separative work units (SWUs) produced in 1974.[4] Beginning in 1968, the production capacity of the three plants was increased in response to demand from the commercial nuclear power sector.

The U.S. enrichment program has relied on the gaseous diffusion process. The feed material for a GDP is uranium hexafluoride ($UF_6$) gas, which is produced at other industrial facilities using natural uranium and delivered to the GDPs. The enriched $UF_6$ product from the GDPs is sent to other plants for fabrication into uranium products such as reactor fuel. A $DUF_6$

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[4] Enrichment capacity is typically measured in SWUs (see Glossary).

gas stream resulting from the enrichment process is collected and stored in cylinders, which are placed in outdoor storage yards at the three GDP sites (see Chapter 7).[5]

The Oak Ridge GDP was built between 1942 and 1945 under the auspices of the Manhattan Engineering District Project and began operation in 1945. The Oak Ridge GDP had the capability to enrich uranium up to 90 percent. The second plant, the Paducah GDP in Kentucky, was built between 1951 and 1955 to produce uranium to enrichment levels no greater than 2 percent. The third plant, the Portsmouth GDP in Ohio, began operation in 1956 and was designed to accept natural uranium feed, as well as the product from either the Oak Ridge or the Paducah GDP, and produce enriched uranium ranging from 2 percent to greater than 97 percent $^{235}$U. When all three plants were operational, they constituted an integrated production complex (see Figure 1-1 for the geographic locations of the plants).

The Oak Ridge GDP ceased production of highly enriched uranium (with enrichment levels greater than or equal to 20 percent) in 1964 because of insufficient demand. Low-enriched uranium (with enrichment levels less than 20 percent) was produced until 1985, when the plant was placed in a standby mode because of declining demand for low-enriched uranium from the commercial nuclear power sector; the plant was permanently closed in 1987. Since cessation of enrichment operations at the Oak Ridge GDP in 1985, the two plants at Portsmouth and Paducah have constituted a two-site complex. Both plants receive natural and partially enriched feed. The Portsmouth high-enrichment section has been closed since November 1992. The enrichment level capacity of certain parts of the Paducah plant was increased to 2.75 percent in 1995.[6]

The cost estimate prepared by Ebasco Environmental (Ebasco) assumes both operating plants would close in 2005, at which time other lower cost enrichment technologies would be expected to be used in the United States. The time of closure of the plants is uncertain, depending on the world uranium enrichment market and competitive forces. The Ebasco estimate assumed a sequential cleanup, Oak Ridge followed by Paducah, with Portsmouth last. The Ebasco cost estimate assumed the physical decommissioning to occur from 2002 to 2030 (DOE, 1991a). If either the Paducah or Portsmouth plant were to close sooner, there might be cost or other incentives to change the sequence or schedule of D&D activities for the three plants.

## THE UNITED STATES ENRICHMENT CORPORATION

EPACT restructured the government-owned uranium enrichment enterprise, which was under the management of DOE, by creating the USEC. The corporation was established as of

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[5] This depleted $UF_6$ is sometimes referred to as "tails," although that term is not universally favored (Lemons et al., 1990).

[6] Personal communication from Michael Buckner, Lockheed Martin Utility Services, Paducah, Kentucky, to James Zucchetto, NRC, June 1, 1995. The USEC has contingent approval from its current regulator, DOE, to operate at this enrichment level, but as of January, 1996 no uranium has been enriched at this plant above 2 percent. Modifications to the plant required to satisfy the contingent approval are expected to be in place by the time the Nuclear Regulatory Commission assumes regulatory authority over the plant, sometime in 1996.

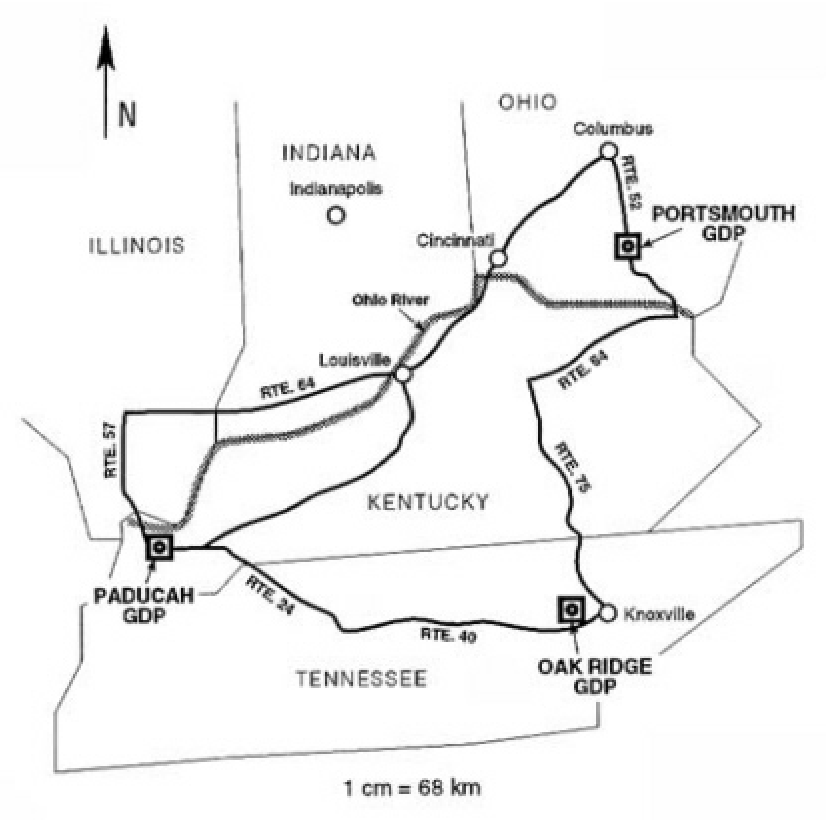

**FIGURE 1-1** The geographic relationship of the three GDPs.

July 1, 1993, as a wholly owned government corporation that is an agency and instrumentality of the United States. USEC is structured as a self-financing entity "to operate as a business enterprise on a profitable and efficient basis" to "help maintain a reliable and economical domestic source of uranium enrichment services." Ownership of the corporation is to be transferred eventually to private investors (U.S. Congress, 1992).

The corporation is currently leasing the Paducah and Portsmouth GDPs and related property from DOE for a period of 6 years from the transition date (July 1, 1993). The lease does not apply to those DOE facilities at Portsmouth necessary for the production of highly enriched uranium. Lockheed Martin Utility Services (formerly Martin Marietta Utility Services [MMUS]) is the USEC managing contractor for the uranium enrichment plants (USEC, 1993). The organization is responsible for plant operation and maintenance in accordance with work programs and budgets prepared in cooperation with the USEC. Lockheed Martin Energy Systems (formerly Martin Marietta Energy Systems [MMES]) is DOE's management contractor for environmental restoration and waste management activities at the Paducah and Portsmouth sites. USEC is not involved with the nonoperating facilities at the Oak Ridge GDP. The management and operations contractor at the Oak Ridge GDP is Lockheed Martin Energy Systems.

EPACT stipulates that DOE is responsible for any cost of D&D with respect to conditions existing before the transition date.[7] The corporation is obligated to return the facilities in the same condition as they were received and to remove deposits of uranium that represent a criticality risk (DOE, 1993).[8,9] This arrangement is not necessarily optimal for subsequent D&D efforts. Substantial uranium deposits would probably still remain in the process equipment. A large percentage of these deposits could be removed from the intact, functioning cascade through a gaseous decontamination process, or through other approaches. This was not done for a substantial part of the Oak Ridge plant when it stopped operations (see chapters 2 and 3). The degree to which gaseous decontamination, or other approaches, should be used at the Paducah and Portsmouth plants to reduce the amount of uranium deposits will involve calculating a number of tradeoffs to determine the most cost-effective approach for D&D of the cascade equipment (see chapters 3 and 6).

## THE D&D FUND

EPACT established a Uranium Enrichment Decontamination and Decommissioning Fund (D&D Fund) to finance cleanup efforts of the uranium enrichment facilities by the federal government. EPACT specifies that payments per fiscal year of $480 million, adjusted for inflation, shall be made into the D&D Fund for 15 years, with up to $150 million per year from a special assessment on electric utilities, proportional to their purchases of uranium enrichment services (measured in terms of SWUs) from DOE through October 24, 1992, and the balance of the payments from annual appropriations from the federal treasury. The special utility assessment is thus capped at $2.25 billion. If all payments are made as planned, a total of $7.2 billion will be contributed to the D&D Fund. EPACT stipulates that all D&D activities are to be paid for from the D&D Fund until such time as the Secretary of Energy certifies and Congress concurs, by law, that such activities are complete. EPACT also stipulates that the annual cost of remedial action at the gaseous diffusion facilities shall be paid from the D&D Fund to the extent that the amount available in the fund is sufficient. To the extent the amount in the fund is insufficient, DOE shall be responsible for the cost of remedial action (U.S. Congress, 1992). A recent court decision has raised questions about the expected utility contributions (Newman, 1995).

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[7] EPACT stipulates: "The payment of any costs of decontamination and decommissioning, response actions, or corrective actions with respect to conditions existing before the transition date, in connection with property of the Department leased … shall remain the sole responsibility of the Department."

[8] Section 4.4 of the USEC lease specifies in subparagraph (b): "… Remove solid deposits of $UO_2F_2/UF_4$ to the extent necessary to prevent criticality …;" and in subparagraph (e): "Place structures to be returned at the facility in a safe secure condition, removing any immediate threats to human health and safety. …"

[9] In a nuclear criticality event, an assemblage of enriched uranium results in a self-sustaining nuclear chain reaction generating heat, radioactive contamination, and gamma and neutron radiation. Usually a criticality event is self-limiting because the energy release disrupts the geometric configuration of the enriched material that caused the criticality. If the assemblage reforms again, another criticality event will occur. Hence, some criticality events are pulsed events.

## THE CHALLENGES OF A D&D EFFORT

The GDPs constitute a complex of large buildings, with hundreds of acres of floor area and thousands of large pieces of equipment (see figures 1-2 and 1-3 and Chapter 2). In addition to the process buildings, there are auxiliary buildings, electrical switchyards, and connecting piping and electrical systems. The process equipment at the nonoperating plant at Oak Ridge contains significant quantities of solid deposits of uranium of all degrees of enrichment. Large quantities of hazardous substances, such as asbestos and polychlorinated biphenyls (PCBs), will have to be dealt with at all three sites. Despite the large scale of the facilities, the effort will essentially be a large disassembly and deconstruction project. The repetitive and common designs throughout the GDPs should allow for economies of scale in D&D, and there is a potential to

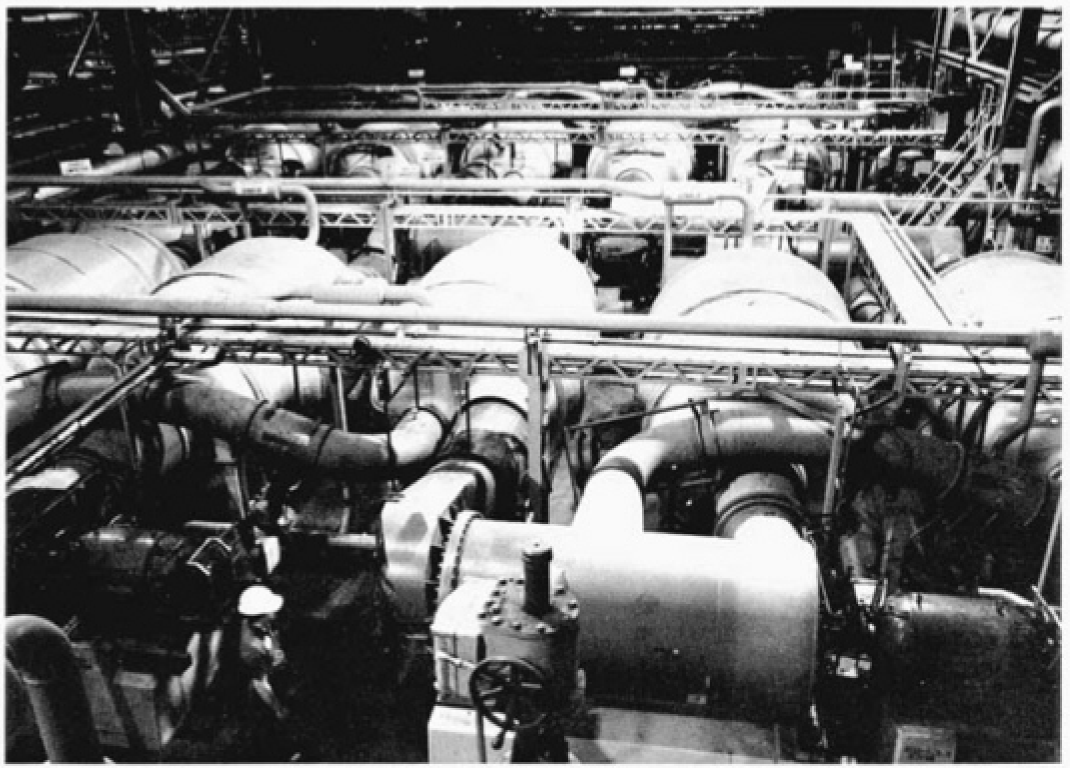

**FIGURE 1-2** Photograph of the interior of a process building showing the repetitive arrangement of the cascades.
SOURCE: Briefing material from the committee meeting at the Oak Ridge GDP, February 3-4, 1994.

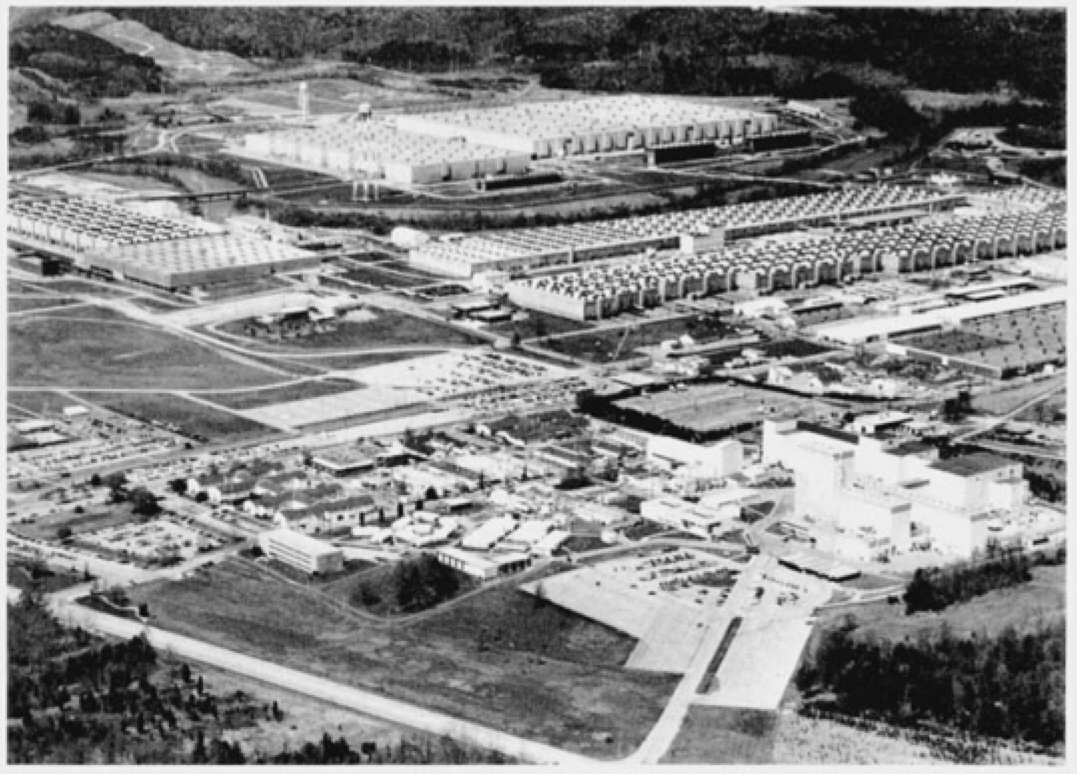

**FIGURE 1-3** The Oak Ridge GDP site.
SOURCE: Briefing material from the committee meeting at the Oak Ridge GDP, February 3-4, 1994.

recycle significant quantities of metals with commercial value. Careful removal of enriched uranium deposits will be required to avoid criticality accidents and to ensure material accountability. These deposits, some highly enriched as in the K-25 building at Oak Ridge, present a distinguishing problem, namely, the prevention of a criticality accident, which is germane to few other facilities requiring cleanup. Requirements for preventing criticality will increase costs at Oak Ridge and Portsmouth compared to Paducah, where deposits are at much lower enrichment levels.

Perhaps the greatest challenge to reducing D&D costs is effectively managing this large effort, which involves numerous regulatory authorities, spans several decades, and faces many uncertainties. A number of issues need resolution: the regulatory requirements that define to what extent the sites must be cleaned up; the future uses of the sites; the extent to which materials can be decontaminated and recycled; and the disposal costs and site location for wastes resulting from D&D. There is a complex multi jurisdictional regulatory regime under which D&D must be undertaken. Stakeholders must be brought into D&D planning. The amount of money that will be available from the D&D Fund could affect the schedules and timing of D&D operations. These uncertainties have important implications for the success of the D&D program and its associated costs.

DOE is also responsible for a total of over 500,000 metric tons of $DUF_6$ contained in about 46,000 steel cylinders in outside storage yards at the three sites. Future uses have been suggested for this material (see Chapter 7). However, concern about deterioration of the storage cylinders over time, which could result in the release of hazardous material, and difficulties in cylinder handling, could very well favor conversion of the $DUF_6$ into a more stable chemical form. It was not evident to the committee whether DOE intends to closely coordinate the disposition of the $DUF_6$ with the D&D of the facilities.

## D&D COSTS

Financial assessments were made by the federal government in developing a plan for restructuring DOE's uranium enrichment enterprise. The assessments required the cost for environmental cleanup of the three uranium enrichment sites including the D&D of the facilities (i.e., the major buildings and structures housing the GDPs), remedial actions at areas outside of the major buildings and structures, and disposition of $DUF_6$ held in storage. An independent financial assessment by Smith Barney, Harris Upham & Company (1990), recommended that a complete D&D cost study be undertaken, based on the conclusion that the costs associated with D&D would be high and significantly affect the economic viability of the uranium enrichment enterprise and any proposed restructuring (Timbers, 1990). The Smith Barney study also recommended that D&D costs associated with operations prior to any transfer of ownership should remain a direct liability and obligation of the federal government.

Following on this financial assessment, DOE commissioned two cost estimates for D&D of the GDP facilities (see Chapter 4). Ebasco prepared a preliminary cost estimate that assumed "prompt dismantlement," with the facilities to be cleaned of radioactive and hazardous materials and restored to a condition such that a future occupant would not be exposed to harmful substances (DOE, 1991a). An initial D&D cost estimate by Ebasco amounted to almost $46 billion, but a set of reevaluations, redefining the scope of the effort, resulted in a final estimate of $16.1 billion (1992 dollars), not including environmental restoration activities for the sites or management and disposition of the stored $DUF_6$ (Table 1-1).

TLG Engineering (TLG) was contracted by DOE through Systematic Management Services to "estimate the costs of decommissioning … from the standpoint of a Decommissioning Operations Contractor performing the work at the lowest competitive cost"

TABLE 1-1 Estimated Costs for Prompt Dismantlement of the Gaseous Diffusion Plants (billions of 1992 dollars)

| **Contractor** | Oak Ridge | Paducah | Portsmouth | D&D Total |
|---|---|---|---|---|
| Ebasco | 7.5 | 3.3 | 5.3 | 16.1 |
| TLG | 7.3 | 3.1 | 3.5 | 13.9 |

SOURCE: DOE (1991a; 1991b).

(DOE, 1991b). Some assumptions were different from those used in the Ebasco study. TLG developed an estimated cost for the D&D of the three GDPs of about $13.9 billion (see Chapter 4).

MMES estimated the cost of converting the stored $DUF_6$ at the three sites to uranium oxide and aqueous hydrogen fluoride (HF) at between $1.3 billion and $4 billion (1992 dollars) (see Chapter 7; Charles et al., 1991; DOE, 1991a). This study assumed an inventory of about one million tons of $DUF_6$, including both the DOE legacy and future accumulations estimated to be produced through 2005 from the operation of the plants.

## ORGANIZATION OF THE REPORT

As seen above, the D&D of the GDPs and associated cost estimates involve a number of issues, such as the state of the sites and the scope and extent of cleanup, technologies for accomplishing the D&D, and the regulatory environment and standards under which the D&D will occur.

Chapter 2 of the report discusses the current situation at the GDP facilities describing the gaseous diffusion process and the equipment used for uranium enrichment, the buildings and sites, the radioactive and nonradioactive contaminants in the buildings that have to be removed, and the risks subsequent to closure of the facilities. Chapter 3 addresses the technologies that could be, or have been, used to accomplish D&D of GDPs, including those used by BNFL at the Capenhurst gaseous diffusion plant in the United Kingdom. Chapter 3 also identifies research and development needs. The committee has reviewed the Capenhurst experience in some detail because it represents the only GDP of design similar to that of the U.S. plants that has undergone D&D.

Chapter 4 reviews the cost studies that have been prepared for the D&D of the U.S. GDPs, including the Ebasco and TLG estimates and an analysis of the Ebasco estimate by Science Applications International Corporation (SAIC). Major projected cost drivers in D&D are identified. The cost data reported for the actual D&D of the Capenhurst plant is also presented, along with a scaleup analysis the committee conducted that estimates the cost of D&D for the U.S. GDPs based on the Capenhurst experience.

Chapter 5, on D&D program planning, emphasizes the point that D&D of the GDPs involves more than just technology. A number of groups and individuals (the stakeholders) have an interest in the process of D&D and in the eventual end states of the sites. Regulations play an important role in the cost of cleanup because they determine to what extent the facilities will need to be cleaned and whether recycling of materials to the commercial market will be allowed. Specification of different end states for the sites also has a significant impact on cost; for example, carrying out D&D of the buildings for reuse compared to removing radioactive and hazardous substances, demolishing the buildings, and burying all the waste. Chapter 5 also presents a D&D planning approach to minimize conflict and delays.

Based on all the preceding material, Chapter 6 delineates opportunities for cost reduction grouped according to the categories used in the Ebasco cost estimate: program integration, radioactive and hazardous waste management, decontamination and decommissioning, and support facilities. Chapter 6 also addresses how changes in the cost estimate assumptions could lead to reduced costs. Chapter 7 addresses the issues, management options and related cost estimates for the $DUF_6$ inventory at the sites. The chapter also discusses potential uses for the $DUF_6$ and evaluates technologies for conversion of the $DUF_6$ into other chemical forms. Finally, Chapter 8 presents the committee's major recommendations. The appendices provide a variety of supporting material.

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# 2

# The GDP Sites: Process, Facilities, Inventories, and Risks

The physical and environmental state of the GDPs and the factors affecting risks subsequent to plant closure are summarized in this chapter.

## THE GASEOUS DIFFUSION PROCESS

Uranium enrichment can be accomplished in a number of ways, including gaseous diffusion, gaseous separation using centrifugal force, electromagnetic separation, and atomic vapor laser isotope separation. The only method currently in commercial use in the United States is the gaseous diffusion process, which is based on the slight difference in mass between the $^{235}U$ and $^{238}U$ (uranium-235 and uranium-238, respectively) isotopes (Glasstone, 1950). Uranium, in the form of $UF_6$ (uranium hexafluoride) gas, flows through a barrier tube with porous walls (see Figure 2-1). Part of the gas (nearly 50 percent) diffuses through the tube wall. The lower molecular weight $^{235}UF_6$ molecules have a higher molecular velocity and diffuse more readily through the barrier pores. Consequently, the fraction of the gas that passes through is enriched in the $^{235}$ U isotope and the gas that does not pass through is slightly depleted in $^{235}U$. The efficiency of the enrichment process depends on control of the size of the holes in the barrier.

The enrichment obtained in a single diffusion operation is quite small.[1] To enrich uranium for use in nuclear power plants and nuclear weapons, this operation must be repeated hundreds to thousands of times by coupling many diffuser units in a series arrangement called a cascade. The basic building block of a cascade is called a stage, which is composed of a converter vessel, gas compressor, motor, control valve, and associated piping (see Figure 2-2). The largest converters in the U.S. GDPs are 3.96 m (13 ft) in diameter by 7.31 m (24 ft) long and contain tightly packed diffusion barrier tubes that perform the isotopic separation and heat exchangers to control system temperature (see Figure 2-3). These large converters are located in the low enrichment section of the cascades; smaller converters are found in the higher enrichment sections. The size of the compressors varies directly with the size of the attached converters. The stages are connected into cells consisting of up to 12 stages, several cells are

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[1] For one diffuser, the $^{235}UF_6$ gas molecules diffuse slightly faster than the $^{238}UF_6$ gas molecules, resulting in a slight enrichment of the escaping gas (theoretically, on the order of 1.0043, the square root of the ratio of the molecular weight of $^{238}UF_6$ to $^{235}UF_6$).

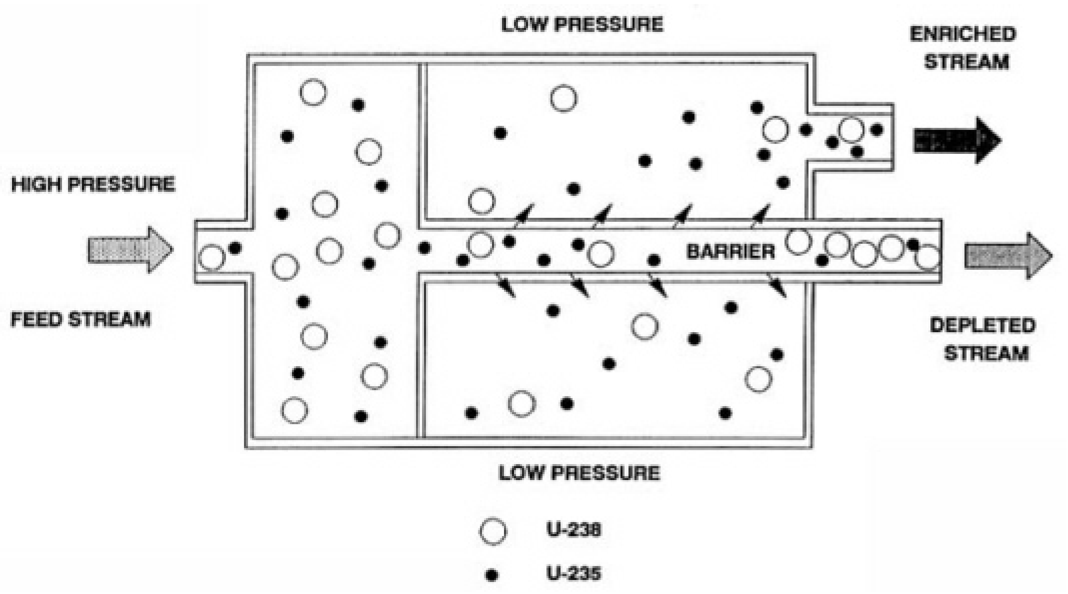

**FIGURE 2-1** Operating principle of a converter.
SOURCE: DOE (1991a).

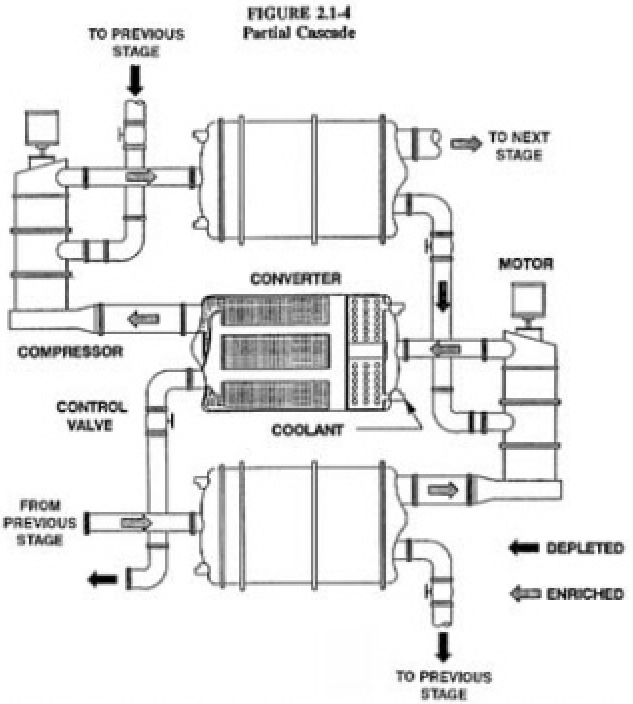

**FIGURE 2-2** Gaseous diffusion stage schematic.
SOURCE: DOE (1991a).

connected into units, and several units are connected within a building (see Figure 2-4 and Figure 1-2). The large size and large number of the components require large process buildings in which to house the enrichment equipment. The process buildings contain thousands of enrichment stages with connecting piping, valving, and compressors, and there are additional connections between the process buildings.

Both axial flow and centrifugal compressors are used to compress the $UF_6$ gas to the pressures needed for it to flow through the barrier tubes and from one stage to another. A gas cooler removes about 95 percent of the energy added by the compressor. Cooling is accomplished by a special chlorofluorocarbon (CFC) gas, CFC-114, which is in turn cooled by water. Control valves adjust the gas flow and pressure to optimize stage and cascade performance. Large block valves between successive cells permit isolating stages for maintenance.

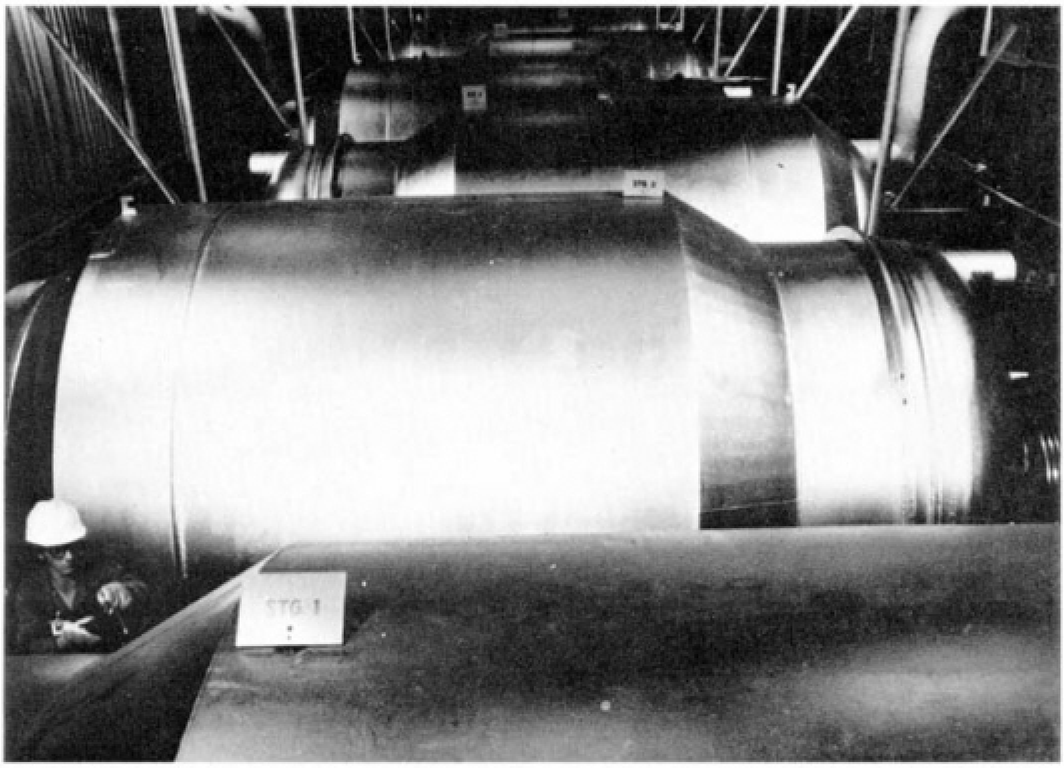

**FIGURE 2-3** Photograph of a large converter.
SOURCE: DOE (1994a).

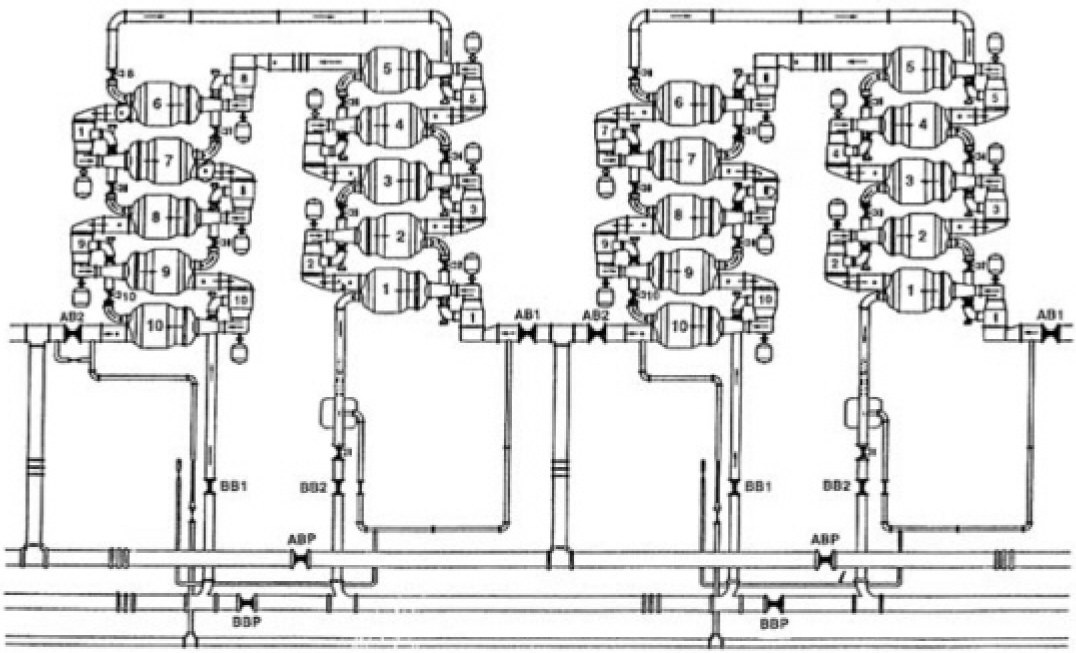

**FIGURE 2-4** Arrangement of large converters showing 2 cells with 10 stages each.
SOURCE: DOE (1991a).

Enriched product is withdrawn from product withdrawal stations at the top (high enrichment section) of the main cascade into steel cylinders, allowed to cool to ambient temperature and solidify, and shipped to customers. $DUF_6$ (depleted uranium hexafluoride) is withdrawn at tails withdrawal stations from the bottom (low enrichment section) of the main cascade and stored in 10- to 14-ton cylinders on site in a solid form. Light gases, which are readily separable from the heavier $UF_6$, are removed in a special "purge cascade."

In addition to the process stage equipment, the GDPs require auxiliary systems, such as $UF_6$ feed and withdrawal, electrical power distribution, and cooling towers to dissipate the waste process heat.

## SITE DESCRIPTIONS

The GDPs are large facilities, covering hundreds of acres and having many major structures (see Figure 1-3). They are located in relatively remote areas with relatively small population centers nearby (Table 2-1). The Oak Ridge GDP complex in southeastern Tennessee, sometimes referred to as the K-25 site,[2] is 13 miles west of downtown Oak Ridge and approximately 40 miles northwest of Knoxville; the Portsmouth GDP is in southern Ohio, 4 miles southeast of the town of Piketon, 20 miles north of the city of Portsmouth, and approximately 80 miles south of Columbus; and the Paducah GDP is in western Kentucky, 16 miles west of Paducah, and 135 miles northwest of Nashville, Tennessee. The operating plants at Paducah and Portsmouth are significant employers in their localities.

All three plants are located near water bodies: Poplar Creek runs through the Oak Ridge GDP site and the Clinch River and Watts Bar Lake bound the site; at Portsmouth, the Scioto River, which flows into the Ohio River, is 3 miles to the west; and at the Paducah GDP, the Big and Little Bayou Creeks bound the site and flow into the Ohio River, approximately 3 miles to the north. All the sites encompass large land areas, extensive building floor space, and large structures. At Paducah, the surrounding land is part of the West Kentucky Wildlife Management Area.

In 1989, the Oak Ridge GDP site was given a new mission, which includes environmental restoration (D&D of the facilities and remediation of contaminated soil, water bodies, and buried wastes), waste management (waste storage and incineration), and environmental cleanup technology development. In May 1993, the Oak Ridge GDP site was designated as the Center for Environmental Technology and the Center for Waste Management for the DOE Oak Ridge Operations Office.

In addition to the GDP site, the Oak Ridge government reservation encompasses the Oak Ridge National Laboratory, Y-12 complex, and other DOE activities. Owned by DOE and operated by Lockheed Martin Energy Systems (formerly MMES), the Toxic Substances Control Act of 1979 (TSCA) incinerator is also located at the GDP site. This facility processes hazardous organic wastes that may contain low-enriched uranium and PCBs and has already processed over 7.6 million pounds of such wastes.

There are several contaminated waste areas at the sites. At the Oak Ridge GDP, there are other waste disposal areas near the site that include radioactive, hazardous, and mixed wastes, such as the K-1070-C/D and K-1070-A waste disposal sites. At Portsmouth, buried wastes are located on site, such as in the X-749 low-level radioactive waste landfill, X-749A classified materials disposal facility, and X-701B holding pond (MMES, 1993a). The C-404 radioactive waste burial ground and C-746-S landfill are located at the Paducah site, as are several contaminated and classified scrap metal yards. The sites also have contaminated soils and groundwater, but the study scope excludes attention to remediation of these conditions.

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[2] K-25 was the World War II code name and was also the name for the first gaseous diffusion process building. The various buildings at this site are designated with the letter "K." Buildings at Paducah are designated with the letter "C," and buildings at Portsmouth with the letter "X."

TABLE 2-1 Characteristics of the Uranium Enrichment Facilities

| **GDP Site** | Land Area[a] (acres) | Security Area (acres) | Number of Buildings[b] | Process Building Floor Area[c] (million $ft^2$) | Employees | Local Population[d] |
|---|---|---|---|---|---|---|
| Oak Ridge | 1,500 | 772 | 125 | 10.9 | 3,000 | 27,000[e]; (68,000) |
| Paducah | 3,423 | 748 | 161 | 6.4 | 1,850 | 27,000[f]; (63,000) |
| Portsmouth | 3,708 | 500 | 109 | 8.2 | 2,600 | 1,700[g]; (24,000) |

[a] 1 acre = 43,560 square feet.

[b] Not all buildings were included in the cost estimates or are expected to be included in the D&D program. For example, 13 gas centrifuge buildings at Oak Ridge were not included in the cost estimates. As of spring 1995, 82 buildings at Oak Ridge and 8 buildings at Portsmouth have entered the D&D program. The D&D program at Paducah consists of surveillance and maintenance of 15 small facilities that are shut down.

[c] The process buildings account for about 90 percent of the under-roof area in the buildings at the GDPs. There are five process buildings at Oak Ridge (K-25, K-27, K-29, K-31, and K-33), four process buildings at Paducah (C-331, C-333, C-335, C-337), and three process buildings at Portsmouth (X-326, X-330, and X-333).

[d] City and county populations to nearest thousand from Rand McNally (1992).

[e] City of Oak Ridge (Anderson County).

[f] City of Paducah (McCracken County).

[g] City of Piketon (Pike County).

SOURCE: Briefings to the committee during site visits to the Oak Ridge, Paducah, and Portsmouth GDPs, and the Ebasco cost estimate (DOE, 1991a, 1993a, 1994; MMES, 1993b).

## BUILDINGS AND EQUIPMENT

The process buildings, which house the enrichment cascades, are arranged in an open layout and include overhead cranes and wide access doors for ease of equipment maintenance. These features may also simplify decontamination operations. The process buildings are steel-framed structures with concrete floors and columns and transite (an asbestos-concrete mixture) siding. Much of the concrete floor surfaces have fluorinated, hardened coatings to prevent infiltration of spilled materials. Tie lines between the process buildings transport gaseous $UF_6$ through the cascade. Typical heating, ventilation, and air conditioning systems are present throughout the complex, as are support systems for supplying water, power, lighting, fire protection, instrumentation, and security. The gaseous diffusion process requires a great deal of electrical power. Thousands of capacitors, transformers, and electrical switches are found at the sites, many of which contain PCBs that will require disposal.

Although about 90 percent of the total area under roof at the Oak Ridge GDP site is contained in the five process buildings, numerous support buildings and facilities must also undergo D&D. This is the case at the other two sites as well (DOE, 1991a). These support buildings include decontamination facilities, analytical laboratories, feed and withdrawal stations, and waste management facilities such as incinerators. However, the process buildings account for most of the estimated D&D cost for the GDPs (see Chapter 4). For the Oak Ridge site, the Ebasco cost estimate indicates that the five process buildings account for 92.6 percent of the D&D cost.

An active surveillance and maintenance program exists at all three sites. The current costs for surveillance and maintenance at the Oak Ridge site are close to $40 million per year (Table 2-2). Projections for surveillance and maintenance costs in DOE's Life Cycle Baseline Summary for the D&D of the Oak Ridge GDP amount to about $926 million over the period 1993 to 2019 (DOE, 1993a). A number of the buildings at the three sites have been placed in standby or shutdown mode because of changing production requirements. Most notably, the high enrichment buildings, K-25 and K-27, at the Oak Ridge GDP were shut down in 1964, and the remainder of the GDP was shut down in 1987. Some buildings have been converted to other uses such as waste storage. For example, at the Oak Ridge GDP site, hazardous wastes, low-level radioactive wastes, mixed wastes, and strategic and classified materials are being stored in the ground-level vaults of the K-25, K-31, and K-33 buildings (DOE, 1993b; Gilbert, 1995). Removing these wastes may delay the D&D of the facilities and also engender costs during the D&D, such as cleanup of contamination from waste drums, that should not be ascribed to D&D operations at the GDPs.

The large size of the facilities entails large quantities of various materials, including potentially valuable metal. Converters are generally constructed of nickel-plated steel; their weights range from about 3.3 metric tons (3.7 tons) for the smallest units to 29 metric tons (32 tons) for the largest units. Because there are thousands of these converters, the weight of metals in the process equipment is substantial, in excess of 60,000 metric tons at each site (Lemmon, 1994). Table 2-3 indicates the total amounts of metal expected to result from the D&D of the

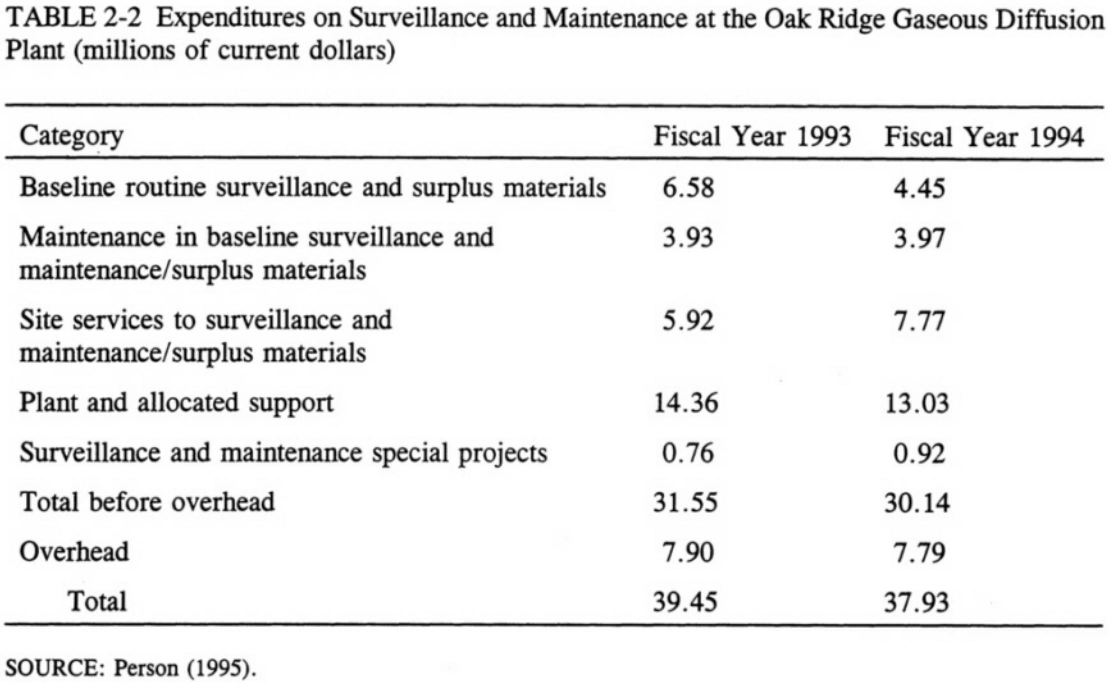

TABLE 2-2 Expenditures on Surveillance and Maintenance at the Oak Ridge Gaseous Diffusion Plant (millions of current dollars)

| Category | Fiscal Year 1993 | Fiscal Year 1994 |
|---|---|---|
| Baseline routine surveillance and surplus materials | 6.58 | 4.45 |
| Maintenance in baseline surveillance and maintenance/surplus materials | 3.93 | 3.97 |
| Site services to surveillance and maintenance/surplus materials | 5.92 | 7.77 |
| Plant and allocated support | 14.36 | 13.03 |
| Surveillance and maintenance special projects | 0.76 | 0.92 |
| Total before overhead | 31.55 | 30.14 |
| Overhead | 7.90 | 7.79 |
| Total | 39.45 | 37.93 |

SOURCE: Person (1995).

TABLE 2-3 Estimated Radioactive Scrap Metal Streams from the D&D of the GDPs (thousands of tons)

| **Category** | Oak Ridge | Paducah | Portsmouth | Total |
|---|---|---|---|---|
| Ferrous metals/steel | 103.7 | 74.0 | 91.4 | 269.1 |
| Aluminum/copper | 8.5 | 6.1 | 7.6 | 22.2 |
| Copper wire tubing/valves | 17.6 | 11.7 | 15.0 | 44.3 |
| Monel pipe/valves[a] | 1.7 | 1.2 | 1.5 | 4.4 |
| Nickel | 22.1 | 15.9 | 19.8 | 57.8 |
| Miscellaneous | 123.2 | 81.9 | 105.0 | 310.1 |

NOTE: Ferrous metals and steel excludes some structural steel left in place in decontaminated building structures. Miscellaneous includes electrical instrumentation equipment and housings.

[a] Monel is a high-nickel–content alloy containing about 27% copper, 68% nickel, and 2% to 3% iron.

SOURCE: DOE (1993b).

GDPs.[3] In addition, about 45,000 metric tons (50,000 tons) of brick and concrete block will result from D&D of the Oak Ridge facility (DOE, 1991a, 1993b). These large quantities of materials also result in the potential for large amounts of low-level radioactive waste from D&D. For example, the Ebasco and TLG cost estimates assumed minimal recycle of material and calculated large but different quantities of low-level radioactive and hazardous wastes under different assumptions (see Appendix J).

DOE pursued gas centrifuge enrichment technology from 1960 to 1985 as an advanced technology to replace gaseous diffusion. Thirteen buildings at the Oak Ridge site and six buildings at Portsmouth house gas centrifuge enrichment facilities that are covered by the D&D program. These facilities are contaminated and contain classified equipment and materials. While these buildings are excluded from the scope of this study, some of this study's findings and recommendations may be applicable to their decommissioning.

## CONTAMINATION

Most of the data on building contamination reviewed by the committee pertains to the Oak Ridge site. Health physics and other data were reviewed to assess building contamination. Data sufficient for D&D planning needs are not available. (A pilot cell characterization project was planned at Oak Ridge, but it was not carried out.) Environmental audits at Portsmouth and Paducah provided another source of data (Faulkner, 1994b; Faulkner and Dykstra, 1994). Briefings to the committee during its site visits provided additional data.

### Radiological Contamination

The main radioactive element to be characterized is uranium, which is both the feed and product of the gaseous diffusion process in the form of $UF_6$. Natural uranium was the most common feed. It consists of the isotopes $^{238}U$, $^{235}U$, and $^{234}U$ in trace quantities, and a few relatively short-lived radioactive decay products. Uranium recycled after use in nuclear reactors, primarily from military plutonium production reactors at Hanford and Savannah River, was occasionally fed to the cascades (MMES, 1992). The actinides and fission products that remained in the feed to the plants after uranium recovery, purification, and fluorination were technetium-99 ($^{99}Tc$), $^{236}U$, and traces of plutonium-239 ($^{239}Pu$) and neptunium-237 ($^{237}Np$) (see Appendix E, Table E-1).[4] Reactor return feeds were shipped directly to Paducah (88 percent) and Oak Ridge (12 percent). Contamination also occurred at the Portsmouth plant. The decay characteristics of the principal radionuclides present at the GDPs are summarized in Table 2-4. (See Appendix E for additional information on radionuclides present at the GDPs.)

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[3] In early 1995, commercial metal prices were about $1.00/lb for aluminum and copper, 7¢/lb for steel scrap, and $5.00/lb for nickel. Such prices are highly volatile and can fluctuate significantly over short time periods.

[4] Almost 700 kg of $^{99}Tc$ and 19 kg of $^{237}Np$ were fed to the cascades.

TABLE 2-4 Radionuclide Decay Characteristics

| **Radionuclide** | Radioactive Decay Products | Half-Life (years) | Radiation[a] | | | |
|---|---|---|---|---|---|---|
| | | | | | gamma | |
| | | | Alpha (MeV) | Beta (maximum MeV) | (MEV) | (%)[b] |
| $^{238}$U | | $4.47 \times 10^{9}$ | 4.2 | — | — | — |
| | $^{234}$ Th | $6.60 \times 10^{-2}$ | — | 0.19 | 0.093 | 16 |
| | $^{234m}$Pa[c] | $2.22 \times 10^{-6}$ | — | 2.29 | 1.001 | 0.9 |
| $^{234}$U | | $2.45 \times 10^{5}$ | 4.7 | — | — | — |
| $^{235}$U | | $7.04 \times 10^{8}$ | 4.4 | — | 0.185 | 54 |
| | $^{231}$Th | $2.92 \times 10^{-3}$ | — | 0.31 | 0.084 | 8 |
| $^{236}$U | | $2.34 \times 10^{7}$ | 4.4 | — | — | — |
| $^{99}$Tc | | $2.14 \times 10^{5}$ | — | 0.29 | — | — |
| $^{237}$Np | | $2.14 \times 10^{6}$ | 4.8 | — | 0.086 | 14 |
| | $^{233}$Pa | $7.39 \times 10^{-2}$ | — | 0.57 | 0.312 | 34 |
| $^{239}$Pu | | $2.44 \times 10^{4}$ | 5.1 | — | — | — |

[a] — = not applicable

[b] % = 100 × (number of gamma/second)/(number of disintegrations/second); only the most intense gamma ray is listed.

[c] m = metastable.

Most of the uranium now at the GDPs is the depleted fraction, stored in cylinders on site. After process shutdown, some solid deposits of uranium and its impurities will remain within the cascade. A small fraction is distributed throughout the sites due to leaks, spills, repairs, cascade upgrading, and storage of product and waste. More uranium compounds will undoubtedly be spread by dismantling activities, although great care will be taken to avoid the spread of radioactive or hazardous materials in amounts above that permitted by DOE Orders or federal and state statutes.

The extent of contamination on external surfaces in the facilities, such as floors, walls, structural steel, and exterior surfaces of process equipment and instrumentation, is not well known. The data available from the Oak Ridge GDP (Person, 1995a; DOE, 1991b) show uranium and $^{99}$Tc contamination to some degree in all process buildings and in some support buildings (Table 2-5). In areas where the extent of contamination is 90 percent of surface area or greater, both uranium and $^{99}$Tc are present. One hundred percent of the interior of the process equipment is assumed to be contaminated.

An extensive nondestructive assay survey for $^{235}$U deposits in the process equipment (100,000 individual measurements) has been completed for the 54 units in the K-25 building and

TABLE 2-5 Estimated Percentages of Surface Areas at the Oak Ridge GDP Contaminated with Radioactive Materials

| **Site Facilities** | $^{235}$U Enrichment | Building Floor Space | Building Walls | Structural Steel | Nonprocess Equipment | Process Equipment Housings | Process Electrical Systems | Uranium Processing Equipment |
|---|---|---|---|---|---|---|---|---|
| K-25 process building (94%) | 20-90 | 15 | 10 | 10 | Unknown | 90 | —[a] | 100 |
| 311-1 Area (6%) | 3-5 | 95 | 90 | 90 | Unknown | 100 | —[a] | 100 |
| K-27 process building (80%) | Up to 20 | 15 | 15 | 15 | Unknown | 90 | —[a] | 100 |
| 402-9 Area (20%) | 3-5 | 90 | 80 | 80 | Unknown | 100 | —[a] | 100 |
| K-29 process building | 2-10 | 90 | 80 | 85 | Unknown | NA | —[a] | 100 |
| K-31 process building | 1-4 | 15 | 10 | 10 | Unknown | 50 | —[a] | 100 |
| K-33 process building | 0.2-2 | 5 | 5 | 5 | Unknown | 50 | —[a] | 100 |
| Process support buildings | 0.2-5 | 15 | 10 | 10 | Unknown | 70 | —[a] | 100 |
| Decontamination buildings | 0.2-5 | 95 | 90 | 90 | Unknown | 100 | —[a] | 100 |
| Water and electrical facilities | NA[b] | —[c] | —[c] | —[c] | Unknown | NA | NA | NA |

NOTE: This assessment is based on limited data collected during facility operation; detailed characterization has been delayed until D&D activities are initiated in the buildings. Surfaces are considered contaminated if 5,000 disintegrations per minute (dpm) or more can be detected. Surface contamination can be found from 5,000 dpm/100 cm$^2$ to greater than one million dpm/100 cm$^2$. Most of the contamination is either uranium or $^{99}$Tc. Areas 311-1 and 402-9 are the purge cascades for the K-25 and K-27 buildings respectively. Area 311-1 operated until 1977 and 402-9 operated until 1985.

[a] Due to the difficulties in surveying motor and transformer windings, these components have been treated as contaminated in previous maintenance programs.

[b] NA = Not available.

[c] Spot contamination may be found.

SOURCE: Faulkner (1994a, b).

the nine units in the K-27 building at the Oak Ridge site (MMES, 1992). The technique used has not been validated and may be subject to considerable error.[5] Less detailed surveys were conducted of lower enrichment sections found in the other buildings. The results indicate that there is a large amount of uranium (on the order of tons) present in the process equipment (Table 2-6). Some uranyl fluoride ($UO_2F_2$), and uranium fluoride-metal reaction products are found, in a fairly thin coating covering the inside surfaces of the operating equipment. In addition, substantial deposits of $UO_2F_2$ occur at many locations, presumably at the sites of past leakage or spills.[6] Although $^{235}U$ is present in the process equipment, the major nuclide present is, of course, $^{238}U$. Small concentrations of $^{234}U$ will also be present and contribute disproportionately to activity of the products. Of the several tons of uranium deposits, much of it is enriched and could present a criticality hazard in the presence of water.[7] A number of the stages at the Oak Ridge and Portsmouth GDPs will contain highly enriched uranium as well as moderately enriched uranium having enrichment levels between 5 and 20 percent (Murray, 1994).

Most of the radioactive contamination, both within the process equipment and on exposed areas in the plants, occurs on the surface of materials and should be easily removable. Some, however, is "buried" within the material or painted over. For example, the diffusion barrier, which is made of nickel, contains some uranium within the diffusion pores; concrete may contain radioactive contamination within cracks; and small-diameter tubing may contain internal deposits. For deposits of uranium inside some piping and small-diameter tubing, and for such surfaces as compressor bearings, balding, and valve bodies, contamination may be difficult to access and remove. It would also be difficult to measure levels of contamination in such pieces of equipment to verify compliance with surface contamination standards.

### Nonradioactive Contamination

A number of hazardous chemicals and materials, such as PCBs, asbestos, oils, coolants, lead, and other miscellaneous materials must be dealt with in cleaning up the facilities (see Table 2-7). Gaskets used on ventilation ductwork contain PCB oils. Tens of thousands of gaskets are in place at each plant. A Federal Facilities Compliance Agreement requires each plant to have a control and removal program for PCBs. A multimillion dollar program at the Portsmouth and Paducah GDPs has just been completed to install troughs for all PCB gaskets to prevent leaks of PCBs onto the floors. At the Oak Ridge GDP the current plan is to destroy these PCBs during D&D. The committee believes this is a sensible approach that avoids the large and useless expenditure of removing and replacing the PCB-impregnated gaskets, only to remove and destroy the clean replacements after decontamination operations.

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[5] The uncertainty currently used for the nondestructive assay technique is ±50 percent for mass and ±20 percent for assay. One goal of the DOE deposit removal program is to assess these uncertainties.

[6] The cascades operate with $UF_6$, a very reactive form of uranium, which reacts with metal to form and deposit thin wall films of solid $UF_4$ (uranium tetrafluoride). The $UF_6$ also reacts quickly with moisture from in leakage of air to form solid deposits of $UO_2F_2$.

[7] Water acts as a moderator that slows down neutrons and enhances the chance of a $^{235}U$ nucleus capturing a neutron and fissioning (see Chapter 3 and Appendix G).

TABLE 2-6 Estimated Uranium Deposits at the Oak Ridge GDP

| | **Compressors** | | | Converters | | | |
|---|---|---|---|---|---|---|---|
| Building | Typical Surface Deposition (kgU) | % Equipment with Large U Deposits (% > kgU) | Maximum Deposit Measured (kgU) | Typical Surface Deposition (kgU) | % Equipment with Large U Deposits (% > kgU) | Maximum Deposit Measured (kgU) | Total (kgU) |
| | K-27 | 0.4 | NA[a] | 1 | 1 | NA | 1 1,000 |
| K-29 | 0.5 | 7% > 2 kgs | 60 | 1 | 5% > 2 kgs | 120 | 5,0000 |
| K-31 | 0.5 | 1% > 5 kgs | 20 | 2 | 9% > 5 kgs | 130 | 6,000 |
| K-33 | 0.5 | 3% > 30 kgs | 100 | 3 | 8% > 30 kgs | 120 | 11,000 |
| Total | | | | | | | 23,000 |

NOTE: Data for the K-25 building, which housed the enrichment equipment for achieving highly enriched uranium, is not shown because information on amounts of highly enriched uranium is classified. The deposits indicated in the table do not necessarily represent a criticality risk but are shown to indicate the extent to which uranium is still in the equipment.

[a] NA = Not applicable.

SOURCE: Faulkner (1994a,b).

TABLE 2-7 Estimates of Key Hazardous Contaminants at the Uranium Enrichment Facilities

| **GDP Site** | Asbestos ($ft^2$)[a] | PCBs | Lubrication Oils (thousand gal) | Freons®[b] (thousand lb) |
|---|---|---|---|---|
| Oak Ridge[c] | 3,230,000 | 20,000 gaskets; 125 drained transformers; 500 capacitors | Negligible | Negligible |
| Paducah | 3,000,000 | 16,000 gaskets; 73 transformers (285 metric tons of PCBs); 5,084 capacitors; 2,800 metric tons of PCB waste | 500 | 7,100 (in cascade) |
| Portsmouth | 4,962,000[d] | 155 transformers (700 metric tons of PCBs); 11,110 capacitors; 2,200 metric tons of PCB waste in storage | 600 | 6,700 (in cascade) 1,100 (in tank car storage) |

NOTE: Additional contaminants include $^{99}$Tc, $^{237}$N, chromated cooling water, mercury (in switches), cadmium, nickel, and various acids. Portsmouth also has 68 million pounds of lithium hydroxide in storage, the disposition of which is not included in the D&D cost estimates.

[a] As transite building siding, ceiling panels, and floor tiles (nonfriable) and as insulation for power cables, cable trays, water liner/heaters, and steam/condensate lines (friable). Significant quantities may also be radiologically contaminated; some may also be PCB contaminated.

[b] Primarily, CFC-114. Most material from the Oak Ridge GDP has been transferred to the Portsmouth and Paducah plants.

[c] Asbestos and PCBs are being removed from Oak Ridge, so estimates of PCBs and asbestos will change over time. For example, removal and disposal of approximately 9,500 PCB-containing capacitors has occurred; 20,000 gallons of lubrication oil has been incinerated; and the Freons® were sent to the Paducah GDP for reuse.

[d] There are also approximately 50 miles of asbestos insulation on pipes, 804,000 linear ft of asbestos cloth on instrument lines, and 10,000 linear ft of asbestos wiring.

SOURCE: Briefings to the committee during site visits and the Ebasco cost estimate (DOE, 1991a).

PCBs are also present in electrical components, such as transformers and capacitors. Where possible, transformers have been or are being drained, cleaned, and refilled with non-PCB oil. Capacitors are being incinerated and new non-PCB capacitors are being installed at the operating plants as required. Removal and disposal of about 9,500 PCB capacitors at the Oak Ridge GDP has occurred. A large number of PCB-contaminated components, including tens of thousands of capacitors, remain to be removed during D&D.

Asbestos is largely present in two forms: as nonfriable transite siding and as potentially friable insulation around piping. Miles of piping are insulated by asbestos products. Removal has already begun at the Oak Ridge GDP. To the extent that buildings are left standing and reused, removal of some transite walls could be avoided. BNFL experience during the D&D of the Capenhurst GDP in the United Kingdom showed that walls can be cleaned of radiological contamination and sealed to control asbestos dust prior to building reuse. All remaining asbestos piping insulation will require removal and disposal in an appropriate landfill. Hundreds of thousands of cubic feet of other materials containing asbestos, such as roof flashing, are also present.

Large quantities of lubricating oils and process coolants (CFCs) are used at the GDPs. At the Oak Ridge GDP, efforts were recently completed to dispose of these materials (DOE, 1993a). For example, the oil was burned at the Oak Ridge TSCA incinerator. The inventory that will remain at the Oak Ridge GDP and be considered a D&D cost is unknown but will likely be small. At the other two plants, alternative non-CFC coolants are being examined to replace existing coolants. USEC will be responsible for the disposal of non-CFC coolants whose disposal costs are expected to be lower than those for CFCs.

Because of the age of the buildings, much of the paint used over the years was lead-based. No estimates of area covered by this paint are available, but it is probably large. The cooling towers contain wood contaminated with chromium, which have been demolished and disposed of appropriately. Miscellaneous chemicals and contaminants include mercury, chromates, cyanides, fluoride compounds, organic solvents, and lead. To deal with lead paint, for example, the TLG cost estimate assumed removal by scabbling (DOE, 1991b). The surface material removed would have to be appropriately disposed of, and some sampling would probably be required. Cleanup of these materials does not represent a large component of the D&D cost estimates.

## STORAGE OF DUF$_6$

DOE has responsibility for the 528,000 metric tons of DUF$_6$ that are stored in approximately 46,000 steel cylinders at the 3 sites. The largest amount is at the Paducah site (Snyder, 1994). Since the Paducah and Portsmouth GDPs are operating plants, they continue to accumulate cylinders containing DUF$_6$. However, the DUF$_6$ produced since the USEC started operating the facilities is the responsibility of the corporation.

## SITE DIFFERENCES

While the three GDPs have many similarities, they have differences that can affect D&D cost. The three GDPs differ in the number, size, and physical arrangement of the stages and in the number and type of ancillary structures. Table 2-8 compares the number of stages, cells, and units by equipment size found in the process buildings at the three GDP sites.

The Portsmouth and Paducah GDPs are still operating. Current plans are to remove uranium remaining in the cascades at the end of their operating life through in situ gaseous decontamination using chlorine trifluoride ($ClF_3$), both to remove a significant amount of the uranium deposits and to eliminate nuclear criticality risks for remaining deposits in the cascade. As noted earlier, the removal of uranium deposits representing criticality risks is the responsibility of the USEC. If the in situ gaseous decontamination process is as effective for removal of uranium deposits at the U.S. GDPs as at the Capenhurst GDP, a planned and orderly shutdown that removed uranium deposits should significantly reduce concerns about criticality accidents and special nuclear material accountability during the disassembly and decontamination of cascade components.

In 1992, DOE ceased operations of the high-enrichment cascade at the Portsmouth GDP. The agency has been removing uranium deposits in this cascade using in situ gaseous decontamination, but some uranium deposits will remain. There are plans to test gaseous decontamination at room temperature (the temperature that would exist for this procedure in the nonoperating plant at Oak Ridge) using high concentrations of $ClF_3$.

When the K-25 and K-27 buildings at the Oak Ridge GDP site ceased operations in 1964, and the remainder of the plant shut down in 1985, no systematic in situ gaseous decontamination or mechanical removal was used to remove uranium deposits. As a result, the cascades contain deposits of enriched uranium, some quite large, and represent a potential criticality risk during D&D, especially in the K-25 building, which contains the high-enrichment section of the cascade. For this reason, as well as for control of special nuclear materials, the DOE has initiated a deposit removal program to remove, either mechanically or with low temperature gaseous treatment, highly enriched uranium deposits. The goal of phase I of this program is to remove deposits of more than 500 g in an unfavorable geometry from about 60 components in the Oak Ridge process equipment. The components, however, would not be cleaned to free-release levels. Tests by DOE on the low temperature gaseous decontamination process are aimed at assessing the applicability of the process to the Oak Ridge cascade.

The Paducah GDP differs from Oak Ridge and Portsmouth in that the maximum uranium enrichment level was about 2 percent, although its enrichment level increased to 2.75 percent in 1995. The low enrichment level diminishes the concern with nuclear criticality accidents and the need to safeguard highly enriched uranium. Thus, costs for safeguards, security, and criticality monitoring at the Paducah GDP should be less than for the other plants. The modification of the Paducah GDP to 2.75 percent $^{235}U$ product may increase somewhat the risk of a criticality accident during D&D.

TABLE 2-8 Cascades and Stages in the Process Buildings at the Three GDP Sites

| | | **Converter Equipment Size**[a] | | | | | |
|---|---|---|---|---|---|---|---|
| GDP | Item | 25 | 27 | 0 | 00 | 000 | Total |
| Oak Ridge | Stages | 3,018 | 540 | 300 | 600 | 640 | 5,098 |
| | Cells | 507 | 90 | 30 | 60 | 80 | 767 |
| | Units | 54 | 9 | 3 | 6 | 8 | 80 |
| | Buildings | 1 | 1 | 1 | 1 | 1 | 5 |
| Portsmouth | Stages | 1,620 | 720 | 600 | 500 | 640 | 4,080 |
| | Cells | 140 | 60 | 60 | 50 | 80 | 390 |
| | Units | 7 | 3 | 6 | 5 | 8 | 29 |
| | Buildings | 0.7 | 0.3 | 0.5 | 0.5 | 1 | 3 |
| Paducah | Stages | 0 | 60 | 0 | 800 | 960 | 1,820 |
| | Cells | 0 | 10 | 0 | 80 | 120 | 210 |
| | Units | 0 | 1 | 0 | 8 | 12 | 21 |
| | Buildings | 0 | 1 | 0 | 2 | 2 | 5 |
| Total | Stages | 4,638 | 1,320 | 900 | 1,900 | 2,240 | 10,998 |
| | Cells | 647 | 160 | 90 | 190 | 280 | 1,367 |
| | Units | 61 | 13 | 9 | 19 | 28 | 130 |
| | Buildings | 1.7 | 2.3 | 1.5 | 3.5 | 4 | 13 |

[a] The weights of the equipment can be found in Chapter 4, Table 4-8.

SOURCE: Faulkner (1994a); Person (1995b).

## RISKS SUBSEQUENT TO GDP CLOSURE

Subsequent to closure of a GDP, there may be risks to human health if some pathway allows significant exposure to the hazardous materials within the facilities. It does not appear to the committee that there is any current appreciable risk of exposure of the public to these contaminants (e.g., at the Oak Ridge GDP) because the vast majority of the contamination is contained within the plant systems. As the facilities age, and the containment integrity of the process equipment and buildings begins to fail, the risk of exposure of the public to the contaminants will tend to slowly increase.

Exposure to these hazard sources could develop in a variety of ways. If high levels of loose surface contamination are exposed to the atmosphere, contamination can be resuspended and transported inside and outside the structure. However, very high levels of loose surface contamination would be necessary for this pathway to be significant for public health, and, so far as the committee is aware, this situation is not the case. Human and industrial actions within the buildings could resuspend loose asbestos fibers, leading to airborne concentrations of friable asbestos and asbestos dust. These pathways are primarily of concern to building occupants, and techniques, such as removal, fixation, over painting, or ventilation, are available to control these risks. A major fire in the facilities could give rise to updrafts that send contamination into the atmosphere to be deposited on and off site and could also create toxic combustion products. A major fire could result in exposure of the public to contaminants, although it is likely that the bulk of the contamination would be deposited on site because of the relatively high settling velocities of particulates.

Rainwater, particularly after significant roof and process equipment decay, can transport contaminants into groundwater and surface water supplies. Public exposure could then result from the use of the affected water supplies for drinking, irrigation, or recreation. Atmospheric moisture and natural disasters (such as fires, earthquakes, high wind conditions, or flooding) could also accelerate degradation of the structures now restricting the mobility of contaminants. Failures of water services within the buildings, such as fire protection systems, could also wash contamination down through floor drains and over sills into the external environment. Continued exposure of $DUF_6$ cylinders to the environment could result in corrosive failure of the cylinders, particularly if they have been damaged during previous handling operations (DOE, 1992; DNFSB, 1995). A failed cylinder at ambient temperature could slowly release the $DUF_6$ and any other contamination from within a cylinder, although experience to date indicates that release rates would be very low.

Industrial safety risks from falls and falling objects is increased by degradation of the structural integrity of parts of the buildings, such as roofs, stairways, or handrails. These worker risks are a function of both building degradation and worker activity levels within the building and thus will increase during surveillance and maintenance and D&D activities. Because structural degradation will likely progress as time goes by, these risks will tend to increase over time. Maintenance can reduce these risks by correcting safety problems, although surveillance and maintenance workers would be subject to increased risks as a result of working in the aging facilities.

D&D activity allows other types of exposures, primarily to D&D workers. Cutting, grinding, and scabbling can result in liberation of vapors and particulate matter to the atmosphere. Industrial safety concerns during the extensive moving and lifting operations in dismantling process equipment would be significant, particularly if the structural integrity of the buildings were allowed to deteriorate before the start of D&D. Handling of the $DUF_6$ cylinders could also lead to worker exposures to hydrogen fluoride (HF) in the event of a cylinder rupture. HF is a reaction product generated when $UF_6$ gas comes into contact with moisture-laden air. It is an extremely corrosive vapor, even when diluted in air, and can cause ulceration of the larynx and trachea. Acute exposure to HF vapor, such as from the high-temperature rupture of a cylinder containing $UF_6$, can be fatal. However, HF dissipates relatively quickly, and concentrations at the site boundary from such a rupture could be expected to be minimal, although they would depend on atmospheric conditions. (See Chapter 7 for more discussion of potential hazards to workers and the public.)

Uranium (like many heavy metals) is nephrotoxic, causing kidney damage if ingested in sufficient quantities (Maynard and Hodge, 1949). The health effects associated with the heavy metal toxicity of uranium may be more significant than its radiological effects, particularly in the case of low specific activity isotopes such as $^{238}$U. The health effects of exposure to radioactivity are well documented (NRC, 1990). The radionuclides of concern in the diffusion plant complex emit primarily alpha particles and low-energy beta particles and therefore pose a health risk only if ingested or inhaled. Alpha and beta contamination inside process equipment does not pose an exposure threat to building occupants because the radiation associated with the contaminants is absorbed by the process equipment material. External surface deposits can pose an exposure risk, but occupant protection can be maintained by removal, partial removal, over painting of the deposits, or the use of appropriate respiratory protection. Gamma-emitting radionuclides, such as $^{235}$U, can create an external exposure risk, but this radionuclide appears to be present in significant quantities only in small portions of the Oak Ridge plant, for example, primarily in the high-enrichment sections of the process equipment.

PCB compounds are classified as probable human carcinogens (EPA, 1993) based on animal studies. PCB compounds are also toxic to the liver and reproductive system, and dermal exposure to concentrated PCB compounds can cause chloracne (Crine, 1988). Also, although PCB compounds are flame-retardant (which is the reason for their use), they can ignite at very high temperatures, and their combustion products can be extremely toxic. However, PCB compounds are typically composed of a mixture of chlorinated biphenyl isomers, and the physical and toxicological properties of these compounds vary widely.

Inhaled asbestos fibers are classified by the EPA as human carcinogens based upon epidemiological studies of occupationally exposed workers (EPA, 1993). Inhalation of high levels of asbestos fibers can also lead to asbestosis, an occupational hazard to building occupants, if high concentrations of asbestos fibers are allowed to persist and appropriate protection is not used.

Because of the presence of enriched uranium in areas of the facilities, the potential exists for an uncontrolled nuclear criticality event (see Appendix G for a discussion of the causes and consequences of such events). Criticality events create an acute risk to any nearby workers, which is dependent on the magnitude of the neutron burst during the event. These events also lead to the creation of fission products. Criticality risk varies with the degree of enrichment in $^{235}$U, the mass of enriched uranium, the presence of a moderator (such as water), and the geometry of the solid uranium mass (see Appendix G). Sufficient masses of enriched uranium to create a criticality risk may be present in deposits internal to process equipment, or may accrue from waterborne transport of soluble uranium (either in the process equipment or during improper aqueous decontamination operations). Within the facilities, water (either rainwater leaking through roofs or breaks in water service mains) may enter process equipment through breaches in the equipment. Such breaches can result from the removal of parts from shutdown process units or from seismic events or collapse of external structures. Finally, the process equipment was not designed to ensure safe geometries for uranium in aqueous solution. It appears that current efforts to remove uranium deposits from the equipment, combined with procedures to avoid water leaks into process equipment, will be adequate to avoid significant risks of criticality. However, active management and maintenance will be required until the enriched uranium deposits are removed from the process equipment.

## CONCLUSIONS

In summary, the GDP sites are large facilities with substantial quantities of contaminants. Conclusions pertinent to the D&D include the following:

1. Although the presence of radioactive and hazardous materials constrains the approach that can be taken to the D&D of these facilities, the D&D of the GDPs is basically a demolition project.
2. The repetitive layout and large numbers of pieces of enrichment equipment, and the open layout of the process buildings including overhead cranes and wide access doors, offer opportunities for simplified D&D activities and for economies of scale in the operations.
3. Large quantities of valuable metals are present in the GDPs. These include the nickel barrier membrane, which contains uranium deposits and some $^{99}$Tc contamination within its porous structure, and many miles of copper tubing that will have to be stripped of insulation.
4. Deposits of enriched uranium compounds are present within the process equipment, have been characterized reasonably well, and are large enough to present a criticality hazard in the presence of a moderator, such as water. The largest deposits occur at the Oak Ridge GDP.
5. Some deposits of uranium will be difficult to access in small-diameter tubing and piping, on compressor bearings and balding, and on valve bodies.
6. Data indicate that uranium and $^{99}$Tc contamination exists to some degree in all process buildings and in some support buildings.
7. The risks associated with the GDPs after shutdown are principally from DUF$_6$ cylinders and any remaining enriched uranium. Deteriorating structures will increase the risk. The risks to the surrounding communities are small, but they are not so small that these plants can be abandoned. Risks will increase with time, and D&D will be necessary.

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# 3

# Decontamination Processes

## INTRODUCTION

The major technology options for the D&D of the GDPs are outlined in this chapter. In addition to a brief description of the processes, comments are offered on the advantages and disadvantages of the technologies, with particular attention to their effectiveness, safety, and potential for cost reduction. The D&D experience at the BNFL Capenhurst GDP in the United Kingdom is also reviewed.

The normal sequence of decontamination operations is as follows:

- characterization or measurement of the contaminants present (radioactive and nonradioactive);
- removal of large uranium deposits;
- equipment disassembly and decontamination of surfaces;
- cleanup and demolition of buildings (assuming "greenfield"[1] scenario); and
- waste management (distribution of waste products to disposal or recycling).

The sequence of processes and options is illustrated schematically in Figure 3-1. D&D operations are conducted under strict regulations in hazardous environments and require extensive safety and health protection equipment, as well as criticality controls.

Characterizations of both radioactive and hazardous materials must be carried out before, during, and after decontamination. The techniques and instruments required for characterization of the GDPs are known and have been widely used (see Appendix E).

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[1] The term "greenfield" refers to the status achieved in returning a formerly contaminated site to free-release conditions, typically to a grassy field devoid of all buildings, former structures, and chemical or radioactive contamination.

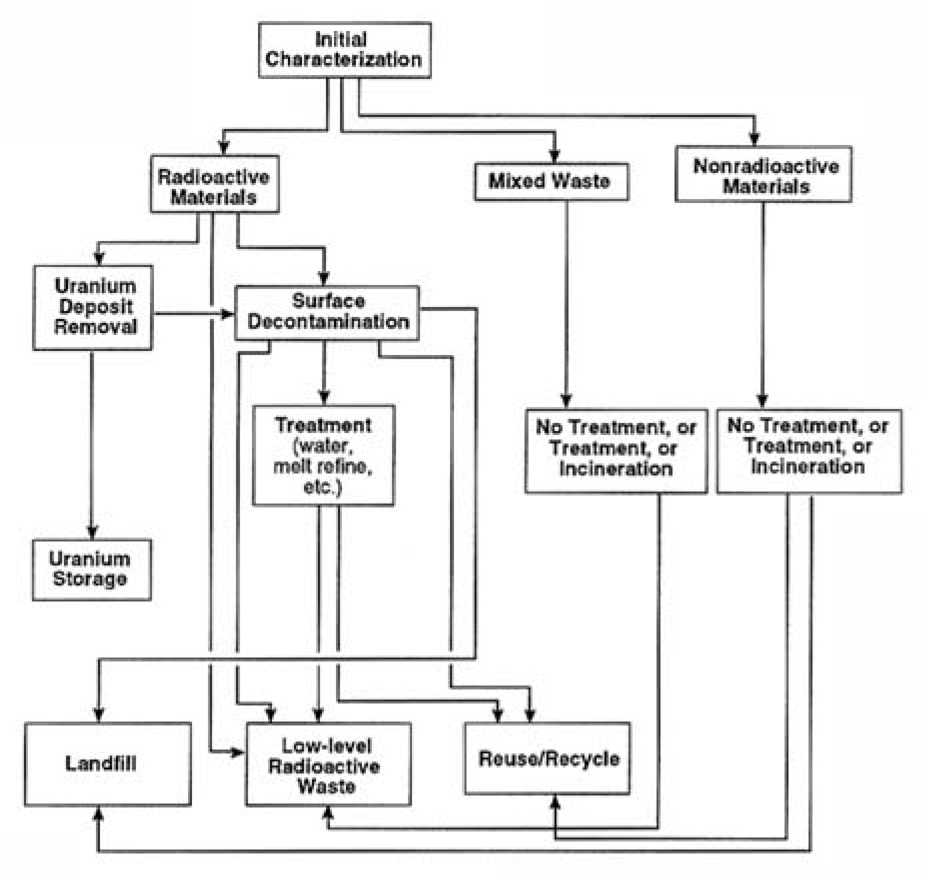

**FIGURE 3-1** Simplified decontamination flow diagram.

The removal of bulk deposits of enriched uranium compounds from the process equipment is conducted first, both to reduce the possibility of nuclear criticality and to resolve security concerns regarding special nuclear materials. Two major technologies for deposit removal have been demonstrated: hot gaseous decontamination, normally performed while the process train is in operating condition; and mechanical removal, normally performed on nonoperating units after disassembly.

Following bulk uranium deposit removal, internal surfaces of the process equipment are additionally cleaned. Candidate technologies include further gaseous decontamination, chemical removal using aqueous solutions, high-pressure water jet decontamination, and dry mechanical removal technologies (abrasive or carbon dioxide [$CO_2$] particle blasting). The last three processes require disassembling the process equipment and supporting systems.

Where building surfaces or external process equipment surfaces are contaminated, they can be cleaned by washing and wiping procedures, if contamination is light, or by various mechanical procedures, such as scabbling,[2] if surfaces are deeply contaminated, or abrasive blasting, if they are contaminated by tightly adherent coatings (e.g., paint).

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[2] Scabbling is a scarification (physical abrasion) process used to remove concrete surfaces. Scabblers incorporate pneumatically operated piston heads that strike the surface to chip off the concrete (DOE, 1994).

The technologies for performing the above decontamination operations are well known and have been demonstrated to be effective, for example, by the British D&D at Capenhurst and by the cascade improvement and cascade upgrade programs (CIP/CUP) of the U.S. GDPs. (Gaseous decontamination and aqueous washing were used during CIP/CUP, but there was no attempt to decontaminate to free-release levels; see "Capenhurst Technologies" and "CIP/CUP Technologies" later in this chapter.) Hazardous materials, such as PCBs, CFCs, asbestos, and lead paint, are known to be present in the GDPs and can also be handled with proven decontamination technologies.

The waste streams generated from the decontamination processes must be purified to release levels, recycled, or disposed of in burial sites. The waste management technologies are well established for the most part. As the cost of waste burial is increasing, or uncertain at best, a general guideline is to minimize the volume of any waste stream that is created by decontamination.

In the remainder of this chapter, the key features of technologies for each stage of the decontamination process are considered, together with opportunities for improvement. The discussion of cross-cutting areas, namely, characterization and robotics, follows the sections on deposit removal, decontamination, and waste management. The committee considered the potential of automation and robotics technology to reduce operating costs and improve safety conditions. Given the extensive technical literature on decontamination (see, for example, DOE, 1994b; DOE, 1995; DOE and IAEA, 1994), the committee felt that detailed descriptions of candidate technologies were inappropriate in the context of the present report.

The committee cannot assess the cost-benefit relationships of all of the various decontamination technologies as not only was comparative cost data lacking, but many uncertainties exist; for example, the degree and extent of contamination, the site end-states, waste release criteria, disposal sites, and disposal costs. New technologies continue to be proposed and the more promising should be investigated briefly; the committee, however, feels that it is important to initiate the D&D process without more years of delay. As mentioned above, the Capenhurst experience indicates that D&D can be performed in a cost-effective manner with existing techniques.

## NUCLEAR CRITICALITY

The presence of radioactive materials, specifically uranium, renders the D&D of the GDPs more complex and expensive than the demolition of large industrial plants without radioactive contamination. One distinguishing feature of the GDPs is the potential for nuclear criticality. Preventing criticality can be expensive, requiring intensive monitoring and small-scale processing under strictly controlled conditions. Thus, cost-effective D&D requires a clear understanding of where criticality will be a major concern, where it will be a relatively minor concern and easily handled, and where it is of no concern. At the GDPs, the risk of criticality during D&D is related to the sizes of deposits of uranium compounds in the process equipment, $^{235}$U enrichment levels, and the potential for the presence of a moderator (water) (see Appendix G).

The criticality hazard at the GDPs varies by site and among the buildings at each site; it can be ranked using historical characterization data, information on enrichment levels at each stage, and determinations of deposit size and location. The major concern with criticality during D&D is likely to be at the Oak Ridge GDP, particularly in the K-25 and K-27 buildings, where $^{235}U$ enrichment levels are highest. It has been noted that, for these buildings, the potential for a criticality incident is greater than any potential for health physics or worker safety problems associated with D&D operations (MMES, 1992). Some deposits reported at Oak Ridge GDP (Table 2-6), if they occurred near the top of the cascade, could present a criticality hazard during D&D, even in the absence of a moderator. Under these circumstances, preliminary removal of deposits—as in the ongoing K-25 Site Deposit Removal Program (see below)—is imperative. In contrast, at $^{235}U$ enrichment levels of less than 1 percent, it is essentially impossible to achieve criticality even with the most unfavorable geometry in the presence of water. Hence, there are many hundreds of stages at all three plants where criticality is not an issue during D&D.

Approaches to criticality prevention are addressed as appropriate in the following discussion of decontamination processes. Cost issues associated with criticality avoidance during D&D are considered in Chapter 6.

## URANIUM DEPOSIT REMOVAL

The first decontamination activity to be performed on GDP equipment is removal of any large uranium deposits. These deposits are the result of accidental occurrences, usually the leakage of moist air into the equipment, causing the formation of crusts of solid uranium compounds. The bulk of the crusts can be removed by gaseous treatment with $ClF_3$ or by mechanical means. The application of gaseous deposit removal techniques differs between operating plants, such as Portsmouth and Paducah, and nonoperating (or static) plants, such as Oak Ridge, because the operating plants can heat the $ClF_3$. The uranium deposits in the Oak Ridge plant have been characterized (Table 2-6) and must be removed to assure criticality safety and to conform to requirements for the safeguarding of special nuclear material.

The main features of both gaseous and mechanical treatments for deposit removal are summarized in the following sections. Ongoing or planned deposit removal activities at the Oak Ridge and Portsmouth GDPs are addressed. The primary objective of the K-25 Site Deposit Removal Program is to bring the Oak Ridge GDP site into compliance with DOE Order 5480.24 by removing, safely packaging, and relocating quantities of enriched uranium contamination deposited in piping and equipment (DOE, 1994a).[3] DOE plans to remove highly enriched uranium deposits that are greater than 500 g of $^{235}U$ and in a potentially unsafe geometry by 1999 (DOE, 1994a). Subsequent phases of this program plan for further removal of enriched uranium deposits. The use of both mechanical and gaseous methods for deposit removal is planned. Cleanup of the high-enrichment section at the Portsmouth GDP includes deposit removal (MMES, 1994). Work began in November 1991 and should be completed by the end

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[3] DOE Order 5480.24, "Nuclear Criticality Safety" (August 12, 1992), requires the risk of criticality to be less than $10^{-6}$.

of fiscal year 1995. Nondestructive assay measurements are made to estimate uranium compound deposit sizes, which are then reduced to below "safe mass" using in situ gaseous treatment. If equipment inoperability precludes in situ treatment, such as at the Oak Ridge plant, equipment disassembly and mechanical deposit removal are necessary.

The survey by MMES (MMES, 1994) for the Oak Ridge GDP shows that the $^{235}$U content in most converter stages amounts to less than 100 g per stage, which would not present a criticality concern during cleanup of individual converters; it will be a concern for deposits at the high-enrichment ends of the cascade. (Data on criticality limits for $^{235}$U compounds in solid form and in aqueous solution are provided in Appendix G.) Eliminating the criticality concerns for individual converters would reduce subsequent decontamination costs (Lacy, 1994). The extent to which additional deposit removal efforts will be necessary in the high-enrichment sections at Oak Ridge and Portsmouth subsequent to the deposit removal programs must await the results of these programs.

The Ebasco cost estimate (DOE, 1991) proposed uranium deposit removal by gaseous decontamination in three ways:

- hot in situ removal in an operating plant prior to final shutdown (suitable for Portsmouth or Paducah);
- in situ deposit removal in physically isolated sections using a portable gaseous decontamination unit at relatively low temperatures (suitable for Oak Ridge); and
- removal of the process equipment and piping followed by treatment in a specially designed hot gaseous decontamination cell in a high-assay decontamination facility or a low-assay decontamination facility.

## Gaseous Removal of Deposits

Gaseous removal of deposits can be carried out at an elevated temperature in operating cascades by introducing $ClF_3$ to the closed system. The $ClF_3$ fluorinates the solid uranium compounds present (primarily uranyl fluoride, $UO_2F_2$, and various other uranium fluorides) and removes them as $UF_6$ (uranium hexafluoride) gas.

The principal advantage of the gaseous decontamination process is that, for the operational Portsmouth and Paducah facilities, it could be applied at elevated temperature during an organized, planned shutdown.[4] Reported experience at the Capenhurst GDP in the United Kingdom, where approximately 80 percent of the uranium deposits were removed by treatment with gaseous $ClF_3$ prior to shutdown, suggests that much of the deposit removal can be conducted in situ (Clements and Cross, 1994). In contrast to mechanical deposit removal (see below), worker exposure to radioactivity in this process is minimized because it is totally contained in gas-tight equipment. In addition, criticality concerns are reduced because no

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[4] The time required for an organized shutdown could vary from several months to 2 or 3 years depending on the process conditions and desired extent of deposit removal (MMES, 1994).

hydrogen-containing materials, such as water, are used; the concentration of the $UF_6$ gas is low; and aggregation of uranium deposits is unlikely. $ClF_3$ treatment is an expensive operation.[5] However, removal of uranium deposits using an elevated temperature gaseous treatment has the potential to reduce costs substantially during subsequent decontamination of the cascade equipment as a result of reduced security controls, worker protection requirements, and contamination containment needs (Bundy and Munday, 1991). This advantage would apply primarily to the high-enrichment sections of the cascades.

The major disadvantages of gaseous decontamination are the danger in handling the toxic and highly reactive $ClF_3$, the difficulty of applying the technique at ambient temperature to partially dismantled process equipment as in the Oak Ridge plant, and uncertainty about the amount of uranium that will be removed.[6] In most cases the objective of past treatments was not decontamination but rather the improvement of gas flow impeded by the deposition of solids inside the process equipment or the removal of radioactive surface deposits to an extent that would allow operators to perform tasks requiring direct contact.

At Oak Ridge there is no in situ equipment (compressors) for heating isolated cascades, and the reactions are so slow at ambient temperatures that a cleaning cycle for one cell would likely require many months. However, a long-term, low-temperature gaseous process for deposit removal has been proposed that could be applied in situ to isolated portions of nonoperating plants as well as to operating systems (Bundy et al., 1994).[7] It has been suggested that this process might be capable of reducing uranium contamination to free-release levels with a sufficiently long treatment time (Bundy, 1994). Two demonstrations of the long-term, low-temperature treatment have been proposed. Work has commenced at the Oak Ridge GDP on a mobile $ClF_3$ demonstration unit to treat small units of the cascade equipment, such as converters and pipe sections. Heating of the unit may be tried to accelerate the removal process. A demonstration of the long-term, low-temperature process for deposit removal and subsequent decontamination is planned for an entire cell that was used for highly enriched uranium production at Portsmouth. The demonstration at the Oak Ridge GDP should be informative in choosing a bulk uranium removal process for this plant. The results from both demonstrations

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[5] The cost to clean a cell (8 to 12 stages) in the shutdown high-enrichment section of the Portsmouth GDP to a critically safe condition using $ClF_3$ is currently estimated to be $250,000 to $500,000 (Meehan, 1995). However, these costs represent those for a cascade that has already been shut down and could be considerably less for an organized shutdown of an operating plant, which preliminary estimates indicate would cost about $6.3 million over a 1-year period for each operating plant (personal communication from Richard Faulkner, Oak Ridge National Laboratory, to James Zucchetto, NRC, August 23, 1995), a cost of $31,000 per cell. Such projections are uncertain, and the actual cost is unclear to the committee.

[6] The technical bases for the gas-phase removal of deposits are at present incomplete. While the fundamental reactions of $ClF_3$ with $UO_2F_2$ or uranium tetrafluoride, $UF_4$, are well understood and kinetic data have been obtained under well-controlled laboratory conditions, the data obtained during the treatment of plant equipment over a period of many decades are not readily available. Uranium recovery rates of 70 to 98 percent have been reported (Bundy and Munday, 1991). In tests at Portsmouth, Netzer found that repeated fluorinations were not successful in totally removing uranium deposits (Netzer, 1994).

[7] The process operates at ambient temperature (75°F [24°C]).

should be useful in determining the degree of decontamination that can be achieved through treatment with $ClF_3$, although a decision to use this technology would also depend on cost.

The porous nature of the nickel barriers—and their correspondingly large surface areas—impose special decontamination requirements. The evidence presented to the committee indicates that gaseous treatment with $ClF_3$ will remove the bulk $UO_2F_2$ deposits but is unlikely to remove all of the adsorbed uranium on the barriers (Bundy, 1994). Further decontamination using aqueous or other techniques will probably be necessary. Research and development is currently in progress to determine whether an ion exchange process can be developed in which specific ions are introduced to stimulate the extensive removal of uranium and $^{99}$Tc (technetium) retained by the barrier material during gas phase treatment.[8]

## Mechanical Removal

Uranium deposits can be removed by mechanical means, which requires the disassembly and dismantling of the process equipment, such as converters and compressors. The internal surfaces are then scraped, wire-brushed, or abrasive-blasted to remove the uranium crusts, a labor-intensive process requiring extensive health and security precautions. A glove box in a special deposit removal room has been used at Oak Ridge to demonstrate the feasibility of removing deposits mechanically from certain components, such as pipe sections and compressor parts, where criticality is an issue. Critically safe vacuum systems are used to collect and package the removed deposits in critically safe containers.

## Aqueous Spray Removal

During CIP/CUP at the U.S. GDPs between 1974 and 1981, gaseous deposit removal using $ClF_3$ was followed by aqueous solution spray booth treatment of disassembled process equipment for further uranium removal (Faulkner, 1995). Pieces of equipment were run through spray booths (analogous to a car wash), where they were washed using aqueous solutions, such as 5 percent nitric acid, and then rinsed with water. Cleaned pieces were surveyed for remaining contamination and sent through the spray booth system a second time if necessary. The objective was not to clean to free-release standards but to remove transferable contamination so that the equipment could be reassembled for use without the risk of spreading contaminants.

The diffusion barriers were removed from the converters and also run through the spray booths, but removal of uranium was difficult. The barriers were subsequently cut up using high-pressure water jets or mechanical saws. The nickel was separated from other material and the nickel pieces were packaged in 30-gallon drums. The drummed nickel pieces were eventually shipped to Paducah and the nickel barriers melted into ingots.

In the spray booths, criticality was avoided by keeping the bulk wash solutions in piping and troughs that had critically safe geometries. For example, pipe diameters were limited to 5 inches. The spray booths at each GDP were designed to provide criticality safety for the levels

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[8] Personal communication from Earl Munday, Martin Marietta Energy Systems, to Alfred Schneider, Member of the Committee on Decontamination and Decommissioning of Uranium Enrichment Facilities, March 13, 1995.

of enrichment at the plant. However, only low-enriched material was of concern during CIP/CUP activities.

Again, deposit removal can be accomplished in several ways: using gaseous $ClF_3$, mechanical removal, or an aqueous spray. The choice of an approach depends on the cost effectiveness of each of these processes for any particular case, and in some cases, on criticality considerations. It is likely that some combination will be optimal. For example, criticality is not a problem for low-enrichment cells, and simple dismantling, cutting up, and aqueous spray removal could be used. At Portsmouth, $ClF_3$ was used effectively at the time of shutdown for the high-enrichment cells. The reported high cost of $ClF_3$ treatment ($250,000 to $500,000/cell; Meehan, 1995) suggests that mechanical and aqueous spray need to be considered, though better estimates are needed for the cost of $ClF_3$ treatment during an orderly shutdown of an operating plant. For higher enrichment cells at the Oak Ridge GDP, the difficulties of applying $ClF_3$ favor mechanical removal or possibly aqueous spray removal. The spray booth technique is not suitable for all deposit removal. Criticality concerns can limit the use of aqueous spray methods, depending on the geometry of the materials, mass of the deposit, and $^{235}U$ enrichment level. The washing process can result in criticality before the wash solutions enter the critically safe piping system of the spray booth. Under such circumstances, addition of a moderator (water) should be avoided, and the deposits would most likely be removed by dry techniques.

## DECONTAMINATION OF CASCADE EQUIPMENT

The use of aqueous decontamination techniques for the GDP cascade equipment is addressed immediately below; further details of the aqueous process used at the Capenhurst GDP are given later in the chapter. Despite some suggestions that gaseous treatment with $ClF_3$ might be used for decontamination of cascade equipment to free-release levels, available data from maintenance programs and CIP/CUP activities indicate that some uranium deposits are slow to react and will be difficult to remove with $ClF_3$.[9] In the committee's opinion, cleanup of the cascade equipment to free-release levels will require aqueous decontamination methods and cannot be reliably achieved solely by gaseous $ClF_3$ treatment.

### Disassembly

Large process equipment components (such as converters, compressors, motors, valves, and coolers) need to be disassembled and decontaminated. Subassemblies are removed (cut out) from major components and carried to a central location for further dismantling and decontamination. The repetitive nature of the operations may favor the use of automation and robotics.

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[9] Based on presentations at the committee's Portsmouth meeting (Crawford, 1994) and committee member Alfred Schneider's classified visit to the Oak Ridge site.

## Aqueous Decontamination

The removal of uranium deposits by aqueous solutions is a well-established procedure and was used at the Capenhurst GDP in the United Kingdom to decontaminate most of the equipment. The principal contaminant, $UO_2F_2$, is readily soluble in water. The behavior of lower valence state uranium fluorides and oxyfluorides is less well characterized (see, for example, Ritter and Barber, 1991), but these species are successfully removed by aqueous solutions of acids in the presence of air or other oxidizing agents. Since cleanup of the wash solutions is an important contributor to the cost of aqueous treatments, care is needed in the selection of the solutions to minimize the waste disposal problem.

Two different physical arrangements have been used in aqueous removal of uranium from gaseous diffusion equipment. At Capenhurst, cut-up pieces of equipment were dipped in a series of washing tanks. During CIP/CUP activities at the U.S. GDPs in the 1970s, pieces of equipment were run through aqueous solution spray booths, as described. An attractive arrangement for D&D might be to use both of these physical arrangements (Faulkner, 1995). Following removal of residual large deposits of uranium by mechanical means (e.g., at K-25), the cut pieces of equipment could be run through spray booths to remove most of the uranium, and then through a series of dip tanks for final decontamination. It is likely that many pieces—perhaps the majority—would be sufficiently clean initially to bypass the spray booths and go directly to the dip tanks. The spray booth treatment could still make unnecessary much of the labor-intensive mechanical removal, while giving good uranium recovery in a criticality-free arrangement.

Metal surfaces may be contaminated with $^{99}$Tc, as well as uranium, and with very minor quantities of other radionuclides (see Chapter 2). While these contaminants are not expected to be a problem in most of the cleanup, there may be occasions when modified wash solutions may sometimes be needed to remove these contaminants to acceptable levels. $^{99}$Tc was particularly difficult to remove during the Capenhurst D&D.

When uranium is mixed with water, the danger of criticality is greatly increased because the presence of the light element hydrogen slows or moderates neutrons and increases their chances of fissioning $^{235}$U nuclei (see Appendix G). Criticality is affected by the mass of uranium present, the degree of $^{235}$U enrichment, the presence of moderators, and the nature of material surrounding the fissioning material that can reflect neutrons back toward the $^{235}$U. The geometry of the system can either enhance or limit the loss of neutrons from the system, and some materials, such as boron, cadmium, and gadolinium, can absorb neutrons and prevent them from fissioning $^{235}$U. In an aqueous process for decontamination, criticality prevention can be attained by several means:

- limiting the mass of $^{235}$U through continuous monitoring of its concentration, as was done at Capenhurst;
- using geometrically safe equipment, as was done in U.S. facilities during upgrading of GDP equipment; or

- inserting of neutron absorbers, or "poisons," such as boric acid. The preferred form is solid, but soluble poisons may also be used. However, soluble poisons may inadvertently precipitate from solution.

Measures to avoid criticality conditions engender additional costs. Attention must be paid to the double-contingency principle, which requires that no single mishap, regardless of its probability of occurrence, can lead to criticality. This principle requires that two unlikely, independent, and concurrent changes in process conditions occur before criticality is possible.

The aqueous decontamination process produces radioactive wastes that must be managed safely. The uranium can be removed and recovered from the wash solutions by evaporation, precipitation, ion exchange, or solvent extraction. The bulk of the water can be reused. Solid wastes containing uranium and $^{99}$Tc compounds will be produced. Organic acids in the decontamination wash solutions can be reused, biodegraded, or chemically destroyed.

For the D&D of Capenhurst, the British had a volumetric contamination standard for the free-release of cleaned material. Although analogous volumetric standards do not currently exist in the United States, it seems probable that decontamination from uranium can be successfully accomplished at the U.S. GDPs by an aqueous process. The specific aqueous treatment to be used merits some development work to determine the best alternative for design of the washing equipment and the choice of cleaning solutions. Replacement of citric acid (used at Capenhurst) by oxalic acid has been suggested (Anderson, 1994). Work at Battelle Columbus Laboratories indicates formic acid may be a desirable alternative.[10] These two proposals, and possibly others, merit consideration.

As noted above, the nickel barrier contains uranium deposits within its porous structure. The removal of $^{99}$Tc, which may be present in some of the barriers, must also be addressed. Information on the efficacy of aqueous treatment for decontamination of the barriers is ambiguous. Experience in decontamination processes, notably during the CUP, provides some basis for optimism that aqueous methods can be used successfully for barrier decontamination. However, the chemical nature of the uranium complexes and the physical characteristics of the barrier material suggest that aqueous treatment with the usual decontamination agents may not be adequate.

Three possible alternative methods have been proposed for decontamination of the barriers; namely, aqueous electrolytic dissolution and redeposition, conversion to nickel carbonyl (Mond process), and melt refining. Melt refining is not expected to remove the $^{99}$Tc. There is evidence that electrochemical techniques can be used to remove $^{99}$Tc and reduce the radioactivity level to meet unconditional clearance levels of 0.3 Bq/g (8 pCi/g) recommended by the International Atomic Energy Agency (see Table E-7). This electrochemical process is estimated to cost $2/lb of nickel (Carder, 1994). Because of the value of the nickel, the committee believes that a limited effort is justified in seeking a cost-efficient process for decontamination of the barrier material.

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[10] Personal communication from Rajiv Kohli, Battelle Columbus Laboratories, to James Zucchetto, National Research Council, December 12, 1994.

## DECONTAMINATION OF SUPPORT SYSTEMS AND BUILDINGS

### Radioactively Contaminated Support Systems

The large-scale equipment of the cascades is supported by a great deal of piping, ductwork, electrical equipment, instrumentation tubing, and so forth, which is contaminated with small amounts of uranium. Easily cleaned pieces could be treated by aqueous wash, but much of this equipment, for example, small-diameter piping, is not amenable to such cleaning. In some cases, it may be worthwhile to decontaminate through melt refining. In other cases, the best disposition option may be compaction and low-level radioactive waste disposal. In practice, the extent of decontamination will depend on both waste disposal costs and recycle standards.

### Radioactively Contaminated Interior Building Surfaces

Mechanical decontamination techniques for uranium contamination of parts of floors, walls, and structural components of the buildings, including washing, blasting, grinding, scabbling, scarifying, drilling, electropolishing, and ultrasonic cleaning, appear to be the most promising for these applications.[11] In some cases, simple wiping with a rag may suffice. In other cases, removal of the surface to an appreciable depth may be necessary, as for example for contaminated concrete floors. Robotic equipment may be effective for much of the work, as discussed below. The large volume of material resulting from such mechanical decontamination processes will require disposal as low-level radioactive waste.

### Removal of Nonradioactive Hazardous Material

As noted in Chapter 2, significant quantities of nonradioactive hazardous materials are present at the GDP facilities, including PCBs, CFCs, asbestos, and lead-based paints.[12] There are also smaller quantities of other hazardous materials present, such as lubricating oils and greases, mercury in electrical switches, and chromium-contaminated wood in the cooling towers.

Proven technologies are available for removal of all of the contaminants identified at the GDP sites. In most cases, off-the-shelf, commercial technologies, such as incineration, can be used if there are no radioactive residues mixed with the hazardous materials. If radioactive contamination is present, then these methods may have to be modified to handle the materials before, or as a part of, final disposal. An exception occurs at Oak Ridge, where the TSCA incinerator handles mixed waste. Melt refining might be used to treat metal ducts contaminated with both radioactivity and PCBs. The committee believes that robotic devices may be useful in activities such as dismantling contaminated ductwork, stripping asbestos from piping, and stripping paint from structural steel to significantly reduce decontamination costs.

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[11] An extensive listing of mechanical decontamination technologies is given in the Decommissioning Handbook (DOE, 1994).

[12] The disposal of CFCs is unlikely to be a major problem, since these compounds are currently being used to extinction at the GDPs. PCBs are persistent, and it is therefore undesirable to add them to a landfill. At concentrations above 50 ppm their disposal is regulated, and burial is not permitted.

## WASTE MANAGEMENT

Some general guidelines govern waste management. The creation of secondary wastes from treatment should be minimized because such wastes usually must be treated and disposed of. For example, if floors are washed with large quantities of water, that wash water must be cleaned before it can be released. High disposal costs suggest that serious consideration be given to reduction of waste volumes. For example, a waste compactor should be included as part of the low-assay decontamination facility as assumed in the Ebasco cost estimate. Waste materials are either cleaned sufficiently for free-release, recycled, or buried. The disposition of the waste is governed by the level of radioactivity compared to release standards, the demand for and acceptance of recycled materials, and the cost of burial.

All decontamination processes yield some form of waste that must be managed safely and economically. These waste streams vary considerably, ranging from fragments of solids removed mechanically from converters to water from washing down walls. Accordingly, waste management must deal with handling solids, liquids, and gases containing various quantities of hazardous and radioactive materials. Established technologies exist for waste management (DOE, 1994b). A more detailed discussion of waste management issues is given in Appendix I.

The only materials at the GDPs with sufficient value for recycling are probably some of the metals (steel, stainless steel, nickel, copper, aluminum, and small quantities of mercury) and possibly the CFC refrigerants. Much of the structural steel is uncontaminated or very lightly contaminated and would require only minimal cleaning before release. As noted above, CFC refrigerants from the Oak Ridge GDP have been put to use at the other GDPs. It is likely that the current refrigerants used at the Portsmouth and Paducah plants will be replaced before the plants close; remaining refrigerants might be sold, converted to other useful compounds, or destroyed.

Melt refining, or liquid melt-slag technology, is suitable for compacting and purifying contaminated metal process equipment and accessory equipment after initial deposit removal or after subsequent surface decontamination (Worcester et al., 1993). Metals that can be treated by this process to remove uranium include mild steel, stainless steel, nickel, and copper. Thermodynamic considerations indicate that uranium cannot be removed from aluminum by melt refining. A melter unit currently operating at the Scientific Ecology Group facility at Oak Ridge has been used to treat iron and steel. Melt refining is a technically attractive option for recycling steel because the uranium can largely be removed in the slag, with the residual uranium being on the order of 1 ppm (Cavendish, 1978). Any $^{99}$Tc present that was not removed in a previous aqueous decontamination step, however, will not be removed to any great extent in the slag and will likely require special treatment. Melting substantially reduces the volume of material that must be disposed of, so disposal costs should be reduced accordingly. An additional benefit of melt refining is that organic surface contaminants, such as PCBs, are destroyed in the process.

The recycled metal may be released for unrestricted use if release standards are met or for restricted use in DOE facilities. In the latter case, it could be used for shielding blocks or waste canisters, thereby avoiding both the cost of procuring virgin metal and the cost of disposal. A dedicated facility located at a nuclear site—such as the Scientific Ecology Group facility at Oak Ridge—is necessary to melt, cast, roll, and fabricate the lightly contaminated material. While metal waste canisters would be buried, some safeguard would be needed to ensure that other contaminated steel (e.g., shielding blocks) was not inadvertently released to the commercial market.

To determine the cost effectiveness of recycling the metals from the GDPs, additional data are required on the cost of recycling and the capability of melt refining (or other techniques) to remove radioactive contaminants, as well as the cost of disposal. However, without clearly defined release standards (see Chapter 5), the cost effectiveness of recycling technologies cannot be determined with confidence. The availability of uniform release standards in the near future would greatly expedite recycling tradeoff studies.

The cost of waste disposal at low-level radioactive or toxic waste sites depends on the volume to be stored. Consequently, chemically or thermally treating asbestos to increase its density and create a non-toxic waste form might be attractive. The economic payoff might arise from the savings in long-term storage and the avoidance of double bagging normally required for asbestos. A cost study of such an option would be worthwhile.

## CHARACTERIZATION

Characterization of hazardous substances to determine their identities, forms, amounts, and locations will be needed before, during, and after the D&D operation. An initial survey will identify contaminated areas and estimate the magnitude of the cleanup effort needed at that location, where existing data are insufficient for these purposes. Monitoring will be performed during D&D for worker protection and criticality prevention and to determine the effectiveness of cleanup. Following D&D, characterization will again be needed to ensure compliance with regulatory limits before releasing the site, wastes, or reusable materials and equipment. The following discussion addresses the characterization approach and technologies for radionuclides and for hazardous nonradioactive substances.

### Radionuclide Measurement Techniques

Survey techniques and detection instruments for radionuclides have been widely used at the three GDPs for monitoring routine operations, repairs, and plant upgrading. The suitability of available procedures and instruments and of systems under development for characterization associated with D&D has been evaluated (DOE, 1993b, 1994b; Appendix E). Existing characterization techniques should be adequate to ensure compliance with limits prior to the release of GDP sites, wastes, or reusable materials, unless the new concentration limits now under development as decommissioning limits or guidelines are significantly lower than current values. Appendix E discusses recent developments in radiation monitoring that may be applicable to D&D. Opportunities for the use of robotic systems to characterize both radionuclides and hazardous nonradioactive materials are discussed below.

In general, a carefully planned combination of field and laboratory measurements is needed to provide reliable information. In most instances, the radionuclides other than uranium cannot be determined by in situ monitoring, but require laboratory methods since they are difficult to detect in the presence of uranium or are contained in enclosed spaces.[13] Special studies have identified locations where these other radionuclides are concentrated. In particular, the general locations of $^{99}$Tc at the Oak Ridge and Paducah plants—and probably also at the Portsmouth plant—are reasonably well known.

The initial survey to locate uranium accumulation within the cascade system can be performed by gamma-ray or neutron measurements with detectors placed on external surfaces.[14] In the structures that house the cascades, an extensive initial survey for contamination external to the cascades can be avoided for several reasons: monitoring will be performed in the next phase of decontamination operations for worker protection, low-levels of gamma radiation near cascade units will be overshadowed by radiation from uranium and decay products within the units, and contamination on surfaces may be increased by the cascade dismantling process.

Information on radionuclide levels of areas and structures beyond the actual cascade facilities that are known to be contaminated should be available in reports of routine monitoring and incident responses. A site-wide survey will be necessary for this purpose only if the available data are not sensitive or complete enough or if they are so difficult to convert to a consistent database that a new survey would be more cost effective. An initial survey of areas and structures believed to be uncontaminated is desirable to confirm that these locations are available for storing decontaminated materials and ready for dismantling and other activities leading to release of the site.

### Hazardous Nonradioactive Materials

The methods for characterizing the hazardous materials present at the GDPs are well established (DOE, 1994b). No development work is necessary. The challenge will be to identify the number of samples required for adequate coverage and yet keep the characterization costs to a minimum. The use of available records and inventories should help minimize the amount of physical sampling. The repetitive nature of the process equipment and building structure can also be used to advantage to minimize the physical and chemical characterization program for hazardous materials.

## AUTOMATION AND ROBOTICS

The enormous physical size of the GDPs and the many modules of repetitive, standardized equipment may provide opportunities for automation of processes and data management. However, the degree to which robotics and automation can be used cost effectively in the D&D of the GDPs is currently uncertain. Successful implementation of automated and

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[13] The non-uranium isotopes, $^{239}$Pu, $^{237}$Np, and $^{99}$Tc cannot be monitored in the presence of uranium. The higher level of radiation from uranium masks the presence of the other isotopes that are present in very low concentrations. In addition, uranium is monitored using neutron interrogation devices. However, $^{99}$Tc, for example, is a soft beta emitter that is difficult to monitor on exposed surfaces and undetectable when inside piping or equipment.

[14] A very extensive nondestructive assay survey for $^{235}$U deposits in the process equipment has already been conducted at the Oak Ridge site (see Chapter 2).

robotic systems will require carefully planned and well-defined processes and techniques, based on experience with manual operations, to take advantage of the "learning curve." A focused, application-driven robotics development program in DOE's Office of Technology Development (EM-50) is addressing many of the areas discussed by the committee (see Chapter 6 on cost reduction and Appendix F for more detailed discussion of automated and robotic systems for D&D, including related DOE programs).

Various automated and robotic devices are commercially available for use in labor-intensive decontamination and disassembly processes. Automation and robotic technologies offer the possibility of cost reduction and improved safety for characterization, disassembly, decontamination, and material handling operations. For some tasks, hostile environments may justify the use of simple remotely controlled (teleoperated) devices for specialized work that is not labor intensive. For large numbers of repetitive tasks in structured environments, development of specialized automation (robotic and telerobotic devices) may be justified. These developments do not require fundamental research or new technologies but rather the adaptation of proven systems to specific D&D applications. Many of these opportunities and examples of such systems have been identified and discussed (DOE, 1993a, 1994b). In most cases, demonstrations are necessary to analyze the benefits, to develop the most effective operational techniques, and to train existing operators in the new systems and techniques. Logic diagrams to assess technology have been developed for environmental restoration/waste management problems at the Oak Ridge GDP site (DOE, 1993b) and have identified numerous opportunities for robotics during the D&D (Bundy et al., 1993).

Characterization will be a continuing activity during D&D operations as has been noted. Characterization consists of two operations: sampling and analysis. Manually, these are labor-intensive, repetitive operations—often requiring personnel protection and possibly large numbers of sampling points to obtain statistically reliable results. Since robots are consistent, repetitive, and patient under these conditions, their use can result in better quality data. The Mobile Autonomous Characterization System, a mobile robot, is under development at Oak Ridge National Laboratory, and evaluation tests are planned for the Oak Ridge GDP (see Appendix F; Richardson, 1994).

Characterization of less accessible areas, such as walls and ceilings, the cluttered areas around piping and process equipment, underground piping, and the internal surfaces of tanks, is not as easy for robots and will require some development work and demonstrations. However, there could be a large payback for developing of these systems. Commercial teleoperated pipe crawlers have been developed to work inside pipes and ducts. These systems may be appropriate for the GDPs.

A centralized computer database to integrate and coordinate the total information system, including both planning and operational processes, is desirable for the complex environment of the GDPs. Although real-time processing of data is desirable, a large amount of off-line processing and analysis may also be required. Automated analyses of samples collected during characterization are potentially attractive given the large volumes of data that must be handled. Such analyses are very labor intensive and time consuming.

In a highly automated system, most equipment might be dismantled and decontaminated at central facilities rather than in situ. Robotic systems for disassembly, dismantling, and transportation to a central decontamination facility are feasible and are currently under development (Thompson and Dockstader, 1994). Large systems could be dismantled remotely, eliminating the need for many of the operational personnel to wear protective clothing, and transported to a contained central disassembly/decontamination facility for further dismantling, cut-up, and aqueous decontamination.

Miles of contaminated piping and ductwork must be removed. Robotic systems are being developed for these specialized operations (see Appendix F). Removal and compaction of asbestos from pipes and ducts is a viable application. Technology demonstrations and analysis for an asbestos removal system are currently underway (The Robotics Institute, 1995). In practice, automated methods may be limited to long straight sections of pipe, which are the majority of ducts and piping at the GDPs.

The mobile robotic systems under development for characterization tasks might be re-equipped with the necessary tooling and re-employed for the decontamination of floors, walls, and ceiling surfaces. Remote and/or autonomous operations for mechanical tools, such as concrete scabblers, torches, cutting tools and scrapers, and water jets and other blasting operations, have been demonstrated and rated as a high priority need in an assessment of decontamination needs (Bundy et al., 1993). Most of this equipment is commercially available and requires only minimal adaptation to existing automated and robotic systems.

## CAPENHURST TECHNOLOGIES

The Capenhurst GDP was operated by BNFL in the United Kingdom from 1956 to 1982. The plant was very similar in design to the U.S. GDPs, although significantly smaller in production capacity and physical size.[15] D&D of the facility commenced in 1982 and is scheduled for completion in late 1995 (Baxter and Bradbury, 1991; BNFL plc, 1990; Clements, 1992; Clements and Cross, 1994; Cross, 1995; Spencer, 1988). The most significant task remaining is the cleanup of approximately 4,000 tons of metals (1.5 percent of the materials from the plant) contaminated with uranium, $^{99}$Tc and neptunium ($^{237}$Np) that could not be treated cost effectively by the aqueous decontamination process. The costs of D&D for Capenhurst are presented and analyzed in Chapter 4, and other details are presented in Appendix H. The present discussion provides a brief overview of the decontamination processes used at Capenhurst, many of which are applicable to the U.S. GDPs.

With regard to decontamination processes, the most significant differences between Capenhurst and the U.S. GDPs are as follows:

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[15] The maximum electric power usage at the Capenhurst plant was 300 MW, compared to 1,725 MW at the Oak Ridge GDP. The total area of the Capenhurst plant was 64.4 acres, compared to 250.2 acres for the Oak Ridge GDP.

- At Capenhurst, the process piping and converters were mostly made of aluminum, although many were nickel-plated steel; at the U.S. GDPs these components are made of nickel-plated steel.
- The feeding of reactor-recycled $UF_6$ containing $^{99}Tc$ to the cascades was more prevalent at Capenhurst than at the U.S. GDPs.[16] Therefore, there should be a smaller concentration of $^{99}Tc$ in the material to be removed at the U.S. plants.
- In the United Kingdom, the Radioactive Substances Act (Substances Exemption Order, 1986) provides the framework for unrestricted release of materials for recycling.[17] Comparable volumetric release criteria do not currently exist in the United States.
- At Capenhurst, the cascade equipment was located on the first floor of the process building, whereas at the U.S. plants the cascade equipment is located on the second floor.

### Removal of Uranium from the Capenhurst Enrichment Cascades

At the Capenhurst plant, gaseous $ClF_3$ (chlorine trifluoride) was circulated through the cascade equipment prior to shutdown and dismantling to convert residual uranium deposits to volatile fluorides prior to opening up the cascade system. This $ClF_3$ treatment removed an estimated 80 percent of the $UO_2F_2$ deposits, substantially reducing the probability of a criticality accident during subsequent decontamination operations. Following gaseous treatment, further cleanup and pretreatment operations were carried out on the static plant to remove any significant remaining pockets of contamination and permit safe and cost-effective intrusions into the plant during the dismantling campaigns. Cleanup techniques included vacuuming, ridding, and machining. At the time the plant was shut down, radiological and criticality data were gathered for use in D&D planning and execution.

### Decontamination of Equipment from the Capenhurst Cascades

The initial phase of disassembly involved the cut-out, removal, and storage of compressors, coolers, valves, large-diameter pipe, and large process stage units.[18] Specialized workshops were built for component stripping and dry cleaning of equipment from the high-enriched section of the plant. Protection of personnel was achieved by effective ventilation and extensive alpha-in-air monitoring throughout the facility. Strict criticality prevention systems were applied at each stage of the dismantling.

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[16] Only natural uranium feed was used in the high enrichment section of the Capenhurst plant.

[17] Release levels are 0.4 Bq/g (0.01 pCi/g) total alpha and beta with an exemption for uranic alpha of 11.1 Bq/g (0.3 pCi/g) (Cohen and Associates, 1994).

[18] The cascade equipment was removed and stored outdoors for up to 9 years until the new decontamination facility was available.

Large components, such as converter shells, piping, and compressors, were reduced in size and weight to meet the physical size limitation requirements of the aqueous decontamination plant and the melter. Both hot and cold cutting methods were developed and used. Cold cutting was preferred over hot cutting for aluminum components because cold cutting does not generate fumes or airborne aluminum oxide fines, thereby reducing the need for costly heating, ventilation, and air conditioning systems. Robotic plasma-arc cutting was used for size reduction of large aluminum converter shells, and remotely controlled oxyacetylene methods were used for cutting steel converter shells and other steel components.

A wet decontamination process was used to reduce uranic contamination down to free-release levels (Anderson and Faulkner, 1989). While chemical treatment for the removal of uranium and its daughter products is a well-established process, $^{99}$Tc is difficult to remove effectively. A means of removing $^{99}$Tc had to be developed before effective disposal routes could be determined. Following extensive laboratory and pilot plant investigation, a full-scale decontamination plant was built in 1989. The flowsheet was based on achieving plant discharges having a negligible impact on the environment and on satisfying the United Kingdom's statutory regulations for recycling scrap metals to the open market.

The decontamination was achieved by dipping the metal pieces in a series of 10 tanks alternately containing wash and water-rinse solutions. The first tank contained citric acid, the third and seventh sulfuric acid, and the fifth and ninth disodium citrate as the main decontaminant. Most of the uranium and $^{237}$Np were removed in the first tank while the $^{99}$Tc came off in the third, fifth, seventh and ninth tanks.

Separate processing systems were used to clean up the spent citric acid, sulfuric acid, and disodium citrate decontamination liquors. Details of these systems are proprietary, although the following information on BNFL plans in 1989 for its decontamination process is reported by Anderson and Faulkner (1989). Uranium, along with $^{237}$Np, was recovered from the citric acid solution by evaporation. The spent sulfuric acid solutions were treated with lime to precipitate calcium fluoride, calcium sulfate, aluminum hydroxide, ferric hydroxide, and some of the $^{99}$Tc, presumably as $^{99}$Tc dioxide. The remaining solution was then passed through an anion exchanger to remove more of the $^{99}$Tc.

The spent solution from the fifth and ninth tanks containing traces of metal ions, pertechnate ion, and disodium citrate plus hydrogen peroxide, was neutralized to pH 6, filtered, and passed through a bed of activated carbon to decompose the hydrogen peroxide. The liquid was then passed through an ion exchange column containing an iminodiacetate resin that removed both the pertechnate ion and the various metal ions present.

The waste streams arising from the process were spent ion exchange resins and cleaned process liquors. The total volume of spent ion exchange resins arising from the aqueous decontamination process was about 100 yd$^3$ for the whole plant. The liquors were neutralized, filtered, and run through ion exchange columns to remove heavy metals and radioactive species prior to release to the environment via heavy dilution with other plant wastewater streams to stay within allowable discharge concentrations.

Strict controls for criticality prevention were maintained, with detectors placed at key points in the decontamination facility. The activity of each individual piece was monitored after decontamination to ensure it met the applicable release criteria.

Following disassembly of the converters, the barriers were removed and stored in a secured area. BNFL staff report that, following a number of tests and trials, they now have a satisfactory method of recovery and recycle of the nickel from the barriers.[19]

### Decontamination of Supporting Systems and Building Surfaces

Following process equipment removal, the remaining cell enclosures were demolished. Hazardous materials, such as asbestos, PCBs, lubricants, and laboratory chemicals, were removed and disposed of using conventional technologies such as land burial (asbestos) and incineration (PCBs). The building shell was removed from about one-half of the total structure. The floors were scabbled and removed, returning that portion of the structure to greenfield site status. A number of ancillary buildings and structures were also demolished, including 11 large natural draft cooling towers, their pump houses, and an electrical substation. Including the floor slab, this operation produced 46,000 metric tons of clean concrete rubble for off-site disposal. In practice, many items, such as structural steel and concrete, required only minimal decontamination.

### Waste Management

Metallic materials recovered from the plant were categorized based on their potential for sale to the commercial market:

- clean scrap;
- contaminated scrap that could be economically decontaminated to de minimis level; and
- contaminated scrap that could not be economically decontaminated to de minimis level.

Clean scrap, such as cell cubicle structures, base plates, and some motors, was sold directly to the metals market. Scrap that was economical to decontaminate to de minimis levels was size-reduced, decontaminated and/or melted to homogenize the contamination, and sold. This class of metal included most of the steel, copper, and aluminum components. Scrap that was uneconomical to recover, consisting primarily of small-bore pipe, instruments, and swarf (metallic particles and abrasive fragments resulting from cutting or grinding), was dispatched to the low-level radioactive waste site at Drigg. Approximately 99 percent of the materials removed from the Capenhurst plant (excluding the barrier material) were recycled to the commercial markets, including bulk concrete as well as metals.

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[19] Personal communications from James Cross, British Nuclear Fuels, to James Zucchetto and Jill Wilson, National Research Council, July 13, 1995.

A melter was used to handle metallic components that were otherwise difficult or impossible to decontaminate cost effectively by chemical means. The main purpose of the melter was to homogenize the radioactivity in 4,500 metric tons of steel, nickel, aluminum, and other metals to provide for cost-effective monitoring.[20] The melter was also used to reduce waste volume.

## Characterization

The initial characterization to identify and quantify residual radioactive contaminants was performed following gaseous decontamination. Nonintrusive gamma-ray spectroscopy and neutron activation were used to characterize $^{237}$Np and $^{235}$U deposits. Counters and scintillation monitors were used to identify $^{99}$Tc and $^{237}$Np deposits. The characterization provided data on the magnitude and location of uranic alpha and soft beta $^{99}$Tc radionuclides throughout the plant.

## General Considerations

Criticality prevention during aqueous decontamination was achieved by three principal methods: removing as much uranic contamination as possible during the $ClF_3$ pretreatment and mechanical decontamination stages, designing the decontamination facility to minimize the likelihood of criticality incidents, and using batch-metering techniques to control the movement of spent citric acid solutions and their concentrations of $^{235}$U.

Research and development on cost-effective techniques for D&D formed a significant part of the Capenhurst D&D effort, constituting about 20 percent of the total project cost.[21] Given the repetitive nature of GDP process equipment and building structures, the percentage of total D&D project cost spent on research and development should be much smaller for larger plants. The development of metal melting and wet chemistry decontamination processes for transuranic and fission products on metals permitted minimization of waste from the Capenhurst D&D and allowed extensive materials recycling to commercial markets. High land burial costs (greater than \$2,000/yd$^3$ [\$74/ft$^3$]) were a major driver in developing decontamination and recycling technologies in this case.[22]

A key principle underlying much of the Capenhurst development work was to look outside the nuclear industry for off-the-shelf equipment that would meet the D&D program needs—possibly with some modification. As noted above, robotic techniques were used during disassembly of the cascades; off-the-shelf systems were used for plasma-arc cutting to minimize costs.

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[20] Personal communication from David Clements, British Nuclear Fuels, to James Zucchetto, National Research Council, June 29, 1994.

[21] Personal communication from David Clements, British Nuclear Fuels, to James Zucchetto, National Research Council, June 29, 1994.

[22] Figures quoted for low-level radioactive storage in the United States range from \$7/ft$^3$ at the Nevada Test Site to \$300/ft$^3$ at Barnwell, South Carolina.

Regarding health and safety, static personnel air samples and film badges were used throughout the project. Whole-body monitoring was performed twice yearly for every D&D worker. No special dispensation or relaxation of exposure limits was given for this work. Very low-levels of exposure were experienced by the work force; the mean total dose for 1993 was 0.03 mSv (3 mrem).

## CIP/CUP TECHNOLOGIES

In response to increasing demand for low-enriched uranium for civilian nuclear power plants, the efficiency and capacity of the three U.S. GDPs were increased in the 1970s and early 1980s under the CIP/CUP. CIP increased the separative efficiency of the GDPs by installation of more efficient gaseous diffusion barriers and larger equipment and by improving the flow of the $UF_6$ gas. CUP substantially increased the production capacity of the plants (DOE, 1993c). Some of the technologies used during CIP/CUP activities are relevant to D&D of the U.S. GDPs. However, the requirements for maintenance, upgrading, and improvement intended to enhance equipment use impose different constraints on technology applications than D&D, during which most equipment is cut up and destroyed.

One goal of the CIP/CUP activities was to reuse as much equipment as possible (Snyder, 1994). Well-known wet decontamination methods using citric acid, nitric acid, and ammonium carbonate were used to clean the process equipment for reuse. During aqueous decontamination, a tradeoff was necessary between maximizing uranium removal and recovery and avoiding damage to the nickel plating on equipment destined for reuse. Thus, although CIP/CUP made extensive use of aqueous methods for cleanup, and related data are available, decontamination to free-release standards was not demonstrated.

Scrap metal—notably aluminum and nickel-plated steel—was generated during CIP/CUP activities. The aluminum was melted and either reused or stored. The nickel-plated steel is still stored at the sites. The discarded barriers were melted and stored.

## CONCLUSIONS AND RECOMMENDATIONS

### General

#### Conclusions

1. Decontamination and decommissioning of nuclear facilities is not a new activity; it has been demonstrated successfully worldwide for many years. A substantial arsenal of safe, cost-effective technologies has been developed, including those used at the Capenhurst gaseous diffusion plant in the United Kingdom.
2. Opportunities exist to optimize and reduce the cost of some decontamination technologies for application to the U.S. GDPs. However, no large research and development effort is needed to identify new decontamination technologies. Large cost reductions by developing breakthrough technologies are not anticipated.

### Recommendations

1. The committee recommends that a limited number of highly focused technology demonstration programs be funded to evaluate the effectiveness and system costs for specific decontamination processes (see below).
2. Given the historical trend of increasing future costs of waste disposal, particular consideration should be given to processes that create a minimum volume of waste for disposal or that decontaminate sufficiently for the resultant material to be recycled or buried as nonradioactive waste.

## Uranium Deposit Removal

### Conclusions

1. The large deposits of uranium can be removed by three methods: gaseous $ClF_3$ treatment, mechanical scraping, or in some cases, the aqueous spray wash approach.
2. At Capenhurst, 80 percent of the uranium was removed by hot $ClF_3$ treatment at the time of shutdown, For CIP/CUP, hot $ClF_3$ treatment followed by spray booth wash was used to remove visible deposits.
3. At Paducah and Portsmouth the opportunity will exist to remove major uranium deposits by hot $ClF_3$ treatment at the time of shutdown. At Oak Ridge, cold treatment is being tried.

### Recommendation

The deposit removal treatments to be used at each site should be carefully considered to select the most cost-effective processes. At Oak Ridge, mechanical removal or spray booth treatment appear to be the most attractive methods for most of the deposits. At Portsmouth and Paducah, $ClF_3$ treatment at shutdown followed by spray booth treatment for removal of visible uranium deposits could be used, although spray booth treatment alone may suffice. Low-enrichment and high-enrichment cells may receive different treatments.

## Decontamination of Cascade Equipment

### Conclusions

1. There is no obvious impediment to achieving the necessary level of decontamination of the cascade equipment (excluding the diffusion barriers) with an aqueous process. It seems likely that uranium can be decontaminated successfully using the Capenhurst treatment or an analogous liquid process.
2. Aqueous washing of enriched uranium (about 2 percent enrichment and above) from metal parts will require double-contingency criticality controls; approaches include restriction

on amounts of material and solution handled, its geometry (e.g., use of thin layers), and possible use of neutron poisons.

3. A special decontamination problem exists for the diffusion barriers. They contain a large amount of valuable nickel, with internal deposits of uranium and $^{99}$Tc.
4. The criticality problem is greatly reduced for material with low enrichment levels. For this material, the cleanup system can be simplified and its costs reduced.

### Recommendations

1. A focused demonstration program should be conducted to determine the choice of cleaning solutions and the best design for washing equipment. In choosing a set of wash solutions for aqueous decontamination, particular attention should be given to minimizing the volume of waste liquids generated; the experience at Capenhurst should be taken into account.
2. Focused research and development should be conducted to establish the most economic procedure(s) for decontaminating the nickel diffusion barriers to acceptably low-levels.

## Decontamination of Support Systems and Buildings

### Conclusion

There is no need to pursue extensive research and development programs on new building decontamination technologies because many existing technologies have been demonstrated to work.

## Waste Management and Recycling

### Conclusions

1. Existing technologies are generally adequate for waste management. There is no need for major programs to develop new technology, and large expenditures for research and development are not warranted.
2. The decision of whether materials should be decontaminated and recycled, disposed of as nonradioactive waste, or disposed of as low-level radioactive waste will be based upon social values, relative costs, and applicable standards and laws.

### Recommendations

1. Radioactive wastes should be partitioned into forms for permanent disposal and forms that can be released or considered to be nonradioactive wastes.
2. Priority should be given to thorough cleanup of surfaces to meet existing release standards.

3. Serious consideration should be given to the recycling of metals, either for sale in commercial markets or for restricted use within the DOE complex.

## Characterization

### Conclusions

1. Characterization of radioactive and hazardous substances is needed before, during, and after the D&D program: initially, to delineate areas for cleanup; during cleanup, to protect workers, control the spread of pollutants, and monitor progress; and finally, to ensure compliance with limits. Various characterization techniques and instruments will be needed due to the complexity of the sites.
2. Instruments for monitoring uranium levels at gaseous diffusion facilities have been used and improved over 30 years for routine operations, repairs, and plant upgrading. Existing techniques can be directly applied to characterization for D&D if the radiological limits for cleanup are not much lower than past detection requirements. Laboratory techniques exist for more sensitive uranium measurement but are considerably more expensive to apply than field monitoring. In most cases, characterization of $^{99}$Tc at the GDPs will require laboratory (radiochemical) measurements.
3. The cost of characterization, particularly for equipment and building surfaces, could be reduced by replacing manual surveys by extensive use of robotics.

### Recommendation

The mobile robotic floor characterization system under development by Oak Ridge National Laboratory should be evaluated at the Oak Ridge GDP.

## Robotics

### Conclusions

1. The repetitive layouts of GDP equipment and large, easily accessible floor surface areas offer many opportunities for improved D&D operations using robotics.
2. D&D tasks conducted manually are labor intensive, inefficient, and time consuming and could benefit from the use of robotics. Further, D&D operations are conducted in environments that, under current and anticipated future regulations, often require extensive safety and health protection programs for implementation. The use of robotics could eliminate some safety risks and costs of corresponding worker protection measures.
3. The DOE EM-50 robotics program has applications-driven developments under way to address primary D&D problems. These demonstrations are necessary for systems analysis, evaluation, and training of operators.

### Recommendations

1. The use of robotics should be considered as a possible way to reduce costs, improve safety, and enhance data quality in D&D. Emphasis should be placed on the use of commercial robotic systems to minimize development costs.
2. Funding should be provided in a timely fashion to support the EM-50 demonstrations of robotic D&D equipment.

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# 4

# Analyses of the D&D Cost Estimates for the GDPs

Two cost estimates for the D&D of the U.S. GDPs were developed in 1991 in developing legislation to establish the USEC. Under contract to the DOE, Ebasco and TLG developed two separate cost estimates incorporating different assumptions (DOE, 1991a,b). In addition, MMES had developed an earlier cost estimate in 1988, and subsequent to the Ebasco and TLG work, DOE employed SAIC to review the Ebasco estimate and provide an additional estimate (MMES, 1988; DOE, 1991c, 1992). These four estimates, which are summarized in Table 4-1, are reviewed in this chapter to identify and compare the major cost elements in the D&D of the GDPs. (See Appendix J for further details on the cost estimates.)

These cost estimates are also considered together with actual D&D experiences at other nuclear facilities. For example, the D&D of the Capenhurst GDP in the United Kingdom by BNFL is particularly valuable because the Capenhurst plant had components, systems, and structures very similar to those of the U.S. plants (Baxter and Bradbury, 1991a,b; Clements, 1993, 1994a; Spencer, 1988). The D&D of the Shippingport Atomic Power Station in Pennsylvania, which is well documented, is also relevant because this power plant was a DOE-owned facility that was decommissioned following DOE orders and U.S. regulatory requirements (Crimi, 1987, 1988a, 1988b, 1992, 1994). The Capenhurst and Shippingport D&D projects are also reviewed in this chapter, and conclusions are drawn on aspects of their success relevant to the D&D of the GDPs.

## PREVIOUS COST ESTIMATES

The cost estimates summarized in Table 4-1 are reviewed and compared in the following sections, and the principal reasons for the differences are identified. Every cost estimate depends on its assumptions. Thus, when comparing cost estimates for the same job, it is important to compare the underlying assumptions to ensure that they are similar or that those assumptions that differ can be identified. For example, in the cost estimates developed by Ebasco and TLG, some assumptions were specified by DOE, with additional assumptions made by Ebasco and TLG (see Appendix J for these assumptions).

TABLE 4-1 Summary of Previous GDP D&D Cost Estimates (1992 dollars)

| **Estimator** | Total Cost (billions $) | Total Years | Average Annual Spending (million $/Year) |
|---|---|---|---|
| MMES | 12.3 | NA[a] | NA |
| Ebasco | 16.1 | 38 | 420 |
| TLG | 13.9 | 17.5 | 800 |
| SAIC | 9.5 | 26 | 365 |

[a] Not available.

SOURCE: MMES (1988), DOE (1991a,b,c, 1992).

## The 1988 MMES Study

In July of 1988, MMES produced the "Modernization Study D&D Review" at the request of the Energy Projects Branch, Richland Operations Office, DOE. This review projected the costs for D&D of the shutdown facilities at the Oak Ridge GDP. The costs, calculated in 1990 dollars, were developed by applying the "Hanford Cost Estimating Formula" to the Oak Ridge GDP. This method applies a broadly based unit cost factor (in dollars/ft$^3$ of waste) for each of three scenarios (protective [safe] storage, entombment, and return to greenfield status) to the volume of waste estimated to result from D&D at the Oak Ridge GDP. Under the protective storage assumption, the initial cost was projected to be $166 million, with annual costs of $22 million (MMES, 1988). Under the entombment scenario, the costs rose to $2.3 billion. Under the greenfield assumption, costs rose to $8.10 billion, including a 40 percent contingency (all costs given in 1990 dollars).

Estimated remedial action costs at the Oak Ridge GDP of $2.75 billion are included in the MMES 1988 greenfield estimate. Eliminating the cost of remedial action (because site remediation of soils and groundwater was not included in the Ebasco or TLG estimates) reduces the original $8.10 billion estimate to $5.35 billion. Converting the $5.35 billion estimate to 1992 dollars yields the estimate of $5.72 billion.[1]

Because the MMES estimate is for the Oak Ridge GDP only, the committee extrapolated this estimate to arrive at a value for all three GDPs. This extrapolation was performed by calculating the ratio of the total cost for D&D of all GDPs to the cost for D&D of the Oak Ridge GDP, using the Ebasco cost estimate. The Ebasco cost estimate was used in calculating this ratio because of the more detailed analysis of the Paducah and Portsmouth plants as compared with the TLG estimate. Multiplying the MMES Oak Ridge GDP estimate by this ratio

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[1] The conversion was calculated using the gross national product implicit price deflators of 1.039 for 1991 and 1.029 for 1992 (Clinton, W.J., 1994, p. 276).

(2.17) results in an estimate for the total GDP complex of $12.3 billion in 1992 dollars, including contingency. The validity of this calculation depends on the assumption that the population of support facilities and other site resources considered in the MMES-Hanford estimate is the same or quite similar to the population examined in the Ebasco estimate.

### The 1991 Ebasco and TLG Estimates

Four bottom-up estimates were prepared by Ebasco in 1991, beginning in May and ending with the final version in September (see Appendix J, Table J-2; DOE, 1991a). The principal differences in the consecutive Ebasco estimates were reductions in scope, changing some of the original assumptions, and a reduction in overhead rates. The total cost for the final Ebasco estimate was $16.1 billion in 1992 dollars, including contingency. Ebasco examined the Oak Ridge GDP in detail, using available drawings to develop inventories of equipment and building surface areas. The estimates of the direct labor and materials costs were prepared using unit cost factors, that is, calculating the costs for labor and equipment needed to perform a task once and multiplying that unit cost factor by the number of times that task would be performed during the D&D, to obtain the total cost for the activity. D&D costs for the Portsmouth and Paducah GDPs were then estimated by scaling the Oak Ridge D&D estimates by the ratio of the gross square footage of buildings at the Portsmouth and Paducah plants to the gross square footage of similar buildings at the Oak Ridge GDP.[2]

Such an approach is reasonably good for structures that are very similar in size and content but becomes less and less reliable as the similarity of the structures and their contents diverge. The approach also neglects differences in local labor rates, productivity, and other site-specific cost parameters. Costs to prevent criticality during D&D should be greatest at Oak Ridge. Paducah has low enrichment levels, and criticality is not a significant concern at the plant. DOE is using gaseous $ClF_3$ (chlorine trifluoride) to remove deposits from the highly enriched uranium sections at Portsmouth, and the USEC is obligated to remove uranium deposits from the two plants that represent a criticality risk. Hence, extrapolating D&D costs from Oak Ridge should provide an overestimate of D&D costs for the other two sites.

A major cost element in the Ebasco estimate was the construction and operation of two large facilities for the decontamination and volume-reduction of the plant components, the high-assay and low-assay decontamination facilities.[3] The function of the first was to decontaminate and disassemble material contaminated with highly enriched uranium. Each of these structures was postulated to be about the size of a gaseous diffusion process building and to contain a multitude of process systems for the decontamination and segmentation of the system components. In addition, the Ebasco estimate postulated the construction of a new administration building at the Oak Ridge GDP, with space for several thousand persons, to house administrative functions during the multiyear decommissioning process.

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[2] For example, the D&D cost for the X-333 building at Portsmouth, based on the D&D cost for the K-33 building at Oak Ridge, would be given by: Cost (X-333) = Cost (K-33) [gross square footage (X-333)/gross square footage (K-33)].

[3] These are referred to in the Ebasco estimate as the High Assay Decontamination Facility and the Low-Assay Decontamination Facility.

Another bottom-up estimate was prepared by TLG (DOE, 1991b). This estimate used the same plant equipment inventories developed by Ebasco and included the same new decontamination and administration facilities as the Ebasco estimate. TLG used some unit cost factors for D&D operations that they had developed during their many years of estimating decommissioning costs for nuclear power plants and developed other new unit cost factors for D&D of the specialized equipment in the GDPs, such as converters and compressors. The TLG D&D cost estimate amounted to $13.9 billion in 1992 dollars, including contingency.

### Comparison of the Ebasco and TLG Estimates for the Five Process Buildings at the Oak Ridge GDP

Table 4-2 compares some of the principal parameters affecting the Ebasco and TLG estimates for the five gaseous diffusion process buildings at the Oak Ridge GDP. The two estimates differ significantly in estimated waste volume and waste management costs, differ about 4 percent in labor hours and about 5 percent in D&D (including the decontamination facilities) cost, but cannot be directly compared in the area of scrap/salvage because they relied on different units.

Both Ebasco and TLG postulated the construction and operation of two large new facilities for a multiplicity of decontamination and segmentation processes for the contaminated process equipment removed from the process buildings. These processes include gaseous $ClF_3$ treatment and high-pressure water washing decontamination, plasma-arc and oxyacetylene segmentation, and incineration of selected wastes.

The large differences between Ebasco and TLG in estimated waste volume and waste disposal cost arise from different assumptions. Ebasco assumed significant volume reduction of major components, while TLG postulated sealing the openings on the major components and shipping them to the disposal site intact. Ebasco assumed very short transport distances, with burial near the plant site. TLG assumed transport to the Nevada Test Site for burial. Ebasco assumed disposal charge rates ranging from about $\$14/ft^3$ to $\$33/ft^3$, and TLG assumed a value of $\$8/ft^3$ for waste disposal. Despite its assumed low disposal charge rate, the TLG waste management cost estimate of $634 million is about 1.8 times larger than the Ebasco estimate of $352 million because of the assumed much larger waste volume (3.5 times larger) and the much longer transport distances.

The total direct labor hours to dismantle and remove equipment and to decontaminate and demolish the structures are very similar, differing by only about 4 percent. However, this result may be fortuitous because, although both studies used the same equipment inventories, the unit cost factors they assumed for removal of the components vary widely, as shown in Table 4-3. The ratio of the TLG unit cost factor to the Ebasco unit cost factor (TLG/Ebasco) for the same activity ranges from about 0.3 to nearly 7. Obviously, in any new cost estimate it will be necessary to review all unit cost factors to ensure that the factors reasonably represent the realities of a decommissioning job.

Historically, the unit cost factor approach results in a conservative (high) estimate of the cost of accomplishing a series of tasks, especially for performing the same set of tasks many

TABLE 4-2 Comparison of Major Parameters in the Ebasco and TLG Cost Estimates

| **Parameter** | Ebasco | TLG |
|---|---|---|
| Waste volume | 9.072 million $ft^3$ | 32.14 million $ft^3$ |
| Waste management cost[a] | $352.3 million (1992 $) | $633.8 million (1992 $) |
| Scrap/Salvage | 1,527,168 $ft^3$ | 5,571 tons |
| Direct labor | 41.31 million person hours | 42.98 million person hours |
| D&D costs[a,b] | $3.3 billion (1992 $) | $3.7 billion (1992 $) |
| High- and low-assay decontamination facilities[c] | $2.1 billion (1992 $) | $1.45 billion (1992 $) |

NOTE: Values are for the five process buildings at the Oak Ridge GDP only, not including support buildings.

[a] Values include packaging, transport, disposal, and contractor overhead and profit but not contingency.

[b] Includes waste management costs but not for the high-assay and low-assay decontamination facilities costs.

[c] Includes both construction and operation costs. The difference in the estimates arises primarily from the different operating lifetimes postulated by Ebasco (11 years) and TLG (8 years).

TABLE 4-3 Comparison of Selected Unit Cost Factors for Equipment Removal Used in the Oak Ridge GDP Cost Estimates

| **Activity** | Units | Ebasco | TLG | TLG/Ebasco |
|---|---|---|---|---|
| Process piping | ($/linear foot) | 303.52[a] | 89.12 | 0.29 |
| Fire protection | ($/linear foot) | 36.42[a] | 15.95 | 0.44 |
| Converters | ($/unit) small | 10,852 | 27,835 | 2.56 |
|  | ($/unit) large | 16,019 | 32,917 | 2.05 |
| Light fixtures | ($/unit) | 96.14[a] | 279.51 | 2.91 |
| Decon structures | ($/square foot) | 15.06[a] | 48.57 | 3.22 |
| Raceways | ($/linear foot) | 3.36[a] | 23.42 | 6.96 |

NOTE: Values include contractor overhead and profit.

[a] Average values, derived by dividing total cost over five GDP process buildings by total number of linear feet, units, or area, as appropriate, given by Ebasco for those five buildings.

times, because the performance improvements from learning will generally reduce cost (McNeil and Clark, 1966). For the D&D of the GDPs, if the plants are cleaned up sequentially, as assumed in the Ebasco estimate, experience gained from the D&D in the first building should certainly improve performance in the rest of the buildings at the first plant and subsequent plants.

Ebasco and TLG used different bases for estimating project overhead costs, but arrived at similar results. The management structures postulated in the two estimates contain similar cost elements. However, because of the manner in which the costs were developed in the two studies, it is difficult to make direct comparisons. Both structures include significant levels of staffing for the category Program Integration, which includes program management, obtaining permits from appropriate regulatory agencies, and large staffs providing engineering, operations, and health and safety services. Staffs are also provided for industrial safety, waste management, and analytical services. Other cost elements included are security staff (Ebasco only), nuclear insurance and taxes (TLG only), planning and procedure preparation (Ebasco only), and miscellaneous items such as utility costs. By collecting all elements appropriate for program integration for each estimate, the results are similar: Ebasco, $1.897 billion, 30.0 percent of the total; TLG, $1.967 billion, 32.6 percent of the total. TLG postulated 1,430 people/year on the overhead staff during the 8 years of D&D at the Oak Ridge GDP. An indirect measure of the number of overhead staff postulated by Ebasco suggests about 500 people/year during 11 years of D&D at Oak Ridge. The smaller number of indirect staff assumed in the Ebasco estimate is balanced by the much longer period of D&D operations it assumes, resulting in similar total indirect costs.

## SAIC Analysis of the Ebasco Estimate for DOE

DOE hired SAIC to evaluate the Ebasco cost estimate and to develop a revised estimate based on the Ebasco estimate (DOE 1991c, 1992). The SAIC estimate, identified as the Working Decommissioning Cost Estimate, used a top-down analysis, developed by examining the cost impact of changing key Ebasco assumptions, rather than an independent bottom-up estimate, like those developed by Ebasco and TLG. The basic differences between Ebasco and SAIC estimates are summarized in Table 4-4 (see Appendix J for details).

Although the SAIC estimate details dozens of potential cost reductions, much of the potential cost decrease it proposes results from reductions in the categories of Support Facilities and Waste Management and in indirect costs and contingency (DOE, 1992).

In the SAIC estimate, the direct cost of the support facilities was reduced from $2.436 billion in the Ebasco estimate to $359 million. This $2 billion decrease resulted from eliminating the high-assay decontamination facility, decreasing the capital cost of the low-assay decontamination facility from $646 million to $294 million, primarily by lowering the cost estimates for the facility's decontamination systems, and reducing its annual operating costs from $40 million to $14 million as a result of its reduced treatment capacities. An assumed lower disposal rate of $8/ft^3$, and on-site disposal, reduced direct costs for waste management from $689 million to $446 million for low-level radioactive and hazardous wastes. (See Appendix J for more details on waste management costs.)

TABLE 4-4 Ebasco and SAIC Estimated D&D Costs for the GDPs (billions of 1992 dollars)

| | **Estimated Costs** | |
|---|---|---|
| Cost Element | Ebasco | SAIC |
| Direct costs | | |
| Waste management | 0.689 | 0.446 |
| D&D activities | 3.412 | 3.931 |
| Support facilities | 2.436 | 0.359 |
| Total direct costs (D) | 6.537 | 4.736 |
| **Indirect (I) (% of direct)** | 2.811 (43) | 0.663 (14) |
| Subtotal (D+I) | 9.348 | 5.399 |
| **Construction management (CM) (% of D+I)** | 0.467 (5) | 0.270 (5) |
| Subtotal (D+I+CM) | 9.815 | 5.669 |
| **Contractor**[a] (% of D+I+CM) | 0.491 (5) | 0.283 (5) |
| Total (D+I+CM+ contractor) | 10.306 | 5.952 |
| **Contingency (% of total)** | 3.195 (31) | 1.190 (20) |
| Total (D+I+CM+contractor+contingency) | 13.501 | 7.142 |
| **Program Integration (PI) (direct)** | 1.796 | 2.251 |
| Indirect (% of PI direct) | 0.772 (43) | 0.000 (0) |
| **Grand Total** | 16.069 | 9.393 |

[a] For example, the management and operating (M&O) contractor.

SOURCE: DOE (1991a,c, 1992).

Finally, the largest reductions from the Ebasco estimate resulted from changes in the indirect rates (43 percent to 14 percent) and contingency rates (31 percent to 20 percent), which are multipliers of direct construction and operations labor costs in preparing the total cost estimate. In addition, the indirect rate applied to the Program Integration function was reduced from 43 percent to zero, based on the reasoning that program integration is an indirect cost. These reductions recommended in the SAIC cost estimate decreased the total estimated cost from about $16.1 billion to about $9.3 billion (1992 dollars).

## IDENTIFICATION OF MAJOR COST ELEMENTS

The five principal cost elements in the Ebasco and TLG studies are summarized in Table 4-5. The focus in this comparison is on estimates for D&D of the Oak Ridge site, because all of the bottom-up cost analyses were performed for the Oak Ridge GDP. (The Portsmouth and Paducah D&D costs were developed from the Oak Ridge GDP costs using ratios of gross square footages for similar buildings, as described previously.)

Ebasco's estimated base cost for the Oak Ridge GDP was about $5.40 billion, including contractor overhead and profit, but without the 5 percent adders for construction management and management and operating contractor operations and without contingency. The TLG base cost was about $5.15 billion, including all indirect costs, but without contingency. Both values include the cost of construction and operation of the high- and low-assay decontamination facilities. The totals differ by about 5 percent. However, there are wide disparities in the relative magnitudes of the major cost elements, which are related to the differences in the unit cost factors used by each study and to differences between the studies in assumptions about the levels and locations of contamination within the facilities.

The components of the equipment removal cost element show large differences between the two studies, as shown in Table 4-6. Because these costs are based on the same inventories of materials, the large cost differences arise from the large differences in the unit cost factors developed for these activities by the two contractors.

A review of removal costs during the CIP/CUP at the Paducah and Portsmouth GDPs (see chapters 3 and 6, and Table 6-2) and, more recently, in removing converters from the Oak Ridge GDP for transfer to Portsmouth or Paducah, suggests that when the closure and decontamination activities needed to permit transport between sites are eliminated, the likely cost for removal of a large converter will be between $4,000 and $5,000; considerably less than either the $16,000 postulated by Ebasco or the $33,000 postulated by TLG. Using this newer estimate, converter removal costs would be between $20 million and $25 million for the Oak Ridge GDP, compared with the $62 million estimated by Ebasco, and the $145 million estimated by TLG.

The wide difference in structure decontamination costs in the Ebasco and TLG estimates appears to arise from the TLG assumption that all walls and ceilings are contaminated, and the costs for decontaminating these surfaces are much higher than for floors. The average TLG unit cost factor for building decontamination is $48.57/ft$^2$ of surface. The Ebasco average unit cost factor is $15.06/ft$^2$ of surface, which is more representative of floors only.

TABLE 4-5 Principal Cost Drivers for the Oak Ridge GDP (billions of 1992 dollars)

| | Ebasco | | TLG | |
|---|---|---|---|---|
| Cost Element | Cost | Percentage of Total Estimate | Cost | Percentage of Total Estimate |
| Remove equipment from structures | 1.25 | 23.1 | 1.55 | 30.1 |
| Construct and operate the new facilities[a] | 2.10 | 38.9 | 1.45 | 28.2 |
| Decontaminate the empty structures[b] | 0.26 | 4.8 | 0.83 | 16.1 |
| Indirect staffing | 1.44 | 26.7 | 0.69 | 13.4 |
| Waste management | 0.35 | 6.5 | 0.63 | 12.2 |
| Total base cost | 5.40 | | 5.15 | |

[a] Includes high- and low-assay decontamination facilities and administration building.

[b] Includes floors, walls, ceilings, and building structural members.

TABLE 4-6 Comparison of Estimated Costs for Equipment Removal and Decontamination Activities at the Oak Ridge GDP (millions of 1992 dollars)

| **Component** | Ebasco | TLG |
|---|---|---|
| Fire protection | 78 | 36 |
| Converters | 62 | 145 |
| Process piping | 215 | 63 |
| Light fixtures | 3.2 | 9.3 |
| Electrical raceways | 12.2 | 85 |
| Building decontamination | 260 | 830 |

As discussed in Chapter 6, the waste management costs estimated by Ebasco were inflated by the arbitrary selection of small waste containers for which list price was paid and by the construction and operation of multiple waste processing and disposal sites. The TLG estimated waste management costs were inflated by lack of volume reduction of equipment, by the long transport distance to the low-level radioactive waste disposal site, and by construction and operation of multiple waste processing facilities.

Two general observations can be made, based on the above discussion. First, careful attention must be paid to the detailed development of the many unit cost factors used in the analyses to ensure that these factors are reasonable; even small errors in these factors are important because of the many units to be dealt with in these huge facilities. Second, the size of the support staff and services, which represents about 27 percent of the Ebasco and 13 percent of the TLG base cost, should be minimized to the extent possible.

## TIME PROFILE OF INCOME AND EXPENDITURES FOR THE D&D FUND

EPACT, which set forth the conditions for privatizing the U.S. gaseous diffusion enrichment facilities, established a fund for the D&D of the GDPs. EPACT also provided for the remediation of the sites and provided the government's share of the remediation costs at a number of sites that produced uranium and thorium for the government's nuclear energy programs in the past to the extent that available funds will allow.

As noted in Chapter 1, EPACT called for deposits to the D&D Fund of $480 million per fiscal year (to be annually adjusted for inflation) for 15 years, for a total of $7.2 billion (1992 dollars). The nuclear electric utilities that had utilized the products of the enrichment facilities in the past were required to provide funding of up to $150 million per year for 15 years, for a total of $2.25 billion (1992 dollars). To make up the balance, the federal government was to make appropriations of $330 million (1992 dollars) annually for 15 years. The fund is also limited in how much can be expended from it each year; namely, the annual government appropriation (supposedly $330 million) or the balance contained in the fund, whichever is less.

During fiscal years 1993 and 1994, the fund received electric utility payments of $303 million and government appropriations of $198 million and received interest payments on its assets of $10 million (Fulner, 1994). During those 2 years, the fund dispersed $165 million for environmental restoration projects, including remedial action and D&D projects (DOE-OR, 1994). Future utility contributions are uncertain. For example, a recent court decision ordered DOE to refund $15 million, with interest, to Yankee Atomic. The utility had paid $15 million into the D&D Fund because their plant had been permanently shutdown prior to enactment of EPACT and because their enrichment contracts had been on a fixed-price basis (Newman, 1995).

The postulated annual expenditures and the number of years of duration of the D&D projects at the GDPs are given in the Ebasco, TLG, and SAIC cost estimates (DOE, 1991a,b; 1992). Ebasco forecast an average spending rate of $420 million per year for 38 years, for a total of $16.1 billion in 1992 dollars. TLG forecast an average spending rate of $800 million per year for 17.5 years, for a total of $13.9 billion in 1992 dollars. SAIC forecast an average spending rate of $365 million per year for 26 years, for a total of $9.5 billion in 1992 dollars.

Comparing these estimated expenditures with the level of funding proposed for the D&D Fund shows that the fund would be inadequate to cover just the costs of D&D of the GDPs, without considering the expenditures being made for remedial actions at several other sites—even if the federal government were to make its payments into the fund regularly. Thus, it appears that controls will be required on expenditures from the fund to ensure that at least some of the needed funds will be available when D&D of the GDPs begins.

## ESTIMATING U.S. GDP D&D COSTS FROM CAPENHURST D&D COSTS

Valuable experience has accumulated through the D&D of nuclear fuel processing plants and nuclear power stations. The project most relevant to the U.S. enrichment plants is the D&D of the Capenhurst GDP in the United Kingdom (see Chapter 3 for more on the technologies used at Capenhurst and Appendix H for additional detail on its D&D). Although Capenhurst was a foreign plant, its D&D planning and execution nevertheless provide a roadmap for developing an effective management approach, selecting appropriate D&D techniques, and estimating the cost of the D&D for the U.S. enrichment plants (Clements, 1994a, 1993).

### Capenhurst Plant Description

The Capenhurst GDP was a uranium enrichment facility operated by BNFL from 1956 to 1982. The facility produced highly enriched uranium for military purposes and low-enriched uranium for commercial nuclear power reactors. D&D was initiated following plant shutdown in 1982, with completion scheduled for late 1995.

The Capenhurst enrichment cascade consisted of 4,808 stages, each containing a converter housing the diffusion barrier material that separates the $^{235}$U and $^{238}$U isotopes, a compressor and associated drive motor, a cooler, and interstage piping and valves. Cascade components were housed in a single process building 1,200 m long by 150 m wide. The 4,808 stages were on the ground floor, and auxiliary equipment (such as electrical systems and heating, ventilation, and air conditioning systems) was located on the second floor. There were seven different sizes of converters and compressor drive motors, the latter ranging up to 300 hp. The cascade equipment was arranged in process cells containing 8 to 12 stages each.

Although the physical size of the Capenhurst plant was substantially smaller than the U.S. GDPs, there are many similarities between these facilities:

- similar process flowsheets and cascade arrangement;
- multistory, steel-frame and concrete buildings with transite siding;
- stages grouped into cells;
- Freon®-cooled stages;

- same species of radiological contamination, including uranium (depleted through fully enriched), $^{99}$Tc, and $^{237}$Np;
- large quantities of hazardous materials, such as asbestos and polychlorinated biphenyls (PCBs), and Freon®;
- mixture of aluminum and nickel-plated stage components;
- steam-heated autoclaves for feed vaporization; and
- purge cascade for removal of light gases.

The principal differences between Capenhurst and the U.S. GDPs are the following:

- Physical size and separative work capacity of the U.S. plants are substantially larger, by a factor of five or six.
- Most of the large interstage piping at Capenhurst was aluminum, whereas U.S. GDPs use nickel-plated steel exclusively.
- U.S. GDPs have a larger number of support facilities requiring D&D than did Capenhurst.
- Capenhurst cascade equipment was located on the first floor of the process building, whereas such equipment is located on the second floor in the U.S. plants.
- A part of the Capenhurst site is to be used for other enrichment activities; no return to greenfield status is assumed for the entire site; it is not certain whether the U.S. GDPs will be cleaned to greenfield status.

## Capenhurst Project Description

A great deal of effort went into researching and developing cost-effective methods for the Capenhurst D&D, including the following:

- selection of a cost-effective and safe means of disassembling the plant;
- suitable size-reduction techniques and compatible ventilation/filtration systems;
- decontamination processes to deal specifically with transuranic and fission products on steel, aluminum, copper, and other metals;
- engineering of safety into process equipment;
- ensuring compatibility of waste streams with regulatory constraints; and

- maximizing the recycling of decontaminated materials for the commercial market.

The main objectives of the development activities were to minimize the waste streams resulting from D&D by maximizing recycling of system materials for unrestricted reuse and to find off-the-shelf commercial equipment that, with or without modification, would meet the D&D program needs.

Before shutting down the plant, radiological and criticality data were gathered for use in planning and executing the dismantling, decontamination, and disposal operations. Gaseous decontamination using $ClF_3$ was used to remove the bulk of the residual uranium deposits.

A detailed D&D plan was developed. The initial phase involved cutout, removal, sealing, and outdoor storage of the cascade components, which allowed part of the process building housing the cascade to be demolished, and the land was reused for siting a gas centrifuge enrichment facility. Other parts of the process building were reused to house equipment for size reduction, chemical decontamination, and melting of metal pieces that were difficult to decontaminate.

The D&D was accomplished with a relatively small health physics staff. Capenhurst health physicists participated extensively in the D&D planning effort. Procedures were written defining the health physics requirements for the various D&D operations. D&D workers were then thoroughly trained to qualify them to perform the work according to these procedures and make the surveys necessary to ensure protection of worker health and safety. Health physics support required during D&D execution was, therefore, minimal during routine operations. Health physicists were consulted from time to time to address special problems. Very low-levels of exposure were experienced by the work force. (For example, the mean total dose for 1993 was 0.03 mSv; see Appendix H.)

The decontamination and disassembly process consisted of the following activities:

- build small special shops within existing structures for removal of high-assay material;
- gaseous decontamination, prior to plant shutdown, to convert solid uranium deposits, primarily $UO_2F_2$, to volatile fluoride compounds for removal in the gaseous phase;
- plant characterization to identify and quantify residual deposits of radioactive materials;
- removal of nonradioactive hazardous materials, such as asbestos and PCBs;
- removal and interim storage of plant equipment, and removal of cell structures;
- size-reduction of components and dry mechanical removal of uranium deposits;
- aqueous chemical decontamination;

- melting of metals that were difficult to decontaminate;
- removal of process and ancillary building structures; and
- disposal of radioactive and hazardous wastes.

Many plant materials, such as structural steel and concrete, required only minimal decontamination before disposition.

### Estimating Oak Ridge Costs by Scaling Capenhurst Costs[4]

Because the technology used in the Capenhurst plant is very similar to that in the U.S. enrichment plants, the reported D&D costs at Capenhurst can be scaled to estimate the costs for D&D at the Oak Ridge GDP. The reported total cost (funds expended) of the Capenhurst D&D project (£86 million) are broken down into 12 cost elements in Table 4-7. Adjusted for currency exchange rates and inflation to 1994 dollars, the £86 million becomes $160 million (Clements, 1994a,b; Lobsenz, 1995). The adjusted cost elements themselves are then scaled to estimate D&D costs for the Oak Ridge GDP using ratios appropriate for each cost element, as described below.

Some of the cost elements are related to the amount of process equipment (converters, compressors, piping) in the plant. To approximate this ratio of Oak Ridge to Capenhurst equipment, the weights of converter shells are used, derived from data in Table 4-8 and from the following text. The number of converters in the Capenhurst plant was 4,808 with a total weight of 14,300 tons, and the fraction of converter weight from converters having steel shells is 0.33 (Clements, 1995). The converter shall weights are used as surrogates for equipment volumes, hazardous and radioactive waste volumes, pretreatment surface areas, disassembly labor, and equipment surface areas decontaminated, as described later in this section. It is necessary to adjust the weight of the Capenhurst aluminum shells to the weight those shells would be if they were made of steel because all of the Oak Ridge GDP shells are made of steel. This adjustment is made by calculating the weight of the aluminum shells and multiplying that weight by the ratio of densities (steel, 7.86 g/cm$^3$; aluminum, 2.7 g/cm$^3$). The weight of the Capenhurst shells, steel plus adjusted aluminum, is found to be 25,933,334 lb and the weight of the steel shells at the Oak Ridge GDP is 57,053,640 lb. The resulting ratio of shell weights (Oak Ridge to Capenhurst) is 2.20.

Other cost elements are proportional to the areas of the surfaces in the structures, and most are affected by the difference in direct labor rates at Capenhurst and in the United States. The derivations of all of the appropriate scaling factors are presented in the following paragraphs and are applied to the Capenhurst cost elements in Table 4-7 to develop a cost estimate of the cost of D&D at the Oak Ridge GDP. The estimated Oak Ridge GDP costs are then multiplied by the ratio of the D&D cost for all three GDPs to the Oak Ridge GDP cost, based on the Ebasco cost estimate, to estimate the cost of D&D for the total U.S. GDP complex.

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[4] The number of figures shown for computed numbers in this section is for computational accuracy and does not imply precision to that many significant figures.

TABLE 4-7 Scaling of Capenhurst Costs to Estimate D&D Costs for the Oak Ridge GDP

| | **Capenhurst** | | Oak Ridge Estimate | |
|---|---|---|---|---|
| Cost Element | (million £) | (million $)[a] | Scaling Factor[b] | (million $) |
| Pretreatment | 2 | 3.72 | 2.00 | 7.44 |
| Planning and management | 10 | 18.60 | 1.80 | 33.49 |
| Technology development | 17 | 31.63 | 1.50 | 47.44 |
| Characterization | 2 | 3.72 | 3.885 × 1.35[c] | 19.52 |
| Disassembly | 20 | 37.21 | 3.144 × 1.35[c] | 157.93 |
| Removal and treatment of hazardous materials | 2 | 3.72 | 2.20 × 1.35[c] | 11.05 |
| Decontamination | 10 | 18.60 | 2.598 × 1.35[c] | 65.25 |
| Metal melting | 2 | 3.72 | 6.76 × 1.35 | 33.96 |
| Health and safety | 2 | 3.72 | 3.885 × 1.50 | 21.68 |
| Monitoring (including analytical) | 7 | 13.02 | 3.885 × 1.35 | 68.30 |
| Radioactive waste treatment and disposal | 3 | 5.58 | 2.97 × 1.35[d] × 1[e] or × 20[f] | 22.38; 447.57 |
| Overhead | 8 | 14.88 | 1.50 | 22.33 |
| Total | 86 | 160.0 | | 510.77[e]; or 935.96[f] |

[a] Escalated to 1994 pounds Sterling converted to dollars using a currency conversion of $1.60 per pound Sterling.

[b] The number of significant figures shown is for computational accuracy and does not imply precision to that many significant figures.

[c] This 1.35 factor is the ratio of wage rates for Oak Ridge to Capenhurst.

[d] This 1.35 factor is the ratio of low-level waste disposal rates in the United States and the United Kingdom (see text).

[e] Assumes 95% recycle, 5% waste as at Capenhurst (see text).

[f] Assumes 0% recycle, 100% waste.

SOURCE: Clements (1994a,b); Lobsenz (1995).

TABLE 4-8 Weight of Process Equipment at the Oak Ridge GDP

| | **Type of Converters (size)** | | | | |
|---|---|---|---|---|---|
| | "25"[a] | "27" | "0" | "00"[b] | "000"[b] |
| Number of converters | 3,018 | 540 | 300 | 600 | 640 |
| Weight of a unit (lb) | 7,392 | 10,175 | 24,820 | 26,890 | 63,500 |
| Weight of all units (tons) | 11,154 | 2,747 | 3,723 | 8,067 | 20,320 |
| Total weight | 46,011 tons = 92,022,000 lb | | | | |
| Shell weight | 0.62 × 92,022,000 lb = 57,053,640 lb | | | | |

[a] Comprised of four sizes (1, 2, 3, 4).

[b] Average weight for "00" and "000" converters may actually be somewhat higher, but there are actually many weights depending on components used during assembly.

SOURCE: Person (1995); MMES (1992).

The ratio of floor surface areas of the Oak Ridge to Capenhurst buildings is another important parameter in some of the scaling factors (250.2 acres/64.4 acres = 3.885). The direct labor rates also influence many of the cost elements. From the 1991 Ebasco estimate, the fully burdened direct labor cost (including all the indirect costs and fees identified in Table 4-4) is about $60,540 per person per year, while the same cost for the Capenhurst operations was about $45,000 per person per year, with a resulting scaling factor of 1.35.

Assuming that the pretreatment process uses the mobile gaseous $ClF_3$ system postulated in the Ebasco estimate, the corresponding materials costs (proportional to equipment internal surface area) and labor costs comprise about 76.7 percent and 23.3 percent of the total, respectively. Thus, the pretreatment scaling factor is (0.767)(2.200) + (0.233)(1.350) = 2.00.

Planning and management costs are scaled by the ratio of exempt labor costs ($150,000/person year at the Oak Ridge GDP and $100,000/person year at Capenhurst), or 1.5. This cost element is also increased by the much larger number of buildings to be handled in the U.S. GDPs. However, because the buildings are so similar, an increase of about 20 percent is postulated to be adequate. Thus, the total scaling factor becomes 1.5 × 1.2 = 1.8.

Technical development costs are scaled by the ratio of exempt labor costs, 1.5, and characterization costs should be proportional to the ratio of building floor surface areas, 3.885.

Disassembly costs should be proportional to the amount of process equipment disassembled and to the amount of building support equipment disassembled. From the 1991 Ebasco estimate, the fraction of total disassembly cost due to process equipment is about 0.44, and the fraction due to building support equipment is about 0.56. Thus, the scaling factor is (0.44)(2.200) + (0.56)(3.885) = 3.144.

The scaling factor for hazardous materials removal and treatment is assumed to be proportional to the amount of asbestos present, which is proportional to the amount of process equipment, represented by the scaling factor 2.200.

Decontamination should be proportional to the amount of process equipment cleaned and to the amount of building surface cleaned. From the 1991 Ebasco estimate, the fractions of decontamination costs arising from process equipment and from building floor surfaces are about 0.764 and 0.236, respectively. The resulting scaling factor is (0.764)(2.200) + (0.236)(3.885) = 2.598.

Metal melting costs should be proportional to the amount of metal melted. Assuming the same fractions of total metal are melted at both locations, the scaling factor is the ratio of the full-density volumes of metals from the plants (see Table H-3 in Appendix H) or 6.76.

Health and safety activities should be proportional to the total size of the plants, or the plant floor areas, 3.885.

The radioactive waste disposal costs at Capenhurst ($_{cp}$) and at Oak Ridge GDP ($_{or}$) can be expressed by

$$C_{cp} = V_{cp}\, S_{cp}\, F_{cp}$$

and

$$C_{or} = V_{or}\, S_{or}\, F_{or}$$

where V is the volume of waste generated, S is the unit cost for disposal (in \$/ft$^3$), and F is the fraction of the total waste generated that is disposed of in a low-level radioactive waste disposal facility, with the rest of the waste having been cleaned and recycled. The volumes of waste generated are proportional to the quantity of process equipment, that is, $V_{or} = 2.200\ V_{cp}$, and

$$V_{cp} = C_{cp} /(S_{cp}\, F_{cp})$$

Then

$$C_{or} = \{2.200\ C_{cp} /(S_{cp}\, F_{cp})\}\ S_{or}\, F_{or}$$

or

$$\begin{aligned} C_{or} &= 2.200\ C_{cp}\ (S_{or}/S_{cp})(F_{or}/F_{cp}) \\ C_{or} &= (2.200C_{cp})(100/74)(1 \text{ or } 20) \\ C_{or} &= 2.97\ C_{cp}\ (1 \text{ or } 20) \end{aligned}$$

The third factor in the equation (100/74 = 1.35) is based on an assumed average disposal charge for low-level radioactive waste disposal in the United States of \$100/ft$^3$ and in the United Kingdom of \$74/ft$^3$.[5] The last term in the equation is 1 when the same fractions (assumed to be 5 percent) of waste are disposed and is 20 when all of the Oak Ridge GDP waste from D&D

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[5] Clements (1994) stated a cost of \$2,000/yd$^3$ at Driggs in the United Kingdom. The assumed \$100/ft$^3$ for the United States is higher than costs assumed in the cost estimates but well below costs being predicted for some private U.S. low-level radioactive waste disposal facilities.

is disposed (100/5). Because disposal rates dominate this cost element, the differences in direct labor rates are neglected.

Table 4-7 shows the scaling factors and the costs for the D&D of the Oak Ridge GDP derived using these scaling factors. The resulting total cost for the Oak Ridge GDP, based on scaling the Capenhurst costs by appropriate factors, is about $510 million when 95 percent of the waste is recycled, and about $936 million when none is recycled. To estimate the cost for D&D of the total U.S. GDP complex, the cost derived for the Oak Ridge GDP is multiplied by the ratio from the Ebasco cost estimates for Oak Ridge to that of the total GDP complex, namely 2.17, which yields estimated costs of about $1.11 billion or $2.03 billion, respectively, for the recycle and no-recycle cases for the whole U.S. GDP complex.

The committee recognizes that using simple ratios of quantities to make an order-of-magnitude estimate of the cost of D&D for a much larger plant such as the Oak Ridge GDP is a very simplified approach to a complex comparison with many uncertainties. This approach understates the Oak Ridge D&D costs somewhat because this plant has substantially more ancillary facilities and structures than does Capenhurst. The size of the equipment at Oak Ridge is considerably larger, and the base cost at Capenhurst reflected the savings that resulted from recycling decontaminated materials. On the other hand, factoring should clearly overstate the Oak Ridge D&D costs because it does not reflect the potentially significant cost savings associated with economies of scale. In any event, it is not readily apparent to the committee why the current U.S. cost estimate should be from 8 to 15 times larger than the cost obtained by scaling the Capenhurst cost according to plant size and material quantities.

Although this very simplified factoring of the Capenhurst estimate is clearly no substitute for a detailed cost comparison, it nevertheless provides a reasonable approximation for the potential cost reductions that might be achieved in the U.S. GDP D&D program.

## THE SHIPPINGPORT REACTOR D&D PROJECT

The Shippingport Atomic Power Station consisted of a four-loop nuclear steam supply system, a radioactive waste processing facility owned by DOE, and a 100 MW (electric) turbine-generator and balance-of-plant owned by Duquesne Light Company. The station, located 35 miles north of Pittsburgh, Pennsylvania, was shut down in 1982 and defueled in 1984. Planning for D&D began in 1979 and was completed in 1984. Actual D&D began in 1985 and was completed in 1990. This project is an example of a successful DOE D&D project, in that it was completed ahead of schedule and below budget (Murphie, 1991).

The decommissioning operations were managed by General Electric, the decommissioning operations contractor, which reported directly to DOE, without any management and operating contractor on the site. Much of the active D&D effort was carried out by fixed-price subcontractors. The Shippingport Station Decommissioning Project was estimated to cost $98.3 million and take 5.5 years. It was completed 6 months ahead of schedule at a cost of $91.3 million, $7 million under budget (Crimi, 1987, 1988a, 1988b, 1992, 1994).

The Shippingport project posed management and technical challenges similar to those that will be faced in D&D of the U.S. GDPs, including removal of hazardous materials, such as asbestos and PCBs, and fluids processing to remove radioactive contaminants. The principal differences are the much larger scale of the GDP D&D, the possibility of a criticality accident at the GDPs, and the repetitive nature of the GDP systems and structures that would permit more extensive use of robotics and automated systems. Three important lessons were learned from the Shippingport project: careful planning and preparation avoid undue delays and work interruptions and are cost effective; simplifying the project organizational structure is cost effective; and, finally, using available commercial technology to the greatest extent possible also saves money and time. These lessons are directly applicable to the D&D of the GDPs.

## CONCLUSIONS AND RECOMMENDATIONS

### Previous D&D Cost Estimates

#### Conclusions

1. The cost estimates were developed for a defined scenario, apparently without using tradeoff studies to determine the most cost-effective approaches for D&D. Thus, many of the scenario bases are less than optimal, resulting in high cost estimates.
2. The Ebasco and TLG estimates were based on a common inventory of buildings and equipment and arrived at similar results. However, this agreement appears somewhat fortuitous considering the wide differences between the unit cost factors and the waste treatment and disposal assumptions. Both estimates ignored the potential cost and schedule reduction from productivity increases that characteristically result when performing repetitive activities. Also, the staffing levels postulated in both estimates appear excessive, reflecting the generally very conservative unit cost factors developed and used in the analyses.
3. The largest single element in the cost estimates is the construction and operation of low- and high-assay decontamination facilities, an assumption that represents 30 to 40 percent of the total D&D cost and reflects the large size of the structures, the multiplicity of decontamination and volume-reduction technologies postulated to be used in them, and the very large staffs assumed to operate these processes. Apparently, the choice was made in the Ebasco study to include these large, new facilities without any tradeoff evaluations to determine the optimal processes to be used or whether it was feasible to use existing structures to house the decontamination and volume-reduction processes.

#### Recommendation

Tradeoff evaluations to determine optimal D&D processes and the feasibility of using existing structures should be performed to help establish the technical baseline for the project prior to beginning detailed planning and cost estimating for D&D of the GDPs.

## Cost to D&D the GDPs

### Conclusion

Previously estimated D&D costs for the three U.S. GDPs range from about 60 to 100 times the expected final cost of $160 million for the D&D of the Capenhurst GDP (over 90 percent complete at the end of 1994). Considering that the size of the three GDPs combined is only about 10 to 12 times larger than Capenhurst in physical size, the previous U.S. estimates appear extremely high.

### Recommendation

DOE should very carefully review its earlier estimates and have a new cost estimate developed that would evaluate the various opportunities for cost reduction identified in this report (see Chapter 6) and should incorporate those approaches that appear most cost effective. The cost-estimating methodology used should incorporate recent advances in sensitivity analysis to calculate the influence of alternative assumptions and their probability distributions on the estimated total cost of D&D.

## Adequacy of the D&D Fund

### Conclusion

The planned cash flows into the D&D Fund of $480 million per year for 15 years, for a total of $7.2 billion, will not be sufficient to support the expenditures projected in the Ebasco, TLG, or SAIC cost estimates, even without taking into account the ongoing expenditures from the fund for various remediation activities throughout the GDP complex. It appears almost certain that the fund will be expended well before the GDPs can be completely decommissioned or that the D&D must be completed for far less than indicated by any of the previous cost estimates. Thus, it would appear prudent to consider proceeding in a stepwise manner, accomplishing the most important D&D tasks (from a cost and risk viewpoint) first, and continuing with tasks of less immediate importance as funds become available.

## Experience from Other D&D Projects

### Conclusion

DOE's preparation of a new cost estimate to evaluate alternative approaches to D&D of the GDPs should focus on four essential activities:

- establishing the basic D&D criteria, and conducting tradeoff studies and demonstration programs to select the most cost-effective technologies;
- preparing a detailed D&D execution plan;

- minimizing the number of management layers between the funding source (DOE) and the contractors executing the D&D plan; and
- maximizing the use of commercially available technology.

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# 5

# Planning the D&D Program

The D&D of the three GDPs presents an interesting dichotomy. On the one hand, this D&D is a relatively simple operation, consisting of the demolition of large buildings and the removal and disposal of their contents; on the other hand, it is very complex, owing to the number of parties involved, the presence of hazardous substances, the complex regulatory environment, the long time frames for budgets and management, and the large scale of the project. Cost-effective management will require a management structure that is streamlined, orderly, responsive, focused on safety and cost containment, shares information, and is open to scrutiny by others throughout the D&D process. Careful planning is therefore required to ensure program integration, effective stakeholder involvement facilitating trust and confidence, and a responsive management that has the authority and responsibility to move the project to closure in an expeditious manner while protecting workers, the public, and the environment and complying with a large set of current and as-yet undefined regulations. It is a formidable task, but it can be completed successfully if able leaders on site are given the freedom and authority to get on with the task. It will require some changes in current management practices applied to D&D and the definition and implementation of a coordinated set of regulatory requirements.

## PUBLIC AND STAKEHOLDER INVOLVEMENT

Although the U.S. Department of Energy (DOE) and its project management are ultimately responsible for the project and cannot delegate that responsibility, the committee believes that involvement of the public and other stakeholders in the D&D process is an important factor in attaining cost-effective D&D (see, for example, Colorado Center for Environmental Management, 1993, and Confederated Tribes of the Umatilla Indian Reservation, 1995). There are several key constituencies that must be included in each site stakeholder group: the local and broader public, state and local officials, members of Congress, state and national regulators, and the workers. Other affected parties may be included as needed. These groups must not only be represented, but their active participation in providing input into all stages of the decision-making process, providing oversight, and representing the spectrum of views must be integrated. Local public and stakeholder involvement and its integration at the sites should be initiated early in D&D planning. Public involvement must be tied to planning and programmatic decision making early so that the views of the stakeholders can be considered in defining the basic direction of the program.

While DOE and its project management are ultimately responsible for the project, a stakeholder involvement group should serve as a sounding board, consensus builder, and advisor. It is essential that stakeholders be provided with information on costs and technical limitations of the various alternatives to help them develop their recommendations. This arrangement will help to illuminate the positions of the various stakeholders and bring to bear the many positions. Further, it should be the advisory body in which compromises are developed in light of the widely varying and sometimes conflicting interests. The advisory body should also provide a constant view into the project, so that public input is represented in the work as it progresses from planning to implementation to completion. Such a public involvement process is very different from a public information program.

Integrating the public and stakeholders into the D&D decision-making process poses challenges. DOE has shown an increasing understanding of the importance of public participation for the success of its new mission and has charged its Environmental Management Program with developing an integrated public involvement program. This programmatic responsibility is lodged in the Office of Public Accountability (DOE, 1994a). The D&D of the nation's GDPs are a part of the larger Environmental Management Program efforts and will therefore be expected to conform to, and benefit from, the evolving importance of its public participation program.

Site Specific Advisory Boards (SSABs) are a recently developed mechanism to integrate stakeholder concerns. The SSAB provides a representative forum for affected groups at a site. DOE is forming an SSAB at the Oak Ridge Reservation; however, the board's intended relationship with existing public involvement groups is unclear. Funding for SSABs averages $200,000 per year; one (at Hanford) costs $900,000 (Beck, 1994). However, the costs of delay and lost opportunities resulting from failure to work together with these groups can be far higher. Establishing a cooperative relationship early should foster a functional and beneficial role that will enhance D&D, but DOE faces challenges in both integrating of existing groups and staking out a meaningful place in the D&D program for SSABs.

One problem for the SSABs appears to arise out of the *interpretation* of the Federal Advisory Committee Act. While intended to ensure that the federal bureaucracy actively addresses stakeholder issues, the act's requirements may also interfere with the ability of the SSABs to set their own agenda and provide independent advice. This problem needs to be addressed and rectified by DOE to preserve the perceived legitimacy of the SSABs in their communities and to ensure that DOE does not exert too much control over SSAB activities.

Because the public may not readily distinguish D&D from other environmental restoration activities at the sites, D&D stakeholder involvement must be a part of an integrated site stakeholder involvement program that considers the whole site. While each site has unique perspectives and concerns, experience with effective stakeholder involvement mechanisms should be shared among GDP sites.

The committee believes that the SSAB can provide important input to DOE project management at each site during the course of the D&D project cycle. The exact format for stakeholder involvement may vary depending on the site and the individuals involved. An existing group that is functioning well and has broad representation may serve as the basis for an SSAB. The SSAB could include affected public(s), regulators, worker representatives, and others and would be formed at the beginning of the D&D process and operate throughout the D&D project cycle. Although the level of participation of the member groups may vary during the process, all should be actively involved during the planning phase and remain in an oversight role during the implementation phase. Although an SSAB is not charged with decision-making authority per se, meaningful participation implies that the SSABs, or their equivalent, would have an active role throughout the D&D process. For example, they should periodically review the work in progress, particularly when there are major changes to the work plan, significant schedule delays, or major cost overruns.

For each site, stakeholder involvement could be managed through an SSAB or similar format; for the complex as a whole, a steering panel should be formed. The steering panel would provide program-level advice to DOE management on the conduct of the D&D efforts at the three GDP sites. The steering panel would provide input on such issues as focus, timing, priorities, budget, and end states on a GDP complex-wide basis. The panel would also serve the important function of addressing differences that may occur among sites. The panel should include representatives of the SSABs from each site to reflect concerns from the different localities. The Oak Ridge GDP site requires additional coordination with other activities at the Oak Ridge Reservation.

## END-STATE ALTERNATIVES

Past D&D planning by DOE has been predicated on defining certain end states for the GDPs at the beginning of the planning and execution process. It has been assumed that the end state was the primary cost driver and that the same end state was to be obtained at all three sites.

The Nuclear Regulatory Commission has a standard list of possible end points for D&D of nuclear power plants.[1] However, these alternatives were developed for facilities and sites containing short-lived radionuclides, namely, cobalt-60. This is not the case at the GDPs, where $^{238}$U is the dominant radionuclide.

The Ebasco and TLG D&D cost estimates assumed removal, rather than safe storage, of the equipment and hazardous and radioactive substances such that a future occupant would not be exposed to harmful levels of these substances. This approach is termed "prompt dismantlement." However, other end states are possible, and those considered by the committee are given in Table 5-1. This list is meant to be illustrative and is not intended to be complete. The end states are arranged in the order of increasing cleanup activity as follows:

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[1] These end points are referred to as ENTOMB, SAFSTOR, and DECON. The ENTOMB end point entails encasing the radioactive contaminants in structurally long-lived material that is maintained until the contaminants decay to a level permitting unrestricted release of the site. The SAFSTOR option involves maintaining the facility in a safe storage condition, with decontamination to an unrestricted release level deferred until a later date. Under the DECON option, the radioactive contaminants are removed from the equipment, structures, and site to a level permitting unrestricted release of the site shortly after cessation of facility operations.

TABLE 5-1 End-State Alternatives for the D&D of the GDPs

| **End State** | Description |
|---|---|
| No action | Buildings and facilities left in current state; Enriched uranium removed to eliminate criticality and safeguards concerns; Remedial actions halted except for significant, near-term risks; Limited access controls maintained and areas posted to indicate hazardous and radioactive materials present; Surveillance and maintenance continue in perpetuity |
| Entombment, in place | Stabilization of structure; Engineered barrier to minimize contaminant migration; Asbestos and materials contaminated with PCBs left in place; PCB-contaminated bulk fluids removed |
| Entombment, surface burial | Equipment and buildings dismantled and demolished; Contaminated equipment and structures buried in an on-site facility |
| Decontamination, restricted use | Contaminated equipment removed and buildings remain; Loose contamination removed or fixed in place; Buildings reused for alternative activities, such as waste storage |
| Decontamination, unrestricted use, and release to commercial sector | Contaminated equipment removed and buildings remain; Buildings decontaminated; Buildings released to the public for unrestricted use or abandoned and allowed to degrade over time |
| Decontamination, greenfield | Same as for unrestricted use and release, except that the buildings are removed and the site is covered with clean soil and released to the public |

- *No Action* (long-term surveillance and maintenance). The present state of the retired facilities is maintained in perpetuity; access to those facilities is closely controlled, and significant near-term risks, such as highly enriched uranium, are mitigated.
- *Entombment*. The potentially mobile contamination in the structures is removed or fixed in place. The contaminated equipment remains in place, and the structures are sealed within an engineered enclosure to confine contaminants. An alternative entombment approach is to disassemble, demolish, and bury the structure and its contents in an on-site facility.
- *Decontamination*. Three variations of an option are considered in which the contaminated equipment is first removed and the remaining structures are subjected to one of the following:
  - partial decontamination and retention of the buildings for restricted reuse;
  - decontamination, retention, and release of the buildings for unrestricted, alternative reuse (this variation corresponds to the "prompt dismantlement" assumed in the cost estimates); or
  - demolition and complete removal of the buildings, with the site restored to greenfield conditions.

In the *no action* and *entombment* alternatives, the contaminated equipment and structures remain on site for extended periods. Contaminant releases are limited by surveillance and maintenance of the structures in the first case and engineered enclosure limits releases in the second case. Because of the very long half-lives of the uranium radionuclides present at the sites, the contamination levels will be essentially unchanged when the existing buildings or the entombment enclosure collapses. The other hazardous substances also do not decay. Thus, no reduction of the risk associated with the structures and their equipment will have been achieved during the delay period.

The three *decontamination* alternatives all presume removal of the contaminated equipment from the structures and either complete or partial decontamination of the empty structures. If decontamination is achieved, the clean structures may be demolished and the site restored to the greenfield condition, for example, for possible residential use. Alternatively, the structures may be left in place and released for unrestricted reuse. In these situations, the radiological and toxicological risks from the site have been reduced to an acceptable level. If the structures are only partially decontaminated, that is, loose contamination is removed or fixed in place, they may be retained for restricted use, such as storage for low-level radioactive or hazardous wastes, and a small but finite risk from hazardous or radioactive materials remains for the site.

These end states are not mutually exclusive in the sense that at a particular site different buildings may be targeted for different levels of cleanup. For example, some buildings might be cleaned up for reuse, some demolished, and some might be put into a surveillance and maintenance program for cleanup in the future. Perhaps not all the sites would be cleaned up to achieve the same end state. Additionally, the goal of greenfield status, or taking a site back to a pristine condition for future unrestricted use, may not be appropriate if the remainder of the site has contaminated areas. In such a situation, the cleaned-up areas where the buildings once stood would be clean islands within a broader area that would most likely remain restricted because of residual contamination.

### Prioritized Cost- and Risk-Reduction Approach

Choosing an end state as the starting point of D&D is not the only way to begin planning and conducting D&D Because of regulatory and budgetary uncertainty and the often lengthy process of developing consensus of the various groups affected by D&D operations, deciding on an end state could be a time-consuming process. Another approach is to prioritize the costs and risks presented by the site and schedule cleanup activities incrementally, focusing first on those activities that must be performed regardless of the final end state, on those areas where risk is highest, and on those actions that would reduce total costs over the entire D&D effort. Using this incremental approach, an end state need not be determined immediately; site release criteria would not be immediately necessary; and additional opportunities would be available to involve the public and other affected stakeholders.

Furthermore, each of the end-state alternatives has its particular funding requirements and activity schedules and would require significant, sustained levels of funding over the time period specified to achieve the desired end state. Because of the uncertainties of budgetary and appropriations processes and the complex planning required, an incremental approach to D&D may be more appropriate, and work could proceed promptly within available annual budgets.

The following example of the prioritized cost- and risk-reduction approach is provided as an illustration. If this approach were implemented, a complete and thorough determination of the costs and risks would be required. Starting from the baseline of "no action," the first activity would be the abatement of any potential for a nuclear criticality event. This could be accomplished by removal of those deposits of highly enriched uranium large enough to initiate a criticality event under appropriate conditions. This action would not only eliminate a significant risk to site workers, it might also eliminate the special security and accountability functions required by large inventories of special nuclear materials, thereby reducing the ongoing costs of surveillance and maintenance, such as by reducing the size of the security perimeter to reduce security costs.

In the absence of a quantitative risk assessment, the committee believes that at this point, the only high-consequence, significant-probability risks associated with the facilities appear to be fire or high winds causing release and transport of friable asbestos, PCBs and/or their combustion products, and loose radioactive surface contamination.[2] Efforts to remove or fix asbestos contamination would mitigate this risk, and effective fire protection measures would substantially reduce the chance of fire borne dispersal of PCBs or loose surface contamination. Draining and replacing PCB fluids in electrical equipment would reduce the hazards associated with a fire in PCB-containing electrical equipment.

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[2] The risk of other natural hazard events, such as earthquakes, should be evaluated.

After these risks have been mitigated, measures to remove potential long-term hazards would be carried out in a prioritized fashion by considering marginal risk reduction versus cost. If carried to completion, this strategy could eventually result in the removal and disposal of all contaminated materials and release of the site for unrestricted use or in permanent restriction of those areas of the sites unsuitable for remediation.

## DEVELOPMENT OF AN INTEGRATED REGULATORY PROGRAM

The D&D of the uranium enrichment facilities will be conducted under the regulatory oversight of several agencies. While large quantities of radioactive and/or toxic materials are found in the GDPs, three predominate: uranium compounds including large amounts of $UF_6$ (uranium hexafluoride), PCBs, and asbestos. Regulations promulgated by states, federal agencies, and internal DOE orders are intended to protect workers, the environment, and the public from toxic and/or radioactive releases into the air or water and to ensure that hazardous, radioactive, and mixed wastes are reduced and treated appropriately. During D&D operations, similar protections will be required. However, regulations can drive up the cost unnecessarily if they conflict with one another or are redundant. Regulatory mandates can also alter the D&D schedule. Similarly, some regulations need to be promulgated to facilitate D&D planning, particularly standards addressing numerical limits for recycled materials and site release criteria. Such standards will enable DOE to target cleanup end states, although planning and initial cleanup must and can proceed in their absence.[3] Costs will be reduced if regulations can be applied in a coordinated fashion to the entire D&D effort.

### Federal Regulations

Together with the DOE, a number of federal regulatory agencies such as the EPA, Nuclear Regulatory Commission, Occupational Safety and Health Administration (OSHA), and Department of Transportation (DOT) have authority over aspects of the D&D program.

EPACT provides the broad structure for health, safety, and environmental oversight during D&D of the uranium enrichment facilities. In addition, numerous environmental laws will bear on D&D. Each of these laws has a major impact on planning and eventual conduct of D&D (DOE, 1991). However, the Comprehensive Emergency Response, Compensation, and Liability Act of 1980 (CERCLA, or "Superfund"), in concert with the Resource Conservation and Recovery Act (RCRA), is the overarching law regulating D&D.

#### DOE

DOE has an unusual role in D&D in that it is both a regulated entity and a regulator. In one role, DOE will be responsible for planning and implementing D&D activities and for this reason will be subject to EPA, Nuclear Regulatory Commission, and OSHA regulations. In its

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[3] Because radionuclides at the GDPs are limited and uranium predominates, the Environmental Protection Agency and the Nuclear Regulatory Commission could accelerate promulgation of regulations for uranium, technetium ($^{99}$Tc), plutonium ($^{234}$Pu), and neptunium $^{237}$Np), which would clarify DOE D&D goals.

other role, DOE will apply a number of internal DOE orders to regulate D&D activities. These orders are designed to protect workers, the public, and the environment, through prescriptive rules on such issues as nuclear criticality safety.

### EPA

EPA has primary regulatory authority over D&D of the three sites under CERCLA. It already has oversight of the Paducah GDP and the Oak Ridge Reservation because they are listed on the CERCLA National Priorities List; the Portsmouth GDP site may be added to the list in the near future, based on its hazard risk ranking score. Other laws and regulations that apply include RCRA, TSCA (Toxic Substances Control Act), the Clean Water Act, Clean Air Act, and Federal Facilities Compliance Act of 1992 (FFCA).

### Nuclear Regulatory Commission

Normally, the Atomic Energy Act exempts DOE facilities from regulation by the Nuclear Regulatory Commission. However, EPACT, which established the USEC, mandated that the Commission certify Portsmouth and Paducah for continued safe operation; the Commission does not have jurisdiction over the Oak Ridge GDP site itself, since it is not an operating or commercial GDP. In contrast to the practice for most facilities under Nuclear Regulatory Commission jurisdiction, the Commission will issue a certificate, rather than a license, for Portsmouth and Paducah. The Nuclear Regulatory Commission has issued a proposed rule, "Certification of Gaseous Diffusion Plants," specific to these facilities and assumed regulatory authority from DOE on October 1, 1995. Although the Commission's role in overseeing the operating facilities is delineated by the EPACT, its role is less clear for D&D operations. An orderly transition plan to move from Nuclear Regulatory Commission regulation of the operating facilities to EPA regulation of the D&D effort could serve to minimize regulatory confusion and cost.

### OSHA

Traditionally DOE facilities have also been exempt from the Occupational Safety and Health Act and OSHA regulation under the Atomic Energy Act. However, under a recently enacted memorandum of understanding with DOE (OSHA, 1994), OSHA will have oversight over DOE facilities, such as those undergoing D&D. Furthermore, the legislation establishing the USEC mandated OSHA oversight of the two leased GDPs during enrichment operations.

OSHA currently provides training for the GDP staffs on hazard identification during enrichment operations. Plans for ongoing worker safety have not made a clear distinction between the different requirements of enrichment operations and D&D. However, routine maintenance activities can involve some decontamination, thus blurring the distinction between operations and D&D.

OSHA has not identified its staffing and budgeting requirements to support DOE in its D&D program. In part, this is because OSHA, like the Nuclear Regulatory Commission, does not have a clearly defined role in D&D. Once OSHA's role is delineated, it could impose an additional cost not reflected in the Ebasco or TLG cost estimates. Because the greatest risk during D&D will likely be to on-site workers, expenditures to reduce these risks will be justified.

### DOT

DOT has served as the regulatory authority for transport of enriched uranium product among the three GDP sites for a number of years. During D&D, it will regulate the safe transport of all waste materials from the sites under Hazardous Materials Transportation Regulations.

Under the Hazardous Materials Transportation Act of 1974, DOT has regulatory responsibility for safety in the transportation of all hazardous materials and radioactive materials (DOT, 1983). This responsibility covers shipments by all modes of transportation in interstate and international commerce and by all means of conveyance, including truck, barge, rail car, vessel, and airplane. DOT and the Nuclear Regulatory Commission operate under a memorandum of understanding, revised June 8, 1979. Under this memorandum, DOT's role includes development of overall safety standards governing all radioactive materials packaging, their clarification, marking, and labeling. DOT has responsibility for packaging requirements for all waste materials expected to be generated from the three GDPs.

### USEC Effects on Regulatory Oversight

The privatization of the two operating GDPs presents legal differences in regulatory oversight. For instance, Nuclear Regulatory Commission and OSHA regulations are not applicable to the Oak Ridge GDP, but are applicable to enrichment operations at the Paducah and Portsmouth GDPs through the USEC under Section 1312 (c) of EPACT. It is unclear whether this regulatory oversight will change or cease upon closure of these GDPs. As part of the regulatory requirements scheduling, DOE should begin to develop regulatory plans for transfer of control of the two operating plants leased by the USEC back to DOE for D&D.[4]

### EPA and Nuclear Regulatory Commission Development of Radiation Site Cleanup Regulation

Both the EPA and Nuclear Regulatory Commission, in coordination with DOE and the U.S. Department of Defense, are developing revised risk-based radiation site cleanup regulations. EPA is drafting applicable regulations for federal facilities, with a final rule due to be published in 1996. The Nuclear Regulatory Commission is also developing risk-based radiation site cleanup standards for its licensees,[5] based on a proposed limit of 15 mrem/yr of total effective dose equivalent, including a 4 mrem/yr water quality requirement, for unrestricted

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[4] DOE is developing a plan of action to develop a regulatory strategy for the turnover of the GDPs to DOE after plant shutdown (DOE, 1995).

[5] Existing cost estimates have used Nuclear Regulatory Commission Regulatory Guide 1.86 and DOE Order 5400.5 for site release criteria.

site release.[6] A total effective dose equivalent of 15 mrem/r is approximately a $4 \times 10^{-4}$ lifetime fatal cancer probability. Congressional pressure has been exerted recently on these agencies to reconcile their radiation protection standards and risk assessment methodologies (GAO, 1994a; Lobsenz, 1994), and EPA has been asked to lead this effort (Lobsenz, 1995). DOE should continue to participate in and support these efforts.

The issue of acceptable risk levels is politically sensitive, and delays in development of criteria are possible. However, once risk-based cleanup regulations are developed, appropriate future use scenarios should be used to determine site-specific exposure limits appropriate to the GDP sites.

## State Regulation

Each of the GDPs is located in a different state and each state has a different set of laws and regulatory agencies that oversee the GDPs. There may be economic merit in developing uniformity across state lines: if DOE can create one master plan for cleanup for all three plants that is acceptable to all three state regulators, and state regulations are consistent, costs could be reduced.

The state agencies differ in structure and in the history of their dealings with federal agencies.[7] For example, the Ohio Environmental Protection Agency has sued DOE to dispose of the $DUF_6$ (depleted uranium hexafluoride) inventory as waste (Van Kley, 1994). DOE characterizes this material as a national asset, rather than a waste. Moreover, DOE and the Ohio agency have different positions about whether, even if this material were deemed a waste, it would be regulated under RCRA and thereby subject to strict state monitoring and enforcement. (See Chapter 7 for a more complete discussion of $DUF_6$.)

For such reasons, establishment and development of a new working relationship among all the regulatory agencies, including those at the state level, will be required. State law suits and inspections and efforts by agency and contractor personnel to correct violations can increase the costs of D&D. The committee believes that if facility personnel and regulators work together and carry on an open dialogue, the emergence of major problems and violations can be better anticipated and avoided to a great extent. DOE involvement in the continuing deliberations of one of the national-level stakeholder groups, the State and Tribal Government Working Group, as well as its efforts with the National Governors Association, is a good start in establishing a smooth working relationship. Direct involvement of the state regulators at the sites is essential in the planning stages to minimize conflicts during D&D.

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[6] Restricted release scenarios may also be allowed, with adequate institutional controls in place. The standards would then be set such that if all institutional controls failed, the public would not be exposed to doses in excess of 100 mrem/yr.

[7] Some state agencies are funded solely through the state, others through DOE funds transferred through other agencies.

### Challenges and Current Developments

Some aspects of the regulatory arena contribute to uncertainty in planning work and developing cost estimates for cleanup of the three GDPs. One of the most significant, as the discussion above has indicated, is the fact that there are many agencies with jurisdiction over D&D, with insufficient coordination among agencies to integrate laws and resulting regulations. A prime example of this is regulation of mixed waste, that is, waste that is classified as both hazardous and radioactive. Significant quantities of mixed waste could be generated during D&D, although no quantitative estimates appear to be available. The Nuclear Regulatory Commission and DOE regulate mixed waste under the Atomic Energy Act, and EPA regulates it under the RCRA. These two regulatory programs prescribe different solutions to the mixed waste disposal problem. For example, radioactive wastes must be buried, while hazardous wastes are not allowed to be buried. This regulatory quandary has resulted in complex disposal systems (Thompson and Goo, 1993).

Few of the environmental protection laws were legislated mindful of D&D requirements of the federal facilities, much less the GDPs. The FFCA is an exception in that it was specifically drafted to require federal facilities to comply with environmental laws. Its implementation clearly reflects the difficulties in obtaining the necessary coordination and cooperation of states, Indian tribes, and other key stakeholder groups. The multiple federal agencies involved in D&D, however, must compete for dollars allocated by Congress, while producing regulatory redundancies that do not provide additional checks and balances but create inconsistencies (Thompson and Goo, 1993). A General Accounting Office report, citing the various EPA, Nuclear Regulatory Commission, and DOE regulations, suggests that there has been a "historical lack of a unified federal framework for protecting the public from radiation exposure" (GAO, 1994a). Although it may be tempting to avoid compliance if regulations appear to conflict with one another, it is incumbent on decision makers to find creative integrating mechanisms that enhance environmental protection rather than avoid it.

Under the FFCA, DOE is required to submit mixed-waste treatment plans either to host states that are authorized to regulate hazardous materials or to EPA (GAO, 1994b). The three states within which the GDPs are located are at various stages in negotiating mixed-waste plans with DOE. Waste management issues are illustrative of the difficulties of integrating state and federal oversight, conflicting regulations, and predicting the cost and schedule impact of future regulations.

For materials that have surface contamination, standards exist that allow free-release if sufficient decontamination is achieved. These surface standards are currently under review by EPA and the Nuclear Regulatory Commission. There are no volumetric free-release standards for materials recycling in the United States. Waste regulations that have yet to be promulgated are those for recycling of materials, particularly metals and other materials that have been exposed to radioactive contamination. While most of the GDP materials only have surface contamination, some, such as the nickel barrier materials, have geometries that make decontamination difficult. Recycling potential would be enhanced with a volumetric standard. Both the Nuclear Regulatory Commission and EPA have begun preliminary work on surface and volume contamination standards. Once finalized,[8] such regulations could facilitate recycling of scrap metal, which could allow significant reductions in D&D waste volumes and consequent disposal costs.[9]

Due to the complexity and overlapping nature of the regulations likely to govern D&D work, involvement and coordination of federal, state, and internal DOE regulators early in the project are essential to ensure that regulatory requirements are clearly understood prior to planning the work and to ensure that the planned D&D process will meet all applicable and agreed-upon regulatory requirements.

### Safeguards and Security

Certain aspects of gaseous diffusion technology are classified as secret based on technical and national security concerns. This classification will impact D&D costs due to the increased security area and cleared personnel required to administer classified materials and clearances. Special nuclear material accountability procedures will also be required, involving high levels of security, extensive record-keeping, and other procedures that could hamper D&D operations. Decreasing the areas that have to be guarded and secured by reclassifying the material at the GDPs as special nuclear material of low strategic significance could reduce ongoing surveillance and maintenance costs as well as D&D costs. The committee believes that, during the planning phase, innovative approaches should be developed that would reduce the number of cleared personnel and safeguards and security requirements. (See Chapter 6 for further discussion of costs of safeguards and security.)

## Coordinated Planning

DOE has treated the three GDP sites separately for D&D planning, although the cost estimates all derive from a site planning exercise for the Oak Ridge GDP. DOE has also developed a remediation plan for the GDPs and a plan for the management of $DUF_6$ stored in cylinders. All the plans are in different states of development. Yet remediation and D&D are both paid for from the D&D Fund.

Plans are required at three levels: for DOE, for the GDPs complex-wide, and for each site. These plans must be integrated with other related activities, including site remediation, financial planning, and others, particularly at Oak Ridge. The Oak Ridge GDP site is a special

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[8] This is an issue, however, that can elicit extensive public debate. An earlier rule was proposed in 1986 for materials that the Nuclear Regulatory Commission called "Below Regulatory Concern" (Federal Register, 1986). Public interest groups and states that were trying to site low-level radioactive waste facilities joined forces to stop the rule. To ensure full public input in its deliberations, the Nuclear Regulatory Commission has engaged in an enhanced participatory rulemaking on D&D. The Commission should similarly ensure that the promulgation of a recycling rule involves appropriate public participation.

[9] Characterizing post-cleanup waste and verifying that it meets the required standard is costly and may hinder some recycling.

case because the site plans and work must be coordinated with activities on the remainder of the Oak Ridge Reservation.

## DOE-Level Planning

A plan should be developed at the department level to address such issues as financing the D&D; integration with other DOE activities; the general management approach, including contracting; and regulatory coordination. These and other issues are important to the DOE establishment and should be provided at the departmental level. Provision of stakeholder involvement should also be planned for at this level. Thus, this plan would set major goals and provide guidance on policy issues to ensure consistency of the approach with related activities.

To minimize total D&D costs, D&D operations will be most cost effective if the organizational structure minimizes the number of layers of supervision and management. As discussed in Chapter 6, in the Ebasco cost estimate, the program integration component of total cost is excessive, and a simplified management organization is needed. A thorough review should be undertaken of the management layers, in view of the number of workers who will execute the physical disassembly and decontamination, to eliminate redundant layers of supervision.

## Complex-Level Planning

The plan for the three-site GDP complex should address all items required for a successful D&D including management of $DUF_6$ and remediation. This complex-level plan will be the basis for site-level planning and must cover several areas:

- the technical baseline;[10]
- schedule of tasks, such as GDP characterization;
- personnel and funding requirements over time;
- management and contracting approach;
- applicable regulations, such as site release criteria;
- waste management; and
- public and stakeholder involvement.

The complex-level plan should be modular and flexible to facilitate changes and incorporation of experience during D&D and should be organized to readily permit changes in performance period, funding assumptions, and introduction of new D&D technology. The should

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[10] The technical baseline would include a conceptual or preliminary design of the D&D support facilities, design basis, choice of technology, key criteria, applicable codes and standards, and regulatory requirements.

also incorporate the results of sensitivity analyses and assessment of the impact of design alternatives on project objectives (costs, risks, and social values). One useful method is to use decision and systems analysis. This method will be useful at this level to frame the alternatives and explore and communicate the consequences of potential decisions, as well as the uncertainties in these consequences. Early analysis allows identification of significant constraints (e.g., funding, public acceptance, or technological limitations) and minimizes the likelihood that infeasible solutions will be pursued.

### D&D Organization and Staffing

Once the scope of work has been defined, the project organization and staffing should be planned by DOE. Prior D&D experience indicates that operation and maintenance personnel have valuable experience that should be used in developing the D&D plan and that continuity of key personnel enhances productivity. The requirements of labor laws and existing site labor agreements need to be integrated with the overall contracting strategy to strive for the optimal number and type of D&D workers.

### Plant Characterization Program

A cost-effective characterization program is essential to identify and quantify radiological and other hazardous contaminants, and it is critical to project success. However, complete characterization of the GDPs is not necessary at the planning stage. The implementation of a data quality objectives approach to characterization will help in tailoring the characterization plan to support achievement of the desired end state. A data quality objectives approach identifies the level of data needed to support a given decision (e.g., to release the sites for unrestricted use), and the characterization plan is designed to provide data to within a desired level of accuracy. Such an approach will help avoid over design of characterization plans.

### Regulatory Plan

An integrated plan should cover regulations and regulators governing the conduct of D&D at all three GDPs. The plan should also cover interface points with the appropriate government regulatory agencies and identify different standards that may apply to the sites in different states.

### Waste Management Plan

Large quantities of waste materials will be generated during D&D. Management of this waste will entail either construction of new on-site treatment or storage and disposal facilities or transportation of these materials off site to new or existing facilities.

Selection of a waste management approach will be influenced by costs, regulations, end-state decisions, availability of waste facilities, and the public's views. The costs and risks of packaging, transport, and off-site disposal must be weighed against the costs and regulatory hurdles inherent in constructing on-site facilities. For example, some waste is already being stored at the Oak Ridge GDP, which could affect D&D. Even if low-cost waste storage and disposal capacity is readily available off site, the political climate may not allow transportation to out-of-state facilities. There are also long-term uncertainties about the local acceptance of storage of low-level radioactive or mixed wastes.

Because of the large volumes of radioactive, mixed, and hazardous wastes likely to be generated during D&D, DOE needs to start now to develop a waste disposal plan. The plan should consider low-level radioactive, mixed, and hazardous wastes and should address the issues of on- versus off-site waste treatment and disposal and expected disposal costs. The plan's goal should be to minimize secondary and mixed wastes and to maximize recycling where it is economical and safe to do so.

Three sets of factors to be considered are scheduling and sequencing of D&D operations, end-state alternatives, and waste management. These factors are illustrative of the many issues that DOE must address in its planning.

The complex-level plan should provide for coordination at and across the three facilities within the complex. This major planning document should be flexible enough that site-level planning can adopt and modify it to meet the specific needs of each of the three sites. The complex-level D&D plan will serve as the planning interface with the other activities required to manage the sites, including remediation of soils and groundwater and the management of the $DUF_6$ stockpile.

## Site-Level Planning

A detailed decommissioning plan, which does not currently exist, is essential to define the project baseline, cost estimate, D&D operations sequence, and schedule. The Ebasco cost estimate was performed in a short period of time without the benefit of a detailed decommissioning plan and a well-defined technical baseline. Ebasco did not have enough time to conduct a thorough evaluation of alternative D&D technologies, waste disposal options, or optimizing D&D operations sequence and schedule. The lack of technical, cost, and schedule baselines for the current cost estimate undermines its credibility. When a new cost estimate is prepared, it should be structured to allow determining the cost impact of changes in the principal variables, such as period of performance, inflationary increases in labor, materials and disposal costs, funding assumptions, and introduction of new D&D technology. The work plan should be prepared after discussion with the stakeholders about the D&D priorities. Planning should proceed expeditiously without waiting for all regulations to be issued and for other uncertainties to be resolved.

Planning at the site level will consist of two parts. The first is application of the complex-level plan to the site by making necessary modifications so that the plan is site-specific. This plan may include such elements as specific time schedules, regulatory scenarios particular to the site, and detailed stakeholder identification. This plan should also detail the goals and objectives for the site and the broad outlines for the scope of work. The second part of planning should include a detailed work breakdown structure for D&D and sufficient detail to develop a budget-level cost estimate and bid solicitation for the work to be performed.

## Execution of the Planning

Planning should be a continuing effort allowing modifications to reflect regulatory changes, funding constraints, obstacles encountered, and alterations made. Although site planning should be done almost in parallel at the three sites to form the basis for a new cost estimate, the plans for the sites should be modified and updated to incorporate lessons learned from ongoing D&D. Thus, if Oak Ridge undergoes D&D first, experience from this activity should be reflected in modifications of the D&D plans for the other two sites. Plans should be subject to change to take advantage, for example, of changes in regulations or stakeholder input. Plans will also be affected by other factors, such as the schedule for D&D.

Based on the experience and knowledge base for the D&D of the GDPs, the committee judges that the first part of the site-level plan should be completed within 12 months and the second part of the site-level plan should take no more than another 6 to 12 months to complete. The plan should begin well in advance of the need for a detailed cost estimate and certainly while personnel knowledgeable of current operations are available. Planning should be performed by an independent contractor who is not currently managing the D&D planning or execution at the three GDP sites. There would be a learning period for such an independent contractor, but the committee believes that a fresh approach could be brought to D&D planning that is not tied to existing site practices and procedures relevant to an operating facility. This contractor could draw on the knowledge of experienced personnel at the sites and at the same time would not be constrained by preconceived notions of how to accomplish the D&D.

## Scheduling and Sequencing

The current D&D program schedule envisions the D&D of the Oak Ridge GDP first, followed by that of the Portsmouth and Paducah GDPs. The Ebasco cost estimate assumed Oak Ridge followed by Paducah with Portsmouth last (DOE, 1991). The schedule and sequence of D&D activities will impact project cost and funding requirements. For example, the D&D of the three sites could be conducted in series to minimize annual funding requirements. Alternatively, the activities could be conducted in parallel. This strategy could reduce the total program schedule and cost, for example, by reducing the annual expenditures for surveillance and maintenance. Shortening the time period would also reduce overhead and program management costs. The D&D program could also be conducted using a staggered schedule that maximized the transfer of experience among the sites and might limit the number of subcontractors required. The annual contributions to the D&D Fund and the accumulations that accrue will constrain the rate at which D&D can be accomplished.

Similarly, the sequence of activities among the three GDPs can be varied. For example, processing of the $DUF_6$ could begin at Paducah first because it has the largest inventory and the greatest amount of the lowest $^{235}U$ assay material, which is the least attractive for possible alternative uses (see Chapter 7). However, there are reasonable arguments for processing the $DUF_6$ at Portsmouth first; the Ohio Attorney General has pressed for extensive monitoring, if not near-term disposition, of the $DUF_6$ inventory.

Different factors may influence the choice of a given schedule, in some cases accelerating and in others slowing down D&D operations. For example, delayed D&D or an extended program allow some technology demonstration efforts to reduce uncertainties and more detailed D&D planning, workforce planning and restructuring, and public involvement. Delayed D&D also allows DOE to address more immediate, high-risk concerns in its weapons complex. However, extending the schedule increases the cost of annual surveillance and maintenance, neglects those site risks that will increase over time, and increases the chances that D&D Fund resources are spent on activities other than D&D. Of course, accelerating the cleanup schedule too drastically introduces the possibility of wasted efforts and resources if some tasks must be redone.

### Effects of Early Plant Shutdown

The current surplus in worldwide uranium enrichment capacity and the inherent high cost of the inefficient gaseous diffusion technology compared with modern gas centrifuge enrichment plants may lead the USEC to cease operations of one or both of the operating facilities prematurely. Such action might affect the order of planned site cleanup. For example, it might be prudent to begin full-scale D&D with a newly closed plant. Because its process piping would still be intact and support services would be readily available, it might be easier to reduce near term concerns as well as facilitate subsequent D&D. Furthermore, because of the personnel safety requirements of an operating plant, a newly closed plant would represent a less contaminated starting point and might be more useful for technology demonstration efforts.

DOE needs to plan now for this possibility, including how an early plant shutdown might affect D&D scheduling, planning, and resource requirements.[11]

### Effects of D&D Program Delay

*Increasing Future Risks*. Lacking a quantitative site risk assessment, it appears to the committee that the risks to the public of the sites are low at present, based on the limited amount of contaminant exposure. However, these risks will likely increase in the future because of degradation of the existing facilities and $DUF_6$ cylinders. These increasing risks will be borne both by the local public and, more immediately, by the D&D workers. Increased requirements for plant personnel protection could increase D&D costs and will certainly increase surveillance and maintenance costs.

*Intergenerational Equity*. Cleanup delays would also postpone the potential benefits to the public (economic, environmental, and political) of a "clean" site. Extended delays have the effect of transferring the problem to future generations if funds are not set aside for eventual D&D. If the D&D inflation rate is less than the national discount rate, economic discounting of future D&D costs would imply an economic benefit in delaying the D&D operations but would place a burden on future generations.

*Long-Term Program Support*. Planning a coherent D&D program is difficult because the time span projected for cleanup is great—one of many years and many political administrations. Program delays could hamper managerial focus, increase congressional criticism, and reduce program funding support.

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[11] DOE has initiated contingency planning for the turnover of a GDP from the USEC (DOE, 1994b).

*Competition for D&D Fund Resources*. Compared to the existing cost estimates, the planned resources of the D&D Fund appear to be insufficient to complete the cleanup of the three GDPs. Other environmental restoration activities that are being conducted at the three sites include the remediation of contaminated soils and groundwater and management activities associated with potential $DUF_6$ cylinder disposition. Although some of these efforts may respond to more immediate health, safety, or environmental risks, they are nonetheless competing for D&D Fund resources. Program delays increase the probability that these resources will be exhausted before the D&D of the GDP facilities is completed.

*Regulatory Uncertainty*. The regulatory and political arena has changed considerably in the past 20 years and will continue to change over the next decades. These changes have ramifications for cost and program support of the cleanup effort, particularly for planning and management. In addition, agencies such as OSHA have not yet been included in D&D planning, even though OSHA regulations could be a major factor in the organization, cost, and potential litigation over D&D.

## MANAGEMENT ISSUES

The discussion above has shown how management of D&D is influenced by many activities both within and outside of DOE. Management must be sensitive to these influences and activities and integrate and coordinate them at both the complex and site levels. A management structure needs to be developed that ties integrated planning, management, and stakeholder involvement to the D&D project cycle, for example, see that shown in Figure 5-1. It

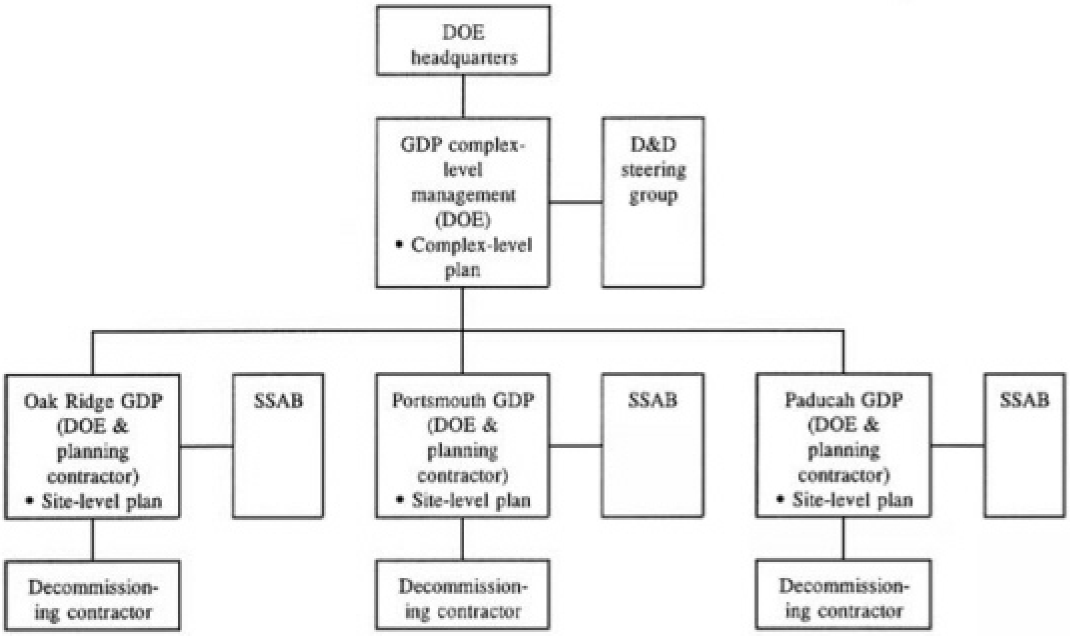

**FIGURE 5-1** Organizational framework for D&D of the GDPs.

is particularly important at the complex level that attention be paid to complex-wide resource allocation as well as regulatory, waste management, and disposal issues. It is also important that integration of the D&D, $DUF_6$, and remediation programs is managed at the complex level.

At the site level, management will be more concerned with detail. While DOE personnel will provide oversight and coordination, day-to-day management will rest with a contractor, as discussed below. Coordination at the site level, including SSAB involvement, will be required to ensure that site and local needs are considered and met. Coordination with other site activities, such as environmental restoration and waste management, will be required to ensure success.

The management structure across the entire complex must be evaluated to ensure that there is the proper level of coordination and oversight. Layers of management should be reduced wherever possible. Increasing the direct labor to management labor ratio across the complex should be an early goal of management during planning. DOE should use as a benchmark the resource allocations that were effective in similar programs, such as in the D&D of the Shippingport facility. A detailed discussion of the management structure and contracting approach is presented in Chapter 6.

## RECOMMENDATIONS

This chapter's findings and recommendations are summarized in Table 5-2 and are discussed in more detail below.

### Public and Stakeholder Involvement

1. DOE needs to integrate the involvement of the various stakeholder groups at the sites. Use of an SSAB-type group may be a way to coordinate the involvement of these various groups, although SSABs are not without problems. Because the public may not readily distinguish D&D from other environmental activities at the sites, D&D stakeholder involvement must be integrated with other site stakeholder involvement programs at the sites. Although each site is unique, lessons learned should be shared among sites.
2. Public involvement must start early in the D&D planning process. DOE should move expeditiously to achieve public involvement in setting D&D priorities, examining of future uses of sites and facilities, and waste disposal decision making. Stakeholders should provide advice and consultation to DOE and its contractors during project planning for each site.

### Regulatory Issues

1. DOE needs to work with regulators early in D&D planning to couple regulatory requirements to the D&D schedule.
2. A mechanism for coordination between DOE and appropriate federal and state regulators should be developed to enhance D&D planning.

TABLE 5-2 Suggested Approach for Managing the D&D Process

| **Areas** | Current Approach | Recommended Approach |
|---|---|---|
| Public and stakeholder involvement | Historical context implies lack of trust between DOE and the public. | Build on new DOE goal of meaningful citizen participation, possibly along the model of an SSAB. |
| | Multiple stakeholder groups are involved, and there is a lack of integration. | Examine existing citizen participation programs for applicability to D&D, with the goal of establishing a site-level stakeholder involvement group.<br>Use D&D steering group to provide stakeholder involvement at the GDP-complex level.<br>Begin interaction with stakeholders immediately to solicit input early in the D&D planning. |
| Regulatory issues | Multiple regulators have jurisdiction over GDP sites. There is lack of coordination among regulators, including state regulators. | Develop creative mechanisms and models for regulatory coordination between DOE and appropriate federal and state regulators. |
| | Regulatory issues have not been integrated into the D&D schedule. | Work with regulators to couple regulatory requirements to the D&D schedule. |
| | Currently, there is no plan for regulatory hand-off of operating GDPs from the USEC to DOE. | Plan for return of leased USEC assets back to DOE control for D&D. |
| | There are no standards for site cleanup or recycling of volume-contaminated materials. | Continue DOE participation and support in the interagency working group on radiation standards. Use projected future use of the sites to guide release criteria. |

| **Areas** | Current Approach | Recommended Approach |
|---|---|---|
| Planning | Each GDP is treated as a separate unit in planning D&D. | Develop a complex-wide, detailed decommissioning plan for the three sites that provides a technical baseline; plans for uniform site characterization; a schedule of tasks based on cost and risk priorities; personnel and funding requirements; management, contracting and integrated regulatory approaches; and waste management and stakeholder involvement. |
| | Oak Ridge GDP was operated and shut down without preparation for D&D. For the Portsmouth and Paducah plants, operations are planned for many more years before D&D, although a contingency planning effort was begun in 1995 for possible shutdown. | Develop plan for possible early closure of Portsmouth and Paducah, so that shutdown operations do not hinder, and perhaps will enhance, D&D. |
| | End states are expected to be chosen before D&D planning and execution can begin. | Begin prioritized cost- and risk-reduction process, while engaging all stakeholders and regulators in priority setting for D&D. Make decommissioning plans modular to accommodate prioritized cost- and risk-reduction approach.<br>Develop waste management plan to minimize secondary and mixed waste and maximize recycling where economical. |
| Management issues | There are multiple layers of DOE and contractor oversight, as well as outside committee oversight. | Simplify management structure. Restructure workforce to increase the ratio of direct to indirect D&D personnel. |
| | There is a lack of inter- and intrasite coordination; different DOE entities administer D&D, environmental remediation, $DUF_6$ management, waste management, and site landlord functions. | Develop complex-wide and site-specific integration of environmental restoration functions (D&D, $DUF_6$ management, environmental remediation, and waste management). |

3. At the state-level, DOE needs to emphasize a new cooperative approach with the states to minimize conflicts.
4. The Interagency Working Group on Radiation Site Cleanup Standards should proceed expeditiously to develop a consistent set of regulations that can be applied to D&D. Application of these new standards should use site-specific exposure scenarios appropriate to these sites.
5. To minimize costs and contamination, DOE needs to start now to develop regulatory plans for transfer of control of the GDP assets from the USEC back to DOE for D&D.

### Planning

1. DOE should develop a complex-level plan that covers a number of areas:
    - technical baseline;
    - schedule of tasks, such as GDP characterization;
    - personnel and funding requirements over time;
    - management and contracting approach;
    - applicable regulations, such as site release criteria;
    - waste management; and
    - public and stakeholder involvement.
2. Because of the possibility of early plant shutdown, DOE needs to prepare now by examining how early shutdown would affect scheduling options, costs, and planning.
3. DOE should use a prioritized cost- and risk-reduction approach to proceed with D&D in the face of the many uncertainties about D&D. This strategy allows work to begin from the start of planning, which integrates annual surveillance and maintenance costs and slowly increasing risks, does not foreclose end-state options, and demonstrates commitment to cleanup.

### Management Issues

1. For the GDP complex as a whole, DOE should coordinate D&D, environmental remediation, management of $DUF_6$, and waste management activities.
2. At each site, DOE should coordinate D&D, landlord functions (such as maintaining buildings and infrastructure services, such as water, electricity, and security), environmental restoration, $DUF_6$ management, and waste management to minimize annual surveillance and maintenance costs and to avoid actions that could hamper or delay D&D.
3. A management approach should be taken that is streamlined, efficient, and increases the ratio of direct to indirect labor required.

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# 6

# Opportunities for D&D Cost Reduction

Although developing a cost estimate for the D&D of the U.S. GDPs is beyond the scope and resources of the committee's study, the committee has identified cost reduction opportunities. In this process, the committee assessed alternative D&D technologies (Chapter 3), reviewed the Ebasco and TLG cost estimates (Chapter 4), and analyzed the planning, management approach, and contracting methods (Chapter 5) for the D&D of the GDPs. This effort, combined with an analysis of the costs and lessons learned about D&D by BNFL from its experience with the Capenhurst GDP in the United Kingdom and several U.S. nuclear power plants and other uranium fuel cycle facilities, helped to identify a number of cost reduction opportunities (BNFL, 1994; Crimi, 1987,, 1992; Kingsley, 1994). Although detailed studies will be required to quantify the cost savings, the committee's judgment is that a total D&D cost reduction of at least 50 percent relative to the $16.1 billion cost estimate prepared by Ebasco (DOE, 1991a) is a reasonable expectation. The magnitude of this estimated cost reduction is based largely on engineering judgment and is subject to considerable uncertainty; nevertheless, an $8 billion cost appears to be very conservative relative to the $1.11 billion to $2.03 billion that results from scaling the actual costs of the essentially completed D&D of the Capenhurst plant to cover all three U.S. GDPs (Chapter 4).[1]

To better compare potential cost reductions relative to the Ebasco estimate, the principal cost reduction opportunities the committee identified were grouped according to the four cost categories used by Ebasco, plus a fifth, "cost estimate assumptions:"

- program integration;
- radioactive and hazardous waste management;
- D&D;
- support facilities; and
- cost estimate assumptions.

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[1] The scaled value of $1.11 billion assumes recycling of 95 percent of the materials recovered from D&D, whereas the $2.03 billion assumes no recycling (i.e., all material buried as low-level radioactive waste).

The cost reduction opportunities associated with each category are summarized in Table 6-1 and discussed in the sections that follow.

## PROGRAM INTEGRATION

Ebasco defined program integration as including management, permitting, engineering, operations staff, health and safety, industrial safety, quality assurance and control, procurement, waste management, and analytical services. Ebasco estimated these costs at $2.57 billion for the three-plant complex, or 21.6 percent of total D&D cost before adding contractor markups, construction management fees, and the operations contractor effort (DOE, 1991a). Many of these program integration costs are for oversight functions only. There are substantial additional costs included in the estimate for monitoring health and safety, quality assurance and control, and waste management in the field. After adding markups and fees, the total cost of management, administration, and professional staff accounts for approximately 50 percent of the total Ebasco D&D cost estimate of $16.1 billion. The committee believes that adopting a more cost-effective D&D project management approach offers a major opportunity to reduce D&D costs.

### Management Approach

The Ebasco cost estimate assumed that the site M&O contracting approach would be used for the D&D project. Engineering would be performed by the site architect-engineer, and construction would be managed by the site construction contractor. This approach results in significant overlap and duplication of management functions. For example, project integration occurs at three places in the organization: the contractor executing the work, the project integration contractor, and DOE.

An independent study of environmental restoration and waste management projects (Independent Project Analysis, 1993) found that DOE projects have characteristically experienced substantially higher costs, higher cost overruns, and longer schedules than those managed by other government agencies and the private sector. They cited "high project management costs and project system practices" as major contributors to these higher costs. One of their principal findings was the following:

> DOE employs both Management and Operating (M&O) contractors and on-site Architectural and Engineering (A&E) firms. The resulting total project management costs are more than double the amount spent by other government agencies, and nearly four times the amount spent by the private sector. This figure excludes DOE personnel and unrelated infrastructure cost components.

### An Alternative Management Approach

The committee believes that substantial cost savings can be realized by abandoning the M&O approach and hiring an independent DOC (Decommissioning Operations Contractor) to manage the D&D effort. With such an approach, the existing M&O staff currently associated with D&D planning and execution would either be hired by the DOC (at the DOC's discretion),

TABLE 6-1 Cost Reduction Opportunities

| **Cost Category** | Current Approach | Recommended Approach |
|---|---|---|
| Program integration | | |
| Management/contracting approach | M&O contractor serves as program integrator, supported by site architect-engineer and constructor, resulting in excessively large staff, multiple layers of management, and overlapping responsibilities. | Select a Decommissioning Operating Contractor (DOC) through competitive bidding, with total responsibility for project execution. Have the DOC report directly to the DOE. Fixed price contracts, with incentives for cost and schedule reductions, should be used where possible. |
| D&D planning | A detailed D&D plan, which is essential to establish the technical, cost, and schedule baseline, does not exist. | An independent contractor, qualified by successful D&D projects experience and selected through competitive bidding, should prepare the D&D plan. Tradeoff studies should be performed to determine the most cost-effective D&D technologies and optimal approach. |
| **Radioactive and hazardous waste management** | | |
| Material disposition | Virtually all recovered materials are considered waste and ultimately are sent to a low-level waste repository or burial ground. | Work with DOE and regulatory authorities to set free-release standards quickly and permit recycling of recovered metals (within the DOE complex or for sale to the commercial market) where economically feasible. |
| Waste containers | Standard waste containers are used. | Optimize the shape and size of waste disposal containers. |
| **D&D** | | |
| Automation and robotics | Automation and robotics are minimally used. | Where cost effective, maximize the use of automation and robotics for repetitive operations, such as characterization, disassembly, decontamination, certification, and waste packaging. |
| Technology demonstration | Demonstration of D&D technologies is proceeding slowly, with limited funding. Timely information to support planning effort is not available. | Support maximal use of commercial technology and appropriate limited demonstration of existing technology. Increase funding and accelerate completion of demonstration testing to support D&D planning and technology selection. |

TABLE 6-1 Cost Reduction Opportunities (continued)

| **Cost Category** | Current Approach | Recommended Approach |
|---|---|---|
| Safeguards and security | Current safeguards and security site practices and procedures for the operating facilities are assumed. | Remove high-assay uranium deposits as soon as possible. Simplify approach to safeguards and security to reduce adverse impact on worker productivity and achieve lower labor cost. |
| Surveillance and maintenance | Very large surveillance and maintenance costs are assumed to continue over the life of D&D operations. | Eliminate nonessential activities. Consider outsourcing this activity to reduce costs. |
| Sampling/assaying | An ultraconservative approach (many samples and measurements) is used for sampling and assaying. | Take a statistical approach to reduce the sampling and assaying effort. |
| **Support facilities** | | |
| Decontamination facilities | It is assumed that expensive, labor-intensive high-assay and low-assay decontamination facilities, using gaseous decontamination, will be constructed in new buildings. | Remove the bulk of the uranium deposits in situ and eliminate the high-assay decontamination facility. Use aqueous rather than gaseous decontamination in the low-assay decontamination facility. Use existing buildings. |
| New office building | The assumed very large staff required construction of a new office building at Oak Ridge and large building refurbishment costs at Paducah and Portsmouth. | Use existing buildings (adequate for the much smaller staff of the committee's proposed alternative management approach). |
| **Cost estimate assumptions** | | |
| Site practices and procedures | The cost estimate is based largely on existing site practices and procedures (i.e., those applicable to an operating facility). | Identify opportunities for less stringent practices appropriate for D&D, assuming special nuclear material will be removed from the cascade early in the program and equipment will not be refurbished and reused. Review the approach to criticality prevention. |
| Use of historical data | The current cost estimate reflects past operations and maintenance experience with regard to person hours needed to disassemble and decontaminate equipment. It does not reflect the fact that D&D is a demolition job, not a construction or maintenance operation. | Reduce person hours, inasmuch as close-tolerance, maintenance-related operations will not be necessary during demolition. Reflect the large productivity improvement from the learning curve associated with repetitive operations. |

would be transferred to the environmental remediation effort, or would be terminated. To provide surveillance and maintenance, maintain infrastructure, and provide other services, a greatly reduced M&O may be needed or these functions could be carried out by the DOC. The cost reduction would result from hiring a DOC with a proven record for cost-effectively managing a large D&D operation as a project and not being wedded to past practices and procedures. (Ideally, one contractor would be selected for both D&D and environmental restoration.) The DOC management concept was used successfully to manage the Shippingport and Fort Saint Vrain nuclear power plant decommissioning projects (Crimi, 1987). Compared with the M&O approach, the DOC organizational structure significantly reduces the management layers and large "rollup" of fees associated with using an M&O contractor. The owner's management staffs on the two aforementioned projects were relatively small, and the plant operating staffs provided selected support services needed for D&D operations to the DOC.

The DOC should be selected through open competition based on demonstrated qualifications in successfully managing other D&D projects of comparable complexity and on its management commitment and proposed technical approach to cost, schedule, and quality control. This is different from M&O contractor selection, which is based on the capability to manage site operations rather than major D&D projects. The DOC should have total responsibility and accountability for executing the work and should report directly to DOE. A performance-based contract should be negotiated that offers strong financial incentives to the DOC and its subcontractors and vendors to complete the project within mutually agreed-upon costs and schedule. The DOC could perform certain tasks with its own forces and could subcontract other tasks to outside contractors. The DOC, with no other operating responsibilities, would be focused on a single goal and would be selected based on experience in managing subcontractors under stringent cost and schedule controls. The DOC would have much more freedom to select the most qualified personnel and tightly control the size of its management staff. The DOC might be assigned responsibility for site services related to D&D, such as security and surveillance and maintenance. Fixed-price subcontracts should be used to the extent possible, especially for those activities for which the scope of work can be relatively well defined.

The TLG cost estimate was based on using a DOC, but the size of the postulated DOC organization appears very large relative to the size of the craft labor force performing the work (Guasco, 1994). For example, for the Oak Ridge GDP, the "management staff level" assumed during D&D operations was 1,430 people, compared with the estimated craft labor peak of 4,307 people.[2] There are 30 area superintendents in the K-33 building alone. This appears to the committee to be a very high management-staff level for a demolition-type project as compared with the construction of a nuclear facility where there are exacting construction and material standards and stringent quality control and quality assurance requirements to ensure that the plant will achieve its operating performance requirements.

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[2] The term "management staff level" is somewhat misleading in that the 1,430 people included in the DOC staff cover such activities as site support services to operate and maintain plant systems and to provide fire protection and site security. The staff, nevertheless, appears very large for this type of project.

The total number of Oak Ridge GDP staff assumed in the TLG estimate includes 48 health physicists and 434 radiation control technicians. This large oversight group reflects TLG's estimate that to remove a converter from the cascade will require from 75.6 hours (for type 0 converters) to 89.9 hours (for the type 000 converters). Removal of all 5,122 converters in the proposed 7-year schedule would require 33 crews operating in parallel to complete the work. The committee's analysis indicates that in a demolition environment, where an entire building will be decontaminated and decommissioned, a converter could be removed in approximately 8 hours once the permitting and procedures are in place, thereby reducing the number of crews by a factor of 10. Substantial reductions in removal time are likely to be achieved for other plant components as well.

The Capenhurst experience demonstrated how a major D&D project can be executed with a relatively small health physics staff. Considering the repetitive nature of the work, it appears to the committee that once a substantial D&D experience base is in place and the procedures for contamination control and worker exposure have been demonstrated successfully, the health physics and radiation control staffs could be reduced substantially. This would further reduce staffing requirements. While there appear to be opportunities for health physics staff reductions, worker protection strategies would require coordination with OSHA.

### Contracting Strategy

The contracting strategy selected for the DOC and its subcontractors should incorporate the most efficient contracting methods permitted by federal law and DOE orders. The strategy should address the type, size, and length of the contracts, degree of risk-sharing between the government and the contractors, and the amount of DOE oversight to be applied. The contracts should provide incentives to the DOC and its subcontractors to maximize quality on-time performance at minimum cost. The contracting strategy should explicitly define the roles of DOE, on-site contractors such as the M&O contractor, and other subcontractors.

### Planning

The committee feels strongly that the D&D plan should be prepared by an independent contractor that has a good experience base in planning D&D efforts and submits the most attractive preliminary plan (or approach) in its proposal. An independent contractor will not be inhibited by past practices at the GDP sites and should bring innovative approaches to the planning process. The M&O contractor tends to be influenced by past site practices associated with requirements for an operating facility. DOE should provide broad criteria to the independent contractor to guide the planning, but should allow the contractor maximum flexibility to challenge existing practices and introduce innovative approaches to reduce cost. The M&O contractor would support the planning contractor by conducting technology demonstrations, providing information on plant systems and status of the facilities, and continuing surveillance and maintenance until the start of D&D. At the conclusion of the planning effort, the DOC would be selected through competitive bidding as described above. The planning contractor, as well as the M&O contractor, should be permitted to compete for the contract to perform D&D.

### Contracting Cost

Another area of potential for cost reduction is the fees for the management contractors. The Ebasco cost estimate includes a management fee of 5 percent for the M&O contractor, a construction management fee of 5 percent, and an additional cost of 25 percent for program integration (see tables 4-4 and J-3; DOE, 1991a). As discussed in Chapter 4 and Appendix J, the management structure proposed for the D&D project results in rollup of these fees through successive management layers, resulting in a 42 percent increase over the already fully burdened (direct + indirect) costs. A simplified contracting approach, using a DOC, should reduce the total cost of these rollups. The principal cost savings would result from reducing the 25 percent cost of program integration by reducing the amount of management oversight.

## RADIOACTIVE AND HAZARDOUS WASTE MANAGEMENT

Over 700,000 tons of nickel, steel, copper, and other potentially valuable metals will result from D&D operations (DOE, 1993b). The cost of disposing of these metals as low-level radioactive waste, as well as the large quantities of concrete, hazardous wastes, and some mixed waste, was estimated by Ebasco and TLG to be $1.0 billion and $1.5 billion, respectively (DOE, 1991a, b; see Appendix J). The two most important opportunities for reducing waste management costs are reducing the quantity of wastes to be disposed and designing the waste management approach to minimize the total cost of waste certification, packaging, transportation, and disposal.

### Reducing Waste Quantity

The principal means of reducing the quantity of waste requiring disposal is to decontaminate radioactive materials, primarily metals, to a level sufficiently low to permit their direct sale to the commercial market. There are precedents for large-scale recycling of decontaminated materials. The D&D of the Capenhurst GDP in the United Kingdom, for example, resulted in 161,770 metric tons (178,000 tons) of waste materials (Clements, 1994a). Excluding concrete, 100 percent of this material was contaminated. Following decontamination, over 99 percent of the metal was recycled, the majority of which was sold on the commercial market, thereby greatly reducing the quantity of waste and its disposal cost and generating revenues that partially offset D&D costs. Some of the metals that could not be decontaminated economically with gaseous and aqueous methods were successfully decontaminated to free-release standards by melting and subsequently sold.[3] Over 99 percent of the concrete was uncontaminated and was given to commercial contractors at no cost for use in road building and other construction projects, thereby avoiding the substantial costs for its transportation and disposal.

The vast majority of equipment and materials in the U.S. GDPs are surface-contaminated only. Criteria governing release of surface-contaminated radioactive materials for unrestricted

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[3] Production-scale melting at Capenhurst started in December 1994 and is expected to be completed in approximately 9 months.

use are promulgated in Regulatory Guide 1.86, issued by the Nuclear Regulatory Commission and adopted by DOE in DOE Order 5400.5. However, DOE has often taken the very conservative position that previously contaminated material cannot be released into general commerce, even if the material has been decontaminated sufficiently to merit the criteria adopted in DOE 5400.5. This position increases the volume of waste requiring disposal substantially, because almost nothing is released. New criteria and DOE orders are being developed that will permit both surface- and volume-contaminated materials to be recycled, provided they meet the requirements for free-release. A DOE commitment to permit such release once the new criteria have been approved is essential.

Waste disposal costs can be cut further by an aggressive waste minimization program reducing the quantity of miscellaneous wastes created during D&D, such as contaminated clothing, tools, chemicals, and supplies. D&D experience has demonstrated that the quantity of such materials can be reduced substantially if there is a strong management commitment to waste minimization from the outset and strict enforcement of waste minimization procedures and practices project-wide during D&D execution.

### Waste Disposal Site and Unit Disposal Cost

The location(s) of the site(s) that will accept waste from the three GDPs and the unit costs of such disposal are uncertain. Wastes could be stored on site at each of three enrichment plants or shipped to remote locations such as the Nevada Test Site or the Hanford Site. Estimates of waste disposal unit costs range from $\$8/\mathrm{ft}^3$ at the Nevada Test Site (assumed in the TLG cost estimate) to $\$300/\mathrm{ft}^3$ and higher at new commercial disposal sites (DOE, 1991b). Quapp (1995) indicates costs at the Nevada Test Site as of July 1995 to be $\$17/\mathrm{ft}^3$ and recommends using a figure of $\$30/\mathrm{ft}^3$ for planning, in anticipation of increases. Selecting disposal sites and negotiating unit disposal prices may prove difficult and lengthy because of political and institutional sensitivities. The unit cost of waste transportation and disposal can vary appreciably with disposal site characteristics and location. Unit disposal cost, in turn, affects the economic feasibility of recycling materials, compared with direct burial, and may determine the preferred D&D technologies as well. The waste disposal siting issue should be resolved as soon as possible to support D&D planning.

### Waste Packaging, Transport, and Disposal

Waste packaging costs in the Ebasco estimate are overestimated because waste container pricing (for boxes and 55-gallon drums) does not reflect the substantial quantity discounts that will be realized when purchasing the very large number of containers needed. D&D planners, working closely with prospective commercial container and transportation equipment suppliers, need to perform cost tradeoff studies to determine the optimal type and size of containers. Using the maritime–truck–rail reusable containers that are available for intermodal transportation should be considered. Container selection should be integrated with the optimization of the entire waste management process; that is, waste certification, packaging, transportation, and disposal.

The Ebasco cost estimate assumes that approximately one-third of the Paducah and Portsmouth wastes will be transported to the Oak Ridge Decontamination Facility for processing and returned after processing to the originating sites for final disposal. Providing on-site processing capability at Portsmouth and Paducah for all waste generated on those sites would reduce waste transport costs between sites and potentially reduce total waste management costs by about $66 million.[4] The cost, however, of designing, constructing, and operating new waste processing facilities at Paducah and Portsmouth may offset the savings in waste transport costs. A tradeoff study should be conducted to determine the most cost-effective alternative.

The Ebasco estimate assumes two waste disposal facilities at each GDP site, one for Class I low-level radioactive wastes and hazardous waste covered under RCRA (Resource Conservation and Recovery Act) and the other for Class III low-level radioactive wastes. Class I waste is defined as waste that would not result in an off-site dose to the public of more than 10 mrem/yr. Class III waste is defined as waste that would not result in an off-site dose to the public of more than 100 mrem/yr. Using a single multipurpose disposal facility may decrease disposal costs through economies of scale and avoid the siting, construction, and operation of three additional facilities (one per site). Using a conservative estimate, assuming a 25 percent reduction in disposal cost, savings in total waste management costs would be about $105 million.[5] However, the additional complexity of licensing multipurpose facilities may extend the licensing schedule.

Contracting waste packaging and transportation functions to commercial vendors through competitive procurement should reduce costs. The preferred approach would be to include direct responsibility for planning, operations, and management in the vendor's scope. Because waste management costs are based primarily on the purchase of goods and services and are independent of D&D operations, a much lower indirect cost should be assessed (instead of 51 percent, a 10 to 20 percent add-on would be appropriate).

## Risk That Waste Management Costs May Be Higher

Total waste management costs could be significantly higher if recovered metals are not recycled. In that case, unit disposal costs are likely to be significantly higher than assumed in the current estimates. Commercial low-level radioactive waste disposal costs have increased markedly in recent years. If wastes arising from the D&D of the GDPs are not recycled because of regulatory constraints or public opposition, the quantity of material requiring disposal will be very large, so that any increase in unit disposal cost will have a major impact on total D&D cost. The risk posed by increasing disposal costs can be reduced substantially by volume reduction, waste minimization, and reuse of decontaminated materials within DOE or by sale to the commercial market if it proves a feasible alternative. Commercial sale is preferred because it would provide revenues to partially offset D&D costs.

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[4] Savings from avoided transportation from Paducah and Portsmouth to Oak Ridge (assuming local transportation is $0.53/ft$^3$) would be about $66 million. This is calculated by taking values from tables J-13 and J-14 (2.43 million ft$^3$ ($12.17/ft$^3$ - $0.53/ft$^3$) + 3.04 million ft$^3$ [$13.09/ft$^3$ - $0.53/ft$^3$]).

[5] Disposal facility costs for Oak Ridge, Paducah, and Portsmouth for Class I and III wastes is about $105.4 million. See Table J-15 for the following in millions of dollars: ($100.4 + $66.6) + ($67 + $45.3) + ($85.9 + $56.6) = $421.8. Then, 0.25 × $421.8 million = $105.5 million.

### Hazardous Waste Disposal Costs

As discussed in Chapter 3, there are opportunities to reduce the cost of disposing of hazardous waste. Manual removal of the gaskets contaminated with PCBs from the heating, ventilation, and air conditioning system ductwork is a particularly labor-intensive, expensive operation. Cutting the ductwork into segments and smelting the segments to destroy the PCBs is a possibility. While melt refining is an energy-intensive process, it may be significantly less expensive than manual cleaning of the ductwork followed by treatment and disposal.

The current approach for removing asbestos requires leak proof packaging, the usual practice being double bagging prior to burial (40 CFR 60.150). However, the asbestos contained in the large quantity of transite siding is largely nonfriable. Careful removal to avoid damage and exposure of frayed surfaces, possibly eliminating the need for double bagging, may be a much less costly approach without posing any significant increase in risk. Exploration of this alternative with regulatory authorities, the workers, and the public could produce significant cost savings. It also seems advantageous to explore approaches to convert asbestos to a nonhazardous waste form, and reduce its volume, to achieve savings in disposal costs.

## DECONTAMINATION AND DECOMMISSIONING

### Technology

#### Decontamination Process

The committee believes that important parts of the decontamination technology adopted in the Ebasco study were unnecessarily complex and expensive. The decontamination process assumed in the Ebasco estimate depends predominately on gaseous $ClF_3$ (chlorine trifluoride) treatment. At Paducah and Portsmouth, the bulk of the uranium deposits would be removed in situ by circulating $ClF_3$ through the cascades before plant shutdown. The final decontamination would occur in two very large facilities, the high- and low-assay decontamination facilities (see Chapter 4). One stage at a time would be removed and treated with $ClF_3$. Equipment would then be cut up and exposed to high-pressure water spray if there were any residual contamination. Experience with removal of uranium deposits from the high-enrichment section of the Portsmouth GDP also indicates that $ClF_3$ treatment is expensive, although its use for uranium removal during an organized shutdown of the operating plants at Paducah and Portsmouth may be considerably less costly (see Chapter 3).

Based on the experience with the D&D of the Capenhurst enrichment plant, and the CIP/CUP (Cascade Improvement Program and Cascade Upgrading Program) at the three U.S. GDPs, the committee recommends the use of a quite different decontamination technology; namely, aqueous decontamination. Bulk uranium deposits in the nonoperating Oak Ridge cascade should be removed during the Deposit Removal Program supported under the D&D Fund. USEC is responsible for removing solid deposits that represent a criticality risk at Paducah and Portsmouth before returning the facilities to DOE. It is likely that $ClF_3$ treatment will be used during final clean out during plant shutdown. Equipment containing deposits of sufficiently high enrichment, quantities, and unfavorable geometry (e.g., chunks) would be disassembled and mechanically cleaned under dry conditions. The efficacy of the low-temperature, long-term gaseous $ClF_3$ treatment would also be determined as part of this program; however, this treatment will probably not remove sufficient uranium deposits from equipment in the closed Oak Ridge plant. Consequently, mechanical removal is the most likely approach for the deposits representing a criticality risk. The cleaned segments from those stages, and the disassembled segments from the remaining stages that did not contain significant quantities of uranium but which had visible surface contamination, would be passed through an aqueous spray booth decontamination system. Components not showing any visible contamination, as well as those components previously cleaned mechanically and by spray booth operations, would be finally decontaminated to free-release levels in a series of washing tanks containing aqueous decontamination solutions and rinses. The capital and operating costs for aqueous decontamination processes should be much less than those for the Ebasco plan. Furthermore, the Capenhurst and CIP/CUP experiences provide assurance that the aqueous decontamination approach will be successful.

## Melting of Difficult-to-Decontaminate Components

Components with complex shapes that are difficult to decontaminate with conventional methods may be amenable to decontamination by melt refining (Chapter 3). Melt refining was used successfully by BNFL at Capenhurst beginning in December 1994 to decontaminate aluminum and steel. The company also plans to melt refine nickel and other metals recovered from D&D, with most of the recovered metals sold to the commercial market (Clements, 1994b).

Decontaminated metal from the U.S. GDPs will be either buried or recycled. Recycling, either within the DOE complex (for storage or shipping containers for fuel or waste) or to the commercial market, would avoid disposal costs and the use of virgin ores. Commercial sale would also generate revenues, particularly in the case of nickel, which has a market value of approximately $5,000 to $10,000 per ton.[6]

The cost of decontaminating metals for recycling has been estimated to range from $1,000 to $3,000 per ton (Cohen, 1994). Cohen assumed a burial cost of $\$7.05/ft^3$ at the Nevada Test Site, but the total disposal cost, including the 2,000 mile cost of transportation to the disposal site, was near $\$75/ft^3$. Applying Cohen's cost of $375/ton for material cutting and packaging, and assuming a compacted waste density of $100\ lb/ft^3$, would result in a total waste management cost for burial of $1,875/ton, which is within the $1,000 to $3,000 range estimated by Cohen. Figure 6-1 shows the break-even scrap metal recycling value as a function of disposal cost (including transportation to the disposal site), material compaction density, and type of metal. A density of $100\ lb/ft^3$ represents a material with limited compaction, whereas a density of $500\ lb/ft^3$ represents metal after melting. Assuming that nickel scrap is worth $5,000/ton and that Cohen's estimate of recycling costs of $1,000 to $3,000 per ton is correct, Figure 6-1 shows that, because of the high value of nickel scrap, its recycling is economically feasible even if the disposal cost is zero. On the other hand, recycling of steel, assuming a scrap value of only $100

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[6] Prices for metals vary significantly and change rapidly.

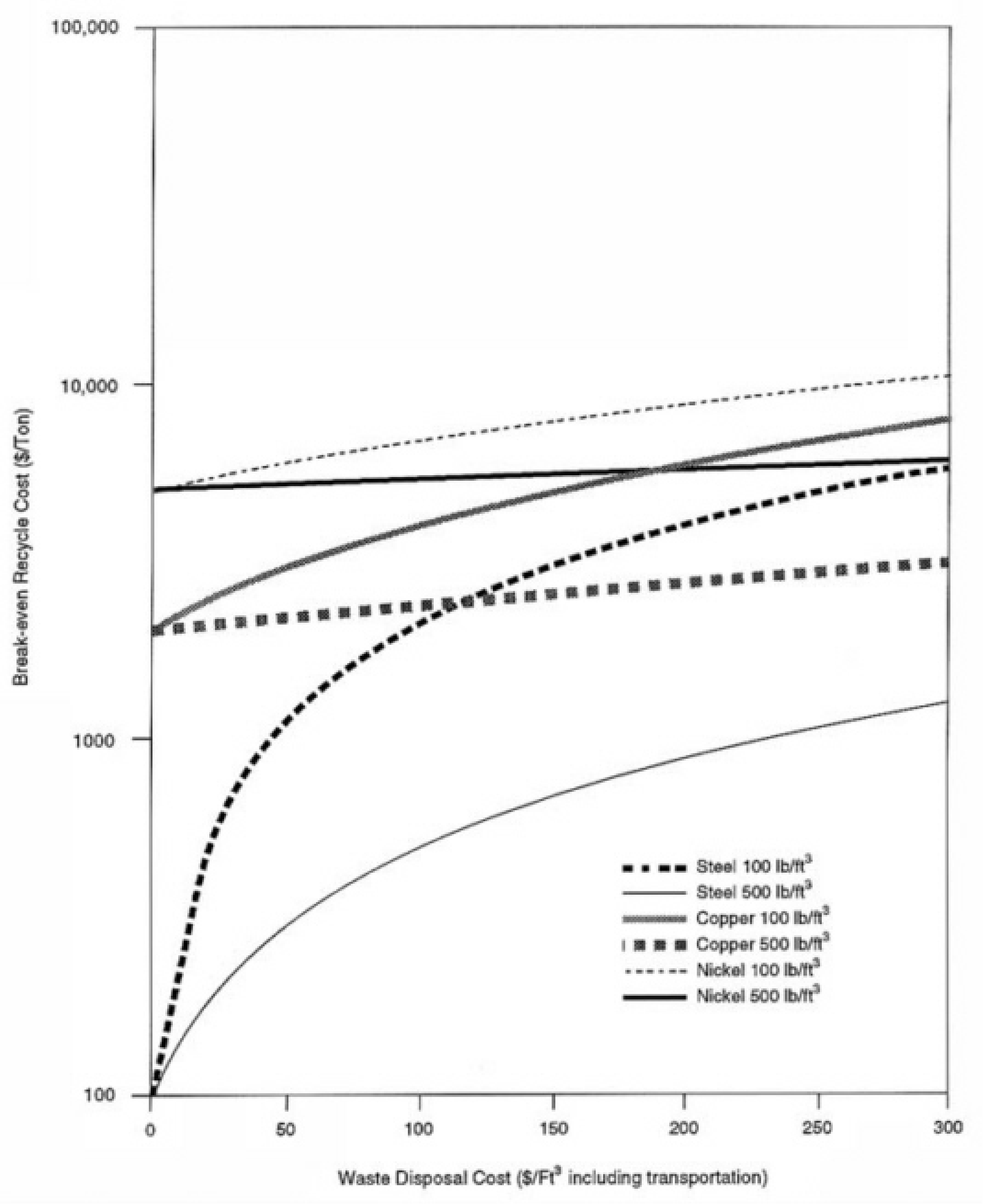

**FIGURE 6-1** Break-even metal recycling value versus total waste disposal costs.

per ton, is not economically feasible except for relatively low-density material, given the high disposal costs. Assuming a scrap value of $2,000 per ton for copper, its break-even value falls within the $1,000 to $3,000 per ton burial cost estimated by Cohen, assuming a density of 500 lb/ft$^3$ (metallic ingots). Lower compaction densities and high disposal costs would clearly favor copper recycling rather than land burial.

## Automation and Robotics

The large number of components of similar design, the extensive material-handling of heavy equipment required, the large areas of concrete on building floors to be characterized and decontaminated, the repetitive operations during disassembly and decontamination, and the desire to minimize worker radiation dose all provide strong incentives to substitute machines for manual labor in executing D&D operations (Chapter 3). BNFL reports that such automated techniques were applied successfully in the D&D of the Capenhurst plant; commercially available robotics technology was modified as appropriate to meet the special requirements of each D&D operation.

Ebasco assumed the initial decontamination would include, in addition to gaseous decontamination, mechanical cleaning to remove residual uranium salts and other contaminants from the inside surfaces of the cascade components. Well-developed robotic techniques should be deployed for such deposit removal, monitoring, and disassembly. This strategy would significantly reduce the number of person hours required and much of the cost of health and safety monitoring. Use of robotic devices to dismantle contaminated ductwork, segment piping, tanks, and other components and to strip asbestos from piping and lead-based paint from structural steel may also significantly reduce decontamination costs. Although it seems to the committee that these operations might realize significant cost savings from the applications of robotics and automation, the cost reduction is uncertain, and tradeoff studies are required to confirm the economic feasibility of the various proposed activities.

Certain surveillance and maintenance activities may benefit from the use of mobile robot systems for routine, repetitive operations. Mobile robots are currently used very effectively in industrial applications such as security patrols and warehouse inventory.

The degree to which robotics and automation are factored into the current D&D cost estimates is uncertain. Economic tradeoff studies should be conducted during D&D planning to identify those applications of robotics and automation that are cost effective and/or reduce the risks to worker health and safety. Processes and techniques should be developed and refined manually before automating.

## Building Decontamination and Removal

As discussed in Chapter 4, the estimated unit cost to decontaminate the large process buildings ranges from $15.06/ft$^2$ (Ebasco) to $48.57/ft$^2$ (TLG). These costs are based on decontaminating the building superstructure surfaces manually using hand-held shot blasting equipment or equivalent processes, while the superstructure is still standing. This is a very expensive process. A more cost-effective approach may be to remove and dispose of the building roofs and outer transite wall surfaces, decontaminate the concrete floors using decontamination solutions and/or mechanical (e.g, scabbling) methods, and then disassemble the building superstructure I-beam by I-beam, passing those beams through an automated decontamination unit that would remove any contamination and paint using shot-blasting or equivalent processes.

There are tradeoffs between the costs of dismantling the structure piecemeal or by explosively razing the structure, and between the costs of decontaminating the beams manually in-place or by using an automated decontamination station. A study should be performed to evaluate the relative costs and health and safety risks of the feasible alternatives for building decontamination. If building characterization data are insufficient, limited characterization should be performed to permit assessment of the relative cost and health and safety implications of each alternative.

## Use of Historical Maintenance Cost Data

There is an extensive experience base on the person hours and costs to maintain and refurbish GDP process equipment. Converters and compressors, for example, are routinely removed from the enrichment cascades at Portsmouth and Paducah to make repairs and are then reinstalled. Labor productivity data for these operations were also obtained during the CIP/CUP. These experiences with removal of GDP equipment are available to guide estimates of the elapsed times and person-hour requirements for these same operations during D&D (Donohoo, 1994). The past efforts focused on removal for repair and replacement in an operating plant and included a number of activities that are not necessary when removing this equipment during D&D of the plant. Table 6-2 compares the activities performed during an operational removal of a large converter with the activities postulated to be required for a removal during D&D. In the following paragraphs, each of these listed activities is discussed, along with the rationale for the postulated number of person hours and time duration appropriate for each activity in removing a converter during D&D.

The person hours postulated in the Ebasco and TLG estimates for converter removal are also shown in Table 6-2, for two sizes of converters. A six-person crew is postulated for converter removal operations. The Ebasco estimates are from 21 percent to 77 percent greater than actual experience from maintenance operations. The TLG estimates are 3.9 to 4.7 times greater than actual experience. Clearly, both estimates are significantly larger than the person hours derived from operational experience and inflate the overall cost estimate. The large difference for the TLG estimates arises, at least in part, to the assumed welding of caps over all openings and decontamination of exterior converter surfaces to allow shipment through the public domain. However, the TLG estimate would exceed the Ebasco estimate and the operational data significantly, even after eliminating those activities. These comparisons illustrate the importance of developing unit cost factors, using the best available information, to ensure that all of the postulated activities are necessary and appropriate for a D&D operation.

The individual activities and corresponding estimated person hours can be analyzed as discussed below.

*Preparation of Work Permits*. Neither preparation of work permits by the operations organization nor preparation of the plant to allow the work will be needed because the plant is

TABLE 6-2 Person Hours and Duration for Converter Removal During Operations and During Decontamination and Decommissioning (in hours)

| | **Operational Removal** | | Postulated D&D Removal | |
|---|---|---|---|---|
| Activity | Labor | Duration | Labor | Duration |
| Operations preparation for work, issue work permits | 28 | 14 | —[a] | —[a] |
| Health physics pre-job survey/job site set-up | 4 | 2 | 3 | 0.5 |
| Pre-job chemical cleaning | 4 | 1 | NA[b] | NA[b] |
| Health physics resurvey, issue radiation work permit | 2 | 1 | 3 | 0.5 |
| Asbestos removal | 8 | 6 | 0 | 0 |
| Maintenance setup time | 50 | 8 | 6 | 1 |
| Severing connections | 50 | 8 | 6 | 1 |
| Lift and transport unit | 25 | 4 | 12 | 4 |
| Clean job site | 25 | 4 | 6 | 1 |
| Totals | 192 | 48 | 36 | 8 |
| Ebasco estimate | | | | |
| Small converter | | | 232 | |
| Large converter | | | 340 | |
| TLG Estimate | | | | |
| Small converter | | | 756 | |
| Large converter | | | 899 | |

[a] Negligible time required. See discussion on preparation of work permit in this chapter.

[b] Not available.

SOURCE: Donohoo (1994) for converter removal during GDP operations. Postulated D&D removal estimated by committee; see text for assumptions.

already in a deactivated status and a general work permit will have been established to dismantle all the equipment in the plant. Thus, this activity would be limited to reviewing the conditions specified in the general permit once per shift and would have negligible labor hours and duration.

*Health Physics Pre-Job Survey, Resurvey, and Radiation Work Permit Issuance*. The pre-job survey by health physics and the issuance of separate radiation work permits for each converter removal are not needed because the whole facility will have been characterized prior to beginning the removal activities. A general radiation work permit will have been issued for the removal of all process equipment, or at least to a large number of units in a given building, not just a single unit. A brief survey of an individual work site would be conducted to identify any conditions that might be outside the conditions of the general Radiation Work Permit. In addition, the Radiation Work Permit would be reviewed at the start of each shift. The duration of these activities should not exceed 1 hour, total.

*Pre-Job Cleaning*. The pre-job chemical cleaning by operations is not necessary because the plant has already been cleaned internally to the extent practicable as part of plant deactivation activities. Thus, this activity would have zero person hours and duration.

*Asbestos Removal*. Asbestos removal will not be necessary because general removal of asbestos throughout the plant will have been completed as a separate activity prior to general equipment removal. Thus, this activity would have zero person hours and duration.

*Maintenance Setup Time*. Installing the cutting equipment to sever connections between the converter and associated systems should require no more than about 1 hour, compared with 8 hours for setup in operational removal. The units will have been exposed by removal of the stage enclosure during insulation removal, making access much easier. Precision placement of the devices to cut the connections is not required because the removed equipment will be scrapped, not repaired and reinstalled. Thus, the duration of this activity would be only about 1 hour and would require about 6 person hours.

*Severing Connections*. The duration of the cutting operations themselves should be about 1 hour rather than 8 hours. A converter has three large diameter pipe connections for $UF_6$ (uranium hexafluoride) circulation, two smaller diameter pipe connections for coolant circulation, and some instrument lines and electrical connections that must be severed before the converter can be removed from its original location to the disassembly/decontamination area. The five pipes would be cut using track-mounted plasma arc torches, and the instrument lines and electrical leads would be cut using mechanical shears. Several track-mounted torches would be clamped in place simultaneously by crew members working in parallel. Cutting the pipes using plasma arc torches is very fast, a few minutes per pipe. With a 6-person crew, it is expected that the converter connections would be severed in a period of about 1 hour, using about 6 person hours.

*Lifting and Transporting Equipment*. Lifting and transporting the freed converter from its normal location to the load-out dock at the building could take up to 4 hours, depending on how many transfers between interior cranes or carrier devices are necessary. However, the whole crew of 6 people would not be needed to perform this activity, and the remaining crew members could be starting the disconnection of the next unit during this time. Assuming that 3 people could handle the transporting of the converter via cranes, the duration of the activity would be about 4 hours and would require about 12 direct person hours.

*Clean Job Site*. The job site would be posted as a radiological control area before the work began and would remain so until final structure decontamination occurred. Thus, it should not be necessary to expend much effort on cleaning up the job site because the ongoing disassembly efforts would continue to generate localized contamination until the removal efforts were complete. Some local contamination control might be needed during the cutting operations. Based on the experience with pipe cutting during the Shippingport reactor D&D (DOE, 1994), blowers with high-efficiency particulate filters can be attached to the piping system to create a reduced pressure inside the pipes, which pulls the oxide particles and contamination inside the piping and onto the filters instead of allowing that material to be deposited around the surrounding work area. This approach was so successful at Shippingport that local contamination control envelopes and respiratory protection for workers on the cutting teams were not necessary. Installation and removal of the contamination control system would extend the duration of the cutting, could add another hour to the duration of the task, and would add about 6 person hours. When the equipment-removal efforts were complete, the decontamination of the whole building would begin, which is a separate D&D activity.

The cleanup efforts would be focused on removing residual instrument lines and electrical leads and generally picking up any miscellaneous debris remaining in the work area. This cleanup effort could be carried out in parallel with the converter transfer operations, while the converter was being transferred from its installed location to the loadout dock, and should increase the total task duration by no more than 1 hour.

Considering the potential reductions in estimated activity duration discussed above, the total elapsed time for a converter removal during D&D should take about 8 hours, compared with the 48 hours needed during operations; and the cumulative person hours should be about 36, rather than the 192 person hours required for the effort in an operational plant. Thus, the person hours and time required for a converter removal should be five times less for D&D than for operations. Even if the committee has underestimated by 50 percent so that 54 person hours are required, it is still a factor of 3 or 4 less than for operations. In either case, the estimate is considerably less than that assumed for the Ebasco and TLG estimates.

## Characterization

Characterization is the collection and analysis of data to determine the type and quantity of radioactive and hazardous material contamination that are currently present in the plants and that will arise from D&D operations. The three successive stages of characterization are as follows: initial site characterization (pre-D&D), operational in-process characterization, and final site characterization. Manual characterization measurements and area surveys are very labor intensive. Automating the GDP characterization process may reduce costs. Examples of promising candidates for automated data collection and analysis include process building floors and waste certification facilities. Avoiding over characterization is also important for minimizing costs. Where possible, statistical sampling methods should be used to support sensing and measurement systems to reduce characterization costs and obtain data for pre-D&D planning and engineering.

## SUPPORT FACILITIES

### Decontamination Facilities

The Ebasco cost estimate assumes that a new high-assay decontamination facility and a new low-assay decontamination facility will be constructed at Oak Ridge. Contaminated equipment and materials from Portsmouth and Paducah would be shipped to the Oak Ridge facilities for decontamination, and new waste certification facilities would be constructed at Portsmouth and Paducah. These four facilities are assumed to require the construction of new buildings. Ebasco estimates total capital and operating cost of these facilities over their assumed 11-year period of operation at $3.47 billion, or approximately 29 percent of the total D&D cost for the three GDP sites, excluding construction management costs, M&O contractor cost, and contingency. The future cost of decommissioning these facilities, which could be substantial, is excluded.

The large capital and operating costs associated with the proposed high- and low-assay decontamination facilities merit further study to reduce costs. Lacy (1994) identified a number of potential opportunities to reduce the cost of these facilities and shorten the processing time required:

- eliminating the high-assay decontamination facility;
- simplifying the low-assay decontamination facility design;
- refurbishing existing buildings to house the low-assay decontamination facility and certification facilities; and
- determining whether a separate low-assay decontamination facility at each site would be less expensive than using a shared facility and shipping equipment and materials to Oak Ridge.

#### Eliminate the High-Assay Decontamination Facility

Because many of the functions performed in the high-assay decontamination facility are also performed in the low-assay decontamination facility, it may be possible to eliminate the high-assay decontamination facility. This possibility will depend on whether safeguards and security requirements can be satisfied under this scenario (see below).

#### Simplify the Low-Assay Decontamination Facility Design

The current low-assay decontamination facility design, which uses a "Purex canyon" concept, with such attributes as thick concrete walls, four containment barriers, air locks, and uninterruptible power supply appears over conservative. Appropriate industrial building codes for the locality should pertain. By adopting a much-simplified design, more like a low-level radioactive waste processing facility, costs could be decreased substantially. The applicable regulations need to be considered in determining the most cost-effective design concept. The gaseous decontamination process, which is expensive and time consuming, should be replaced by aqueous decontamination in the low-assay decontamination facility.

### Use of Existing Buildings

The use of existing buildings for the low-assay decontamination facility and certification facilities should reduce capital costs and would avoid the additional costs of decontaminating the new buildings upon completion of the D&D. BNFL used this approach at Capenhurst, temporarily storing enrichment cascade components outdoors to provide space for size reduction and aqueous decontamination facilities. Another option is to use existing decontamination facilities for converter decontamination. However, the Portsmouth and Paducah decontamination facilities have been modified and may not have sufficient capacity to decontaminate the entire converter train. The D&D facility at the Oak Ridge GDP is no longer operational and may not be suitable for decontamination activities without extensive refurbishment. Nevertheless, this option should be examined in light of the potential capital cost savings, as well as in terms of avoiding future D&D of the proposed new facilities.

### Multiple Low-Assay Decontamination Facilities versus a Single Shared Facility

The shipment of contaminated equipment and materials from Portsmouth and Paducah to the Oak Ridge GDP and the return of associated wastes are expensive and likely to foster political opposition. Providing a separate low-assay decontamination facility at each site may prove to be a less expensive alternative. Existing buildings should be used to the maximum, thereby minimizing the amount of facility decontamination at the completion of D&D.

## New Administration Building

The Ebasco cost estimate includes a new 200,000 $\text{ft}^2$ administration building at the Oak Ridge GDP, at an estimated cost of $25.4 million, to house a projected staff size of 2,000 (DOE, 1991a). The estimated median unit cost of new low-rise office buildings (Means, 1995) is $66.10/$\text{ft}^2$, or $13.2 million for the proposed 200,000 $\text{ft}^2$ administration building at Oak Ridge. If this assumption is made, this calculation implies that the cost of furnishing the $25.4 million administration building proposed for Oak Ridge would be $12.2 million, or approximately $6,000 per employee. Assuming there is a substantial amount of existing furniture and equipment that could be used (due to downsizing of the Oak Ridge GDP or other DOE facilities), the cost of this facility may be somewhat lower. More importantly, by using existing office space, which should be available since each GDP will be shut down before undergoing D&D, a large part of the $13.2 million cost of the new building could be saved. Some renovation of the existing buildings will be necessary, as will modernization to accommodate computer and communications systems. Streamlining the management organizational structure, thereby substantially reducing the size of the management staff, should also reduce the space required and the cost of refurbishing and furnishing the building.

Ebasco's base case assumes that existing buildings at Portsmouth and Paducah would be refurbished in lieu of constructing new administration facilities. Ebasco estimated the refurbishment cost for each building at $12.4 million (DOE, 1991a). Based on the above logic, this refurbishment cost appears high and should offer an opportunity for cost reduction, particularly considering the smaller staff likely to be needed with the use of a DOC.

## COST ESTIMATE ASSUMPTIONS

### Learning Curve

Once detailed D&D planning and engineering for the Oak Ridge GDP have been completed, the cost of these activities for the Paducah and Portsmouth plants should be considerably less because this D&D effort should involve essentially the same technical approach and technology. This cost reduction due to a "learning curve" is not reflected in current cost estimates (McNeil and Clark, 1996). There will be site-specific engineering and implementation costs, but the design similarities of the three enrichment facilities should result in substantial cost savings. The Ebasco cost estimates for Portsmouth and Paducah were developed by scaling the Oak Ridge GDP estimate for differences in plant size. When plant-specific detailed cost estimates are prepared, the savings associated with related planning, engineering, and implementation should be reflected. Additional cost savings will arise, due to the learning curve, as successive sections of the plants are disassembled and decontaminated. The extent of learning will depend on the activity. In general, learning for automated and robotic activities is less than for manual activities once a successful automated process is developed.

### Site Practices and Procedures

Ebasco assumed that existing site practices and procedures and surveillance and maintenance activities applicable to plant operations would apply to D&D as well. Revising plant procedures to reflect D&D rather than operations should offer opportunities for large cost reductions as discussed previously in this chapter.

Detailed procedures are necessary in the GDPs to minimize interruption of production, protect worker health and safety, and safeguard classified technology. However, once the GDPs cease operating, and if the technology is declassified, many procedures and practices can be simplified or eliminated when they do not apply to D&D operations. These changes would increase worker productivity and reduce both execution and oversight costs for monitoring compliance. While the cost savings cannot be quantified without a detailed review of existing site procedures and practices and without definition of the overall D&D process to be used, the savings should be substantial.

### Safeguards, Security, and Classification

The D&D of the gaseous diffusion plants will require the handling of special nuclear material. Meeting the regulatory requirements to safeguard such material increases the D&D cost considerably. Ebasco estimated the cost of safeguards and security during D&D at $794 million (Lacy, 1994), or 5 percent of the total D&D cost. This cost could be reduced significantly if less stringent safeguards and security requirements could be applied.

The question becomes what safeguards and security are required and what incremental benefits are achieved as the effort and cost of these requirements are increased. Lacy pointed out that "the regulations associated with special nuclear material safeguards and security are generally designed to track known quantities of special nuclear material through well-defined manufacturing/processing steps. …" The ability to track such material arising from D&D

operations is much more difficult than for a typical chemical processing or manufacturing operation. An accurate material balance for enriched uranium for D&D is not feasible because the quantity of uranium in the plant initially is uncertain. Also, it will be difficult to determine how much of the deposits have actually been removed by mechanical and chemical decontamination; accurate characterization of residual uranium content on recovered material with complex shapes is difficult. The committee supports Lacy's position that the safeguards be geared to accounting for the $UF_6$ (and/or other forms of uranium if aqueous decontamination is applied) that is recovered from the decontamination operations and to providing just enough information to meet the packaging certification and shipping requirements for radioactive waste.

The Ebasco cost estimate assumed that the technology would be declassified; therefore, no cost allowance was included for the extra effort of managing with classification issues. If the technology is not declassified by the start of decommissioning, D&D workers handling classified components will require "L" clearances. Workers handling special nuclear material will require "Q" clearances, for example, in the K-25 building and parts of the K-27 building at the Oak Ridge GDP (Quist, 1995). While this circumstance would entail extra costs for security, the security provided for operations involving special nuclear material may be sufficient without adding extra security personnel. In a classified regime, there would also be extra costs for handling classified documents and disposing of classified wastes. Foster Wheeler (which has acquired Ebasco Environmental) estimated that if the gaseous diffusion technology is not declassified, the $16.1 billion Ebasco estimate would increase by $2 billion (Snedaker, 1995a).[7] While it is beyond the scope of this study to comment on national security issues, it must be noted that the cost arising from the classification of the technology (primarily the barrier technology) could be very large, and similar technology appears to be widely available throughout the world. It would seem prudent to carefully consider the risks, costs, and benefits of declassifying the barrier technology. If the technology is not totally declassified, it is important to define specifically which components or process conditions will remain classified to develop a sound D&D work plan, cost, budget, and schedule.

The greatest cost impact of safeguards and security represents a combination of increased security, more expensive D&D facilities, and reduced labor productivity. The frequency of safeguards and security monitoring can be reduced by removing special nuclear material from the cascade using cleared plant personnel prior to the start of formal D&D operations, after which, outside, uncleared contractors could be used. Lockheed-Martin Energy Systems plans to remove, by 1999, about 60 components in the high-enrichment section of the Oak Ridge cascade that are known to contain special nuclear material, thus minimizing safeguards concerns and the risk of nuclear criticality during disassembly. This strategy would allow the D&D contractor to disassemble cascade components under much less restrictive conditions and increase contractor productivity.

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[7] Snedaker (1995b) indicates that the $2 billion was estimated based on D&D workers having DOE "Q" clearances; this accounted for about 10 to 15 percent of the cost. The low-assay decontamination facility would have two separate units, one for classified components and one for declassified components; this would lead to duplication of services in the low-assay decontamination facility and account for about 60 percent of the cost increase. The rest of the cost increase would be related to handling classified components.

Several issues need to be resolved regarding safeguards, security, and classification:

- Which Nuclear Regulatory Commission regulations and DOE orders apply?
- What degree of special nuclear material accountability is required?
- What technology, if any, will remain classified?
- Can the high-assay decontamination facility be eliminated and special nuclear material requirements still be met?

## Criticality Prevention

There are a variety of ways to prevent nuclear criticality during deposit removal and decontamination operations. Costs may be reduced if a different approach is taken from that assumed in the Ebasco cost estimate, which was using gaseous $ClF_3$ for the removal of uranium deposits from the process equipment. This dry gaseous approach to uranium removal is attractive for criticality prevention. It motivates experimenting with low-temperature, long-term gaseous $ClF_3$ treatment as part of the Deposit Removal Program, but, as mentioned previously, the committee is not optimistic that this approach will remove sufficient uranium deposits. Consequently, at Oak Ridge, deposits representing a criticality concern may have to be removed under dry conditions mechanically through scraping or criticality safe vacuum-cleaning systems.

At Paducah and Portsmouth, the USEC is responsible for removing uranium deposits that represent a criticality risk before returning the facilities to DOE, which is responsible for subsequent D&D. The removal of highly enriched uranium in the high-enrichment section at Portsmouth, which is not leased to the corporation, is the responsibility of DOE. The removal of these uranium deposits has been undertaken by DOE, but it is not funded by the D&D Fund. Hence, this section will not have critically unsafe deposits prior to D&D. The low enrichment levels at Paducah make it unlikely that uranium deposits of critical size will be present. Furthermore, at both Oak Ridge and Portsmouth, extensive sections of the enrichment cascades should contain relatively low-enriched material. These considerations suggest that the approach to criticality prevention should probably be different from plant to plant and from building to building at each of the sites. For sufficiently low enrichment levels, spray booth treatment followed by aqueous decontamination would be suitable. Criticality will be a concern at all three plant sites where aqueous treatment is used and where the $^{235}U$ concentration can build up in solution. However, criticality prevention measures can be implemented for these situations.

The Ebasco cost estimate scaled up the D&D cost for the Oak Ridge GDP to calculate the D&D cost for the other two sites. Considering that, with regard to criticality, the most difficult situation to manage will be the high-enrichment cascades at Oak Ridge, it seems likely that a different approach to the other two sites can yield cost savings. Given the important cost implications of criticality avoidance, especially the choice of technology, DOE should undertake a careful review of the approach to criticality, which may differ depending on the particular equipment to be decontaminated.

## Surveillance and Maintenance

The objective of the surveillance and maintenance program is to perform periodic building inspections and to correct identified deficiencies that could adversely affect the environment, jeopardize public or worker health and safety, or compromise national security through the loss of classified technology or special nuclear material (Battelle Oak Ridge Operations, 1994). Program responsibilities include identification and implementation of appropriate corrective actions for PCB, oil, roof, steam, and air leaks, safety concerns, and asbestos deterioration. Additionally, fissile storage areas, shutdown equipment, hazardous materials, and hazardous wastes must be properly controlled and maintained in a safe condition.

Annual surveillance and maintenance costs consist of three components: baseline costs, plant and allocated costs, and safe shutdown projects. These costs at the Oak Ridge GDP in fiscal year 1994 were $37.9 million, of which $21.6 million were baseline cost and most of the remainder plant and allocated support costs (Battellee Oak Ridge Operations, 1994). Allocated costs include charges for site-wide services, such as fire protection, utilities, security, and electrical. Annual baseline surveillance and maintenance costs at the Oak Ridge GDP are projected to increase until fiscal year 2000, where they remain at $47 million/yr through 2005, then rise again to $34.7 million/yr through 2014, and finally to $6.6 million/yr from 2015 to 2019 (DOE, 1993a). Many surveillance and maintenance costs are regulatory-driven and may therefore be difficult to reduce. Such allocated costs as fire protection, security, electric power, and utilities are major cost contributors. Considering that the Oak Ridge GDP is a nonoperating facility, alternatives should be explored to ascertain whether these services can be reduced.

A DOE cost review team examined 12 specific surveillance and maintenance issues at the Oak Ridge GDP site to identify potential cost reductions (DOE, 1995). The team concluded that there are numerous opportunities for cost reduction. Examples include centralizing responsibility for surveillance and maintenance, reducing the frequency of facility inspections, reducing the amount of training, downgrading the security classification of the Oak Ridge GDP, removing actively occupied facilities from the D&D program, having building inspectors correct minor problems (e.g., repair leaks), and eliminating fire protection in certain facilities.

Relative to the 1994 surveillance and maintenance cost of $37.9 million (MMES, 1994), the Ebasco D&D estimate projects an annual cost that decreases linearly with time and averages about $12.7 million for 25 years. The committee is uncertain about the basis for this cost estimate, but once hazardous materials (PCBs and asbestos) and special nuclear materials are removed and the enrichment technology is declassified, costs should decrease substantially.

## Labor Agreements

The requirements of labor laws and existing site labor agreements need to be integrated with the overall contracting strategy. The Ebasco estimate used Davis-Bacon Act wages for all hourly paid workers and used mostly higher paid craftsperson labor categories as compared with the Shippingport D&D, where mostly lower paid labor was employed. This is a conservative approach that provides an upper boundary for the cost estimate. Because D&D work is very labor intensive, worker skill levels for major work activities need to be established. The cost of construction-type activities requiring higher skill levels should be estimated using Davis-Bacon

Act wage determinations. Decommissioning activities, which generally require lower skill levels, should be estimated using lower wage levels typical of Service Contract Act wages. However, the determination of what laws and practices apply to a given project will probably need to be determined on a case-by-case basis. Prior to the start of decommissioning activities, labor agreements should be negotiated with the unions. The objective of these negotiations should be to establish work rules specific to D&D activities to stabilize the work environment by minimizing jurisdictional disputes and work stoppages.

## SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

As discussed in Chapter 4, the estimated cost for D&D of the three U.S. GDPs is high compared with experience on other D&D projects, and there are opportunities for major cost reductions. Because the direct cost for construction and operation of new facilities for D&D assumed in the cost estimates alone is on the order of $3.5 billion, the simplification of decontamination processes and use of aqueous decontamination provide a large potential opportunity for cost reduction, especially considering that the D&D cost for the Capenhurst aqueous decontamination facility in the United Kingdom was on the order of $10 million. It also seems that many fewer people could accomplish the D&D by simplifying the management and organization of the effort; reevaluating labor requirements for what, in many instances, are demolition and deconstruction activities; automating some key processes; and reassessing program integration efforts. Together, these efforts could amount to several billion dollars in cost reduction. A different approach to safeguards and security could also save hundreds of millions of dollars. Finally, because low-level radioactive waste disposal costs will probably be very high, reuse of materials could realize substantial cost savings. These major cost-reduction opportunities and other possibilities, as well as the scaleup of the Capenhurst D&D costs yielding about $2 billion for the D&D of the U.S. GDPs, give the committee optimism that major D&D cost reductions can be achieved. While the magnitude of the potential savings is uncertain, it could equal or exceed 50 percent of the current estimate of $16.1 billion. Realizing major cost reductions would require a change in the DOE management approach, with cost-effective planning and execution of the project being assigned a high priority. Every aspect of the D&D effort would have to be examined closely to identify the most cost-effective alternatives for accomplishing each task and to eliminate redundant management layers and excessive overview, while complying with essential health, safety, and environmental protection requirements.

Conclusions and recommendations about the management, and technical and institutional issues in reducing D&D costs are presented below.

### Conclusions and Recommendations

#### Conclusions

1. Based on experience with previous DOE projects, large reductions in cost are unlikely to be achieved under the management and operating contractor approach. Such experience

demonstrates conclusively that this concept results in much higher costs compared to those of similar projects managed by other government agencies or the private sector.

2. Recycling decontaminated metals (representing over 700,000 tons) to the commercial market, which could produce substantial revenues, may be a lower cost alternative than disposal of these materials as low-level radioactive waste.
3. Physical removal of cascade components (converters, compressors, motors, and piping) during D&D should be much less labor intensive than during plant maintenance operations because protecting component integrity to permit reinstallation is unnecessary. Less skilled, lower cost labor appropriate for demolition work can be used.
4. Surveillance and maintenance is a major cost driver. Investigating alternative approaches to eliminate unnecessary activities and perform essential activities much more efficiently should result in significant cost reductions.
5. The massive scale of the D&D effort and the repetitive nature of the disassembly and decontamination activities strongly support the extensive use of automation and robotics.
6. Estimated capital and operating costs of the proposed low- and high-assay decontamination facilities are extremely high because these facilities' excessive flexibility and design features are not required for the mission. The construction of a new administration building is not warranted.
7. Continued security classification for selected components of the gaseous diffusion technology will be a major cost driver if cleared workers are required for D&D.
8. Safeguards and security will be a major cost driver, if current practices and procedures for operating facilities are employed during D&D.
9. The current cost estimate does not appear to reflect the substantial cost savings typically achieved as a result of a learning curve.
10. The approach to criticality prevention has important cost implications and might differ among the three GDP sites as well as among different parts of the enrichment cascades.
11. Demonstration of selected D&D technologies would be beneficial to collect the data necessary to optimize D&D planning and execution to achieve minimum cost.
12. The cost of labor and materials required to disassemble and decontaminate process equipment appears to be overestimated. The person hours and material requirements data obtained during plant maintenance and various plant improvement and upgrading programs have high values for a demolition-type operation where equipment will not be reinstalled.
13. If sufficient funding is available, shortening the D&D project schedule should reduce total costs for activities such as management, security, fire protection, and surveillance and maintenance.

### Recommendations

1. The current approach to managing D&D, which involves three prime contractors (management and operating, architect-engineer, and construction manager), should be abandoned. An independent contractor should be selected to prepare the D&D plan. An independent contractor should be selected through open competition and should be assigned full responsibility and accountability for executing the D&D.
2. The technical, institutional, and economic feasibility of metal recycling should be evaluated relative to burial. Efforts to reduce institutional barriers should be expedited.
3. Alternative, less costly methods for component removal should be developed to reflect the less stringent requirements of demolition.
4. Surveillance and maintenance activities should be reexamined, to reduce or eliminate all those not essential for preparing and executing the D&D effort. Necessary surveillance and maintenance should be performed using a specialty subcontractor under contract to the decommissioning contractor.
5. Those D&D activities that involve repetitive operations (e.g., characterization, disassembly, decontamination, and certification), significant personnel hazard, and inaccessible areas should be examined to determine the cost effectiveness of using automation and/or robotics. The benefits of worker dose reduction should be considered as should reduced costs. Industrial expertise in robotics should be brought into the planning of the decommissioning contractor from the outset. Existing technology should be tailored to the unique requirements of the gaseous diffusion plants.
6. The high-assay decontamination facility should be eliminated and the low-assay decontamination facility greatly simplified to focus primarily on aqueous decontamination. The low-assay decontamination facility should be housed in one of the existing cascade buildings rather than constructing new facilities. Existing facilities should be used to house the management and professional D&D staff rather than constructing a new administration building.
7. To reduce costs without compromising the information security for gaseous diffusion technology, DOE should try to define physical security requirements that allow uncleared workers under adequate supervision to conduct D&D operations.
8. An in-depth evaluation of the safeguards and security requirements during D&D should be undertaken to determine how their impact on D&D cost could be reduced. Special nuclear material should be removed from the high-enrichment sections of the cascade prior to the start of large-scale D&D operations, so that safeguards and security requirements can be relaxed.
9. Experts who design and operate large-scale manufacturing operations should be consulted to quantify the productivity increases likely to be achieved over the life of the D&D project, and this savings should be reflected in the next cost estimate. Engineering costs for D&D of the Portsmouth and Paducah plants should reflect site-specific differences from the Oak Ridge GDP design.

10. A careful review of the alternatives to prevent nuclear criticality should be undertaken to choose the most cost-effective approach.
11. The funding necessary should be provided to demonstrate the decontamination and disassembly of a full-size enrichment stage.
12. Person hours and material costs for removal and decontamination of stage components should be reduced by eliminating those activities associated with retaining the ability to reinstall the equipment.
13. Studies should be performed to determine the effect of schedule duration on total project cost. If Paducah or Portsmouth enrichment operations are shut down early, the sequence of D&D for the three plants should be reexamined to determine the optimal sequence.

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# 7

# Disposition of the $DUF_6$

Virtually all the $DUF_6$ (depleted uranium hexafluoride) produced within the uranium enrichment complex since the mid 1940s has been saved as a future resource, which DOE currently has stored at the three GDPs at Paducah, Kentucky; Piketon, Ohio; and Oak Ridge, Tennessee. The committee has been asked to assess options for the disposition of this stored $DUF_6$ and to review the cost study performed by MMES for the disposition of $DUF_6$ generated at the GDPs. The committee's report is concerned only with $DUF_6$ owned by DOE and generated prior to the establishment of the USEC on July 1, 1993; $DUF_6$ produced after this date is the responsibility of the USEC and will not be considered here, although it cannot be ignored when considering the ultimate D&D of the GDPs.

## $DUF_6$ INVENTORY

The total $DUF_6$ material inventory is more than 500,000 metric tons (357,000 metric tons of uranium). Over half of this inventory is located at Paducah, approximately one-third is at Portsmouth, and the remainder is at Oak Ridge (see Table 7-1). All of the relatively high-assay material, with $^{235}U$ (uranium-235) content from 0.31 to 0.71 weight percent, is stored at Paducah and Portsmouth.

The $DUF_6$ is stored outdoors in 46,422 steel cylinders.[1] The cylinder storage yards at Paducah are illustrated in Figure 7-1. The cylinders are stored in double rows in a stacked two-tier configuration, with the lower cylinders placed on wooden or concrete saddles on concrete-paved or compacted gravel yards (Figure 7-2). The area of the cylinder yards at the three GDPs is about 65 acres. Cylinders of various designs have been used for storing and transporting $UF_6$ (uranium hexafluoride) (DOE, 1991). The heterogeneity of the cylinder population reflects changes in specifications over time, due to both safety concerns and cost constraints (Walter, 1989). About 80 percent of the cylinders used in $DUF_6$ storage are nominal 14-metric-ton $UF_6$ capacity, thin-wall design (5/16-in. wall, code rating of 687 kPa [100 psia]). The remaining cylinders are an earlier thick-wall design with 5/8-in. wall thickness, if 10-metric-ton capacity.

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[1] There are over 50,000 cylinders in the stockpile; over 3,500 contain only residues left from transfer, known as "heels."

TABLE 7-1 DOE $DUF_6$ Inventory at the Three GDPs (as of June 30, 1992)

| $^{235}U$ Assay (weight percent) | Weight (metric tons of uranium) | | | |
|---|---|---|---|---|
| | Paducah | Portsmouth | Oak Ridge | Total |
| < 0.21 | 73,573 | 20,628 | 22,751 | 116,952; (32.7%) |
| 0.21 to < 0.26 | 51,883 | 42,331 | 11,368 | 105,582; (29.6%) |
| 0.26 to < 0.31 | 28,270 | 6,255 | 2,257 | 36,782; (10.3%) |
| 0.31 to < 0.50 | 59,586 | 35,300 | –[a] | 94,886; (26.6%) |
| 0.60 to < 0.71 | 2,931 | –[a] | –[a] | 2,931; (0.8%) |
| Total | 216,243; (60.5%) | 104,514; (29.3%) | 36,376; (10.2%) | 357,133; (100.0%) |

[a] No data available.

SOURCE: Hertzler et al. (1994).

## USES FOR DEPLETED URANIUM

It has been suggested that the large accumulation of a very pure chemical, $DUF_6$, represents a national resource, although the quantity of material may be surplus to anticipated requirements.[2] Suggestions have been made for its use and more are being sought (Federal Register, 1994a). Proposed applications of the material can be grouped on the basis of the properties of $DUF_6$:

- The very high density of uranium and its effectiveness in absorbing gamma rays might be used to provide shielding for spent nuclear power plant fuels. Two types of storage canister have been proposed; one made of metallic uranium and the other made of concrete, where the aggregate normally used is replaced with uranium dioxide ($UO_2$) pellets (Ducrete). Uranium is used for military projectiles to enhance their densities and penetrating power, but this is a very limited market. Its high density could also make uranium attractive for use in flywheels.

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[2] A recent report from the Defense Nuclear Facilities Safety Board notes that "demand for depleted uranium has become quite small compared to quantities available" (DNFSB, 1995).

FIGURE 7-1 DUF$_6$ cylinder storage yards at Paducah. (Yards encompass about 40 acres and contain about 20,000 cylinders or 40 percent of total DOE inventory.)

FIGURE 7-2 Cylinders stored at Portsmouth. (Cylinders are stacked to facilitate visual and ultrasound inspection.)

- The fluorine content of $DUF_6$ offers the possibility of using the material as a fluorinating agent for the production of certain chemicals, for example, fluorine-containing organic compounds. The chemical purity of the $DUF_6$ may be an added advantage for such applications.
- Possible applications that exploit the isotopic content of $DUF_6$ include use as feed for re-enrichment by atomic vapor laser isotope separation (AVLIS), manufacture of uranium oxide breeder reactor blanket fuel or mixed uranium-plutonium oxide fuel for power reactors, and dilution of very high-assay, weapons-grade uranium to an assay suitable for nuclear power plant fuel.

## Shielding Applications

Special casks are being manufactured for the transfer and dry storage of spent nuclear fuel. Metallic uranium with its very high density (about 1.7 times that of lead and 2.3 times that of steel) could be a useful construction material, combining structural requirements and high volumetric efficiency for gamma ray absorption (Hertzler and Nishimoto, 1994). However, there are significant impediments to its use: it is a very high cost material ($10/kg, versus less than 50¢/kg for steel); it has not been certified as a structural material, and the certification process would incur significant test work and costs; and it faces serious competition from existing cask designs and materials, such as concrete or steel/lead composites that appear to perform satisfactorily. For these reasons, the committee believes that uranium is unlikely to capture a significant share of the market for spent fuel casks.

An alternative way to take advantage of the shielding properties of uranium (and its compounds) is to incorporate it into concrete (Haelsig, 1994; Quapp, 1995). $UO_2$ pellets, such as those used in nuclear fuel bundles, have been incorporated into concrete; the pellets replace the aggregate normally used, yielding a very dense concrete that might be used to manufacture casks for storage of spent nuclear fuel or, with appropriate design, for transport. The principal advantage of manufacturing such Ducrete storage casks is deferring the cost of uranium oxide storage. As discussed later, this storage constitutes a significant fraction of the total cost to convert and dispose of the $DUF_6$ inventory. The willingness of utilities to accept Ducrete casks for storage of spent nuclear fuel has not yet been established. Disadvantages of Ducrete are that it takes a very pure material—with impurities only at the parts per million level—and converts it into an impure material, while also increasing the total volume of radioactive material for ultimate storage. The $UO_2$ suggested for Ducrete represents a very high density oxide but is not the thermodynamically stable form; $U_3O_8$ (uranium oxide) has a lower density but is the stable form and would probably be the preferred form for any Ducrete planned for long-term use. Consequently, proposals for the use of Ducrete would not conflict with a decision to convert $DUF_6$ to a more stable oxide (see below, "Conversion Options and Costs").

## Use as a Fluorinating Agent

$UF_6$ can be used as a fluorinating agent in the production of fluorine-containing organic chemicals. Of particular interest has been the possibility of combining the conversion of $UF_6$ into more stable uranium compounds with the synthesis of marketable products such as fluorinated hydrocarbons. These latter compounds are important in the ongoing replacement of ozone-depleting CFCs (chlorofluorocarbons) as refrigerants and cleaning agents.

Considerable research has been conducted to increase the fraction of fluorine contained in $UF_6$ that can be transferred to organic molecules. While it is relatively easy to convert $UF_6$ to uranium tetrafluoride ($UF_4$), this process uses only one-third of the available fluorine value. Processes are under investigation that convert $UF_6$ to $UO_2F_2$ (uranyl fluoride), thereby increasing the fluorine utilization to two-thirds.[3] The remaining one-third is then recovered as HF (hydrogen fluoride), resulting in a uranium oxide product.

An inherent disadvantage of these fluorination schemes using $UF_6$ is the need to introduce uranium into otherwise nonradioactive chemical plants, with the resulting complications of licensing, radiation protection, and low-level waste generation. Thus, it appears that recovery of the fluorine values of $DUF_6$ as HF (aqueous or anhydrous) in dedicated conversion plants would be the preferred approach.

## Re-enrichment or Dilution

### $DUF_6$ Enrichment by AVLIS

The AVLIS process for enriching uranium has been under development at Lawrence Livermore National Laboratory for over 15 years.[4] The technology is partially classified. The USEC has completed a review of the process pursuant to the EPACT and has made a strong recommendation that the technology be commercialized (USEC, 1994).

The AVLIS process is expected to have a lower cost per SWU (separative work unit) than the diffusion process for uranium enrichment. The suggestion has, therefore, been made that AVLIS could be applied to recover additional $^{235}U$ from the existing stockpile of $DUF_6$. Whether this would be economically viable will depend on a number of factors, such as the cost of the AVLIS process and the cost of feeding natural uranium with 0.71 percent $^{235}U$, including the costs of mining and conversion of natural uranium to metal. At current prices (in 1995), it would be more profitable to feed natural uranium, although future developments could change the economics.

AVLIS requires uranium metal feed, so the $DUF_6$ must be converted to metal; this conversion is an expensive process. A further disadvantage of using $DUF_6$ feed for AVLIS is

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[3] Personal communication from John Hewes, Allied Signal, Research and Technology, to James Zucchetto, National Research Council, December 1, 1994. Allied Signal recently submitted a patent application covering the technology, and details of the process remain proprietary. However, it involves a deoxygenative fluorination reaction of certain oxygen-containing organic compounds with $UF_6$. In the presence of a catalyst, multiple fluorination occurs. Other products are anhydrous hydrogen fluoride and uranium oxyfluorides, which can be converted to uranium oxides and more anhydrous hydrogen fluoride using known technology.

[4] The development of AVLIS at Lawrence Livermore National Laboratory had cost approximately $1.55 billion by 1990 (for both uranium and plutonium AVLIS). Estimated development costs in fiscal year 1991 were $154.5 million for uranium AVLIS and $66.5 million for plutonium AVLIS. Approximately 50 kg of uranium had been enriched from 0.7 percent $^{235}U$ to 1.0 percent $^{235}U$ by 1990 (NRC, 1991).

that a given enriched product requires a larger amount (2 to 3 times) of depleted metal feed compared to natural material, and a larger amount of metallic uranium has to be vaporized and condensed in the AVLIS separation process. Research on a less expensive process for making metallic uranium might improve the economics of using $DUF_6$ feed. The added costs of using depleted material for AVLIS feed depend on the $^{235}U$ level; the lower the assay, the greater the added costs. Estimates by the committee suggest that a material with less than 0.21 percent $^{235}U$ (32.7 percent of the $DUF_6$ stockpile) would be impractical for the foreseeable future.[5] Final decisions on AVLIS, in particular the use of $DUF_6$ feed, are probably several years in the future. In the meantime, significant quantities of low $^{235}U$ assay $UF_6$ (less than 0.21 percent $^{235}U$) could be converted to $U_3O_8$ without affecting the potential for use as AVLIS feed.

## Blending Agent

Some highly enriched (e.g., 90 percent $^{235}U$) weapons-grade uranium will be diluted to lower enrichment levels for nuclear power applications. Depleted uranium is a potential diluting (or blending) agent. The alternative blending agent is natural uranium with a higher $^{235}U$ content than depleted uranium. Depleted uranium offers the advantage of lower cost, but natural uranium would yield a larger amount of useful product, that is, it wastes fewer SWUs. The tradeoff depends on the cost of natural uranium versus the value of the SWUs wasted by using depleted uranium.[6] Other factors to consider include the risks associated with uranium mining.

The actual blending technique remains to be selected. There is some evidence that blending needs to be done at the molecular level (i.e., blending liquids or gases, not granular solids). $DUF_6$ would be suitable if the enriched uranium were also in the form of $UF_6$. Most likely, however, enriched uranium from weapons stockpiles will be made available as oxide or metal. The volumes of material required for blending are not large. Thus, the use of $DUF_6$ as

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[5] The committee evaluated the tradeoffs in using $DUF_6$ as a source of uranium metal for AVLIS using very approximate process and cost estimates as follows:

| | |
|---|---|
| Cost of $DUF_6$ feed | \$0/kg |
| Cost of natural $UF_6$ | \$30/kg U |
| Conversion costs | |
| - $UF_6$ to U metal | \$10/kg U |
| - U metal to $U_3O_8$ | \$0.5/kg U |
| Material handling, storage | \$20/ft$^2$ |
| cost of SWUs | |
| - AVLIS | \$20/kg U |
| - diffusion | \$100/kg U |

The USEC has not disclosed any projected AVLIS costs. A low cost estimate by the committee of \$20/kgU SWU was used to give an optimistic (high) value for the portion of $DUF_6$ material in storage that might be used economically as AVLIS feed.

[6] A comparison made with natural uranium priced in the range of \$30 to \$40/kg $UF_6$ has shown that the choice of blending agent remains open. (The cost of $DUF_6$ blending agent was assumed to be zero.) For SWUs at a cost of \$100/kg U (e.g., gaseous diffusion process), blending should be done with natural uranium. For SWUs at a cost of \$30/kg U (possibly using AVLIS technology), blending should be done with $DUF_6$. For an intermediate SWU price (\$60/kg U), blending with $DUF_6$ is economic at an assay exceeding 0.31 percent $^{235}U$, but not with an assay of 0.21 percent $^{235}U$.

a blending agent would have little effect on a decision to proceed with conversion of the $DUF_6$ to $U_3O_8$ (see below, "Conversion Options and Costs").

### Potential Energy Resource for Reactors

The large quantity of $^{238}U$ in the inventory of $DUF_6$ represents a potential energy resource for use in breeder reactors.[7] In a breeder reactor fertile $^{238}U$ material captures neutrons and is converted to fissionable plutonium ($^{239}Pu$), which is used as nuclear fuel. Liquid-metal breeder reactor technology has been under development in the United States and several other nations for over 40 years, although funding for the U.S. program has been sharply reduced in recent years. The deployment of the breeder reactor in the United States is uncertain. Based on an economic analysis, a recent NRC report notes that advanced liquid-metal breeder reactors may become competitive with advanced light-water reactors sometime in the latter part of the 21st century (NRC, 1996). Hence, the potential use of $DUF_6$ as a resource for breeder reactors is relatively far in the future.

One suggestion for reducing the stock of plutonium being recovered from weapons is to use it in fuel for nuclear power generation. Depleted uranium could serve as the source of uranium for mixed uranium-plutonium oxide fuel.

## DEPLETED URANIUM MANAGEMENT OPTIONS

A DOE program has been initiated to select a long-term $DUF_6$ management strategy that would minimize environmental impacts and costs (Bradley, 1995a). Recommendations for management and use of the inventory have been sought from industry, government agencies, and the public (Federal Register, 1994a). An environmental impact statement evaluating significant options is planned and should be completed by early 1998 (Federal Register, 1994b). A decision on the preferred course of action based on the environmental impact statement and cost evaluations is planned for the second quarter of 1998.

Based on the review of possible uses for depleted uranium, the committee does not believe that applications will be found in the near term that will make use of all, or of a large part, of the $DUF_6$ inventory at the GDPs. As the preceding discussion noted, conversion of $DUF_6$ to $U_3O_8$ for retrievable storage is not incompatible with possible uses of the uranium for shielding or re-enrichment. In addition, some of the proposed methods for conversion to oxides of uranium permit the fluorine value of $DUF_6$ to be realized. Therefore, it appears to the committee that two general courses of action are possible for the management of the $DUF_6$ inventory at the GDPs:

- A surveillance and maintenance program could be continued; the material would later be converted to a more stable form for very long term storage.

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[7] In response to a DOE Federal Register request for management options for the $DUF_6$, it was noted that the deployment of 100 breeder reactors would use only about 1 percent of the $DUF_6$ inventory per year (Zoller et al., 1995).

- Conversion to a more stable form could be started as soon as possible rather than being deferred to some future date.

In the following discussion, the factors influencing the choice of a management option are considered.

### Condition of Cylinders

A study of cylinder conditions in 1992 showed that many problems had developed over the long years of storage (DOE, 1992). For example, a large number of cylinders—estimated at 22,400—were inaccessible for inspection, either because rows were stacked too closely or because of settling on the ground so that the bottom could not be inspected. A recent report from the Defense Nuclear Facilities Safety Board also notes such inadequacies in cylinder storage (DNFSB, 1995).

Prior to 1990, routine inspections of the stored $DUF_6$ cylinders were not performed. However, a valve inspection program conducted in 1990 revealed a large number and variety of valve defects at all three sites, and subsequent inspections revealed seven breached cylinders (Table 7-2). The breaches were attributed to accelerated corrosion from either mechanical damage inflicted during stacking or unsatisfactory storage conditions (e.g., contact with wet areas on the ground). Such accelerated corrosion reduces cylinder life below the nominal value of 70 years calculated on the basis of atmospheric corrosion.[8] Two major corrosion problems have been identified; namely, accelerated corrosion associated with cylinder-to-ground and cylinder-to-saddle contacts and crevice corrosion in skirted cylinders (DOE, 1992). Approximately 14,000 cylinders, mostly at Paducah, have experienced either pitting or accelerated corrosion, or both (Bradley, 1995a). Preliminary estimates by DOE and MMES indicate that more than 1,000 cylinders containing over 10,000 tons of uranium have the potential to breach before the year 2020 unless remedial action is taken (DNFSB, 1995).

The cylinder surveillance and maintenance program has been better organized and funded since 1992. Many of the recommendations for improved storage (DOE, 1992) are being pursued. For example, yard refurbishment and construction are under way at Paducah, and planned at Portsmouth and Oak Ridge. Approximately 4,800 cylinders have been restacked, with the goal of having no cylinders left contacting the ground by 1996. Many other recommendations from the 1992 study, such as improved surface preparation and better coatings, are under consideration. The Defense Nuclear Facilities Safety Board recently recommended that significant improvements be made in the condition and storage procedures for the $DUF_6$ cylinders (DNFSB, 1995). These actions would be costly, but, in the committee's opinion, they are essential. Continued deterioration of the cylinders is not acceptable because it would increase the risk of a significant release of hazardous material and complicate later cylinder handling during conversion.

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[8] Internal corrosion of the cylinders occurs at a negligible rate. Cylinder life is determined by external corrosion mechanisms.

TABLE 7-2 Breached $DUF_6$ Cylinders

| **Date Discovered** | GDP Site | Cylinder Location (time in storage yard) | Size of Breach | Probable Cause of Failure | Environmental Impact |
|---|---|---|---|---|---|
| June 1990 | Portsmouth | Upper tier (13 years) | 8" × 16" | Mechanical damage at time of stacking | Air sample near hole contained about 1 ppm HF. Traces of $UF_4$ directly under hole and along short water runoff track. One soil sample with above-background contamination (12 picocuries/g) due to water runoff into ground at edge of concrete pad. Pad and cylinder surfaces decontaminated using conventional swabbing techniques. |
| June 1990 | Portsmouth | Lower tier (4 years) | 2" × 4" | Mechanical damage at time of stacking | Negligible contamination except in immediate vicinity of hole. |
| December 1991 | Oak Ridge | Upper tier; (G yard 17 years, then K yard 7 years) | 5–6" diameter | Accelerated corrosion due to storage on or near ground in G yard | Odor of HF under protective tarpaulins. Radioactivity levels in soil and water samples indicated remedial action unnecessary. |
| January 1992 | Oak Ridge | Lower tier (17 years) | 8–12" wide × 15–17" long | Mechanical damage at time of stacking | Odor of HF under protective tarpaulins. Soil and water sample data not available. |
| January 1992 | Oak Ridge | Lower tier (16 years) | 2" diameter | Mechanical damage at time of stacking | No reaction products detected around breach. Soil and water sample data not available. |
| March 1992 | Oak Ridge | Lower tier (G yard 16 years, then K yard 7 years) | 9" diameter | Accelerated corrosion due to storage on or near ground in G yard, followed by storage in wet area of K yard | Odor of HF under protective tarpaulins. Radioactivity levels in soil and water samples indicated remedial action unnecessary. |
| November 1992 | Paducah | C-745-K yard (time not specified) | Not specified | Mechanical damage (gouge) next to lifting lug, possibly resulting in accelerated corrosion | Smears of area were negative for contamination. |

SOURCES: Barber et al. (1994); MMES (1992); DeVan (1991); Barber (1991).

## Environmental, Safety, and Health Issues

In the event that a cylinder wall is breached, moisture in the in-rushing air first reacts with $UF_6$ vapor leading to the formation of solid uranium oxyfloride complexes and gaseous HF. Initially, the former tend to plug the breach, but the HF attacks the metal, leading to an enlargement of the breach at an estimated increase in diameter of 1 inch per year (DOE, 1992). Some uranium product breaks off and is dispersed to the surrounding area, the extent of contamination depending on environmental conditions. As an indication of the relative hazard posed by a release from a breached cylinder, it has been noted that the EPA requires reporting to the National Response Center if more than 0.1 curies of activity (952 lb of $UF_6$ with 0.5 percent $^{235}U$) or 100 lb of HF (resulting from the reaction of 440 lb of $UF_6$ with water) have been released to the environment over a period of 24 hours (DOE, 1992). For one of the largest breaches discovered so far (at Portsmouth, see Table 7-2), an estimated 110 lb of $UF_6$ were released to the environment over a 13-year period (DeVan, 1991); that is, the release of material to the environment was well below the level requiring EPA notification.

The principal hazard to humans in the case of a gaseous $UF_6$ release is from the production of HF, an extremely reactive and dangerous substance. External contact with HF results in chemical burns of the skin, and exposure to airborne HF causes chemical burns and irritation of the eyes, nose, and throat. However, individuals can smell HF at concentrations two orders of magnitude below lethality (DNFSB, 1995). Since $DUF_6$ is a very pure substance, the toxicity and radiological characteristics of the uranium-containing hydrolysis product are comparable to those of natural uranium. Prolonged worker exposure in the cylinder yards presents a small potential hazard. Information provided to the committee indicates that, following the evaluation of the radiation dose received by cylinder inspectors at the Oak Ridge site, an average of 25 hours per week spent in the cylinder yards was recommended in 1992 to control maximum yearly exposure.[9] This recommendation is based on an average exposure of 1.5 mrem/hour.

Fortunately, the physical properties of solid $UF_6$—notably the self-sealing of cylinder breaches—have so far mitigated the potential hazard inherent in storing vast quantities of a chemically reactive substance. The continuing storage of $DUF_6$ in cylinders does not appear to represent a significant near-term environmental risk or health hazard to site workers and the population at large. However, with the passage of time, the integrity of the cylinders will be reduced by external corrosion, increasing the risk of breaches.

Deterioration of the cylinders also impairs the ability to handle them, notably for the conversion of $DUF_6$ to uranium oxide or transfer of material into new or refurbished cylinders for continued storage. Removal of $UF_6$ from storage cylinders has usually been done by heating the cylinder in an autoclave to temperatures high enough to melt the material and transfer it as a liquid (typically at 113°C [235°F] and pressures over 85 psia). In contrast to the solid $UF_6$ under normal storage conditions, the molten material at this temperature and pressure is quite hazardous. The cylinders must be in good condition for the autoclave heating to be safe.

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[9] Personal communication from Robert Edwards, DOE Paducah Site Office, to James Zucchetto, National Research Council, November 1994.

Transfer from the cylinders can also be carried out by moderate heating, for example, to 60°C (140°F), which is below the melting point. The transfer is then at much lower pressure. The latter is a relatively expensive and slow process compared to the autoclave operation. The time required to empty a cylinder can be increased severalfold—from a day to almost a week.[10]

$UF_6$ transfer operations are more frequent during conversion to oxide operations than during storage. All cylinders will need to be emptied for conversion, not just the corroded or compromised ones. Experience has shown that autoclaving of cylinders is a critical process from the standpoint of health and safety. A breach of containment during autoclaving carries severe occupational and environmental risks. Other risks associated with conversion are industrial accidents and uncontrolled releases of HF and fluorine gas.

## Regulatory Issues

The $DUF_6$ inventory at the GDPs has traditionally been managed as material exempt from the regulatory jurisdiction of both the federal EPA and state agencies with respect to hazardous waste requirements under RCRA (Resource Conservation and Recovery Act). This practice has been based on the assumption that because the material consists solely of $UF_6$, it meets the definition of source material, and as such, should be regulated under the Atomic Energy Act of 1954 (Hertzler et al., 1994).

However, the internal DOE review of cylinder storage (DOE, 1992) noted that self-regulation by federal agencies has been eroded by the many environmental laws of the past 10 years: "In fact, many of the waivers of sovereign immunity contained in various environmental statutes state that the federal government should comply with all federal, state, interstate, and local requirements, both substantive and procedural, in the same manner, and to the same extent, as any person is subject to such requirements." In the case of the $DUF_6$ inventory at the Portsmouth GDP, the issue of applicability of hazardous waste regulations has been raised by the Ohio Environmental Protection Agency. The Southeast District Office of the agency notified DOE in October 1990 that cylinders of $DUF_6$ at the Portsmouth GDP were no longer exempt from regulation as hazardous waste under Ohio Administrative Code 3745-51-04. DOE countered that the $DUF_6$ qualifies as source material and is thus exempt from regulation under RCRA and Ohio law.

Assessment of these legal issues is beyond the scope of the present study. The assessment of options for future management of the $DUF_6$ inventory presented below is independent of any legal ruling defining the status of the material as either source material or hazardous waste.

No federal regulation requires conversion of the $DUF_6$ to a more stable form. On the other hand, the Nuclear Regulatory Commission has proposed limiting the quantity of $DUF_6$ in storage at the proposed commercial gas centrifuge plant in Louisiana to 80,000 metric tons of $UF_6$ or 15 years of production, whichever comes first (Zeitoun, 1994). Regulations introduced

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[10] Cogema in France is using mostly the higher temperature liquid $DUF_6$ transfer but is equipped for the lower temperature vapor transfer.

in France in 1976 impose a storage limit of 50,000 metric tons of $UF_6$, which is much smaller than the amounts stored at either Paducah or Portsmouth (Shallo, 1994; see Table 7-1).

## Continued Surveillance and Maintenance: Requirements and Costs

The DOE review of cylinder storage recommended improved storage practices, and a recent report from the Defense Nuclear Facilities Safety Board also recommended changes (DOE, 1992; DNFSB, 1995).

Restacking of the cylinders is currently under way, and projects to construct new concrete-paved storage yards and a cylinder refurbishment facility are planned. The total funding required for cylinder upgrading projects at Paducah through 1998 is estimated at $42.7 million (Fields, 1994).

Expenditures for cylinder management for fiscal year 1994 through 1996 have been estimated at $54 million (Bradley, 1995b). This figure includes $36 million for operations such as cylinder restacking and painting, and $18 million in construction costs for new cylinder storage yards, painting facilities, and cylinder handling machines. Further expenditures will be required beyond fiscal year 1996 for both operations and construction. It is anticipated that cylinder management costs may decline once the existing deficiencies in storage practices have been remediated and the cylinders upgraded. Costs for long-term management of the cylinders cannot be predicted with certainty at present, although an estimated annual cost of $10 million for cylinder surveillance and maintenance has been suggested (Bradley, 1995b).

## Conversion Options and Costs

A number of alternative methods have been proposed for the conversion of $DUF_6$ to a stable form suitable for indefinite storage or disposal. In the view of the committee, it would be desirable to recover the fluorine value of the $DUF_6$ material in the course of such a conversion to allow fluorine recycling for industrial applications. Such recycling is currently practiced by Cogema in France (see below). Uranium oxides are generally suitable forms for storage. Under atmospheric conditions, $U_3O_8$ is the preferred compound because of its thermodynamic stability (Lemons et al., 1990; Hertzler et al., 1994).[11]

Processes for the conversion of $UF_6$ to $UO_2$, $U_3O_8$, and $UO_3$ (uranium trioxide) have been used for many decades in a variety of applications. The preferred "dry process" used by the nuclear fuel industry for converting low-enriched $UF_6$ to $UO_2$ for nuclear fuel reacts gaseous $UF_6$ with steam to produce $UO_2F_2$ and HF; the $UO_2F_2$ is then reduced by $H_2$ to $UO_2$, which is pressed into pellets. These reactions are carried out in gas-phase or flame reactors and either fluidized-bed reactors or rotary kilns.

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[11] A risk characterization of alternate chemical forms of uranium is provided by Lemons and coauthors (Lemons et al., 1990).

Excess capacity currently exists in the U.S. nuclear fuel industry for the conversion of $UF_6$ to uranium oxides, although the volumes of material that could be converted are small compared to the $DUF_6$ inventory. It may be possible to use the excess capacity to start conversion of the $DUF_6$ on a limited scale. Conversion costs are estimated to be not less than $2/kg U, and could be significantly higher, particularly if it were necessary to relicense an existing facility.[12] This approach would require transport of $DUF_6$ from the GDP sites to other facilities. It would also require transfer of the $DUF_6$ from the current storage cylinders to cylinders compatible with the existing conversion facilities.

In France, Cogema has successfully operated a conversion plant since 1984, producing 7,000 metric tons of $U_3O_8$ and 4,300 metric tons of 70 percent aqueous HF annually. Thus, the Cogema conversion process has been proven for large-scale application. In 1995, the plant capacity was doubled with the addition of two new processing lines (Shallo, 1994). From the standpoint of chemical engineering, the Cogema process is attractive because of its simplicity. It uses moderate processing conditions with no high-pressure steps or expensive catalysts. The materials of construction for the process equipment are well known, and the process is run continuously rather than in a batch mode. A number of these features are in marked contrast to those of the relatively unknown conversion processes discussed below (e.g., very high temperature plasma processes).

The 70 percent aqueous HF product has a uranium content of less than 0.1 ppm and has been routinely recycled to industrial users. Some of the $U_3O_8$ product (150 metric tons of uranium) has been used in the manufacture of mixed uranium-plutonium oxide fuel for light-water reactors. The remainder has been stored in large rectangular carbon steel containers stacked inside ground-level storage facilities designed to be usable for extended periods of time and resistant to seismic disturbances.

Cogema currently estimates the cost of converting $DUF_6$ to HF and $U_3O_8$ to be in the range $4 to $6/kg U ($2.7 to $4.1/kg $DUF_6$) (Shallo, 1994). This cost does not assume any credit for the sale of HF and does not include any storage or disposal costs for $U_3O_8$. The cost to convert the entire DOE inventory of $DUF_6$ at the GDPs (357,000 metric tons of uranium) would be between $1.4 and $2.2 billion.

A defluorination process patented in the United States by Allied Signal has the advantage of producing anhydrous rather than 70 percent aqueous HF. In certain applications (e.g., the production of natural $UF_6$ feed for enrichment plants and certain fluorocarbons), only anhydrous HF can be employed. The Allied Signal process has been demonstrated on a laboratory scale. A very preliminary estimate suggests that disposition costs are on the order of $1/lb of $DUF_6$ ($2.2/kg of $DUF_6$, $3.3/kg U). This estimate includes a small charge for burial of $U_3O_8$ (assuming $10/ft$^3$ burial cost) and a substantial credit for the sale of HF equivalent to about 25¢/lb $DUF_6$ (Rock, 1994). Allowance for these costs would yield an estimate for conversion alone of about $2.7/kg $DUF_6$, $4.0/kg U.

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[12] Meeting between representatives of Westinghouse Electric Corporation, Commercial Nuclear Fuel Division, Columbia, South Carolina, and Frank Crimi and Alfred Schneider, members of the Committee on Decontamination and Decommissioning of Uranium Enrichment Facilities, February 3, 1995.

There have been some brief references to other, less mature technologies for the conversion of $DUF_6$ to uranium metal or oxides, but none appears to be sufficiently developed to offer hope of significant cost reduction compared to established processes.

Several proposals have resulted in modest research programs using plasma reduction of $DUF_6$, although the effectiveness of such techniques has not been demonstrated. Some work conducted at Tomsk in the former Soviet Union was hampered by degradation of reactor materials due to the extreme temperatures involved (about 10,000K) and resulted in an impure $U_3O_8$ product containing up to 2 percent HF and 0.4 to 0.7 percent $UO_2F_2$ (Rock, 1994). Other plasma reduction experiments have been conducted at Los Alamos National Laboratory and Idaho National Engineering Laboratory. The former work involved a shielded hydrogen plasma torch operating at about 10,000K to produce uranium metal, but no yield or cost figures are available (Adams et al., 1990); the latter project used similar hydrogen plasma technology to produce either uranium metal or oxide. The committee believes that some plasma processes could result in damage to containment vessel materials, because of the extreme operating temperatures, and in a contaminated product.

In May 1995 the USEC and M4 Environmental L.P. (a partnership between Lockheed Martin Corporation and Molten Metal Technology) signed a 1-year contract to study the recycle of $DUF_6$ using Quantum-CEP™ technology (USEC, 1995). This process is believed to be based on the principles of melt refining (see Chapter 3). The contractor claims that the process would recover both uranium and anhydrous HF, but technical details and estimated costs are not available.

Pacific Northwest Laboratory has conceived a method for the treatment and disposal of $DUF_6$ in a molten glass reactor based on in situ vitrification technology (Buelt et al., 1987). A 5-year research and development program would be required to determine feasibility and costs.

While by far the largest cost element in the ultimate disposition of $DUF_6$ is conversion to $U_3O_8$, the second largest cost item is expected to be for disposal or permanent storage of $U_3O_8$ (Lemons et al., 1990). Disposal costs are included in the analysis below.

### Assessment of Alternative Management Options

Two options for $DUF_6$ management were evaluated by the committee: conversion to oxide and continued surveillance and maintenance. The issues raised by these options are compared in Table 7-3. The comparison is qualitative and by no means exhaustive, but it does identify the major considerations. On the basis of all factors except cost, conversion to oxide is the preferred option; conversion would require a substantial initial investment.

## ANALYSIS OF COST ESTIMATES FOR CONVERSION

MMES estimated the cost to convert the $DUF_6$ at the Oak Ridge GDP using the Cogema process (Charles et al., 1991). The plant size was chosen to provide the same nominal operating capacity as the Cogema plant in France; that is, to be capable of converting 35,000 metric tons

TABLE 7-3 Comparison of Management Options for $DUF_6$

| **Evaluation Factor** | Conversion to Oxide | Continued Storage |
|---|---|---|
| Cost | High initial investment. | Final disposition cost deferred. |
| Health and Safety | Reduces hazard by conversion to more stable form. Potential for occupational exposure and injury during conversion. | Hazard from storage of very reactive $UF_6$. Hazard greatest during periodic transfer into new containers and if exposed to fire. |
| Environmental | Land use requirements lower for storage of $U_3O_8$ versus $UF_6$. Resource requirements increased for the conversion plant, but recovery of fluorine is a benefit. | Land use requirements higher. |
| Regulatory | Conversion required for private enrichment companies (U.S.) and for Cogema (France). | This option limited to a maximum volume of $DUF_6$ by Nuclear Regulatory Commission and French regulators. No such requirement for DOE. |
| Future Considerations | No legacy to future generations. Oxide can be used as feedstock or disposed of. | Decommissioning of GDP site cannot be completed with this option. $DUF_6$ still requires ultimate disposition. |

of uranium over a 5-year period. Provision for D&D of the plant at the end of the period was included in the cost estimate. The study was the basis for a further analysis by EG&G Idaho (Hertzler et al., 1994) that included an estimate for final disposition of the $U_3O_8$ at a western site. Data from these two analyses have been used by the committee to estimate costs for conversion and disposition of the entire DOE legacy of $DUF_6$; significant changes have been introduced in the analysis that modify the final cost estimate.

The MMES plant had an assumed life of only 5 years to eliminate the small Oak Ridge inventory. The committee has assumed a life of 20 years to eliminate the entire inventory at the three GDPs. The capital cost of the single plant is amortized over a longer period for a larger volume of material; the unit cost ($/kg U) is reduced as a result.

The plant size required for conversion of about 360,000 metric tons of uranium over a period of 20 years is larger than the MMES study design by a factor of 2.55. The capital investment would be larger, but not in direct proportion to plant capacity. A rule-of-thumb exponent factor of 0.6, based on practical experience in the chemical industry, has been applied to scale to the larger size plant, that is, costs of most equipment items will increase by $(2.55)^{0.6}$. This scaleup will also reduce the unit cost ($/kg U converted).

The production and handling of the HF in the conversion process can have a large cost impact. As noted earlier, Cogema produces aqueous HF that is readily marketable because of its high purity. The alternative is to neutralize the HF to produce calcium fluoride ($CaF_2$). The latter material has been considered to have no market value; instead, the plan has been to dispose of it as low-level radioactive waste in long-term storage. Costs associated with the neutralization facility and the long-term storage of the $CaF_2$ would be very large, adding about $4/kg U to the cost of $DUF_6$ disposition (Charles et al., 1991).

The committee has chosen to follow the Cogema model and assume that the HF can be marketed. Annual HF production over the planned 20-year plant operation represents a small fraction (about 2 percent) of the present North American market for HF, estimated at 255,000 tons per year.[13] The HF produced would replace a corresponding amount of imported fluorspar from the market. While a small credit is taken for the sale of the HF, the major cost impact is in eliminating its neutralization and the storage of $CaF_2$.

The $U_3O_8$ product from the conversion plant is very fine powder that will pack to a very low density of about 1.3 g/cm$^3$. Even after some compaction, the density is only 3 g/cm$^3$—much below the theoretical (material) density of 8.3 g/cm$^3$. The value of 3 g/cm$^3$ is a very undesirable form for long-term storage, although the committee has used this value to estimate the costs of long-term storage. However, it appears possible to improve on this value with a large cost savings, as is discussed later. Other assumptions made in the committee estimate include the following:

- The product $U_3O_8$ would be sent to a western site or to the Nevada Test Site for long-term storage. Estimated transportation costs have been taken from the EG&G study (Hertzler et al., 1994).
- Costs of long-term storage are uncertain. A figure of $30/ft$^3$ has been assumed for the Nevada Test Site; a high figure, $58.70/ft$^3$, has been assumed for Hanford. (Potential storage problems for this material at either site are discussed later.)
- Conversion costs per unit of $DUF_6$ ($/kg) could be reduced by consolidating all of the material at one site and operating one large plant rather than three small plants. This would require shipping $DUF_6$ cylinders to one site. The choice of Paducah would minimize shipping volume. Many of the cylinders have suffered enough corrosion that they no longer qualify as shipping containers and would require overpacking. Shipping costs are uncertain as a consequence. The cost estimate for this must be considered approximate.
- A conversion plant maintenance cost for the 20-year life of the plant at 5 percent of capital cost per year has been assumed. This is in the middle of the usual range for industrial plant maintenance costs.

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[13] Personal communication from Robert Pratt, Allied Signal to the Technology Panel of the Committee on Decontamination and Decommissioning of Uranium Enrichment Facilities, Metropolis, Illinois, October 19, 1994.

- Declining surveillance and maintenance of the cylinders in storage has been assumed, based on an initial value of $10 million for the first year, zero for the last year, and a uniform rate of decline.

The costs are summarized in Table 7-4. The breakdown is that given by Charles et al. (1991), with additions for other items as indicated above. The total cost from the MMES study has been scaled from 1991 to 1995 dollars, using *Chemical Engineering* plant cost indices.

A simple criterion for comparison of various alternatives has been used, namely, the total costs over the lifetime of the plant per kilogram of uranium processed. The comparison makes no allowance for the time-value of money. Table 7-5 shows the conversion cost only (i.e., excluding transportation to a western site and final storage) and compares this to data from the original MMES study based on a small plant for Oak Ridge only.

Transportation to a western site and long-term burial costs add significantly to the total costs, from $283 to $432 million (depending on the unit burial cost). These values represent an additional cost of $0.80 to $1.20/kg U above the costs shown in Table 7-5.

The costs shown in the MMES base study (as well as the scaled-up costs of the committee) do not include the "normal" annual charges for a private venture plant, such as depreciation, insurance, taxes, and profit margin.[14] An allowance of 15 percent of the capital cost per year (a low figure) would increase total costs over 20 years by a large amount. For the committee's analysis, the conversion cost over 20 years would become $2,268 million. For the MMES study, based on a 5-year operation, costs would increase to $478 million. Corresponding unit costs are shown in Table 7-6.

These costs represent a simple summation over the lifetimes of the plants (5 and 20 years). Construction costs will occur early in the time period; other costs, including conversion operations, maintenance, and business expenses, will extend over the entire lifetime. A "present value" analysis recognizing the time value of money would show lower costs than those in Table 7-6.

## OPPORTUNITIES FOR COST SAVING

The analysis above has highlighted a number of opportunities to reduce costs for disposition of the $DUF_6$.

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[14] The time-value of money decreases the present value, whereas adding a profit margin increases the present value. These two factors offset each other; that is, the time-value of money is equivalent to the opportunity cost of capital reflected in the profit margin. The committee's approximate analysis makes no allowance for the time-value of money.

TABLE 7-4 Conversion and Waste Management Costs (millions of dollars)

| | **Base Case MMES (35,000 MTU[a]/5 years)** | | | Committee Scaleup (357,133 MTU/20 years) | |
|---|---|---|---|---|---|
| | Base | Contingency | Total | Scaling Factor | Total Cost |
| Storage facility | 0 | | 0 | 0 | |
| Feed and cylinder handling | 17 | 5 | 22 | $(2.55)^{0.6}$ | 38.6 |
| Conversion and waste handing facility | 76 | 30 | 106 | $(2.55)^{0.6}$ | 186.0 |
| Support facility | 11 | 3 | 14 | $(2.55)^{0.6}$ | 24.6 |
| Construction management fee | 17 | 5 | 22 | $(2.55)^{0.6}$ | 38.6 |
| Construction support | 10 | 3 | 13 | $(2.55)^{0.6}$ | 22.8 |
| Program planning | 12 | 4 | 16 | 2 | 32.0 |
| Design and Title III | 15 | 4 | 19 | 1 | 19.0 |
| Total capital in 1991 dollars | | | 212 | | 362.0 |
| Total indexed to 1995 dollars[b] | | | 216 | | 369.0 |
| Declining surveillance and maintenance | | | | | 100.0 |
| Transport to central site | | | | | 30.0 |
| Conversion operations | 36 | 7 | 43 | | 302.0 |
| Plant maintenance @ 5% of feed and cylinder handing; conversion and waste handling facility; and support facility | | | | | 249.0 |
| D&D | 39 | 16 | 55 | | 96.5 |
| Total conversion in 1991 dollars | | | 310 | | 1,139.0 |
| Total indexed to 1995 dollars[b] | | | 316 | | 1,161.0 |
| Transportation to long-term storage | | | | | 127 |
| Long-term storage[c] | | | | | |
| For storage cost of $30/$ft^3$ | | | | | 156.0 |
| For storage cost of $58.70/$ft^3$ | | | | | 305.0 |
| Cost over plant life in 1995 dollars | | | | | |
| For storage cost of $30/$ft^3$ | | | | | 1,444.0 |
| For storage cost of $58.70/$ft^3$ | | | | | 1,593.0 |

[a] MTU is metric tons of uranium.

[b] *Chemical Engineering* plant cost indices; 1991—361.3; 1995—368.3; index factor 368.3/361.3 (McGraw Hill, New York).

[c] Assuming density of 3 g/$cm^3$, resulting in 5.2 million $ft^3$.

TABLE 7-5 Cost Comparison for the Conversion of $DUF_6$ to Oxide ($/kg U)

| | **Estimate** | | | |
|---|---|---|---|---|
| HF Credit | Hetzler et al. (1994)[a] | committee[b] | Cogema | Allied-Signal |
| No HF sale[c] | 8.86 | 3.19 | 4-6 | 4.0 |
| HF sale[d] | | 2.39 | | |

[a] Based on the MMES study (Charles et al., 1991) assumption of converting 35,000 metric tons of uranium in 5 years.

[b] Converting 357,133 metric tons of uranium in 20 years.

[c] No credit for sale of HF.

[d] Assumes $0.25/lb of $DUF_6$ ($0.55/kg $DUF_6$, $0.80/kg U) credit for sale of HF (Rock, 1994).

TABLE 7-6 Comparison of Unit Conversion Costs Including Annual Private Capital Costs ($/kg U)

| | **Assumption** | |
|---|---|---|
| Estimate | No Credit for HF Sale | Credit for Sale of HF |
| MMES | 13.66 | NA |
| Committee scaleup | 6.35 | 5.55 |

Note: Includes annual charge of 15 percent of capital investment.

## Plant Scale

There is a significant unit cost saving by going to a large plant. The conversion plants discussed above are small by conventional chemical plant standards. Although in the preceding analysis the plant size was scaled to handle the DOE legacy material, processing costs could be reduced by sizing a single plant to handle all the $DUF_6$, regardless of origin, that is, to convert both DOE legacy material and $DUF_6$ owned by the USEC. The cost of transporting the latter material to a single conversion site would need to be considered in assessing this option.

## Plant Life

The selection of a 20-year plant life is arbitrary, with no attempt to optimize the choice. An extended schedule would seem desirable for two reasons: the plant investment would be reduced; and the HF production rate would be less disruptive for the market. As noted above, a 20-year conversion operation would produce approximately 2 percent of the estimated North

American market requirements for HF annually. In contrast, a 5-year operation would generate about 8 percent of North American HF requirements each year with resulting repercussions on the market. An appropriate choice of plant size and schedule would reduce conversion costs.

## Uranium Oxide Density

The normal conversion product is $U_3O_8$ of very small particle size (a large fraction less than 10 microns) and low density (3 g/cm$^3$ after compaction). Both properties are undesirable for final storage. Fine material will require special handling and possibly grouting. Low density is costly because unit storage cost is normally quoted in terms of volume stored. The storage costs shown in Table 7-4 of $156 million to $305 million could be reduced by increasing the density.

One method suggested for increasing density is a low-temperature sintering with a small amount of a sintering aid—in effect, a brickmaking process (Quapp, 1995). Work at the Idaho National Engineering Laboratory with cerium oxide has demonstrated densities as high as 90 percent of theoretical density. Application of this approach could achieve $U_3O_8$ densities as high as 6 g/cm$^3$. The costs of the process are believed to be low (on the order of a few cents per kg U), and the additive would result in only small uranium dilution. Storage cost savings of $100 million or more might be possible. Research and development on this or other processes for increasing density could yield significant cost savings.

An effective process for converting $U_3O_8$ to high-density bricks might offer another possible saving: it would yield a very stable product of extremely low radioactivity. Such a product would be a good candidate for on-site or near-site storage if a low-level waste repository near the diffusion plant sites were deemed acceptable.

## HF Production and Marketing

The committee has included in its analysis a small credit for the HF produced (see Table 7-5). The credit shown could be much larger if the material gains general acceptance in the market. Much more important is avoiding the alternative, namely, neutralization with lime and storage of the $CaF_2$ produced as waste, possibly low-level radioactive waste. The additional cost of neutralization (capital and operating costs) scaled from the estimate given by MMES (Charles et al., 1991) is approximately $600 million; the storage cost for the $CaF_2$ could be $800 million. (The storage cost is again scaled from an estimate given by MMES and must be considered approximate, inasmuch as long-term storage costs are uncertain at this time. The figure of $800 million appears to be at the high end of the range.)

These costs for making and storing $CaF_2$ translate to an additional cost for disposal of the $DUF_6$ of approximately $4/kg U. There is therefore a large incentive to avoid such costs by marketing the HF produced instead. The French experience in marketing HF has been excellent, and product purity has been acceptable. It will be important to establish the same level of industrial and public acceptance in the United States.

### Use of Existing Facilities

The MMES study included the construction of new facilities that might not be needed if the diffusion plants are shut down. For example, existing feed and cylinder handling, as well as support facilities such as laboratories or office space, could be used. Eliminating such new facility costs results in significant savings, perhaps $0.20 to $0.50/kg U.

### New Technology

The dry processes currently used for the conversion of $UF_6$ to $U_3O_8$ are basically simple, and major cost reductions appear unlikely. However, process modifications might result in somewhat lower conversion costs. Because the stringent criteria controlling ceramic reactivity and physical properties of nuclear fuels are not appropriate for a material destined for waste storage, some changes from the usual fuel technology might be acceptable. For example, a high-capacity "flame" reactor has been suggested as a slightly less costly alternative to the first stage of the usual two-stage conversion process.[15]

The "densifying" process used to increase $U_3O_8$ density from 1.3 g/cm $^3$ to about 3 g/cm$^3$ might not be necessary if the liquid-phase sintering (brickmaking) process is adopted. There would be a small corresponding savings.

## CONCLUSIONS AND RECOMMENDATIONS

### Conclusions

1. $DUF_6$ is not a suitable form for long-term storage of depleted uranium. Good industrial practice calls for limiting the amount of $DUF_6$ in storage to a much smaller level than that in existence today at the GDPs.
2. Defluorination of $DUF_6$ to uranium oxide ($U_3O_8$) and recyclable HF is the most feasible approach to the liquidation of the large inventory.
3. Opportunities exist to reduce the cost for disposition of the $DUF_6$ inventory by about half compared to the 1991 MMES cost estimate.
4. In the short term, the investment required to convert $DUF_6$ to $U_3O_8$ is significantly greater than the expenditure for continued surveillance and maintenance of the $DUF_6$ inventory. However, continued surveillance and maintenance does not address the need for ultimate conversion of $DUF_6$ to a more stable form.

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[15] A. Schillomuller, General Electric, personal communication to committee members Frank Crimi, Walter May, William Prindle, Alfred Schneider, and Dale Stein, July 7, 1995.

5. The $DUF_6$ storage cylinders have a limited life and will always require surveillance and maintenance. Periodic refurbishment is necessary, and eventual transfer of $DUF_6$ material to new cylinders will be needed.

## Recommendations

1. The DOE plan to evaluate alternative $DUF_6$ management options, with a decision in the second quarter of 1998, should proceed as planned. Any new uses for $DUF_6$ that emerge during this planning period should be pursued if they will reduce the ultimate disposal cost.
2. Unless significant new uses are identified by 1998, the $DUF_6$ inventory should ultimately be converted to the more stable form, $U_3O_8$, for final storage consistent with the prioritized cost- and risk-reduction approach. Conversion should begin with those cylinders in poor condition.
3. The cost of converting $DUF_6$ to $U_3O_8$ should be minimized by an appropriate choice of plant size, plant location, and schedule for conversion operations.
4. A business relationship should be explored with the USEC disposal of their $DUF_6$ along with the DOE legacy material. This arrangement may reduce unit costs for both parties.
5. A modest research and development effort should be conducted to improve the physical properties of the $U_3O_8$ for disposal—in particular, to increase particle size and density.
6. Local long-term storage of $U_3O_8$ at the GDPs should be considered, particularly if the research and development on improved physical properties is successful.

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# 8

# Major Recommendations

Those areas that the committee believes are most important for reducing the costs of the D&D of the GDPs are identified in this chapter. These major recommendations address a variety of approaches for reducing D&D costs relative to previous cost estimates and specific technical demonstrations required, as well as providing broader suggestions for planning, management, and regulatory coordination that should lead to a cost-effective D&D process. Management of the $DUF_6$ (depleted uranium hexafluoride) inventory is also addressed.

The committee's review of the two D&D cost estimates by Ebasco and TLG of $16.1 and $13.9 billion, respectively, identified significant opportunities for cost reduction. The case for lower cost is supported by the actual cost data reported for the BNFL D&D of the Capenhurst GDP in the United Kingdom. That effort cost about $160 million, a hundred times lower than the Ebasco cost estimate (see Chapter 4). Compared to the U.S. GDPs, the Capenhurst plant was much smaller, of somewhat different design, and incorporated some different materials. However, even if the Capenhurst D&D costs are scaled-up to the situation for the U.S. GDPs, these scaled-up costs are a factor of 8 to 15 times less than the cost estimate of $16.1 billion.

There have also been a number of D&D projects conducted in the United States for nuclear power reactors. The D&D of the Shippingport Atomic Power Station, for example, indicated the importance of a streamlined management approach and thorough planning, with a decommissioning plan incorporating a detailed technical baseline, as part of developing a cost estimate and engaging in the actual D&D.

Based on reported D&D costs for the Capenhurst GDP, experience from other D&D projects, and a review of the cost estimates, the committee concluded that there are significant opportunities to reduce the D&D costs of the GDPs. While the magnitude of the potential cost savings is uncertain, it could equal or exceed 50 percent of the current Ebasco estimate of $16.1 billion.

> **Recommendation 1.** The technical and management approaches used successfully for the D&D of the Capenhurst gaseous diffusion plant and for recently completed D&D projects with U.S. power reactors should be carefully considered by the DOE to reduce costs for the D&D of the U.S. GDPs.

## COORDINATED PLANNING

Coordinated planning at the DOE headquarters level, as well as across the complex of the three GDPs and at each site, will all be required to ensure that D&D is integrated effectively with other operating or cleanup activities at the sites and that resources are used effectively. DOE headquarters-level planning would outline decisions on D&D financing, on integration of D&D with other DOE programs; and on the broad contracting, regulatory, and stakeholder involvement approaches for D&D. A complex-level master plan for the three-plant enrichment complex as a whole would coordinate such decisions as the sequence of plant cleanup, the priority actions to be taken, allocation of funds among the sites, and cleanup strategies, including approaches to waste management and recycling. Priority setting would be based on analysis of relative risks, costs, and social values. Site-specific plans are also needed to coordinate D&D, environmental remediation efforts, and management of the $DUF_6$ inventory at each of the three sites. For example, it would be costly if previously cleaned areas of soil and the groundwater were recontaminated during D&D operations. For the Oak Ridge GDP, the site plan should be coordinated with the plans for the whole Oak Ridge Reservation. It was not clear to the committee that the idea of cleaning the areas that the buildings occupy to greenfield status makes much sense if other parts of the sites remain contaminated or if $DUF_6$ continues to be stored on site.

Coordinated planning efforts are also called for by budgetary uncertainties. If planned contributions to the D&D Fund continue, a total of about $7.2 billion will accrue. The fiscal year contributions to the fund limit the rate at which D&D could be accomplished. Since the inception of the fund, most of the projects funded have been for environmental remediation. This funding allocation may be driven by the priority given to such important problems as remediation of waste ponds or contaminated soil or groundwater. If such a spending profile persists, however, and better controls on the fund are not established, funding may not be available for D&D of the GDPs.

A detailed D&D plan, which the committee believes should not take more than 18 to 24 months to prepare, needs to be developed delineating the sequence of activities necessary to incrementally achieve the D&D of the facilities. The sequence of tasks should be based on considerations of cost and risk. Uncertainty regarding the final end state should not delay the development of an initial D&D plan, which would be refined as circumstances change. The decommissioning plan should incorporate all major assumptions (technical, cost, and institutional), a proposed management organizational structure for both DOE and the decommissioning operations contractor, tradeoff studies for determining an optimized decommissioning sequence, a detailed work breakdown structure, and a detailed cost estimate and schedule. The detailed work breakdown structure would specify, for example, the sequence of steps required to remove the equipment, decontaminate the equipment and buildings, demolish the buildings, recycle material, and dispose of wastes. A new cost estimate would be derived from the detailed D&D plan and used as a basis for soliciting competitive bids from the private sector for execution of the work; a competitive bidding process would be the most likely process to identify cost-effective approaches.

**Recommendation 2.** DOE should develop three plans, namely, headquarters-level, GDP complex-level, and GDP site-level, that address and integrate the

D&D of the facilities, environmental remediation activities, and management of the $DUF_6$.

## CONTRACTING AND MANAGEMENT

Although the committee's analysis indicates that D&D could be accomplished much more cost effectively, the cost savings may not be achieved without a significant change in the management and contracting approach through which DOE oversees and conducts project planning and execution. DOE has traditionally managed its major projects at operating (or formerly operating) sites using an M&O (management and operating) contractor. This management approach, which was assumed in the Ebasco estimate, includes multiple layers of management and results in an unnecessarily high ratio of the cost of management and professional services to the cost of execution of the physical decommissioning. This approach is inherently more expensive than that used in the Capenhurst D&D and in other private sector D&D projects. Large reductions in D&D project costs are unlikely to be achieved under the currently proposed project management approach using multiple prime contractors. Experience on other DOE projects demonstrates conclusively that this concept results in much higher costs relative to projects managed by other government agencies and the private sector.

A more cost-effective approach would be to use a management structure employing an independent decommissioning contractor, who would assume total responsibility and accountability for all aspects of the D&D. For example, a DOC (decommissioning operations contractor) approach was used for the Shippingport D&D effort. Such a contractor would be selected through an open competitive bidding process based on demonstrated experience in successful management of D&D projects. Improvements in the cost effectiveness of projects could be achieved by incorporating financial incentives in contracts to the DOC and to all subcontractors. As part of the process of reducing costs, every aspect of the D&D effort needs to be examined closely to identify the most cost-effective alternatives for accomplishing each task and to eliminate redundant and excessive management oversight, while complying with health, safety, and environmental protection requirements.

**Recommendation 3.** An independent contractor should be selected through open competition and should be assigned total responsibility and accountability for all aspects of the assigned D&D work.

## PRIORITIZED COST AND RISK REDUCTION

Currently, there is no quantitative risk analysis of the nonoperating plant at Oak Ridge. The committee believes that, because people living near the enrichment plant sites are not exposed to the contaminants within the buildings, the near-term risk to the public is quite low. Although uranium is radioactive, its primary risk to human health is its chemical hazard upon ingestion or inhalation. Uranium in the buildings is contained, for the most part, inside process equipment and does not present a hazard. However, the deposits of highly enriched uranium require a safeguards and security regime to be maintained. The vast majority of the uranium at the GDP sites is in the $DUF_6$: a major release of $DUF_6$ is a very unlikely event. For such a large cylinder rupture, the HF (hydrogen fluoride) concentrations at the site boundary would depend on atmospheric conditions. Very low concentrations of HF below hazardous levels are odorous, presenting a warning to on-site employees; however, a rapidly moving cloud of HF from a short-term, large release could potentially engulf on-site employees under certain conditions. The primary risk during D&D will be worker risk, not only from possible chemical or radioactive contamination but from industrial accidents. Minimizing such risks will require strict adherence to adequate worker health and safety protection. Efforts to reduce D&D costs cannot come at the expense of protecting workers, public health, or safety.

Moving forward expeditiously with the planning and execution of D&D is important for a number of reasons. In the event of delays in D&D, annual surveillance and maintenance costs will lead to substantial expenditures. With time, deterioration of the buildings can exacerbate these costs, and risks to individuals will increase. The risk posed to the workers, the public, and the environment by the present situation may not be large, but it will probably increase with time. The continued presence of highly enriched uranium entails an expensive security and safeguards regime. Furthermore, as noted above, there are uncertainties about the future availability of funds for D&D.

Planning for D&D does not imply that no cleanup is achieved until a plan is finalized. Developing an adequate and robust D&D strategy, detailed plan, and cost estimate will take time. Uncertainties over final decisions, such as site release criteria, end uses of the sites, free-release criteria for cleaned materials, and location of low-level radioactive waste sites, must be considered in developing plans and estimated costs. The D&D of the three sites could very well occur over a period of several decades, and political priorities and budget commitments may also change over that time.

Because of these uncertainties, the committee proposes that a prioritized cost- and risk-reduction approach be taken. Such an approach identifies conditions at the sites that, if not quickly remediated, could lead to increased risks or costs as a result of delay. For example, it appears to the committee that the removal of the deposits of highly enriched uranium from the Oak Ridge process equipment should be a first priority. This approach would reduce the costs of enforcing safeguards and security and reduce the risk of nuclear criticality accidents. The optimal sequence of D&D actions will be decided during the detailed decommissioning planning and cost estimation process. A prioritized cost- and risk-reduction approach allows initiating D&D operations during the planning process by identifying priorities for immediate cleanup. It also allows scheduling of projects within the detailed D&D work plan that will minimize risks and costs to workers and the public and increase the likelihood that D&D efforts will be accomplished given the uncertainty about future available funds. A prioritized cost- and risk-reduction approach should be flexible and should not preclude alternative end states. Such an approach could embody a stepwise, detailed decommissioning plan as a means of sequentially and incrementally achieving the D&D.

> **Recommendation 4.** A prioritized cost- and risk-reduction approach should be used as the basis for developing the D&D plan. This approach should be used to accomplish D&D activities prior to the completion of the entire plan.

## REGULATORY COORDINATION

There are numerous laws and regulations, as well as regulatory bodies at federal, state, and local levels, that will affect D&D. The health and safety of the workforce, as well as the potential impacts on the local community, need to be addressed. Guidelines for decommissioning have been published by the Nuclear Regulatory Commission and DOE. Cooperative efforts to revise them on the basis of current radiation protection concepts are under way by the EPA, DOE, and the Nuclear Regulatory Commission. Available draft proposals have radionuclide concentrations equivalent to annual dose equivalents of 15 mrem per year, based on generic exposure scenarios, for the release of sites and materials. The agencies recommend that each exposure scenario be evaluated for a specific site. The large number of regulators with jurisdiction over the enrichment plants and their decontamination, as well as the large number of applicable laws and regulations, virtually ensure an overlapping, conflicting, and potentially costly regulatory regime under which to conduct D&D.

> **Recommendation 5**. The committee recommends that DOE seek coordination of all regulatory aspects of D&D with the appropriate state and federal agencies early in planning to provide consistency during D&D planning and execution.

## STAKEHOLDER INVOLVEMENT

Site planning and the associated planning for D&D of the buildings should be undertaken in consultation with the stakeholders. This process of communication among various interested parties—public groups, regulators, workers, and DOE—and DOE decision makers should start at the very beginning of planning. For example, a consensus-building process would elicit public advice on the incremental cost- and risk-reduction approach and on the desired end states of the sites, taking into account costs, risks, and social values. Given the contentious issues that have emerged relating to many sites in the DOE weapons complex as a result of past practices, it is essential that a credible and meaningful stakeholder and public involvement process be implemented that ensures smooth planning and implementation of D&D. Increased attention to stakeholders and the public concerning D&D at the three GDP sites can further result in decisions that enjoy wide public acceptance, reduce conflicts among stakeholders and citizens, and minimize costly delays. Effective efforts to integrate the multiplicity of citizen and stakeholder interests are needed to provide meaningful inputs to decision making on such issues as health and safety, budgets, employment, and end states.

> **Recommendation 6**. A stakeholder involvement program should be pursued to obtain timely and substantive public participation and input to ensure that social values are reflected in policy decisions.

## WASTE MANAGEMENT

Waste management is a major cost factor. Large quantities of low-level radioactive waste, hazardous waste, and mixed waste will result from the D&D and will require processing, packaging, transportation, and disposal. Although low-level radioactive waste burial costs are uncertain, recent experience indicates that storage capacity is very limited, costs are increasing rapidly, and some sites are closing. Even if disposal costs are low, the long-lived radioactivity of uranium requires monitoring over millennia or permanent, safe disposal. Opposition to the proposed transportation and disposal of the very large volumes of low-level radioactive waste is likely. These concerns suggest that a strategy of waste minimization should be pursued. The location of the waste disposal sites and the likely cost of waste transportation and disposal need to be resolved.

Generation of mixed waste during D&D should be avoided because its processing and disposal entail a complex and costly regulatory regime. Improperly planned D&D operations could also contaminate otherwise clean material, for example, during asbestos removal operations, or areas around the buildings during D&D operations. Creation of secondary waste streams, such as contaminated water from decontamination processes, should be minimized. Improper management of discarded clothing and protective gear can also generate significant quantities of low-level radioactive waste.

One approach to waste minimization is to decontaminate materials for reuse. For example, concrete might be used for road fill (as was done at Capenhurst), and the large quantities of copper, nickel, and steel could be cleaned to surface release standards and recycled. Metal difficult to decontaminate might be compacted for low-level radioactive waste disposal. The geometric shape of some of the components, such as the diffusion barriers, would make it difficult to ascertain whether adequate decontamination has been achieved. These materials might be melt refined, but release of the subsequent metal would require volumetric standards for free-release of melted metal. Such standards do not currently exist in the United States, although the EPA and Nuclear Regulation Commission have begun preliminary work on surface and volume contamination standards. The cost of low-level radioactive waste burial and the market price of particular materials could economically justify the recycling of those materials to the commercial sector and reduce D&D costs significantly.

In the event that cleaned metals cannot be released to the commercial sector, they might be cleaned to standards adequate for controlled use within the DOE complex. For example, steel might be used for shield blocks or for radioactive waste canisters. The avoided environmental and economic cost of producing such materials from virgin ore would have to be balanced against the costs of recycling and the avoided costs of burial. If material could not be cleaned sufficiently for recycling to the commercial sector, the DOE complex, or the Department of Defense, it would have to be packaged, transported, and placed in low-level radioactive waste disposal facilities. Considering the large costs of low-level radioactive waste management, there are significant opportunities to optimize waste packaging and transportation to achieve cost savings.

The committee notes that radioactive, hazardous, and mixed wastes from other activities on the Oak Ridge Reservation are being temporarily stored within the GDP process buildings. This practice complicates, and could delay subsequent D&D efforts and could also engender costs during D&D that should not be ascribed to the D&D program.

> **Recommendation 7**. An integrated, optimized waste management plan must be developed that encompasses material reuse, recycling, packaging, transport, and

> waste disposal. Consistent with cost reduction and public health and environmental protection, materials should be cleaned to free-release standards and released to the commercial sector for recycling. Material that cannot be cleaned to free-release standards should be considered for recycling within the DOE or Department of Defense complexes in applications where slightly contaminated materials are acceptable, such as for shield blocks or waste containers.

## NEED FOR NEW FACILITIES

Previous cost estimates assume that large, expensive facilities will be required to decontaminate the process equipment, systems, and structures. A high-assay decontamination facility was proposed to decontaminate equipment containing highly enriched uranium deposits, and a low-assay decontamination facility was proposed to decontaminate equipment containing low-enriched uranium deposits. Decontamination techniques to be used in these facilities included mechanical removal, $ClF_3$ (gaseous chlorine trifluoride) treatment, and high-pressure water jets. Metal parts that were difficult to decontaminate would be melted. The variety of technologies and capabilities, as well as the large size of the decontamination facilities, led to very high estimated capital and operating costs.

The committee believes that the decontamination processes in these facilities could be simplified. The need for a new, expensive high-assay decontamination facility could be eliminated by constructing small, limited-purpose shops for removal of highly enriched uranium and housing equipment in existing buildings. Low-assay decontamination could also be housed in existing buildings. Removal of uranium deposits could be accomplished in a number of ways, such as by gaseous decontamination or spray booths, using aqueous solutions and incorporating criticality safe piping, or mechanically. The approach taken would depend on criticality considerations and on a number of factors, such as enrichment level, size of deposits, and cost. After deposit removal, aqueous decontamination with criticality control could be used, as it was successfully for the D&D of the Capenhurst GDP. Selection of the best uranium removal and decontamination technologies and sequence will require systems engineering and cost tradeoff studies along with data from focused technology demonstrations, as discussed below. Simplification of the process and the use of existing buildings would reduce costs.

> **Recommendation 8**. The high-assay decontamination facility should be eliminated; the low-assay decontamination facility should be simplified to focus primarily on aqueous decontamination and should be housed in existing buildings.

The cost estimates assumed the construction of a new administration building at the Oak Ridge GDP site, with space for several thousand people. Such large staffs are a result of the management and contracting approach assumed in the cost estimates. The committee believes that existing space could be modified to provide appropriate office space for administrative functions, especially if the committee's recommended changes in management and contracting are implemented, which should reduce the size of the management and professional staff.

> **Recommendation 9**. Rather than constructing a new administration building, existing facilities should be used to house the management and professional D&D staff.

## D&D TECHNOLOGY ISSUES

Proven technologies are available for the D&D of the GDPs. These technologies include technologies for characterization, disassembly, removal of uranium deposits from the process equipment, decontamination of the process equipment and buildings, melt refining and recycling of metals, and treatment of wastes. However, there are some uncertainties about technical effectiveness, such as the degree to which certain technologies can remove $^{99}$Tc (technetium-99) or decontaminate to required levels, and about what degree of cost savings can be achieved. Determining answers to such questions would require focused demonstrations, not major research and development programs. Such focused demonstration efforts on currently available technologies would help D&D planners select the most appropriate technologies based on considerations of cost, environmental protection, performance, and safety.

The GDP plants are major structures with extensive floor and wall areas, containing large pieces of equipment in a repetitive design arrangement. The committee believes that there are opportunities for automation and robotics in many of the repetitive operations involved in removal and transfer of equipment, size reduction of equipment components, and decontamination process operations. Such opportunities could reduce costs and reduce worker exposure to radiation and hazardous substances. The large areas within the buildings encourage automated characterization.

After treatment of the process equipment with gaseous $ClF_3$, BNFL used aqueous processes at Capenhurst to decontaminate the cascade equipment. There are some uncertainties about the aqueous process, such as the degree to which $^{99}$Tc contamination can be removed. Furthermore, it is not clear that the physical characteristics of the diffusion barrier material, which contains much of the valuable nickel, will allow decontamination to free-release levels by aqueous decontamination. The most effective approach for this material may be melt refining, with the uranium removed in the slag. The best approach for $^{99}$Tc removal is uncertain.

A few, highly focused demonstration programs are needed. By demonstration program, the committee does not mean very large programs involving costly expenditures over many years. Technical and cost effectiveness should be demonstrated at a sufficient scale to allow scaleup of data to actual D&D operations. Much of the decontamination work can probably take place in the laboratory; demonstration of robotic systems may need to take place at a larger scale, such as in the plants.

The most appropriate approach to resolve the technical and cost uncertainties may be to conduct small demonstrations of different decontamination technologies for treatment of a stage or cell from the cascade to obtain required data on operating and decontamination factors. Based on these data, a decontamination process should be chosen and applied to the high-enrichment sections of the cascade. During the early stages of these D&D operations, careful record-keeping, data collection, and analysis should be conducted to serve as a basis for future D&D activities.

> **Recommendation 10**. A few highly focused D&D demonstrations should be undertaken to verify the cost and effectiveness of specific technologies, including the following two:

- optimization of aqueous decontamination to remove radioactive surface contamination from materials and process equipment, with special attention to $^{99}$Tc; and
- support of current DOE robotics programs, with highly focused demonstrations to verify potential cost savings and safety benefits.

> **Recommendation 11**. A modest research program should be established to develop methods to decontaminate the diffusion barrier material effectively.

## SAFEGUARDS AND SECURITY

The assumption was made in the Ebasco cost estimate that the gaseous diffusion technology would be declassified prior to D&D. Costs will be larger if the diffusion barrier remains classified and the D&D has to be carried out in a "secure" environment. Furthermore, the D&D of the GDPs will require the handling of special nuclear materials. The regulatory requirements to safeguard these materials entail significant costs. These costs could be reduced significantly if less-stringent requirements could be applied. For example, special nuclear material should be removed from the high-enrichment sections of the cascade prior to the start of large-scale D&D operations so that safeguards and security requirements can be relaxed.

> **Recommendation 12**. To reduce costs without compromising information security for the gaseous diffusion technology, DOE should try to define physical security requirements that allow uncleared workers under adequate supervision to conduct D&D operations. In addition, DOE should conduct an in-depth evaluation of the safeguards and security requirements during D&D to determine how their impact on D&D cost could be reduced.

## DUF$_6$

A DOE study has found that past practices for storage of DUF$_6$ have been inadequate in several respects. There have been no serious consequences, however, and there is a vigorous program to correct past deficiencies.

There is general agreement, however, that DUF$_6$ is an unsuitable chemical form for long-term storage; it is too reactive and too volatile. Eventually DUF$_6$ needs to be converted to the more suitable form uranium oxide ($U_3O_8$). No large-scale uses for the DUF$_6$ have been identified, and the most promising potential uses do not preclude conversion to oxide.

Estimates prepared for DOE indicate that costs for the conversion of DUF$_6$ to $U_3O_8$ will be high, over $2 billion. It should be possible to realize cost savings by optimizing a number of factors, such as plant size and the conversion schedule. Conversion processes are conventionally used in the nuclear fuel industry, and several alternatives are known. The processes are rather simple, so that large cost reductions through new technology do not appear likely. Considering cost, risk and social values, the most attractive of the known processes can be chosen.

Significant savings in the costs of long-term storage should be possible by improving the physical properties of the $U_3O_8$; in particular, increased particle size and much higher packing density should be possible, which would reduce storage costs based on volumetric fees. This area promises benefits from a limited research and development program.

> **Recommendation 13**. The committee recommends that, if consistent with the prioritized cost- and risk-reduction process, the $DUF_6$ should be converted to the more stable chemical form, $U_3O_8$, for storage or disposal.

# Appendices

# Appendix A

# Statement of Task

The committee will provide independent scientific and technical advice to the U.S. Department of Energy (DOE) consistent with the requirements of the Energy Policy Act of 1992 to conduct a study and provide recommendations for reducing costs associated with the decontamination and decommissioning (D&D) of the uranium enrichment facilities at Oak Ridge, Tennessee; Paducah, Kentucky; and Portsmouth, Ohio. As part of the study, the committee will also assess options for the disposition of depleted uranium hexafluoride held in storage by DOE, but will not assess remedial actions at areas outside of the major buildings and structures at any of the three sites. In the course of its work, the committee will:

- Hold a series of meetings, including a workshop, to receive briefings, obtain information, consider different D&D approaches, conduct analyses, deliberate on findings and issues, and write its final report.
- Review two recent D&D cost studies conducted for the DOE by Ebasco Services, Inc., and TLG Engineering, Inc., including D&D requirements and system level assumptions underlying the cost estimates, and examine D&D options and technologies for the three sites. Review the cost study performed by Martin Marietta Energy Systems on the disposition of depleted uranium hexafluoride generated at the gaseous diffusion plants.
- Seek inputs from the operators of the uranium enrichment facilities, the Congress, the General Accounting Office, the Office of Technology Assessment, executive branch agencies including the Office of Science and Technology Policy (OSTP), the Office of Management and Budget (OMB), the Environmental Protection Agency (EPA), the Nuclear Regulatory Commission, and other interested organizations, and from other countries where relevant D&D activities have been undertaken.
- Review case studies drawn from the D&D of other facilities in the United States and elsewhere. Conduct site visits, examine surveys of facility contaminations (performed by DOE and its contractors), and hold meetings at all three uranium enrichment sites preparatory to evaluating the scientific and engineering knowledge base on which it can make recommendations to the DOE.

- Identify, screen, and evaluate alternative technologies relevant to the D&D and assess the costs and benefits of alternative cleanup methods considering waste containment technologies versus waste destruction technologies as they apply to the various sites. In relation to risks to human health and the environment, examine the potential for reduced D&D costs from federal investments in research and development on new cleanup technologies, and recovery and recycling of radioactively contaminated materials.

# Appendix B

# The Committee's Panel Structure and Panel Statement of Tasks

At its first meeting, February 3–4, 1994, the committee divided itself into three panels (see Table B-1). The panels were each assigned different tasks that, taken together, addressed the committee's full statement of task. The panels operated from the first committee meeting until January 30, 1995, each providing written material that was used as a basis for the committee's report. The panels met separately from the full committee as required, often coordinating their meetings with full committee meetings (see Appendix C). The committee Chair, Dale Stein, and Vice-Chair, Gregory Choppin, provided guidance to all three panels.

The Decision and Process Analysis Panel was staffed by Tracy Wilson, Board on Energy and Environmental Systems (BEES); the Technology Panel was staffed by Douglas Raber, Board on Chemical Sciences and Technology (BCST), Scott Weidman of BCST, and Jill Wilson of BEES; and the Cost Analysis Panel was staffed by Karyanil Thomas, Board on Radioactive Waste Management. James Zucchetto, Study Director, worked with the panels as necessary and, together with Jill Wilson and Tracy Wilson, worked with the committee to produce its final report. Dev Mani, Director of BEES, and Richard Meserve, Vice-Chair of BEES, provided board oversight for the entire study.

TABLE B-1 Committee Panels and Membership

| **Decision and Process Analysis** | Technology | Cost Analysis |
|---|---|---|
| Elisabeth Pate-Cornell[a] | William Prindle[a] | Frank Crimi[a] |
| Eula Bingham | Joseph Byrd | Charles Kimm |
| Joel Cehn | Robert Connick | Peter Lederman |
| Philip Clark | Bernd Kahn | Geoffrey Rothwell |
| Wolter Fabrycky | Peter Lederman | Ray Sandberg |
| Robert Fjeld | Walter May | Richard Smith |
| Alvin Mushkatel | Alfred Schneider | |
| Carolyn Raffensperger | | |

[a] Panel chair

The statement of tasks formulated by the committee for the panels are discussed below.

## Decision And Process Analysis Panel

The Decision and Process Analysis Panel will develop a framework for the decontamination and decommissioning (D&D) of the gaseous diffusion plants (GDPs) and will address the following subjects:

- initial conditions of the three sites;
- regulatory issues;
- public and stakeholder involvement;
- risks to plant workers, the public, and the environment; and
- end points and decision criteria/analysis.

## Technology Panel

The Technology Panel will identify and evaluate technical processes of importance to the D&D of the GDPs and the stockpile of depleted uranium hexafluoride ($DUF_6$). Its investigation will include the following:

- determination of the types and levels of contamination present;
- evaluation of technologies for the removal, collection, and disposal of radioactive, chemical, and mixed wastes (using both domestic and foreign experience);
- identification of new and emerging technologies for monitoring and characterization of both radioactive and chemical contamination and research and development directions that may allow cost reductions;
- evaluation of technologies that aid the disassembly of plant equipment and buildings; and
- assessment of safety issues (chemical, radiation, and nuclear) associated with decontamination and disassembly.

The panel will study these issues as they relate to the D&D of GDPs:

- removal of deposits;
- secondary decontamination;

- procedures for shutdown and disassembly of operating plants;
- enriched uranium and other radioisotopes;
- recycling of metals and other materials;
- asbestos, including its possible contamination with uranium;
- polychlorinated biphenyls (PCBs);
- perfluorocarbons; and
- decontamination of surfaces (concrete, steel, etc.).

For the $DUF_6$, the panel will consider two areas:

- storage options and hazards; and
- conversion and subsequent disposition options.

### Cost Analysis Panel

The Cost Analysis Panel will undertake the following:

- Review U.S. Department of Energy D&D cost estimates conducted by Ebasco Environmental, TLG Engineering, Martin Marietta Energy Systems, and others, including the statements of work, methodology, and assumptions.
- Identify the major cost drivers for each study.
- Examine the implications of new criteria and assumptions for these cost estimates.
- Examine the costs and benefits of different options for D&D.
- Develop guidelines and requirements for a new cost estimate.

Other activities will include review of costs incurred on completed D&D projects. Alternative approaches to effect reductions in cost will be examined.

# Appendix C

# Committee Meetings and Activities

**1. Committee Meeting, February 3–4, 1994, Oak Ridge Associated Universities, Pollard Auditorium, and Site Visit to Oak Ridge Uranium Enrichment Facility, Oak Ridge, Tennessee**

The following presentations were made:

At the Oak Ridge Site:

(a) Gaseous Diffusion Plant Overview, William D. Adams, Assistant Manager for Environmental Restoration and Waste Management (ERWM), Oak Ridge Operations Office, U.S. Department of Energy (DOE); and Thomas Tison, K-25 Site Manager, Oak Ridge Operations Office, DOE
(b) K-33 Demo Cell Tour and K-25, Northeast End, Richard Faulkner, Senior Staff Support, K-25 Site, Martin Marietta Energy Systems (MMES)

At Oak Ridge Associated Universities Meeting Room:

(c) Need for the D&D of the Uranium Enrichment Facilities, Roger Patrick (Pat) Whitfield, Deputy Assistant Secretary, Office for Environmental Restoration, DOE
(d) Current Plans and Approach to the D&D, Robert C. Sleeman, Director, Environmental Restoration Division, Oak Ridge Operations Office, DOE
(e) Highlights of DOE's Cost Studies for the D&D, J. Gary Cusack, Vice President and Program Director, Enserch Environmental (Subsidiary of Ebasco)
(f) Disposition of Depleted Uranium Hexafluoride, Joseph Parks, Acting Assistant Manager for Uranium Enrichment, Oak Ridge Operations, DOE
(g) DOE's Expectations of the Study, Roger Patrick (Pat) Whitfield, Deputy Assistant Secretary, Office for Environmental Restoration, DOE

Other DOE representatives in attendance and offering responses to committee questions were the following:

M. Judson Lilly III, D&D Program Manager, Oak Ridge Program Division, Environmental Restoration and Waste Management, DOE

William Daily, Branch Chief, Enrichment Facilities, Oak Ridge Program Division, DOE

Arnold Guevara, Remedial Action Program, Oak Ridge Program Division, DOE

Frank T. Cionek, Jr., Belfort Engineering & Environmental Services (DOE Contractor)

Bill Adams, Assistant Manager for Environmental Restoration and Waste Management, Oak Ridge Operations Office, DOE

Jane Powell, D&D Program Manager, Oak Ridge Operations Office, DOE

Richard Dye, General Engineer, Office of Planning and Development, DOE

**2. Committee Meeting, March 28–29, 1994, National Academy of Sciences, Cecil and Ida Green Building, Washington, D.C.**

The following presentations were made:

(a) The D&D of the Capendhurst Facility, J.R. Cross and David Clements, British Nuclear Fuels
(b) The Ebasco Cost Study of the D&D of the Uranium Enrichment Facilities, Bob Lenyk, Deputy Program Director, ERWM, Enserch Environmental
(c) Nuclear Regulatory Commission Discussion of Site Endpoints: Draft of D&D Guidance, Robert Meck, Leader, Environmental Policy Section, Office of Nuclear Regulatory Research, Nuclear Regulatory Commission

**3. Committee Meeting and D&D Workship, June 15–17, 1994, National Academy of Sciences, Cecil and Ida Green Building, Washington, D.C.**

The following presentations were made:

June 15, Morning:

Plenary Session

(a) Overview of DOE's Cleanup Program, RADM Richard J. Guimond, Principal Deputy Assistant Secretary for Environmental Management, DOE
(b) Review of the Ebasco Cost Estimate and Draft Program Planning, Alex Murray, SAIC
(c) TLG Preliminary Cost Estimate, Gary Guasco, TLG Services
(d) DOE's Current Plans for D&D of the Gaseous Diffusion Plant Sites, Jane Powell, Oak Ridge Operations Office, DOE
(e) Site Characterization, Richard Faulkner, MMES
(f) Overview of Gaseous Decontamination, Marty Steindler, Argonne National Laboratory (Retired)

June 15, Afternoon:

Focus Session 1: Technology of External Surface Characterization, Monitoring and Gaseous Decontamination [Technology Panel]

(g) Large-Scale Surface Characterization and Monitoring, Bradley Richardson, Oak Ridge National Laboratory; Martin Edelson, Ames Laboratory. Participants: Roger Anderson, Farragut, Tennessee; Jim Berger, Oak Ridge Institute for Science and Education

(h) Gaseous Decontamination, Marty Steindler, Argonne National Laboratory (Retired). Participants: Roger Anderson, Farragut, Tennessee; John Hewes, Allied Signal; Richard Vogel, Calabasas, California

Focus Session 2: Management Issues and Cost Estimates [Cost Analysis Panel]

(i) Management Issues and Cost Estimates. Participants: Gary Guasco, TLG Services; Bob Lenyk, Enserch Environmental; Alex Murray, SAIC; Gary Person, MMES; Jane Powell, Oak Ridge Operations Office, DOE; Blynn Prince, MMES

(j) Contracting and Procurement, Allen Mynatt, Oak Ridge Operations Office, DOE

Focus Session 3: Physical and Environmental Conditions of the Sites [Decision and Process Analysis Panel]

(k) Physical and Environmental Conditions of the Sites. Participants: James Cross, British Nuclear Fuels; Norman Lacy, Burns & Roe Company; Joe Adler, TLG Services; Ray Foley, Oak Ridge National Laboratories; Bob Lenyk, Enserch Environmental

(l) Physical and Environmental Conditions of the Sites. Discussion with Richard Faulkner, MMES

(m) Portsmouth and Paducah Contamination Data. Portsmouth: Richard Meehan, DOE; and William Lemmon and John G. Crawford, MMES. Paducah: Steve Davis, MMES

June 16, Morning:

Plenary Session

(n) Shippingport D&D Experience, Frank Crimi, Committee Member

(o) Formerly Utilized Uranium Sites, Gale Hovey, Bechtel Savannah River

(p) Babcock & Wilcox's Apollo Fuel Fabrication Cleanup: Lessons Learned, James Barrett and Richard Kingsley, Babcock & Wilcox Nuclear Environmental Services

(q) Regulatory Aspects of D&D, Barbara Hostage and Peter Tsirigotis, Environmental Protection Agency (EPA)

(r) Regulatory Aspects for Recycled Materials, John MacKinney, EPA

(s) Barriers to Use of Decontaminated Materials, Gordon Geiger, Minneapolis, Minnesota

June 16, Afternoon:

Focus Session 4: Aqueous Decontamination and Melting Technology

(t) Aqueous Decontamination, Roger Anderson, Farragut, Tennessee. Participants: Martin Steindler, Argonne National Laboratory (Retired); Rajid Kohli, Battelle Memorial Institute [Technology and Cost Analysis Panels]

(u) Efficacy of Melting Technologies for Decontamination, Christopher J. Nagel, Molten Metal Technology. Participants: Richard Fruehan, Carnegie-Mellon University; Ed Joyce, Los Alamos National Laboratory; Gordon Geiger, Minneapolis, Minnesota [Technology Panel]

Focus Session 5: Cost Implications of Gaseous Decontamination Technology [Cost Analysis Panel]

(v) Cost Implications of Gaseous Decontamination Technology, Roy Bundy, MMES. Participants: Marty Steindler, Argonne National Laboratory (Retired); Roger Anderson, Farragut, Tennessee

Focus Session 6: Regulatory Issues and Risk Analysis [Decision and Process Analysis Panel]

(w) Regulatory Issues and Risk Analysis. Participants: Bruce Clemens, University of Tennessee; Judd Lilly, DOE; Scott Dam, British Nuclear Fuels; Norman Lacy, Burns & Roe Company; Gary Guasco, TLG Services; Bob Lenyk, Enserch Environmental; Kate Probst, Resources for the Future, Bob Meck, Nuclear Regulatory Commission

(x) Regulatory Issues and Risk Analysis, Peter Tsirigotis and John MacKinney, EPA

(y) Programmatic Environmental Impact Statement Presentation for the Overall Environmental Management Program, D&D Program at K-25, Portsmouth and Paducah, Curtis Travis, MMES

**4. Committee Meeting, Portsmouth Site Visit, August 22–24, 1994, Radisson Airport Hotel and Conference Center, Columbus, Ohio**

The following presentations were made:

At the Portsmouth site visit:

(a) Site Tour of Plant Exterior and Plant Buildings (on bus), Richard Meehan, DOE; and William Lemmon and John G. Crawford, MMES

(b) Introduction, Eugene Gillespie, DOE

(c) Plant Overview:

(1) Video Presentation and Differences between K-25 and Paducah, William Lemmon, MMES

(2) Future Status and Operations and USEC [U.S. Enrichment Corporation] Involvement in D&D, Lee Fink, USEC
(3) Ohio Environmental Protection Agency Compliance Status of $UF_6$ [Uranium Hexafluoride] Storage, Richard Snyder, MMES

(d) Highly Enriched Uranium Suspension (shutdown procedures, contamination levels, and results of ongoing gaseous decontamination work), Jack Crawford, Martin Marietta Utility Services (MMUS)
(e) Cascade Improvement and Upgrading Program of the 1970–80s, William Lemmon, MMES
(f) Potential Decontamination Technologies, Dave Netzer, MMUS; Ron Parnell, MMES
(g) Current Routine Maintenance and Equipment Decontamination, Dave Netzer, MMUS; Ron Parnell, MMES
(h) Hazardous Materials Overview (Plant Contamination Overview):

(1) PCBs and Asbestos, Pamela Sperling, MMES
(2) Chemical Inventory—Plant and Laboratory, William Lemmon, MMES
(3) CFCs, Bob Winegar, MMUS
(4) Spills at the Plant Site, Dick Snyder, MMES

(i) Radiological Overview:

(1) Health Physics Surveys and Site Characterization, Gary Medukas, MMUS
(2) Technetium, Dave Netzer, MMUS

(j) Portsmouth Stakeholder Involvement Program, Sandy Childers, Portsmouth Community Relations Supervisor, SAIC

In Meeting Room at Radisson Airport Hotel and Conference Center, Columbus, Ohio:

(k) DOE Plans for $UF_6$ Disposition, Carl Cooley, Senior Technical Advisor, Office of Environmental Management (EM-50), DOE Headquarters
(1) Organizational Structure and Schedules for the D&D of the GDPs, Mike Jugan, D&D Program Manager, Oak Ridge Operations, DOE
(m) Status of the D&D Fund, Judy Fulner, Financial Analyst, Office of Environmental Restoration, DOE
(n) DOE Waste Management Plans and Costs for D&D, William Cahill, Environmental Restoration and Waste Management Coordinator, Oak Ridge Operations Office (EW-913), DOE
(o) DOE Stakeholder Involvement Program, Don Beck, Deputy Director, DOE Office of Public Accountability, DOE Headquarters

Panel Breakout Meetings:
Decision and Process Analysis Panel
Short briefings and roundtable discussion with leaders of other stakeholder groups:

(p) Fernald Citizen's Task Force, Tom Wagner
(q) Fernald Residents for Environment, Safety and Health (FRESH), Lisa Crawford, President

(r) Rocky Flats Citizens Advisory Board, Kathryn Johnson, Secretary
(s) Hanford Advisory Board, Sue Gould, President
(t) Pike County Citizens, Marilyn Knicely
(u) Oak Ridge Local Oversight Committee, Amy McCabe, Executive Director
(v) Portsmouth Residents for Safety and Security (PRESS), Vina Colley
(w) Oil, Chemical, and Atomic Workers Union, Portsmouth Local, Mike Neal and Jeannie Cisco
(x) Ohio Attorney General's Office, Jack Van Kley, Assistant Attorney General, Chief, Environmental Enforcement Section

Technology Panel

(y) $UF_6$ briefings, Sanford Rock, Director of Nuclear Services, Allied Signal, Morristown, New Jersey; and William Gumprecht, Dupont Chambers Works
(z) Briefings and discussion about commercial recycle, Val Loiselle, American Ecology Recycle Center; and Bill Carder, Westinghouse Scientific Ecology Group (SEG)

**5. Committee Meeting, Paducah Site Visit, October 19–21, 1994, The Executive Inn, Paducah, Kentucky**

Plant Briefings

(a) Plant Tour, Pat Gourieux, Deputy Site Manager and Manager of Environmental Restoration, MMES; and Chris Mason, Deputy Manager, Chemical, Utilities and Power Operations, MMUS
(b) Introduction (Plant Briefing), Jimmie Hodges, DOE Paducah Site Office; and Jimmy Massey, Site Manager, MMES
(c) Video Overview of PGDP [Paducah Gaseous Diffusion Plant], Steve Davis, Manager, Decontamination and Decommissioning, MMES
(d) Discussion of Plant Operations and Equipment, Parameters Affecting D&D
    (1) Cascade Improvement and Upgrading, Carl Walter, Manager of the Cascade Operations and Technical Services Divisions (Retired), MMUS; David Gourieux, Manager, $UF_6$ Handling Department, Cascade Operations, MMUS; Steve Penrod, Cascade Division Manager, MMUS; Bill Sykes, Nuclear Regulatory Affairs Manager-Coordinator, MMUS
    (2) High Assay Project, Paul Kreitz, Program Manager, High Assay Implementation, MMUS
    (3) Atomic Vapor Laser Isotope Separation (AVLIS), Charles Martin, Site Manager, USEC
(e) $UF_6$ Cylinder Considerations
(1) Storage, Ray Fields, Manager, Facilities Management, MMES
(2) Compliance Status, Danny Guminski, Manager, Environmental Management, MMES; Gail Giltner, Deputy Manager, Environmental and Waste Management, MMES

(f) Current Routine Maintenance: Equipment Change-Out Cycle Times Cycle Time Reduction, Dale Donohoo, Manager, Cascade Maintenance Department, Cascade Operations, MMUS; Dave Sampson, Manager, General Plant Support, MMUS
(g) Current PGDP Equipment Decontamination Methods and Potential Technologies: Recommendations for D&D Cost Reduction, Walt Whinnery, Chemical Engineer, Chemical, Utilities and Power Operation, MMUS; Phil Brown, Section Head, Production Engineering, Cascade Operations, MMUS; Alice Story, Section Head, Environmental Technology, Materials and Equipment Technology, Technical Services, MMUS
(h) Radiological Overview: Health Physics Surveys/Characterization Data/Bioassay Data; Transuranics, Personal Protective Equipment (PPE), Steve Meiners, Manager, Health Physics, MMES; Orville Cypret, Assistant Manager, Safety and Health and Radiation Protection Manager, MMUS
(i) Toxic Substances Control Act (TSCA) Overview

(1) Polychlorinated Bipenlyls (PCBs), Gary Milne, TSCA Specialist, Environmental Management, MMES
(2) Asbestos, Bob Langston, Asbestos Program Manager, Environmental and Waste Management, MMUS

(j) Hazardous Materials Overview

(1) Chemical Inventory, Jerome Mansfield, Emergency Management Staff, Safeguards, Security and Emergency Services, MMUS; Teresa Cooper, Hazard Communication, Industrial Hygiene and Occupational Safety and Health Administration (OSHA) Program, MMUS
(2) Chlorfluorocarbons (CFCs), Paul Kreitz, Program Manager, High Assay Implementation, MMUS
(3) Historic Spill Data, Brad Montgomery, Manager, Program Management, Environmental Restoration, MMES; Danny Guminski, Manager, Environmental Management, MMUS; Gail Giltner, Deputy Manager, Environmental and Waste Management, MMES

(k) Waste Management Overviews: Waste Quantities; Current/Future Generation Rates; Offsite Treatment Storage Disposal (TSD) Options, Richard Kuehn, Manager, Waste Management Operations, MMES; Linda Beach, Manager, MMUS
(l) Paducah Stakeholder Involvement, Dennis Hill, Manager, Public Affairs, MMES

Committee Briefings

(m) The Technetium Issue, Fred Schneider, Committee Member
(n) Recent Oak Ridge Site Visit, Fred Schneider and Joe Byrd, Committee Members

Technology Panel Site Visit and Briefing

(o) Technology Panel Site Visit to and Briefing from the Allied Signal Facility, Metropolis, Illinois, October 19, 1994, Sandford I. Rock, Director of Nuclear Services, Allied Signal

Decision and Process Analysis Panel

(p) Discussion with Union Members at the Paducah Site, David Fuller, President, Oil, Chemical and Atomic Workers Union (Local 3-550) (Paducah, Kentucky)

**6. Committee Meeting, December 12–14, 1994, Arnold and Mabel Beckman Center, Irvine, California**

(a) Briefing on COGEMA Process for $UF_6$ Disposition, Frank Shallo, Vice President, Market Development, COGEMA

**7. Writing Group Meeting, January 23–25, 1995, Arnold and Mabel Beckman Center, Irvine, California**

**8. Committee Meeting, February 22–24, 1995, Arnold and Mabel Beckman Center, Irvine, California**

The following presentations were made:

(a) Management of Depleted Uranium Hexafluoride, Charles E. Bradley, Jr., Office of Uranium Programs, DOE
(b) Contract Reform, Gary Boss, General Accounting Office
(c) Economic Development and Employment Issues, Steven Carter and Robert Walton, Ohio Valley Regional Development Commission (by conference call)
(d) Update on DOE's D&D Program, Judd Lilly, Office of Environmental Management, DOE

**9. Writing Group Meeting, April 10–11, 1995, Arnold and Mable Beckman Center, Irvine, California**

**10. Committee Meeting, May 8–10, 1995, National Academy of Sciences, Cecil and Ida Green Building, Washington, D.C.**

The following presentations were made:[1]

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[1] Office of Technology Assessment's staff were invited to attend but were unavailable. The committee had the benefit of the Office of Technology Assessment report *Complex Cleanup: The Environmental Legacy of Nuclear Weapons Production* (February, 1991).

(a) Discussion: Applicability of Capenhurst Experience to the U.S. Gaseous Diffusion Plants, Richard Faulkner, Oak Ridge National Laboratory; Gary Person, MMES; Robert Lenyk, Foster Wheeler
(b) Declassification of the Gaseous Diffusion Technology, Gerald Gibson, Office of Declassification, Office of Security Affairs, DOE
(c) Waste Management at K-25 Site, Bill Gilbert, Oak Ridge Operations, DOE
(d) Landlord Program, Larry Clark, K-25 Site, DOE
(e) Update on Stakeholder Involvement Program, Don Beck, Office of Public Accountability, DOE
(f) Discussion: Opportunities for Cost Reduction, Gary Bennethum, Energy Branch, Office of Management and Budget; Murray Hitzman, Office of Science and Technology Policy; Dan Burnfield, Defense Nuclear Facilities Safety Board
(g) Shoreham Decommissioning Project, Stephen Maloney, Finance and Administration Department; M. Siva Kumar, Manager, Licensing and Regulatory Compliance Department; Paul Quattro, Shoreham Decommissioning Project, Shoreham Nuclear Power Station

**11. Committee Meeting, July 10–12, 1995, National Academy of Sciences, Cecil and Ida Green Building, Washington, D.C.**

The following presentations were made:

(a) Technologies for Conversion of Depleted Uranium Hexafluoride, William Quapp, Lockheed Martin Idaho Technologies
(b) Plans for Management of Depleted Uranium Hexafluoride, Charles E. Bradley, Jr., Environmental Manager, Office of Facilities, Office of Nuclear Energy, DOE

## Separate Panel Meetings

**1. Technology Panel Meeting, May 9–11, 1994, Arnold and Mabel Beckman Center, Irvine, California**

The following presentations were made:

(a) Informal discussion on key technology cost drivers inferred from the Ebasco cost estimate, plus related topics, Blynn Prince, Project Manager for Strategic Planning, K-25 D&D Program, Environmental Restoration Division, MMES, Oak Ridge, Tennessee.
(b) Presentation on "Overview of the Oak Ridge Logic Diagram and View of How D&D should Proceed," Roy D. Bundy, Head, Applications and Development, Section, Decontamination and Decommissioning Technology, Technical Division, MMES, Oak Ridge, Tennessee.

**2. Cost Analysis Panel Meeting, May 17, 1994, Stanford University, Stanford, California**

**3. Cost Analysis Panel Meeting, September 20–21, 1994, Stanford University, Stanford, California**

### Site Visits and Symposiums Attended by Selected Members of the Committee and Staff

1994 International Symposium on D&D, April 25–29, 1994, Knoxville, Tennessee

Classified visit to the Oak Ridge Uranium Enrichment Facility, June 28, 1994, Oak Ridge, Tennessee (two members of the committee and one staff officer with special clearances)

Mahadevan Mani and Tracy Wilson, National Research Council Staff, met with Sam Fowler of the Senate Energy and Natural Resources Committee Staff, July 11, 1994, Washington, D.C.

The First Annual Nuclear Decommissioning Decisionmaker's Forum, August 30–September 2, 1994, Amelia Island Plantation, Jacksonville, Florida

Additional briefing and site visit to the Oak Ridge Uranium Enrichment Facility, September 30, 1994, Oak Ridge, Tennessee (with specific emphasis on robotics)

American Nuclear Society's 1994 Winter Meeting, November 12–17, 1994, Washington, D.C.

Site visit and briefing at Westinghouse, February 3, 1995, Columbia, South Carolina

Site visit and briefing at the COGEMA plant facility, March 16, 1995, Pierrelatte, France

# Appendix D

# Biographical Sketches of Committee Members and Staff

**Dale F. Stein** (*chair*) retired from his position as professor of materials science at Michigan Technological University and is president emeritus of the university. He has held positions at Michigan Technological University, University of Minnesota, and the General Electric Research Laboratory. He holds a Ph.D. in metallurgy from the Rensselaer Polytechnic Institute. Dr. Stein has served on numerous advisory committees of the National Science Foundation, the U.S. Department of Energy (DOE), and the National Research Council (NRC) and has been a member of DOE's Energy Research Advisory Board. He is an internationally known authority on the mechanical properties of engineering materials. Dr. Stein received the Hardy Gold Medal of the American Institute of Mining, Metallurgical and Petroleum Engineers and the Geisler Award from the American Society of Metals (Eastern New York Chapter), has been an elected fellow of the American Society of Metals and the American Association for the Advancement of Science, and is a member of the National Academy of Engineering. Dr. Stein currently chairs the Advisory Board of the Center for Nuclear Waste Regulatory Analysis, which advises the Nuclear Regulatory Commission on the proposed Yucca Mountain high-level radioactive waste repository.

**Gregory R. Choppin** (*vice chair*) is R. O. Lawton Distinguished Professor of Chemistry and chairman of the Department of Chemistry at Florida State University. He received a B.S. in chemistry from Loyola University, a Ph.D. from the University of Texas, and honorary doctorate degrees from Loyola University and Chalmers University of Technology. He is a specialist in actinide and lanthanide chemistry, serves on the editorial boards of eight scientific journals, and has won national awards in education, nuclear chemistry, and actinide separations. He has published more than 300 research articles and 8 books on actinide science. Dr. Choppin has participated in a number of NRC activities, including chairing the NRC Committee on Nuclear Engineering Education and serving as a member of the Panel on Separations Technology and Transmutation Systems and on the Board on Chemical Sciences and Technology.

**Eula Bingham** is professor of environmental health in the College of Medicine at the University of Cincinnati. She has served as vice president and university dean for graduate studies and research at the University of Cincinnati; assistant secretary of labor, Occupational Safety and Health Administration, U.S. Department of Labor; and in a number of academic positions at the University of Cincinnati. She has a B.S. in chemistry and biology and a Ph.D. in zoology from the University of Cincinnati. Dr. Bingham has received the Rockefeller Foundation Public Service Award, the Julia Jones Award from the New York Lung Association, the Homer N.

Calver Award from the American Public Health Association, and the William Lloyd Award for Occupational Safety from the U.S. Steel Workers. She is a member of the Institute of Medicine and has served on a number of NRC boards and committees, including the Board on Health Promotion and Disease Prevention, vice chair of the Committee on Toxicology, and Committee on Priority Mechanisms for Research on Agents Potentially Hazardous to Human Health. She is a member of the Editorial Board of *Dangerous Properties of Industrial Materials Report*, was a member of the Environmental Protection Agency (EPA) Science Advisory Board, and has served on numerous advisory groups for the U.S. Department of Labor and other government agencies. She formerly chaired the Ohio Governor's Commission on the Storage and Use of Hazardous and Toxic Materials, and currently chairs the Veterans Administration Persian Gulf Advisory Committee and the Advisory Committee for the Agency for Toxic Substances Disease Registry, under the Centers for Disease Control and Prevention, U.S. Department of Health and Human Services.

**Joseph S. Byrd** is professor of electrical and computer engineering and associate chair for computer engineering at the University of South Carolina. He previously held various positions at the DuPont Savannah River Laboratory, Aiken, South Carolina, where he managed the Engineering Development Group, organized and managed the Robotics Technology Group that realized the first robotics applications at the Savannah River Site, and conducted and managed research and development in mobile robotics. He received his B.S. and M.S. in electrical engineering from Clemson University and the University of South Carolina, respectively. His active professional activities include participation in the South Carolina Society of Professional Engineers, the Robotics and Remote Systems Division of the American Nuclear Society (past chair), the Editorial Advisory Board for *RadWaste Magazine*, and the Waste Management External Advisory Committee and the Single-Shell Tank Retrieval Technology Panel (organizer and chair) for Westinghouse Hanford Company. He has given numerous presentations, published extensively on robotics and computer technology, and is coauthor of a textbook on computer architecture.

**Joel I. Cehn** is a certified health physicist and principal, Applied Sciences Company. He has held positions at the Electric Power Research Institute, Pacific Gas and Electric Company, Teknekron Research and Boston Edison Company. He received his B.S. in physics from Worcester Polytechnic Institute and his M.S. in nuclear engineering and mathematics from North Carolina State University. He has been a consultant to EPA on environmental standards for high-level radioactive waste disposal. He has advised electric utility management in the areas of radiation protection, radioactive waste, and nuclear power plant decommissioning. Currently, he conducts characterization studies for contaminated buildings and properties, and prepares decontamination and decommissioning (D&D) plans for clients. He has published technical papers and popular articles on radiation safety.

**Philip R. Clark, Sr.** is president, chief operating officer, and chief executive officer of GPU Nuclear Corporation, which operates and maintains the Three Mile Island nuclear power plant in Pennsylvania and the Oyster Creek nuclear power plant in New Jersey. He is a director, GPU Nuclear Corporation; director, GPU Service Corporation; and director of the Saxton Nuclear Experimental Corporation. He has been associate director for reactors, Naval Reactors Division, DOE and for the U.S. Navy Department; chief, Reactor Engineering Division, Naval Sea Systems Command; and naval architect at the New York Naval Shipyard. He had overall management and direction responsibility for all activities involved in the Three Mile Island 2 reactor accident cleanup. His industry activities have included being a director of the Institute of Nuclear Power Operations, the American Nuclear Energy Council, the Advanced Reactor Corporation, and the Nuclear Energy Institute. He has a B.S. in civil engineering from the Polytechnic Institute of Brooklyn, is a member of the National Academy of Engineering, a Fellow of the American Nuclear Society, and has won the Navy Distinguished Civilian Service Award and the U.S. Energy Research and Development Administration Special Achievement Award.

**Robert E. Connick** is emeritus professor of chemistry at the University of California-Berkeley. He has been chairman of the Department of Chemistry, Dean of the College of Chemistry, and vice chancellor of the Berkeley Campus. Dr. Connick worked on the Manhattan Project. He received a B.S. and Ph.D. in physical chemistry from the University of California. His research interests include inorganic reactions, chemical dynamics, radiochemistry, nuclear magnetic resonance, aqueous solution chemistry of chromium and ruthenium, and sulphur chemistry. Dr. Connick is a member of the National Academy of Sciences.

**Frank Crimi** is Director of Marketing for Lockheed Martin Environmental Systems and Lockheed Martin Environmental Systems and Technologies. He has been vice president, Nuclear Engineering Services, Waste Chem Corporation; manager of decommissioning services, General Electric Company; and manager of plant systems engineering, Advanced Reactor Systems at General Electric. He also held a number of positions at General Electric's Knolls Atomic Power Laboratory. Mr. Crimi received his B.S. in mechanical engineering from Ohio University. His experience includes that in the management of large, complex programs in the nuclear industry, including construction, operation, and maintenance of the DOE naval nuclear reactor plants with special emphasis on D&D of nuclear plants and facilities. He was the Program Manager for decommissioning DOE's Shippingport Atomic Power Station.

**Wolter J. Fabrycky** is Lawrence Professor Emeritus of Industrial and Systems Engineering at the Virginia Polytechnic Institute and State University. He has also served as chairman of the Systems Engineering Department, associate dean of engineering, and dean of research at the Virginia Polytechnic Institute and State University. He has taught at the University of Arkansas and Oklahoma State University. Dr. Fabrycky received the Lohmann Medal from the College of Engineering at Oklahoma State in 1992 for Outstanding Contributions to Industrial and Systems Engineering Education, Research, and Publications. In 1990, he received the Holtzman Distinguished Educator Award from the Institute of Industrial Engineers. Dr. Fabrycky was elected fellow in the Institute of Industrial Engineers in 1978, and fellow in the American Association for the Advancement of Science in 1980. He has coauthored six books and coedits the Prentice Hall International Series in Industrial and Systems Engineering. His research and teaching has included engineering economics, life-cycle cost analysis, systems engineering, applied operations research, and management science. He consults with both the private sector and government. Dr. Fabrycky has served as a systems engineering consultant to the Nuclear Waste Technical Review Board.

**Robert A. Fjeld** is professor of environmental systems engineering at Clemson University. He was assistant professor of nuclear engineering at Texas A&M University. His research efforts are focused on environmental restoration and waste management. Dr. Fjeld has done consulting in operational health physics, risk assessment, radioactive decontamination, and aerosol filtration. He is active in the American Society of Mechanical Engineers Mixed Waste Committee, serving as chairman of the Education/Information Subcommittee, and is a member of the Health Physics Society and the American Nuclear Society. He has a Ph.D. in nuclear engineering from Pennsylvania State University. Dr. Fjeld has experience in risk assessment of hazardous and radioactive contaminants, mixed waste treatment, storage and disposal issues, and radiological characterization and decontamination.

**Bernd Kahn** is director of the Environmental Resource Center and professor in the Nuclear Engineering and Health Physics Program at the School of Mechanical Engineering, Georgia Institute of Technology. He has been an associate chemist in radiochemistry at Oak Ridge National Laboratories and a radiochemist with the U.S. Public Health Service and EPA's Radiochemistry and Nuclear Engineering Branch. He has also worked with the National Environmental Research Center. Dr. Kahn's research has been in analytical radiochemical methods, behavior of radionuclides in the environment, and radioactive effluents from nuclear power stations. He has a Ph.D. in chemistry from the Massachusetts Institute of Technology and is a member of the National Council on Radiation Protection and Measurements, the Health Physics Society, American Chemical Society, American Physical Society, and EPA Radiation Advisory Committee.

**Charles Kimm** is vice president for social and applied systems, Pacific International Center for High Technology Research. His research has focused on public policy, logistics planning, and issues concerning nuclear and hazardous waste management. He was vice president for transportation programs at Battelle Memorial Institute's Project Management Division and was responsible for initiating research programs dedicated to DOE in support of the National Radioactive Waste Transportation Program. He developed and directed the Transportation Management Certification Program for DOE Transportation Personnel and chaired the DOE/Association of American Railroad Emergency Response Planning Committee and the Nuclear Material Transportation Committee. He was also responsible for preparing the volume on transportation for the Mission Plan that DOE submitted to Congress as required under the Nuclear Waste Policy Act of 1982. Mr. Kimm received his M.B.A. in transportation management from Michigan State University and has served on various committees of the Transportation Research Board of the National Research Council, including the Hazardous Materials Transportation Committee.

**Peter B. Lederman** is director, Center for Environmental Engineering and Services, and research professor of chemical engineering, New Jersey Institute of Technology. He has served as vice president of the Hazardous/Toxic Substance Management Division at Roy F. Weston and vice president and general manager at Cottrell Environmental Sciences, Research-Cottrell. He has also held positions at EPA and at the Polytechnic Institute of Brooklyn. Dr. Lederman has a Ph.D. in chemical engineering from the University of Michigan, with a minor in nuclear engineering and mathematics. His expertise includes management and disposal of hazardous wastes and industrial waste treatment, including audits of hazardous wastes, and cleanup and treatment of asbestos and polychlorinated biphenyls (PCBs). He has been awarded the EPA Silver Medal for Superior Service, the Lawrence K. Cecil Award of the American Institute of Chemical Engineers for Contributions to the Environment through Chemical Engineering, and the Stanley E. Kappe Award from the American Academy of Environmental Engineers. Dr.

Lederman also chaired a task force of the American Institute of Chemical Engineering on an engineering approach to the "Superfund."

**Walter May** is professor emeritus of chemical engineering at the University of Illinois. He spent approximately 35 years at Exxon Research and Engineering Company and has experience in process engineering development, large engineering projects, and cost estimation. While at Exxon Nuclear Company, he worked on the development of gas centrifuge uranium enrichment technologies. He also has experience in chemical waste destruction technologies. He has an Sc.D. in chemical engineering from the Massachusetts Institute of Technology and is a licensed Professional Engineer in the State of Illinois. He is a member of the National Academy of Engineering and was elected an American Institute of Chemical Engineers Fellow. He has received the American Institute of Chemical Engineers Award in Chemical Engineering Practice and the American Society of Mechanical Engineers Process Industries Division Service Award. He was a member of the NRC Committee on Alternative Chemical Demilitarization Technologies, which evaluated the technologies proposed for the destruction of chemical warfare agents, and is currently a member of the NRC Committee on Review and Evaluation of the Army Chemical Stockpile Disposal Program.

**Alvin Mushkatel** is professor in the School of Public Affairs, director of the Doctor of Public Administration Program, and director of the Office of Hazards Studies, Arizona State University. He has held positions in political science at the University of Denver, University of Missouri, and St. John's University in Minnesota. Dr. Mushkatel received his Ph.D. in political science from the University of Oregon. He has conducted numerous studies on risk perception, siting of hazardous facilities, and nuclear waste policy. He was a recent member of a DOE Public Participation Seminar Series Panel on public trust and confidence. He has served as a member of the NRC Committee on Earthquake Engineering and a number of its subpanels. Dr. Mushkatel is currently a member of the NRC Committee on the Review and Evaluation of the Army Chemical Stockpile Disposal Program. He has published widely in the fields of hazards policy and risk perception.

**M. Elisabeth Paté-Cornell** is professor of industrial engineering and engineering management at Stanford University. She has held other positions at Stanford and the Massachusetts Institute of Technology, as well as at the Régie Autonome des Transports de Paris. She is a consultant to a number of private corporations, government agencies, and consulting companies. She is also a member of the National Academy of Engineering and the 1995 president of the Society for Risk Analysis. Dr. Paté-Cornell received her Ph.D. in engineering-economic systems from Stanford University. Her areas of expertise are risk analysis, engineering risk management, engineering economics, and decision analysis. She has undertaken numerous studies, on risk analysis in nuclear safety decisions; fire risks in oil refineries and the economic effects of camera monitoring; public risk assessments and safety regulations in the chemical industry; risk management for the space shuttle tiles; and risk management of offshore oil and gas facilities. She is a member of the NRC Marine Board, the Editorial Board on *Reliability Engineering and System Safety*, and the National Science Foundation Panel on Decision, Risk, and Management Science Program.

**William R. Prindle** is currently a consultant and is retired vice president and associate director of the Technology Group at Corning. He was executive director of the NRC's National Materials

Advisory Board, vice president for research at the American Optical Corporation, vice president for research at Ferro Corporation, and general manager for R&D at Continental Can Company, Haxel-Atlas Glass Division. He has served as president of the American Ceramic Society and president of the International Commission on Glass, and on numerous advisory committees for universities and other institutions. He has received a number of honors, including the Phoenix Award (Glass Industry Man of the Year), Toledo Glass and Ceramic Award, the Albert Victor Bleininger Award, and the Friedberg Memorial Lecture (National Institute of Ceramic Engineers). He is a member of the National Academy of Engineering and the Academy of Ceramics. He has a B.S. and M.S. in physical metallurgy from the University of California at Berkeley and an Sc.D. in ceramics from the Massachusetts Institute of Technology. Dr. Prindle served on the Waste Management External Advisory Committee for Westinghouse Hanford Company and on their Low-Level Waste Melter Evaluation Panel.

**Carolyn Raffensperger** is currently coordinator of the Science and Environmental Health Network, a not-for-profit organization. She was the state field representative for the Sierra Club in Illinois from 1983 to 1991, taught archeology at the Chicago Field Museum, and worked for the Dolores Archaeological Project. She has an M.A. in anthropology from Northwestern University and received her J.D. from the Chicago-Kent College of Law. Her activities have included lobbying for the Sierra Club on the Clean Air Act, Superfund, and other environmental legislation. She was a member of the Illinois Low-Level Radioactive Waste Disposal Facility Siting Commission and of the Illinois Citizen's Advisory Committee on Radioactive Waste that advised the Illinois Department of Nuclear Safety on policy and public affairs issues on low-level radioactive waste. She was also president of the Board of Directors of the Illinois Environmental Council.

**Geoffrey S. Rothwell** is senior research associate with the Department of Economics and the Center for Economic Policy Research at Stanford University. He has held teaching and research positions at the University of California-Berkeley and the California Institute of Technology. Dr. Rothwell received his M.A. in Jurisprudence and Social Policy from Boalt Law School at the University of California and a Ph.D. in economics from the University of California-Berkeley. His research has focused on nuclear power plant economics, including measuring productivity, defining standardization, and analyzing the impact of regulations. Dr. Rothwell has written on the economics of spent nuclear fuel transportation and disposal, and on decommissioning nuclear power plants. He coedited a special issue of *The Energy Journal* on nuclear decommissioning economics (July 1991).

**Ray O. Sandberg** is a project manager with Bechtel National. He was planning manager on the Heavy Water-New Production Reactor construction project. He managed the Bechtel design and cost-estimating team in support of the DOE Richland studies on conversion of the WNP-1 reactor to defense materials production; directed development of comparative advanced conceptual designs, construction techniques, cost estimates, and schedules for the $6 million DOE New Production Reactor Study; was manager of Nuclear Fuel Cycle Economics; was Bechtel's technical manager for post accident planning for the recovery of Three Mile Island Unit 2, including the testing of proposed decontamination techniques and removal of the damaged fuel; and was project engineer for the preliminary design of the Alabama Enrichment Plant, a $3 billion gaseous diffusion enrichment complex. He has recently written on reprocessing economics for the report of the NRC's Panel on Separation Technology and Transmutation

Systems. He has an M.S. in chemical engineering from Washington University and an M.B.A. in business management from Golden Gate University.

**Alfred Schneider,** professor emeritus of nuclear engineering, Georgia Institute of Technology, recently retired as a visiting professor and research affiliate from the Massachusetts Institute of Technology. He has a Ph.D. in chemical engineering from the Polytechnic University. Dr. Schneider has held positions at Celanese Corporation of America, Argonne National Laboratory, Martin Marietta Company, and Allied-General Nuclear Services. He received the Antarctica Medal from the U.S. Navy, the Robert E. Wilson Award from the American Institute of Chemical Engineers, and the Gano Dunn Medal from the Cooper Union for the Advancement of Science. His experience has been in nuclear fuel cycle processing, radioactive waste management, isotope separation, chemical aspects of nuclear reactors, and energy conversion. He has been a consultant to industrial companies and state and federal organizations. He served as a member of the Secretary of Energy Advisory Board (Task Force on Radioactive Waste) and as an advisor to the New York State Energy Research and Development Authority.

**Richard I. Smith** is a staff engineer in the Systems and Risk Management Department of Battelle Pacific Northwest Laboratories. He presently contributes to and manages extensive programs sponsored by the Nuclear Regulatory Commission that are examining the decommissioning of licensed nuclear facilities and developing criteria for release of decontaminated sites. His studies on the decommissioning of power and test reactors, fuel cycle facilities, and non-fuel cycle nuclear facilities, which focus on estimating the costs and occupational radiation dose for D&D of nuclear facilities, are known and used throughout the world. He has participated in the development of several reports for the International Atomic Energy Agency (IAEA) on the decommissioning of nuclear facilities, dealing with the status of technology for decontamination, disassembly, and waste management, and is currently a member of an IAEA working group considering the planning for decommissioning of WWER-440 reactors throughout the former Eastern bloc countries. He has also led studies in the storage, packaging, and transport of spent fuel and Greater Than Class C waste. He has an M.S. in applied physics from the University of California-Los Angeles and is a registered professional engineer in Nuclear Engineering.

**Richard A. Meserve** (*Committee Liaison and Vice-Chair of the Board on Energy and Environmental Systems*) is a partner in the law firm Covington & Burling of Washington, D.C. He recently served as vice chair of the NRC's Energy Engineering Board and has served as legal counsel to the President's Science Advisor. Dr. Meserve has extensive experience in the area of environmental law. He has chaired the NRC's Panel on Cooperation with the USSR on Reactor Safety, Committee to Provide Interim Oversight of the Department of Energy's Nuclear Weapons Complex, and Committee on Fuel Economy of Automobiles and Light Trucks. He was a member of the NRC Committee on Scientific Responsibility and the Conduct of Science, and is currently chair of the committee to advise the Secretary of Energy on document declassification under the department's openness initiative. Dr. Meserve has a J.D. from Harvard University and a Ph.D. in applied physics from Stanford University.

## Staff

### Board on Energy and Environmental Studies

**Mahadevan (Dev) Mani** was director of the Board on Energy and Environmental Systems of the NRC from January 1991 through January 1996. He has been with the NRC since April 1989. The board conducts a program of studies and other activities to provide independent advice to the U.S. government and the private sector on issues in energy and environmental technology and public policy. Dr. Mani came to the NRC from TRW, where he had held various positions since 1975. He was director, Federal Marketing Development, for the Federal Systems Group of TRW's Space and Defense Sector from 1987 to 1989. Previously, he was Director, Planning and Analysis, in TRW's Science and Technology department. From 1975 to 1983 he was with TRW's Energy Development Group, responsible for the management of projects undertaken for the U.S. Energy Research and Development Administration, U.S. Department of Energy, the Energy Information Administration, the Oak Ridge National Laboratory, and other clients. Dr. Mani received his Ph.D. in energy management and policy from the University of Pennsylvania, his M.S. in materials engineering from Drexel University, and his B. Tech. in metallurgy from the Indian Institute of Technology, Madras.

**James J. Zucchetto** (*study director*) has recently been made director of the Board on Energy and Environmental Systems. He has been with the NRC since April 1985 and has worked on a variety of energy and related environmental issues affecting public policy. Prior to joining the NRC, he was a faculty member in the School of Arts and Sciences, University of Pennsylvania, and has held research positions at the University of Stockholm's Institute of Marine Ecology and the University of Florida's Department of Environmental Engineering Sciences. Dr. Zucchetto was also a member of the technical staff at Bell Telephone Laboratories. He has conducted research and published in the fields of environmental science, systems ecology, and the environmental and economic impacts of energy technology. He is currently on the editorial advisory boards of the *International Journal of Environmental Engineering and Ecological Modeling*, and the *Journal of Ecological Economics*. He received his Ph.D. in environmental engineering sciences from the University of Florida, his M.S.M.E. from New York University, and his B.S.M.E. from the Polytechnic Institute of Brooklyn.

**Jill Wilson** is a senior program officer with the Board on Energy and Environmental Systems and was study director for the Strategic Assessment of the U.S. Department of Energy's Coal Program. She joined the NRC in March 1993 and has worked on studies in energy, materials engineering, and environmental science. Dr. Wilson was previously a research scientist with a small consulting company in Washington, D.C., investigating aspects of submarine technology. Before coming to the United States, she was responsible for advanced materials development at British Aerospace Military Aircraft Division, Warton, United Kingdom. She received her B.A. in natural sciences and her Ph.D. in physics, both from the University of Cambridge. She also holds a diploma in liberal arts from the University of Toulouse, France.

**Tracy D. Wilson** is a senior program officer with the Board on Energy and Environmental Systems. He previously served with the NRC's Board on Army Science and Technology. Prior to joining the NRC staff in 1993, Mr. Wilson was a senior staff scientist at the Johns Hopkins University and affiliated Applied Physics Laboratory, serving as technical director of the

Chemical Propulsion Information Agency. He has served as an officer in the Air Force, working as a research chemist and project manager at the Air Force Rocket Propulsion Laboratory. Mr. Wilson received a master's degree in National Security Studies from the California State University, writing a thesis on U.S. Nuclear Nonproliferation Policy, and is a distinguished graduate of the Virginia Military Institute, earning a B.S. in chemistry in 1980.

**Susanna Clarendon** is a project assistant and administrative assistant for the NRC's Board on Energy and Environmental Systems. She has been with the NRC since 1992 and previously worked with the Board for more than 2 years on a number of different reports. Prior to her work with the NRC, Ms. Clarendon worked as a legislative assistant for Congressman Gene Snyder of Kentucky, for a trade publication for the television and radio industry, and as a sales secretary and registered representative for a stock brokerage firm.

### Board on Chemical Sciences and Technology

**Douglas J. Raber** is director of the Board on Chemical Sciences and Technology. Prior to joining the NRC in 1990, he was professor of chemistry at the University of South Florida, where his research interests evolved from synthetic organic chemistry, to the structural chemistry of lanthanide complexes, and finally, to computational chemistry and molecular modeling. He earned an A.B. from Dartmouth College and a Ph.D. in chemistry from the University of Michigan.

**Scott Weidman** is a senior staff officer with the Board on Chemical Sciences and Technology. He joined the NRC in 1989, working for the Board on Mathematical Sciences, and moved to his present position with the Board on Chemical Sciences and Technology in 1992. At the NRC he has staffed studies on research funding for the mathematical sciences; research opportunities in spatial statistics, biomedical imaging, computational chemistry, high-performance computing and communications, computational materials science, fossil energy, and probability and algorithms; and chemical options for treatment of radioactive wastes and related materials. After receiving bachelor's degrees in mathematics and materials science from Northwestern University in 1977, Dr. Weidman worked for General Electric Corporation and General Accident Insurance Company before matriculating at the University of Virginia, where he earned M.S. and Ph.D. degrees in applied mathematics. After a postdoctoral year with Exxon Research and Engineering Company, he joined the consulting firm MRJ in Oakton, Virginia, and performed research in parallel computing applied to operations research, image analysis, and air pollution modeling.

**Maria Jones** is senior project assistant with the Board on Chemical Sciences and Technology. She has been with the NRC since 1988 and has worked on several studies on polymer science, biology and molecular biology, catalysis science, high energy density materials, atmospheric science, and materials science. In addition, she has organized various conferences and workshops for the NRC's Air Force Office of Scientific Research Review panels. She is currently pursuing a B.S. degree in business administration. Prior to joining the NRC, Ms. Jones worked for a number of years in the banking industry.

### Board on Radioactive Waste Management

**Karyanil T. (K.T.) Thomas** is a senior staff officer with the Board on Radioactive Waste Management. He has served as a Director of the Bhabha Atomic Research Centre and as a Senior Scientific Officer of the International Atomic Energy Agency (IAEA). He received a bachelor's degree in technology from the Benares Hindu University and a master's degree in chemical engineering from the North Carolina State University. He has been a consultant to the United Nations and has participated in hearings of the World Council of Churches on nuclear energy. He has served as chair and member of many studies and committees to the government and research establishments and has led a large number of IAEA advisory missions on radioactive waste management to member states. He has numerous publications in waste management and disposal, nuclear desalination, and electrolytic and electrothermic processes.

**Verna Bowen** joined the staff of the NRC's Commission on Engineering and Technical Systems in 1982 as an administrative assistant in the Executive Office and later in the Manufacturing Studies Board. She has provided support for several commission activities, including symposia on the National Science Foundation Engineering Research Centers. She recently moved to the NRC's Commission on Geosciences, Environment, and Resources' Board on Radioactive Waste Management. Ms. Bowen is currently on the staff of the NRC's Board on Earth Sciences. She holds a B.Sc. degree in home economics from Oakwood College in Huntsville, Alabama.

# Appendix E

# Radionuclide Characterization and Detection

This appendix supplements chapters 2 and 3 on the radionuclides at the gaseous diffusion plants (GDPs), the characterization process, instrumentation for radionuclide detection, and regulatory requirements on contamination levels.

## Radionuclides To Be Characterized

Table 2-4 in Chapter 2 lists the radionuclides present at the GDPs and the ionizing radiations by which these radionuclides can be detected. Detailed decay schemes, including other radiations that are emitted at very low intensity but may be useful on occasion, can be found in nuclear data tables (Kocher, 1977). The radionuclides present at the GDPs consist mostly of naturally occurring uranium—uranium-238, -234, and -235 ($^{238}$U, $^{234}$U, and $^{235}$U)—with their short-lived progeny. Some material fed to the GDPs was uranium recycled after use in nuclear reactors. This material contains a number of radionuclide contaminants, as illustrated in Table E-1.

Technetium-99 ($^{99}$Tc) is a high-yield (6 percent) fission product. Some $^{99}$Tc accompanies uranium during reprocessing of spent reactor fuel and forms a gas during fluoridation. Hence, recycled uranium is contaminated with $^{99}$Tc. In the cascade, the relatively light $^{99}$ Tc moves toward the enrichment end. Traces of plutonium-239 ($^{239}$Pu) and neptunium-237 ($^{237}$Np) accompany recycled uranium and are present near the feed point of the cascades.

The radioactive impurity shipments to Paducah given in Table E-1 overstate the amounts in the cascade because only about 85 percent of $^{99}$Tc and 25 percent of $^{237}$Np and $^{239}$Pu accompanied the uranium feed (Smith, 1984). At Oak Ridge also, only about 25 percent of the $^{237}$Np and 1.5 percent of $^{239}$Pu present in the recycled uranium entered the cascade. Moreover, many of the contaminants deposited by 1976 were removed during the cascade improvement and upgrade effort during the 1980s (Ritter et al., 1990).

Uranium salts have been deposited within the cascades on surfaces as thin films and in bulk at cool locations and when moisture enters. These salts exist outside the cascades due to leaks or to seals being breached for repairs or changes. Moisture changes the chemical form of the uranium gas by hydrolysis from uranium hexafluoride ($UF_6$) to uranyl fluoride ($UO_2F_2$). The $^{238}$U:$^{235}$U:$^{234}$U ratio in natural uranium feed is 1:0.0072:0.000054 by weight and 1:0.047:1 by activity (decay rate); the ratios of $^{235}$U and $^{234}$U to $^{238}$U increase with enrichment in the cascade.

TABLE E-1 Estimated Radioactive Contaminants Received by Paducah GDP

| **Radionuclide** | Amount (Kg) | Activity (Ci) |
|---|---|---|
| $^{236}$U | 14,000 | 900 |
| $^{99}$Tc | 66 | 11,200 |
| $^{237}$Np | 18.4 | 13 |
| $^{239}$Pu | 0.328 | 20 |

Note: For the period 1953–1976, 758,000 tons of uranium and 100,000 tons of reactor returns were fed to the cascade (Smith, 1984). Activity levels were calculated for the reported amounts, relative to 250,000 Ci activity level for $^{238}$U.

Uranium purification and conversion to gas in preparation for enrichment by diffusion remove the radioactive progeny of the $^{238}$U/$^{234}$U series and the $^{235}$U series. In time, the direct progeny with relatively short half-lives (see Table 2-4) approach radioactive equilibrium again and then decay at the same rate as the parents. Uranium-236 ($^{236}$U) is produced by neutron activation of $^{235}$U (competing with the fission process). Its immediate radioactive progeny is long-lived and would not have accumulated noticeably.

Traces of other radionuclides can be estimated from the amounts of observed radionuclides in Table E-1. The first long-lived progeny in the uranium chains are thorium-230 ($^{230}$Th, with an 80,000 year half-life) following $^{238}$U/$^{234}$U and proactinium-231 ($^{231}$Pa, with a 32,800 year half-life) following $^{235}$U. For these, the average in growth can be calculated to be 0.693 times the ratio of the average in growth period to the half-life; if the period is taken to be 23 years, the fraction of $^{230}$Th to $^{238}$U is 0.00020, and of $^{231}$Pa to $^{235}$U 0.00050. Relative to the values in Table E-1, $^{230}$Th and each of its progeny would amount to 140 curies (Ci), and $^{231}$Pa and each of its progeny to 16 Ci.

Small amounts of other long-lived fission and activation products, including strontium-90, cesium-137 ($^{137}$Cs), various uranium and plutonium isotopes, americium-241 and curium-244, may also have accompanied recycled uranium. $^{137}$Cs has been detected at Paducah and $^{232}$U at Portsmouth.

## Radionuclide Characterization Processes

### Initial or Scoping Measurements

An initial or scoping characterization report must be prepared to plan the decontamination and decommissioning (D&D) program by mapping both the uncontaminated areas and the extent of contaminated surfaces and materials. Much of this information can be compiled from available reports, although some additional characterization will undoubtedly be needed to fill information gaps or improve detection sensitivity. In some instances, performing new surveys may be simpler and more reliable than interpreting obscure documents.

The initial scoping measurements will be concerned with uranium within the cascades that can be located by portable detectors that measure gamma rays emitted by $^{235}$U and $^{234m}$Pa or neutrons emitted by the uranium isotopes. The amount of uranium within the cascade must be estimated from the outside for complex source-detector geometries. Uranium contamination on building surfaces is measured by moving alpha-particle monitors in close proximity to the surfaces. Beta-particle monitors detect $^{234m}$Pa under thin layers and at greater distances, and gamma-ray monitors can detect $^{235}$U and $^{234m}$Pa within solids. Hence, in situ characterization depends on analyzing data from all three types of detectors. Laboratory analysis provides calibration for in situ monitoring, better delineates horizontal and vertical radionuclide distributions, and detects individual radionuclides that are obscured by others in field monitoring.

The minor radionuclides $^{99}$Tc and $^{239}$Pu generally cannot be detected in situ in the presence of much larger amounts of uranium; their presence at specific locations is known from earlier characterization studies using laboratory analyses. Gamma rays emitted by $^{233}$Pa can be detected at locations where $^{237}$Np has become concentrated.

### Characterization During D&D

A second cycle of characterization guides decontamination and maintains control of radioactive materials while ensuring radiation protection for workers and others in the environment. Progress in removing uranium must be monitored for cascade components in situ and, after disassembly, for recyclable materials, building surfaces, and scrap.

Sufficient information is available from plant upgrading and from the Capenhurst decommissioning to prepare plans for characterization during cascade disassembly, component decontamination, and site cleanup, with associated waste processing and radiation protection of personnel.

Decontamination of building surfaces, particularly floors, by washing, scraping, or scabbling requires a complex characterization effort because the radiation to be detected comprises alpha particles, low-energy beta particles, and gamma rays. Alpha particles are hidden by paint and by wash solutions but can be detected on bare surfaces and in airborne dust. All three types of detectors are necessary to trace the movement of uranium, ensure its removal from surfaces, assay the concentration of resulting wastes, ensure worker protection, and measure effluent release rates.

### Compliance Characterization

The third and last cycle is compliance characterization to ensure that materials and equipment are suitable for free-release, continued use within restricted areas, or disposal as waste and to ensure that locations can be opened for uncontrolled access by the public. Measurements must be sufficiently sensitive to demonstrate that radionuclide levels meet regulatory limits and sufficiently comprehensive to represent all materials and locations.

The buildings that contain the cascades are most effectively monitored after they have been emptied. The effects of surface-covering materials, such as paint or sealant, in preventing detection of covered alpha particles must be compensated for by use of gamma-ray detectors. Covered areas, as well as locations at which penetration by radionuclides beneath surfaces is suspected, require depth sampling for analysis in the laboratory. Rubble from surface-decontaminated and dismantled buildings must also be sampled because surface analysis is not sufficiently informative. The vast expanse of the cascade buildings presents a challenge for applying innovative monitoring techniques. For surface monitoring, robotic monitors that can move independently across floors at a rate controlled by the collected radiation count rates and that process measurements for data analysis and mapping could be highly cost-effective. For collecting numerous samples, sampling patterns should be designed to give as complete coverage as possible using a reasonable sampling and analysis load.

## Radionuclide Characterization Instrumentation

Detecting ionizing radiations—alpha and beta particles and gamma and x rays—is the conventional method for measuring the radionuclides present at the GDPs. Contamination amounts are given in radiation units of curies (Ci) or subunits (e.g., picocuries, pCi), although mass units are commonly used at the GDPs.

The more familiar chemical analysis techniques can be applied only to radionuclides that have half-lives so long that they have measurable masses at pCi levels. For $^{238}$U and $^{235}$U, 0.33 pCi and 2.2 pCi, respectively are equivalent to 1 microgram. The masses of shorter-lived radionuclides with correspondingly higher ratios of activity per mass—6.4 pCi/nanogram for $^{234}$U, for example—may be measured by techniques utilizing mass spectrometry.

The heavy elements also emit neutrons at very low rates due to the fission process and the F-19(α,n)$^{22}$Na reaction with the emitted alpha particles that interact with fluorine. The frequency with which neutrons are emitted by spontaneous fission per million alpha-particle disintegrations is 1.1 for $^{238}$U, 0.000022 for $^{234}$U, 0.0024 for $^{236}$U, and much less for $^{237}$Np and $^{239}$Pu. Neutrons of average energies just below 1 MeV are generated at higher rates by the (α,n) reaction in $UO_2F_2$; estimated rates per million alpha particles are 1.4 in $^{238}$U, 0.79 in $^{234}$U, 0.46 in $^{235}$U, and 3.1 in $^{236}$U. Neutron emission rates in $UO_2F_2$ are about 1.6 per minute per gram of natural uranium but above 100 per minute per gram of highly enriched uranium, mostly due to $^{234}$U (Reilly et al., 1991).

Uranium levels have been monitored with the instruments listed in Table E-2 for many years, with some improvements and new developments. The approximate lower limits of detection listed in Table E-2 were estimated to indicate the applicability of specific detectors for various characterization efforts, particularly for checking uranium levels at release limits. In situ measurements are performed to locate uranium accumulated within the cascade and contaminating its components and surroundings and to estimate radionuclide levels of contaminated areas in real time. Laboratory analyses of samples collected from monitored objects and sites are more sensitive and accurate and can distinguish more effectively among several radionuclides that may be present; however, they are much more time consuming and costly.

TABLE E-2 Conventional Radionuclide Characterization Instruments and Techniques

| **Description** | Uranium Detection Limit[a] |
|---|---|
| **In situ** | |
| Gamma-ray survey in cascade | 0.01 g ($^{235}$U) |
| Sodium iodide (thallium) detector | 0.5 g ($^{238}$U) |
| Neutron survey in cascade | 0.8 kg ($^{235}$U) |
| Alpha-particle survey | |
| Zinc-sulfur scintillation | 80 pCi/100 cm$^2$ |
| Gas ionization | 50 pCi/100 cm$^2$ |
| Smear | 50 pCi/100 cm$^2$ |
| Beta-particle survey: gas ionization pancake | 300 pCi/100 cm$^2$ |
| Gamma-ray spectrometer survey | 50 pCi/100 cm$^2$ ($^{235}$U) |
| Germanium (Ge) detector | 1,000 pCi/100 cm$^2$ ($^{238}$U) |
| **Laboratory** | |
| Gross alpha/beta particle sample count | |
| Gas ionization | 5 pCi/g |
| Liquid scintillation | 5 pCi/g |
| Alpha/beta particle smears | 0.5 pCi/100 cm$^2$ |
| Gamma-ray spectrometer | 0.05 pCi/g ($^{235}$U) |
| Sample count | 2 pCi/g ($^{238}$U) |
| Radiochemical analysis | |
| Alpha/beta gas ionization | 0.5 pCi/g |
| Alpha spectrometer | 0.01 pCi/g |
| Neutron activation | 0.01 µg/g ($^{235}$U, $^{238}$U) |
| Fluorimetry | 5 µg/g ($^{238}$U) |

Note: The detection limit can be calculated by:

$$L = \frac{2.71 + 4.65(2b + 2.22\ LEMtf)^{0.5}}{2.22\ EMtf}$$

Where L = detection limit in pCi per area or mass
M = area or mass measured (100 cm$^2$ or g)
t = time of measurement (minutes)
b = background count
f = decay fraction
E = counting efficiency (count/disintegrations)
As a first approximation, the second term within the parentheses is assumed equal to zero.

[a] Actual limits depend greatly on measurement conditions such as geometry and counting time. Values given are indicative of achievable detection limits.

SOURCE: Information on in situ alpha-particle, beta-particle, and gamma-ray survey detection limits was provided in March 1995 as personal communications to Bernd Kahn, member of the committee, from Steven Meiners and Chris Blewett, Martin Marietta Energy Systems, Paducah, Kentucky; Ron Brandenburg, Martin Marietta Energy Systems, Oak Ridge, Tennessee; Richard Mayer, Martin Marietta Utility Services, Portsmouth, Ohio; and James Berger, Auxier and Associates, Knoxville, Tennessee. Other values were calculated based on the above equation and laboratory data.

Uranium within large, thick-walled cascade components (i.e., converters) is measured with fast-neutron detectors that are large and shielded against thermal neutrons. $^{235}$U amounts are inferred from neutrons generated mostly by $^{235}$U alpha particles in fluorine. In smaller cascade components, such as pipes and converters at the high enrichment end of the cascade, germanium (Ge) detectors with portable spectrometers are effective for measuring $^{235}$U and $^{234m}$Pa gamma rays. Uncertainty about the extent of gamma-ray attenuation circumscribes application of this technique for $^{235}$U to relatively thin uranium deposits and walls. Where difficulty in access prevents using a Ge detector with associated cryostat and Dewar flask, a dosimetry survey instrument with a sodium iodide (NaI[T1]) detector can be substituted.

Gamma-ray detectors are also useful to evaluate the progress of decontamination processes, survey areas for contamination, and check equipment and materials for free-release or transfer to waste repositories. Uranium is detected on the surface and within solids and liquids, both nearby and at a distance. By discriminating electronically against the full background energy spectrum and measuring only the characteristic gamma rays, the spectrometer detects smaller amounts and also provides isotopic analysis.

Alpha-particle detectors are most sensitive for measuring surface contamination. Because the alpha particles are stopped by 0.1-mm-thick solids or liquids or by 4 cm of air, application of these detectors is limited to unobstructed surfaces viewed in close proximity. Beta-particle monitors are used to measure the energetic beta particles emitted by $^{234m}$Pa. These beta particles are monitored more conveniently than alpha particles because they are not as readily attenuated. The low-energy beta particles emitted by $^{234}$Th and $^{231}$Th, on the other hand, are strongly attenuated. The detection limit is poorer for these beta particles than for alpha particles because the background is higher.

Surface contamination is characterized as removable or fixed by rubbing approximately 100 cm$^2$ of the surface with a paper or cloth "smear" or "wipe." The "smear" is counted with an alpha-particle, beta-particle, or gamma-ray detector in the field or, for greater sensitivity, in the laboratory.

Sample sizes for laboratory measurements of samples by gross alphaor beta-particle activity are limited, because samples must be thin for counting with gas ionization and solid scintillation detectors or must be dissolved in small volumes for liquid scintillation counting. The sensitivity of laboratory analysis can be improved by processing a sample of several grams to separate uranium from the bulk of the sample medium and other radionuclides and then measuring alpha particles with a solid-state detector or liquid scintillation system and spectrometer for as many as 1,000 minutes. The effort of chemical separation can be avoided by counting gamma rays from a kilogram sample in a calibrated container with a Ge detector and a spectrometer.

Neutron activation analysis provides sensitive laboratory detection capability if an intense neutron flux is available. $^{235}$U can be determined by measuring any conveniently detected fission product; $^{238}$U by measuring the neutron activation decay product, $^{239}$Np. The sensitivity values in Table E-2 were estimated for a thermal neutron flux of $10^{13}$ neutrons/cm $^2$-s and measurement by gamma-ray spectrometer.

Uranium is analyzed chemically by measuring the fluorescence of a sodium fluoride melt in a platinum dish. The isotopic constitution of the sample must be known to convert mass units to the pCi units in which limits are specified.

Measurement in situ of $^{239}$Pu and $^{99}$Tc is not feasible because any emitted radiations would be attributed to uranium or its progeny. $^{237}$Np may be detected by measuring the $^{233}$Pa gamma ray. Only prior knowledge and inferences from combined alpha-particle, beta-particle and gamma-ray monitoring can suggest whether $^{239}$Pu or $^{99}$Tc are present. Smear samples and washing tests may differentiate $^{99}$Tc by its chemical behavior. $^{239}$Pu, $^{237}$Np, and $^{99}$Tc are identified and quantified by laboratory analysis. $^{239}$Pu and $^{237}$Np may be characterized with the same detection limits as uranium by radiochemically separating the elements and counting them, by distinguishing alpha particles by their energies with a spectrometer, or by distinguishing x and gamma rays with a spectrometer. $^{99}$Tc is measured by counting it with gas-filled ionization or liquid scintillation detectors. The detection limit is approximately 1 pCi.

Some recent developments in radiation monitoring are listed in Table E-3. An inductively coupled plasma mass spectrometer can detect the equivalent of 0.2 pCi $^{99}$Tc, 0.007 pCi $^{237}$Np and 0.6 pCi $^{239}$Pu per gram sample and is much more sensitive for uranium analysis. Although expensive, this analytical instrument may well be cost-effective for the numerous samples expected in this program.

A robotic radiation detection instrument carrier, programmed to survey large areas of floors, walls, or ceilings automatically and uniformly, can reduce work force needs and improve data uniformity. Conceptually, the data can be accumulated and promptly processed for conversion to activity per unit surface area and for preparing a radionuclide contamination map. The robot can be programmed to move around obstructions, but it is particularly effective for the large open areas and radiation fields of simple geometry that are expected at these plants. Robots can also survey radiation fields within vessels, pipes, and ducts and in narrow or remote areas, if designed to operate under dimensional restrictions.

The laser fluorescence monitor is more sensitive for uranium detection than a gamma-ray spectrometer, but its response depends on the chemical form of the uranium salts. This type of monitor could be useful as a field instrument even if additional information on chemical forms were required for quantitative analysis.

In long-range alpha-particle detection, the ions generated by alpha particles in air are measured in the air swept from the source to the detector. The technique is useful for detecting radionuclides that emit alpha particles in spaces that are not accessible to an alpha-particle detector; however, it is subject to error due to detecting ionization generated by other processes.

## Regulatory Requirements

Values promulgated as decommissioning limits or guides will not only control the extent of decontamination but can significantly affect disposal decisions and characterization procedures. Characterization instruments must identify and measure radionuclides at the concentration limits specified by regulatory agencies.

TABLE E-3 Recent Characterization Developments

| **Procedure** | Measurement Attributes |
|---|---|
| Inductively coupled plasma mass spectrometry laboratory analysis system | This approach has a detection limit of $10^{-13}$ g/g for U and of $10^{-11}$ g/g for Tc, Pu, and Np. |
| Long-range alpha-particle detection | Alpha particles emitted by radionuclides ionize the ambient air, which is collected and measured for its ionization density. |
| In situ laser fluorescence spectrometer | A tuned laser excites particular uranium compounds and the resultant emitted light intensity is measured. |
| Robotic mobile scanner | Alpha, beta, gamma radiation levels on surfaces are mapped. |

Guides for decommissioning have been published by the Nuclear Regulatory Commission and the U.S. Department of Energy (DOE). Cooperative efforts to revise them on the basis of current radiation protection concepts are underway by these two agencies and the U.S. Environmental Protection Agency (EPA). The International Atomic Energy Agency (IAEA) is also developing guidance for releasing radioactive materials.

The Nuclear Regulatory Commission (Nuclear Regulatory Commission, 1974) published standards for acceptable levels of surface area contamination, as shown in Table E-4, for decommissioning nuclear reactors. This agency does not now have regulatory oversight for the GDPs, but will have this responsibility in 1996. The currently responsible agency is DOE; it has published the same limits in DOE Order 5400.5 (DOE, 1993, Figure IV-1), except for omitting the second line in Table E-4, covering transuranics. Exposure limits for members of the general public were 500 mrem/yr at that time.

The Nuclear Regulatory Commission recently issued the draft regulatory guide (Daily et al., 1994)—the first document to be issued in the current cooperative effort—associated with amending regulations in Title 10 of the Code of Federal Regulations, Part 20 (10 CFR 20), with the values given in Table E-5. The concentrations in soils and on surfaces that would achieve an annual dose of 15 mrem to exposed persons were derived on the basis of the listed scenarios. Compared with Table E-4, the surface concentration values, except for $^{239}$Pu, are lower than would be expected at the lower dose limit.

The EPA is preparing draft radiation site cleanup regulations for soil and plans to develop such regulations for residual structures, groundwater, waste, and recycled materials (EPA,

TABLE E-4 Nuclear Regulatory Commission Acceptable Surface Contamination Levels

| Nuclide[a] | Average[b] | Maximum[c] | Removable[b,d] |
|---|---|---|---|
| U-nat, $^{235}$U, U and associated decay products | 5,000 dpm α/100 cm$^2$ | 15,000 dpm α/100 cm$^2$ | 1,000 dpm α/100 cm$^2$ |
| Transuranics, $^{226}$Ra, $^{228}$Ra, $^{230}$Th, $^{228}$Th, $^{231}$Pa, $^{227}$Ac, $^{125}$I, $^{129}$I | 100 dpm/100 cm$^2$ | 300 dpm/100 cm$^2$ | 20 dpm/100 cm$^2$ |
| Th-nat, $^{232}$Th, $^{90}$Sr, $^{223}$Ra, $^{224}$Ra, $^{232}$U, $^{126}$I, $^{131}$I, $^{133}$I | 1,000 dpm/100 cm$^2$ | 3,000 dpm/100 cm$^2$ | 200 dpm/100 cm$^2$ |
| Beta-gamma emitters (nuclides with decay modes other than alpha emission or spontaneous fission) except $^{90}$Sr and others above. | 5,000 dpm βγ/100 cm$^2$ | 15,000 dpm βγ/100 cm$^2$ | 1,000 dpm βγ/100 cm$^2$ |

NOTE: Here, dpm (disintegrations per minute, 2.22 dpm = 1 pCi) refers to the rate of emission by radioactive material as determined by correcting the counts per minute observed by an appropriate detector for background, efficiency, and geometric factors associated with the instrumentation.

[a] Where surface contamination by both alpha (α)- and beta-gamma (βγ)–emitting nuclides exist, the limits established for alpha- and beta-gamma–emitting nuclides should apply independently.

[b] Contaminants should not be averaged over more than 1 m$^2$. For objects of less surface area, the average should be derived for each such object.

[c] For an area of not more than 100 cm$^2$.

[d] The amount of removable radioactive material per 100 cm$^2$ of surface area should be determined by wiping that area with dry filter or soft absorbent paper, applying moderate pressure, and assessing the amount of radioactive material on the wipe with an appropriate instrument of known efficiency. When removal contamination on objects of less surface area is determined, the pertinent levels should be reduced proportionally, and the entire surface should be wiped.

SOURCE: Nuclear Regulatory Commission Regulatory Guide 1.86 (Directory of Regulatory Standards, 1974).

1994). The soil concentrations given in Table E-6 are estimated to lead to an annual dose equivalent of 15 mrem by three exposure scenarios. The residential pathway values are about threefold lower than those in Table E-5 for uranium and $^{99}$Tc, similar for $^{237}$Np, and higher for $^{239}$Pu.

TABLE E-5 Nuclear Regulatory Commission Default Radionuclide Concentration Values for Various Exposure Scenarios (dose equivalent of 15 mrem/year)

| | **Concentration (pCi/g)** | | | |
|---|---|---|---|---|
| Radionuclide | Residential (soil) | Renovation (surfaces) | Drinking Water (soil) | Surface concentration, dpm/100 cm$^2$ |
| $^{99}$Tc | 52.400 | 996,000 | 52.7 | 1,060,000 |
| $^{234}$U | 19.000 | 1,600 | 10.3 | 889 |
| $^{235}$U | 14.900 | 292 | 10.8 | 944 |
| $^{236}$U | 20.100 | 1,690 | 10.8 | 934 |
| $^{238}$U | 19.700 | 965 | 10.9 | 984 |
| $^{237}$Np | 0.188 | 131 | 22.4 | 152 |
| $^{239}$Pu | 1.890 | 345 | 31.2 | 192 |

SOURCE: Daily et al. (1994, Table B-2).

TABLE E-6 EPA Review Draft Generic Site Concentration Values for Various Exposure Scenarios (dose equivalent of 15 mrem/yr)

| | **Soil Concentration, pCi/g** | | |
|---|---|---|---|
| Radionuclides | Rural Residential | Commercial/Industrial | Suburban |
| $^{99}$Tc | 18 | 62 | 25 |
| $^{234}$U | 7 | 15 | 7 |
| $^{235}$U | 6 | 14 | 7 |
| $^{236}$U | 7 | 16 | 8 |
| $^{238}$U | 7 | 15 | 8 |
| $^{237}$Np | 0.2 | 0.3 | 0.2 |
| $^{239}$Pu | 27 | 192 | 88 |

SOURCE: Table 7-1 in EPA (1994).

Both drafts establish the goal of decontaminating to radiation background but will accept contamination leading to an annual radiation dose of 15 mrem for unrestricted public access or higher radiation levels for restricted access. Both agencies use calculational models that estimate the radionuclide levels that would result in the specified dose rate to humans in selected pathway and exposure scenarios. Neither draft considers maximum and removable contamination versus average contamination as shown in Table E-4, or the extent to which individual measurements should be averaged for comparison with the limit. The agencies recommended that exposure scenarios be evaluated for the specific site.

Although regulatory agencies have not yet established the annual radiation dose limit, for planning purposes the ratios of radionuclide concentration per dose for the GDPs should be developed promptly with site-specific scenarios based on regulatory agency models. The process will be simple because radioactive contamination is due mostly to uranium. Note that uranium differs from most other radionuclides considered in decontamination guides because its concentrations in nature are not far below the limits; its retention by humans is controlled in part by its mass; and its chemical toxicity may be controlling in establishing intake limits.

Other important local factors in developing decommissioning guides for these plants are the contaminated areas contiguous to the GDP structures, the valuable metals on site, and the large structures. For example, the maintenance of access restrictions at a contiguous site may negate the rationale for decontaminating parts of the plant for free access; the radionuclide limit for freely releasing metals may be driven upward by their value or downward by concerns about subsequent radiation-sensitive applications; decisions on retaining structures versus turning them into rubble may depend on the potential value of the former and the disposal cost of the latter.

The concentrations proposed in an IAEA draft report (IAEA, 1993) for unconditional clearance—that is, for release for reuse or as waste—are related to a radiation dose equivalent to exposed persons of 1 mrem/yr. (See Table E-7). They are described as representative values that are generally within a factor of 100 of the reviewed published estimates. The uranium levels are similar to those in Table E-6, while the $^{99}$Tc and $^{237}$Np values are higher; only the $^{239}$Pu values are lower in accord with expectations for the 15-fold lower dose criterion.

Material sent to land disposal facilities for radioactive waste must meet criteria in 10 CFR 61. These include, for Class A waste, concentration limits of 0.3 Ci/m$^3$ for $^{99}$Tc and 10 Ci/m$^3$ for long-lived alpha-particle-emitting transuranic nuclides, and, for Class C waste, 10 times these limits. Class C waste has more rigorous requirements for waste-form stability and protection against inadvertent intrusion at the burial site.

TABLE E-7 IAEA Recommended Unconditional Clearance Levels

| **Radionuclide** | Concentration, pCi/g |
|---|---|
| $^{99}$Tc | 800 |
| $^{234}$U | 800 |
| $^{235}$U | 8 |
| $^{236}$U | — |
| $^{238}$U | 8 |
| $^{237}$Np | 8 |
| $^{239}$Pu | 8 |

SOURCE: Adapted from Table 11 (converted from Bq/g) IAEA (1993).

Waste materials that include radioactively contaminated hazardous substances are categorized as mixed waste. They must be evaluated for disposal in terms of both EPA and Nuclear Regulatory Commission regulations. The complexity of this process suggests the desirability of radioactive decontamination before disposal of hazardous substances as waste.

The decontamination process also must meet regulations for protecting radiation workers and controlling release of radioactive effluent from nuclear facilities. The limits are based on dose equivalent limits of 5,000 mrem/yr to radiation workers and 50 mrem/yr each from airborne and liquid effluent to members of the public according to 10 CFR 834 (in draft) and 10 CFR 835, respectively. Limits are similar for the uranium isotopes, higher for $^{99}$Tc, and lower for $^{237}$Np and $^{239}$Pu. Facility operators also must protect persons in compliance with the requirement that doses be "as low as reasonably achievable."

Characterization at regulatory limits is feasible only if concentrations of radionuclides attributed to the facility can be distinguished from the background. The detection limit is the net amount of radionuclide of interest that can be distinguished reliably from the selected background value, and depends on the variability in these background values. Natural uranium concentrations in rock, soil, and concrete typically range from near zero to several pCi/g. $^{239}$Pu from fallout in surface soil is approximately 0.01 pCi/g. If the limits are near these values, direct characterization may not be feasible. Only analysis by isotopic content, physical characteristics, or chemical behavior may distinguish between contaminant and background at this level.

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# Appendix F

# Automation and Robotics

The area of automation technologies, commonly referred to as robotics, covers a wide range of system complexity and sophistication, from relatively simple mechanical manipulators ("robot arms"), to remote-controlled teleoperated systems, to autonomous systems. These systems can be either fixed in place or mobile.

Robotic systems employed in decontamination and decommissioning (D&D) applications offer potential benefits in terms of decreased personnel radiation exposure and decreased personnel costs. Robotic systems seem particularly suited to the repetitive nature of the gaseous diffusion plant (GDP) process building designs.

Throughout this report discussions of "automation and robotics" are inclusive of process automation, data collection and analysis, commercial robotic devices, and management of the total information database required in the complex D&D process. Opportunities for cost savings and safety improvements through use of well-planned automation and robotics have been identified only after comparison to manual operational experience or when manual operations are not possible because of unsafe or inaccessible conditions.

Emphasis has been placed on the use of commercially available equipment requiring minimal applications development. A focused, application-driven robotics development program is also underway in the U.S. Department of Energy's (DOE's) Office of Science and Technology (EM-50) that addresses many of the concerns expressed in this report.

## Commercial Systems

A variety of robots are commercially available. Industrial robots (robot arms) are available in a variety of configurations from companies in the United States, Europe, and Japan. Typical applications include welding, assembly, painting, and material handling. A wide variety of end effectors (robotic tools) and sensors are available. Special systems are available for nuclear environments. Several commercial systems are available for laboratory sample preparation and analysis. Mobile robot systems are currently working "around the clock" in security applications. Various forms of teleoperated "pipe crawlers" are also available commercially. These systems are generally teleoperated sensor packages used for inspection of interior pipe surfaces inaccessible by humans. Teleoperated mobile systems are available from several companies. During the past 10 years these systems have been variously applied, including in police operations and nuclear process operations (ANS, 1984, 1987, 1989, 1991, 1993, 1995). These commercial systems are potentially adaptable to D&D applications.

## Doe Programs

The Robotics Technology Development Program of the DOE Office of Technology Development in the Office of Environmental Restoration and Waste Management is performing applied research and development for practical robotics for a variety of applications in DOE site cleanup projects and for work directly related to the D&D of GDPs (DOE, 1994).

Emphasis in the robotics decontamination and dismantlement program is on practical systems and capabilities for facility deactivation and on ongoing surveillance and maintenance to reduce costs, enhance safety, and improve the quality of operations. Major opportunities for robotics have been identified in mapping, characterization, inspection, dismantlement, and decontamination. Current major program activities are risk and cost reduction evaluation, an integrated facility mapping system, automated floor characterization, a dual-arm work module, mobile transportation, small pipe characterization, and internal duct characterization.

The Mobile Automated Characterization System (MACS) is based on a commercial mobile robot platform. A demonstration at the Oak Ridge GDP site is planned. Data will be gathered and compared with established manual practices. Funds have not yet been provided for this demonstration. Microrobot satellite concepts to be deployed from such a system as MACS are being explored for use in characterizing hard-to-reach locations around process equipment. For characterization and inspection of small pipes (3- to 4-inch internal diameter), a specialized system is being developed. An internal duct characterization system that contains a radiation detector, lights, and a mechanical tool has been demonstrated successfully in 200 ft of 12-inch duct at the Idaho National Engineering Laboratory. A pipe asbestos insulation removal robot is under development at Carnegie Mellon University for 4-inch to 8-inch diameter pipes. This system will remove, compress, and bag the asbestos at a rate of 4 to 8 ft per hour. A 4:1 waste compaction is anticipated. A remotely operated vehicle, with carbon dioxide blasting for surface decontamination, is being developed to remove paint from surfaces, such as painted floors in facilities at the Oak Ridge GDP.

A public demonstration was recently held for a mobile robotic work platform (ROSIE) under development by Carnegie Mellon and RedZone Robotics. This vehicle is being shipped to Oak Ridge National Laboratory for testing with the laboratory's dual-arm workstation.

The shutdown Oak Ridge GDP facilities provide unique opportunities for testing, demonstrating, and evaluating many of the robotic developments discussed above. The planning and staging of these demonstration systems in the GDP environment prior to the start of actual D&D operations can provide invaluable planning data.

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# Appendix G

# Nuclear Criticality

Much of the uranium deposits to be removed from the U.S. gaseous diffusion plant (GDP) cascades will be enriched in uranium-235 ($^{235}$ U); at Oak Ridge and at Portsmouth GDPs, some will be highly enriched, perhaps 90 percent $^{235}$U. There is the potential for a nuclear criticality accident with enriched material, a well-recognized safety problem. In a nuclear criticality event, an assemblage of enriched uranium results in a self-sustaining chain reaction, generating large amounts of heat, radioactive fission products, and gamma and neutron radiation. The burst of neutrons that occurs can be lethal to anyone exposed.

U.S. Department of Energy (DOE) Order 5480.24 has established a requirement of a low probability of criticality events, less than $10^{-6}$/yr. Operating standards have been established to avoid the problem (ANS, 1983), and general administrative practices have been outlined. The increase in costs associated with these requirements should be recognized.

Accidents have occurred in spite of the safeguards, generally because people improvise during the job, moving outside of the safety limits. Of interest to the decontamination and decommissioning (D&D) of the GDPs is that most accidents have occurred during cleanup operations.

A chain reaction such as the fission of $^{235}$U to release energy is triggered by the reaction of the $^{235}$U nucleus with a neutron of the proper energy level. The reaction can be characterized by a multiplication factor:

$$k = \frac{\text{Number of neutrons in one generation}}{\text{Number of neutrons in the just-previous generation}}$$

or:

$$k = \frac{\text{Neutron production rate}}{\text{Neutron loss rate}}$$

If $k = 1$, the system is critical; if $k < 1$, the system is subcritical; and if $k > 1$, the system is supercritical. A subcritical system releases very little energy, while a critical or supercritical system can release very large amounts of energy and nuclear particles such as neutrons.

## Production And Loss of Neutrons

Criticality depends on the rates of generation and loss of neutrons. Production of neutrons depends on the following factors:

- The nature of the fissile material—primarily $^{235}U$ in this case. $^{238}U$ can also fission, but has a fission threshold energy such that it can be considered inert.
- The mass of the fissile material.
- The degree of enrichment of the uranium.
- Moderation and reflection.

Neutrons produced during fission do not react well with other $^{235}U$ nuclei; they must first be slowed down. This is done by interacting with light-element nuclei, such as hydrogen (e.g., in water). The presence of a moderator such as water is usually necessary for criticality. Water (or other light elements) surrounding the uranium can also slow down and reflect some of the neutrons back to the fissioning material. The presence of a moderator and a reflector will have a major effect on the "critical mass" capable of sustained reaction.

Loss of neutrons depends on the following factors:

- System geometry. A thin slab or a thin column has a large ratio of surface to mass and promotes the loss. A sphere has the minimum area per unit of mass and limits the loss. Some amounts that would be unsafe as a sphere could be handled safely as a thin slab.
- Neutron absorbers. Many materials react with neutrons; some are very effective at removing neutrons (e.g., boron, cadmium, and gadolinium). They are "neutron poisons."

The factors above can limit the extent and duration of a criticality accident through their effects on the system of the large energy release. In a liquid system, for example, there can be rapid boiling, and, as the moderating liquid evaporates, the system reverts to subcritical. However, the sudden large neutron release during the accident can still be lethal to anyone within a few feet of the scene.

## Avoiding Criticality

The aqueous treatment for surface decontamination automatically introduces a moderator into the system, and criticality becomes a possibility. Methods for preventing criticality are based on the variables noted previously:

- Limiting the mass of $^{235}$U present.
- Controlling the degree of moderation, for example, limit the amount of hydrogenous material (under moderation) or limit the concentration of $^{235}$U in solution (overmoderation).
- Avoiding neutron reflection. Water next to a container can be a reflector, for example, in heat exchanger tubing. Concrete can also be a good reflector, as can people.
- Choosing appropriate geometry; for example, a thin layer of solution to maximize neutron loss.
- Using neutron absorbers. The preferred form of such absorbers is solid, such as borosilicate glass Raschig rings in the solution container. Soluble poisons may also be used, although there is concern about inadvertent separation from solution of such poisons (e.g., via precipitation) and selective separation of poisons in ion exchange resins.
- Some of the uranium will have a $^{235}$U enrichment level that is low enough that criticality is impossible under ordinary conditions of water moderation ($^{235}$U less than 1.96 percent.)

An important concept in criticality safety is the "double-contingency principle:"

> In recognition that improbable operational abnormalities cannot be ignored, the ANS-8.1 Standard delineates the double-contingency principle as a generally accepted guide to the proper degree of protection. The principle calls for controls that assure that no single mishap—regardless of its probability of occurrence—can lead to criticality. Stated another way, it requires that two unlikely, independent, and concurrent changes in process conditions occur before criticality is possible (Knief, 1991).

Critical limits for highly enriched uranium in solution are very restrictive (Table G-1). The values shown are "single-parameter" values for pure $^{235}$U solution, any one of which will ensure that the system will be subcritical.

Multiple-parameter controls provide significant relief from the extremely restrictive single-parameter limits of Table G-1. Control of solution concentration is one of the most useful ways to relax the single-parameter limits, but this immediately entails administrative control to ensure that the concentration is kept within specified limits. An example is shown in Table G-2, showing slab thicknesses and uranium concentrations (100 percent $^{235}$U) that will ensure subcritical conditions (Knief, 1991).

TABLE G-1 Single-Parameter Limits for Uniform Aqueous Solution of $^{235}U$

| **Parameter** | $O_2(NO_3)_2$ | $UO_2F_2$ |
|---|---|---|
| Mass of uranium (kg) | 0.78 | 0.76 |
| Solution cylinder diameter (cm) | 14.4 | 13.7 |
| Solution slab thickness (cm) | 4.9 | 4.4 |
| Solution volume (l) | 6.2 | 5.5 |
| Concentration of uranium in solution (kg/l) | 0.0116 | 0.0116 |
| Atomic ratio of H/U (lower limit) | 2,250 | 2,250 |

SOURCE: Clark (1982).

TABLE G-2 Subcritical Limits for Aqueous Solution of $^{235}UO_2F_2$ with a Water Reflector (25 mm)

| **Slab Thickness (cm)** | Uranium Concentration (kg/l) |
|---|---|
| 8.6 | 1.0 |
| 8.0 | 0.5 |
| 9.8 | 0.1 |
| 13.0 | 0.05 |
| 31.0 | 0.015 |

SOURCE: ANS (1983).

The data of Tables G-1 and G-2 apply to fully enriched uranium solutions only (not containing $^{238}U$). Lower enrichment reduces the criticality problem. Criticality is not possible in unmoderated uranium with less than 5 percent by weight $^{235}U$. Subcritical limits for various $^{235}U$ enrichment levels are shown in Table G-3. Heterogeneous systems in water show somewhat lower criticality limits than homogeneous systems (Table G-4). For example, in mixtures of fine solid $UO_2$ in water with excellent reflection and spherical geometry, criticality is possible at $^{235}U$ concentrations of about 1 percent, but with very large critical masses (Knief, 1991).

TABLE G-3 Subcritical Limits for Uniform Aqueous Solutions of Low-Enriched Uranium for Different $^{235}$U Enrichment Levels

| | **Parameter Subcritical Limit** | |
|---|---|---|
| Parameter[a] | $UO_2F_2$ | $UO_2(NO_3)_2$ |
| Mass $^{235}$U (kg) | | |
| 10.00% | 1.07 | 1.47 |
| 5.00% | 1.64 | 3.30 |
| 4.00% | 1.98 | 6.50 |
| 3.00% | 2.75 | — |
| 2.00% | 8.00 | — |
| Cylinder diameter (cm) | | |
| 10.00% | 20.10 | 25.20 |
| 5.00% | 26.60 | 42.70 |
| 4.00% | 30.20 | 48.60 |
| 3.00% | 37.40 | — |
| 2.00% | 63.00 | — |
| Slab thickness (cm) | | |
| 10.00% | 8.30 | 11.90 |
| 5.00% | 12.60 | 23.40 |
| 4.00% | 15.10 | 33.70 |
| 3.00% | 20.00 | — |
| 2.00% | 36.00 | — |
| Volume (l) | | |
| 10.00% | 14.80 | 26.70 |
| 5.00% | 30.60 | 111.00 |
| 4.00% | 42.70 | 273.00 |
| 3.00% | 77.00 | — |
| 2.00% | 340.00 | — |
| Uranium concentration (g/l) | | |
| 10.00% | 123.00 | 128.00 |
| 5.00% | 261.00 | 283.00 |
| 4.00% | 335.00 | 375.00 |
| 3.00% | 470.00 | — |
| 2.88% | — | 594.9[b] |
| 2.00% | 770.00 | — |
| 1.45% | 1190.00[b] | — |

[a] For different percentages of enrichment

[b] Saturated solution

SOURCE: ANS (1983).

TABLE G-4 Critical Parameters for Solid UO2 Dispersal in Water with 300-mm-Thick Water Reflector

| **Wt %** $^{235}$U | Spherical Mass[a] (kg U) | Cylinder Diameter (cm) | Slab Thickness (cm) | Volume (l) |
|---|---|---|---|---|
| 1 | 1,900 | 70 | 42 | 500 |
| 2 | 165 | 34 | 18 | 60 |
| 3 | 76 | 28 | 12 | 32 |
| 4 | 44 | 24 | 11 | 25 |
| 5 | 27 | 22 | 10 | 20 |

[a] Mass shown is mass of total uranium

SOURCE: Knief (1991).

Factors of safety will always be applied to ensure that the critical limits are not reached in operating cleanup equipment. For example, one report (MMES, 1988) considers 350 grams of $^{235}$U as "always safe" for any enrichment of $^{235}$U. Nuclear Regulatory Commission licensing of the special nuclear material burial site in Washington State allows a maximum of 500 grams (a critically safe quantity) of $^{235}$U per container and a maximum of 15 g/ft$^3$. These mass quantities are significantly less than the subcritical limits shown in Table G-1, for example; they have been chosen to provide a factor of safety.

Deposits within diffusion plant converters raise concerns about nuclear criticality. The concerns depend, however, on enrichment level and amount of $^{235}$U in the deposits, which covers a very wide range:

- The low enrichment section of all of these plants (those providing enrichment levels of less than 1.4 percent $^{235}$U, for example) will contain deposits of less than critical mass.
- The Oak Ridge plant has some very large deposits that must be considered critically unsafe and will require great care.
- The enrichment level at Paducah is low enough (2 percent, with an increase to 2.75 percent in 1995) that critical size deposits are very unlikely. The Portsmouth plant is being treated with gaseous chlorine trifluoride to reduce the $^{235}$U content of individual converters to less than 350 grams, a critically safe level.

Criticality will be a concern at all three plant sites where aqueous treatment is used and where the $^{235}U$ concentration could build up in solution. Eliminating the criticality concern at individual converters could certainly reduce D&D costs (Lacy, 1994).

## Summary

Aqueous washing of enriched uranium (e.g., over 2 percent enriched $^{235}U$) from metal parts requires criticality controls: restricting $^{235}U$ amount and geometry (e.g., to occur only in thin layers), and possibly using neutron poisons. Double-contingency planning is needed. One way to reduce this is to do the work remotely, behind barriers.

It is particularly useful to remove enriched material as thoroughly as possible before water is introduced into the system. Dry cleanup (e.g., scraping or vacuuming) minimizes the subsequent criticality problem in the water-moderated system.

The criticality problem is greatly reduced at low $^{235}U$ enrichment. The cleanup system can be simplified in such cases, with cost reduction.

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# Appendix H

# Previous Decontamination and Decommissioning Efforts

This appendix summarizes information from other decontamination and decommissioning (D&D) efforts that the committee examined and identifies lessons learned. The only gaseous diffusion plant (GDP) that has undergone D&D is the Capenhurst GDP in the United Kingdom (see, for example, Baxter and Bradbury, 1991; Clements, 1994a,b; Spencer, 1988). The committee examined this program in detail as discussed below. The committee also benefited from briefings on the D&D of sites that were used to produce nuclear materials and components for the Manhattan Project and to fabricate nuclear fuel. Two D&D projects were reviewed in particular to glean any insights for the planning and execution of the D&D of the U.S. GDPs: the Formerly Utilized Sites Remedial Action Program and the Apollo Decommissioning Project (Kingsley, 1994). The first is an ongoing project to decontaminate and decommission facilities associated with the Manhattan Project (Hovey, 1994). The Apollo project involved decommissioning a fuel-fabrication complex that handled both enriched uranium and plutonium. Because the scope of these projects varied substantially from that of the D&D of the U.S. GDPs (these projects included substantial remedial action, such as cleanup of soils and groundwater), their costs were not useful for evaluating the GDP D&D costs.

The committee believes that the greatest opportunity to minimize the cost of D&D occurs during planning. Timely decisions on key issues are essential to execute the work efficiently within budget and schedule.

## Capenhurst Gaseous Diffusion Plant

### Description of Capenhurst Facility

The Capenhurst GDP enrichment cascade consisted of 4,808 stages in series, each containing a converter housing the diffusion barrier material that separates uranium-235 ($^{235}$U) and uranium-238 ($^{238}$U) isotopes, a compressor and associated drive motor, a cooler, and interstage piping and valves. The cascade components were housed in a single process building 1,200 m long by 150 m wide. The stages were on the ground floor, and auxiliary equipment, such as electrical and heating, ventilation, and air conditioning (HVAC) systems, were located on the second floor. There were seven different sizes of converters and compressor drive motors, the latter ranging in size up to 300 hp. The cascade equipment was arranged in process cells containing 8 to 12 stages each.

Uranium feed from reactor returns was introduced into the cascade in 1962, resulting in contamination of the low-enrichment stages with technetium-99 ($^{99}$Tc) and neptunium-237 ($^{237}$Np). The presence of $^{99}$Tc in particular made the decontamination effort more difficult.

### Approach

Before shutting down the plant, radiological and criticality data were gathered for use in planning and executing the dismantling, decontamination, and disposal operations. Gaseous decontamination using chlorine trifluoride ($ClF_3$), a fluorinating agent, was used to remove the bulk of the residual uranium deposits. Detailed radiological surveys were performed to locate these deposits.

A detailed D&D plan was developed. The initial phase involved cutout, removal, sealing, and outdoor storage of the cascade components. This removal allowed a part of the process building housing the cascade to be demolished and the land returned to greenfield status. Other parts of the process building were reused to house equipment for size reduction of components, chemical decontamination, and melting of metal components and pieces that were difficult to decontaminate.

### Development Activities

A great deal of effort went into researching and developing cost-effective techniques for decommissioning. The key principle underlying this development work was to look outside the nuclear industry for off-the-shelf equipment that, with or without modification, would meet the D&D program needs.

The development activities performed during this period addressed the following technical issues:

- selection of a cost-effective and safe means of disassembling the plant;
- suitable size-reduction techniques and compatible ventilation and filtration systems;
- decontamination processes to deal specifically with transuranic and fission products, copper, and other metals;
- engineering safety in process equipment; and
- ensuring compatibility of waste streams with regulatory requirements.

One of the main objectives of these development activities was to minimize D&D waste by maximizing recycle for unrestricted reuse.

## Decontamination and Disassembly

The decontamination and disassembly process consisted of the following activities:

- gaseous decontamination, prior to plant shutdown, to convert solid uranium deposits, primarily uranyl fluoride ($UO_2F_2$), to volatile fluoride compounds;
- plant characterization to identify and quantify residual deposits of radioactive materials;
- removal of nonradioactive hazardous materials such as asbestos and polychlorinated biphenyls (PCBs);
- removal and interim storage of plant equipment and removal of cell structures;
- size reduction of components;
- aqueous chemical decontamination;
- melting difficult-to-decontaminate metal parts;
- removal of process and ancillary building structures; and
- disposal of radioactive and hazardous waste.

Many items, such as structural steel and concrete, required only minimal decontamination.

### *Gaseous Decontamination to Remove $UO_2F_2$*

Gaseous $ClF_3$ was circulated through the cascade prior to shutdown and dismantlement to convert solid deposits to volatile fluorides (e.g., converting $UO_2F_2$ to uranium hexafluoride, $UF_6$) prior to opening up the system. Gaseous decontamination removed an estimated 80 percent of the $UO_2F_2$ deposits, and substantially reduced the probability of a criticality accident during subsequent D&D operations. Both HVAC and physical methods were used to protect the workers and the environment.

Following gaseous decontamination, further cleanup and pretreatment operations were carried out on the static plant to locate and deal with any significant pockets of contamination that remained to permit safe and cost-effective intrusions into the plant during the dismantling campaigns. Cleanup techniques included vacuuming, ridding, and machining.

### *Characterization*

The initial characterization to identify and quantify residual radioactive contaminants was performed following gaseous decontamination. Gamma spectroscopy and neutron activation were used to characterize uranium deposits. Counters and scintillation monitors were used to identify $^{99}$Tc and $^{237}$Np deposits.

The characterization provided data on the magnitude and location of alpha (uranium) and soft beta (technetium) radionuclides throughout the plant. Nonintrusive gamma spectroscopy and neutron activation measurements provided the necessary data on $^{237}$Np and $^{235}$U.

### *Removal of Nonradioactive Hazardous Materials*

Hazardous materials, such as asbestos, PCBs, lubricants, and laboratory chemicals, were removed and disposed of using conventional technologies, including land burial for asbestos and incineration for PCBs.

### *Equipment and Cell Structures Disassembly*

The initial phase of dismantling and disassembly consisted of cutting out, removing, and storing compressors, coolers, valves, large-diameter pipe, and large-process stage units.

Specialized workshops were built for component stripping and dry cleaning. Protection of personnel was achieved by effective ventilation and extensive alpha-in-air monitoring throughout the facility. A criticality detection system was installed, and strict criticality control procedures were applied at each stage of the dismantling process.

The low-enrichment stages of the cascade had been fed with reactor recycled $UF_6$ during operations for civilian purposes. This material included small but significant quantities of transuranic elements and fission products. Safe handling of contamination such as $^{237}$Np and $^{99}$Tc had to be ensured during dismantling activities.

Following process equipment removal, the remaining cell enclosures were demolished. The materials were sold as clean scrap in the commercial metals market. The building shell was removed from about one-half of the total structure. The floors were scabbled and removed, returning that part of the structure to greenfield site status.

### *Interim Storage of Plant Components*

Before the decontamination plant was available, a large section of the process building (including the building structure and floor slab) was completely cleared to make way for construction of a new centrifuge enrichment facility. The diffusion plant cascade equipment removed was stored outdoors for up to 9 years until the new decontamination facility was available. Approximately 6,000 metric tons of contaminated components were stored, including 700 large stages weighing up to 7 metric tons each.

### *Size Reduction*

Large components, such as converter shells, piping, and compressors were reduced in size and weight to meet requirements of the decontamination plant and the melter. Cold cutting was preferred over hot cutting for aluminum components, because cold cutting does not generate fumes or airborne aluminum oxide fines, thereby reducing the need for costly HVAC systems. Robotic plasma cutting was used for size reduction of large aluminum converter shells, and remotely controlled oxyacetylene methods were used for cutting steel converter shells and other steel components. A total of 1,400 seam-welded steel shells were cut using the latter method.

The HVAC system was divided into two stages. The first stage consisted of a self-cleaning filter unit in which intermittent reverse air pulses dislodged the dust that was collected in bags at the base of the unit. The balance of particulate matter was captured in a high-efficiency particulate air filter system. The effluent air stream was monitored by stack monitors before being released to the atmosphere. Overall filtration efficiency was greater than 99.997 percent.

### *Chemical Decontamination*

A wet decontamination process was used to remove uranium contamination down to free-release levels. While chemical treatment for the removal of uranium and its daughter products is a well-established process, technetium is difficult to remove effectively. A means of removing $^{99}$Tc had to be developed before effective disposal routes could be determined. Following extensive laboratory and pilot plant investigation, a full-scale decontamination plant was built in 1989. The flowsheet was based on achieving plant discharges having a negligible impact on the environment, and on satisfying the United Kingdom statutory regulations for recycling scrap metals to the open market. Most of the uranium was removed with citric acid, followed by sulfuric acid, disodium citrate, and a hot water wash. The majority of the $^{99}$Tc and $^{237}$Np ended up in the citric acid (Anderson and Faulkner, 1989).

Separate processing plants were used to clean up the spent citric acid, sulfuric acid, and disodium citrate decontamination liquors. Ion exchange removed contaminants from the process solutions, substantially reducing the volume of waste. The ion exchange resins were encapsulated in concrete and sent to the low-level waste burial ground at Drigg.

Strict criticality control was maintained, with detectors placed at key points in the decontamination facility. The activity of each individual piece was monitored after decontamination to ensure it met the applicable release criteria.

### *Melting*

A melter was used to handle metallic components that were difficult or impossible to decontaminate cost-effectively by chemical means. The melter had several functions:

- removing impurities from aluminum, steel, and other metals to increase resale value;
- homogenizing the radioactivity in materials with varying degrees of contamination, shapes, and sizes; and
- reducing waste volume.

### *Ancillary Structures Removal*

A number of ancillary buildings and structures were demolished, including 11 large natural draft cooling towers, their pump houses, and an electrical substation. Including the floor slab, this operation produced 46,000 metric tons of clean concrete rubble for off-site disposal.

### *Waste Treatment and Disposal*

Metallic materials recovered from the plant were categorized according to their potential for sale to the commercial metals market as follows:

- clean scrap;
- contaminated scrap economical to decontaminate to de minimis level; and
- contaminated scrap uneconomical to decontaminate to de minimis level.

Clean scrap, such as cell cubicle structures, base plates, and some motors, was sold directly to the metals market. Scrap that was economical to decontaminate to de minimis levels was reduced in size, decontaminated and/or melted to homogenize the contamination, and sold. This approach was used for the bulk of the steel, copper, and aluminum components. Scrap that was uneconomical to recover, such as small-bore pipe and instruments, was dispatched to the low-level radioactive waste site at Drigg.

Approximately 99 percent of the material removed from the Capenhurst plant was recycled to the commercial markets, including bulk concrete as well as metals.

## Personnel Protection During Decommissioning

Personnel protection was achieved through multiple methods:

- strict criticality control with criticality detectors on selected operations;
- extensive alpha-in-air monitoring; and
- special HVAC systems with high-efficiency particulate air filters.

### *Criticality Control*

Criticality control was achieved by a number of actions:

- removing as much uranic contamination as possible during the size reduction, decontamination, and preparation stages;
- designing the plant to minimize the likelihood of criticality incidents; and

- using batch metering techniques to control spent citric acid movements and concentrations of $^{235}$U.

### Air Monitoring

Static personnel air samples and film badges were used throughout the project. Whole body monitoring was performed twice yearly for each D&D worker. No special dispensation or relaxation of exposure limits was given for this work.

Very low-levels of exposure were experienced by the work force. The mean total dose for 1993 was 0.03 mSv. These low-levels were achieved by sound engineering design, safe operational practices, and a methodical approach to safety.

## Similarities And Differences Between Capenhurst And The U.S. Enrichment Plants

Although the Capenhurst plant was substantially smaller than the U.S. GDPs, they have many similarities:

- similar process flowsheets and cascade arrangement;
- multistory, steel-frame and concrete buildings with transite siding;
- stages grouped into cells;
- Freon-cooled stages;
- same species of radiological contamination, including uranium (from depleted to highly enriched), $^{99}$Tc, and $^{237}$Np;
- large quantities of hazardous materials, such as asbestos, PCBs, and Freon®;
- mixture of aluminum and nickel-plated stage components;
- steam-heated autoclaves for feed vaporization; and
- purge cascade for removal of light gases.

The principal differences between Capenhurst and the U.S. GDPs are the following:

- Physical size and separative work capacity of the U.S. plants are substantially larger.
- Most of the large interstage piping at Capenhurst was aluminum, whereas U.S. GDPs use nickel-plated steel exclusively.

- U.S. GDPs have a larger number of support facilities to decontaminate and decommission than Capenhurst had. For example, the D&D scope at the Oak Ridge and Portsmouth GDPs includes centrifuge enrichment facilities. However, these were not included in the cost estimates under review by the committee.
- Capenhurst cascade equipment was located on the first floor of the process building; this equipment is located on the second floor in the U.S. plants.

## Quantity Comparisons Of Capenhurst And The Oak Ridge Gdp

Since the technology employed in the Capenhurst plant was very similar to that in the U.S. enrichment plants, a comparison of various quantities associated with them provides a means to estimate the relative cost of cleaning up the U.S. facilities. Selected quantities and design features of the Capenhurst and the Oak Ridge GDPs are shown in Table H-1. A breakdown of the quantities of various metals at Capenhurst and the three U.S. GDPs is presented in Table H-2. Table H-3 presents the ratio of Oak Ridge to Capenhurst GDP for total metals contained in the cascade, building footprint, total area under roof, weight of largest converter, and peak electric power.

A direct comparison of plant separative work capacities was not possible because the Capenhurst capacity is considered to be proprietary information. However, enrichment plant capacity (in separative work units [SWUs]/year) is nearly directly proportional to power consumption because most plant electric power usage is to drive the $UF_6$ compressors. For example, specific power consumption is reported as 2,433 Kwh/SWU for U.S. enrichment plants and 2,538 Kwh/SWU for the Eurodif plant in France, although these facilities have substantially different stage designs (Kroschwitz and Howe-Grant, 1993). Other things being equal, total $UF_6$ flow through the cascade is proportional to power and plant capacity and would also be indicative of equipment size and its associated D&D cost. Peak power delivered to the Oak Ridge GDP facilities was 1,725 MW, compared with 300 MW for Capenhurst, a ratio of 5.7.

Another consideration is that 19.7 percent of the total Capenhurst D&D cost was for technology development, which is excluded from the Ebasco cost estimate. Subtracting the cost of technology development would reduce the total Capenhurst cost from $160 million to $128 million. The cost of planning for the Capenhurst D&D was 11.6 percent of the total cost. This should not be appreciably larger for a large plant than a smaller plant when the two plants have similar systems, structures, and contaminants. Similarly, the cost of selecting the most cost-effective D&D techniques should not be substantially different, particularly when there is a substantial experience base available from Capenhurst and other successful D&D projects.

There are other factors that may increase or decrease the cost of D&D of the U.S. GDPs relative to Capenhurst. Differences in the management and contracting approach, wage rates, labor productivity, and regulatory requirements are some of the important considerations. Although the Capenhurst D&D was a government program sponsored by the Central Electricity Generating Board and the United Kingdom's Ministry of Defense, there was apparently a very high commitment to cost control, as evidenced by the relatively small number of management

TABLE H-1 Comparison of Capenhurst and Oak Ridge GDP Design Characteristics

| **Plant Design Characteristic** | Oak Ridge | Capenhurst |
|---|---|---|
| Number of buildings/structures | 82 | 19 |
| Process buildings | | |
| Number | 5 | 1 |
| Total area under roof (acres) | 116.3 | 31 |
| Total floor space (acres) | 250.6 | 64.4 |
| Length/width (ft) | | 2,880/480 |
| Structure type | Steel frame/concrete with transite siding | Steel frame/concrete with transite siding |
| Number of stages in cascade | 5,098 | 4,808 |
| Weight of largest converters (tons)[a] | 51 | 7 |
| Total quantity of metal, not including structural steel (tons) | 276.8 | 27.1 |
| Largest compressor motors (hp) | 3,300 | 300 |
| Maximum electric power (MW) | 1,725 | 300 |
| Materials of construction (cascade) | | |
| Process piping[b] | Steel/aluminum | Aluminum/steel/nickel |
| Converters[c] | Aluminum/steel | Aluminum/steel/nickel |
| Compressor balding | Aluminum | Aluminum |

[a] Because the largest Capenhurst converter had an integral compressor, the weight of the converter shown for the Oak Ridge GDP includes the converter and the compressor as well.

[b] The Oak Ridge GDP has a limited quantity of aluminum for small piping. Capenhurst used a limited quantity of nickel-plated steel for large piping.

[c] Oak Ridge GDP has aluminum for the small converters. Capenhurst used nickel-plated steel for the large converters. All steel is nickel plated. Converter barrier material is primarily nickel.

SOURCE: Clements (1993; 1994a,b); DOE (1991); briefings to committee at site visits.

personnel (Clements, 1994b). The management and contracting approach appears to include a much larger portion of the total costs associated with performing the work rather than managing it.

TABLE H-2 Comparison of Capenhurst and U.S. GDP Material Quantities (thousands of tons)

| **Material** | Oak Ridge | Portsmouth | Paducah | 3 U.S. GDPs | Capenhurst |
|---|---|---|---|---|---|
| Aluminum | 8.5 | 7.6 | 6.1 | 22.2 | 8.3 |
| Ferrous metals/steel | 103.7 | 91.4 | 74.0 | 269.1 | 14.2[a] |
| Nickel | 22.1 | 19.8 | 15.9 | 57.8 | 0.4 |
| Copper and brass | 17.6 | 15.0 | 11.7 | 44.3 | --[b] |
| Monel | 1.7 | 1.5 | 1.2 | 4.4 | --[b] |
| Miscellaneous metals | 123.2 | 105.0 | 81.9 | 310.1 | 4.5 |
| Total quantity | 276.8 | 240.3 | 190.8 | 707.9 | 27.4 |

[a] For Capenhurst, nonstructural steel was assumed to be 40 percent of the total quantity of steel; total quantity of steel (building structure plus steel components) in the Capenhurst plant was 35,500 metric tons (Clements, 1994b).

[b] Included in miscellaneous metals.

SOURCE: Clements (1993; 1994a,b); DOE (1991); briefings to committee at site visits.

TABLE H-3 Quantity Ratios of the Oak Ridge GDP to the Capenhurst GDP

| **Quantity** | Oak Ridge | Capenhurst | Ratio |
|---|---|---|---|
| Total metal quantity (tons) | 276,800 | 27,100 | 10.0 |
| Full density volume ($ft^3$)[a] | 1,208,117 | 178,742 | 6.8 |
| Total area under roof (acres) | 116.3 | 31 | 3.8 |
| Total floor space (acres) | 250.2 | 64.4 | 3.9 |
| Weight of largest converter (tons)[b] | 51 | 7 | 7.1 |
| Peak electric power (MW) | 1,725 | 300 | 5.7 |

[a] Calculated from Table H-2 by dividing the weight of each type of metal by its density and summing over all types.

[b] Because the largest Capenhurst converter had an integral compressor, the weight of the converter shown for the Oak Ridge GDP includes the converter and the compressor as well.

SOURCE: Clements (1993; 1994a,b); DOE (1991); briefings to committee at site visits.

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# Appendix I

# Waste Treatment

Waste management covers the safe and economic collection, separation, treatment, and disposal of the products coming from the decontamination process. Two general principles govern waste management: one is to avoid creating large quantities of secondary waste during treatment that must then also be treated; the other is to be guided by the trade-off between the cost of reducing the volume of waste and the cost of disposal to choose the cost-effective solution.

Waste streams vary considerably in their level of radiation contamination; accordingly, wastes from various decontamination activities must be characterized as to whether they can be released or whether they require further concentration to reduce their volume for economical disposal. Following measurement, the appropriate separation method can be selected.

The various wastes after characterization and separation can be categorized based on options for their disposal, namely:

- released without restriction;
- released for restricted use;
- sent to a landfill;
- sent to low-level radioactive waste disposal;
- sent to high-level radioactive waste disposal;
- sent to uranium storage; and
- sent on to further treatment.

A problem at the present time is that some of these classifications are very difficult, if not impossible, to assign without clearly established release criteria.

## Separations

Decontamination processes at the gaseous diffusion plants (GDPs) are likely to produce a number of waste types: gaseous, solid (from mechanical decontamination methods), and liquid (from aqueous methods). For gaseous waste streams, filtration is the major separation process used to isolate contaminants, although it can be preceded by scrubbing or cyclonic separation if there are large quantities of relatively large particles present. To remove smaller particles, the gas streams can be passed through the appropriate type of filter (e.g., bag house, electrostatic precipitator, or high efficiency filter). Any organic compounds present can be removed by combustion, catalysis, or activated carbon filters. These are all well-established technologies in current use for decontamination; detailed descriptions are given in the U.S. Department of Energy (DOE) Decommissioning Handbook (DOE, 1994).

Waste from mechanical decontamination is primarily in solid form and includes waste from scraping, scabbling, grit (or $CO_2$) blasting and related processes. In processing this waste, great care must be taken to collect any dust generated by filter systems and immobilize it, possibly by combining it with cement and disposing of it in either a landfill or as low-level radioactive waste.

Many of the waste streams from decontamination are in aqueous form. Some, such as those from washing external surfaces, may be very lightly contaminated; others, such as those from aqueous decontamination of converter interiors, may be fairly radioactive. Therefore, different technologies must be employed to concentrate the wastes from the water-based streams. The processes used to separate materials from aqueous streams are all existing technologies (DOE, 1994). Some of these processes are listed below:

- *Filtration*, which might be employed on waste streams with appreciable solid matter in suspension. The removed solids, or filter cake could be sent to a landfill or low-level radioactive waste disposal, and the water recycled through the process, or released if clean enough to meet release criteria.
- *Chemical precipitation*, in which reagents are added to an aqueous waste to precipitate as solids the materials to be separated (e.g., uranium compounds). The solids can then be removed by filtration and the water can be recycled.
- *Ion exchange*, in which specific ions (hazardous or radioactive) are removed by ion exchange media from the water, which is then either recycled or released. The ions captured by the ion exchange resins may be removed by regeneration, in which case a secondary waste stream is created that must be treated. Spent ion exchange resins can also be sent to low-level radioactive waste disposal.
- *Evaporation*, in which the excess water either evaporates at ambient temperature (as in a holding pond) or is driven off at elevated temperature. The latter process, however, is energy intensive. The residues, in either case, might be sent to a landfill or low-level radioactive waste disposal.

## Treatment Options

Waste treatment technology is summarized in Section 8.0 of the DOE Decommissioning Handbook (DOE, 1994). The major options are listed below.

- *Incineration* is suitable for organic materials and mixed wastes. Some of the wastes that can be treated effectively by incineration are as follows:
  - solids, such as contaminated soils, absorbents, biological materials;
  - liquids, such as lube oils, polychlorinated biphenyls (PCBs), and solvents; and
  - sludges from various sources.

The Toxic Substances Control Act (TSCA) incinerator at the Oak Ridge GDP is an example of this technology, which has been used successfully to treat thousands of tons of organic wastes.

- *Calcination*, in which various solid salts from precipitation processes are heated to high temperatures to convert the compounds to stable oxides, such as $U_3O_8$.
- *Grouting* is a term for solidification and immobilization of wastes in a cement matrix. This is a technology that has been practiced at some nuclear facilities (Idaho National Engineering Laboratory, Hanford, and West Valley), and a great deal of data exists regarding suitable compositions and extraction rates (Lokken, 1978). Grouting can be used for the treatment of solid wastes from scabbling of concrete surfaces, other solids from mechanical decontamination, dusts trapped by filters, solids filtered from aqueous streams, some slurries and sludges, and similar waste materials. The grout can be poured into burial vaults or containers where it sets or hardens for disposal. It seems appropriate for disposal of low-level radioactive waste.
- *Vitrification*, or solution of wastes in glass, is a treatment that has been proposed for the immobilization of high-level radioactive waste and, recently, for low-level radioactive waste Hanford wastes. Trial units have been constructed at West Valley, New York, and at Fernald, Ohio. These units are scheduled to be run in 1995. Much development work has also been done at both Savannah River and Hanford (Hrma, 1994). Waste volume reductions of up to 80 percent are claimed. Much waste gas treatment is required on these units to handle the large outgassing that occurs, particularly with high water content feeds. Although the product is less leachable than grouted waste, the equipment required (melters) is more expensive and more difficult to operate, with higher operating expenses. This method could be used for the higher activity, low-level radioactive waste; however, the costs should be carefully examined.
- *Compaction*, or mechanical crushing, is suitable for reducing the volume of such items as ductwork, piping or electrical conduit prior to further treatment (such as melt refining) or burial.

- *Melt refining* may produce a form suitably compact and purified for disposal. Melt refining has been demonstrated for removing uranium deposits from iron and other metals (stainless steel, nickel, copper, aluminum, lead, tin, lead–tin alloy). The possibility of breaking down and removing organic contaminants by contact with molten steel has also been under investigation (Nagel, 1994; Aune, 1991). By extension, there is the possibility of removing both types of contaminants together; however, the technology requires further development (Joyce, 1993).

## Recycling

Some materials resulting from the decontamination and decommissioning of the GDPs are amenable to recycling instead of waste treatment. The large volumes of scrap metal, which offer a potential economic incentive, are a particular example. Some of the advantages and disadvantages of recycling radioactive scrap metal (RSM) are given below (Cohen and Associates, 1994). Advantages of recycling RSM are as follows:

- avoidance of disposal costs;
- resource savings from use of recycled RSM in place of virgin metals;
- an immediate solution for the disposition of RSM and avoidance of surveillance and maintenance costs; and
- may be politically preferable to land disposal if the health hazards are low.

Disadvantages associated with recycling RSM are as follows:

- Health risks to workers and the general population are possible during the recycling process;
- Markets for the recycled metal must be identified, either in the nuclear industry or in general commerce. The marketplace may not accept recycled RSM, even if it has been released for unrestricted use; and
- The cost of recycling may exceed the cost of other options.

If surface contamination is low, some materials may be released under DOE guidelines, as has been done in the past (DOE, 1993). A volumetric radiological release standard, such as exists in the United Kingdom, would permit the unrestricted use of much recycled material.

Great care must be taken to ensure that release of lightly contaminated steel does not increase the residual radioactivity already present in the nation's steel supply to some unacceptable level. With the continued recycling of scrap steel, the concentration of unwanted or "tramp" constituents can increase over time to a level that inhibits the unrestricted use of steel. In the past this has occurred with other impurities from scrap gradually building up in the steel to cause problems in properties or processing.

Some lightly contaminated steel has already been smelted and cast into shielding blocks for use in facilities that handle radioactive materials. Stainless steel could be smelted and cast into slabs that could then be rolled and fabricated in a dedicated facility, such as the one at Oak Ridge, to form waste disposal canisters or casks.

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# Appendix J

# Review of Existing Cost Estimates

Several cost estimates have been developed for decontamination and decommissioning (D&D) of the U.S. gaseous diffusion enrichment plants (GDPs). In 1988, Martin Marietta Energy Systems (MMES) prepared an estimate for inclusion in the U.S. Department of Energy (DOE) Complex Modernization Study (MMES, 1988). Subsequently, between May and September of 1991, Ebasco Environmental (Ebasco) produced a series of estimates of the cost of D&D of the GDPs, with the final version, "Preliminary Cost Estimate for the D&D of GDPs," completed in September (DOE, 1991a). This estimate has been adopted by DOE as its baseline for the D&D of the GDPs.

Following the Ebasco estimate, DOE contracted with TLG Engineering (TLG) to prepare another bottom-up estimate of the GDP D&D costs (DOE, 1991b). Finally, DOE contracted with Science Applications International Corporation (SAIC) to perform a top-down review of the final Ebasco estimate and to identify areas where cost reductions could be made (DOE 1992a; Murray, 1991a,b,c, 1992a,b).

The committee reviewed various aspects of these cost estimates through presentations at its meetings (see, for example, Davis, 1994; Faulkner, 1994a,b; Fulner, 1994, Guasco, 1994a; Lemmon, 1994; Murray, 1994b). The committee also sent questions to appropriate representatives of Ebasco, TLG and SAIC. The answers to these questions were used to help the committee to clarify the analyses embodied in the cost estimates (Ebasco, 1994; Lenyk, 1994; Murray, 1994a; Guasco, 1994b). These estimates are summarized and compared in this appendix.

## MMES Estimate

In July 1988, MMES produced the "Modernization Study D&D Review" at the request of DOE's Energy Projects Branch as a part of the weapons complex Modernization Task Force. This review projected the costs for the D&D of the shutdown facilities at the Oak Ridge GDP. This estimate was made by applying the "Hanford Cost Estimating Formula" to the Oak Ridge GDP. This method applies a labor-cost formula to the cubic feet of waste in the Oak Ridge GDP facilities for three scenarios: protective (safe) storage, entombment, and return to greenfield status. Under the protective storage assumption, MMES (1988) projected an initial cost of $166 million (in 1990 dollars) with annual costs of $22 million. Under the entombment scenario, costs rise to $2.3 billion. Under the greenfield scenario, the costs rise to $8.1 billion.

The Hanford formula applies (1) a labor factor, defined as crew years/ft$^3$ of waste, and (2) waste disposal costs to waste volumes. The labor cost formula was modified by MMES, as described in its 1988 report:

> Since ORGDP [Oak Ridge gaseous diffusion plant] D&D activities deal with uranium, PCBs [polychlorinated biphenyls], and chromates and have little, if any work with hard penetrating radiation, fission products, (except Tc [technetium]), activation products or transuranics, the labor crew-years/CF [cubic foot] should be less than that experienced by Hanford. Additionally, the magnitude of the ORGDP facilities and the labor campaigns either to Greenfield or Entomb and one of the Gaseous Diffusion Cascade Buildings would logically dictate the development of site-specific cost-effective methodologies, equipments and techniques. Cost reductions due to learning curve experiences (since many of the operations would be of a repetitive nature) and the benefit of economies of scale also dictate the lowering of the Hanford Cost Formula for ORGDP use.

MMES also modified the calculation of waste disposal costs. For example, the Hanford formula assumes \$13/ft$^3$ for low-level radioactive waste (LLW), but this was increased slightly to \$15/ft$^3$ for Oak Ridge, assuming that massive quantities of LLW could not be shipped off site. Also, the cost of disposing of hazardous and mixed waste at Oak Ridge was assumed to be \$60/ft$^3$, \$25/ft$^3$ lower than the Hanford estimate.

## Ebasco Estimate

Three environmental restoration (ER) activities should be distinguished: (1) D&D of the GDPs, (2) remedial action, and (3) depleted uranium hexafluoride ($DU_6$) management and conversion. Most of the cost of ER is for D&D. For example, Ebasco estimates the costs for the D&D to be \$16.1 billion, for remedial action to be \$3 billion, and for $DUF_6$ management and conversion to be \$1.9 billion (in 1992 dollars). (The costs for remedial action and $DUF_6$ management were originally estimated by MMES and incorporated without review into the Ebasco cost estimate [DOE, 1991a].) The specified D&D activities and the cost estimates do not include environmental restoration of the soils, that is, the cost of decontaminating soil beneath or between buildings.

The Ebasco-estimated cost of D&D of the GDPs was based on two types of major D&D assumptions: DOE-directed assumptions and Ebasco assumptions (see Section 3.1.3 of the Ebasco cost estimate [DOE, 1991a]). As Table J-1 shows, between the May and September forecasts, the cost estimates were decreased by nearly \$30 billion, from \$45.6 to \$16.1 billion.

### Assumptions

#### *DOE-Directed Assumptions*

The following summarizes the DOE assumptions given in the Summary Document of Ebasco's final cost estimate (DOE, 1991a; see Subsec. 5.1.2.1, vol. 1):

TABLE J-1 Ebasco's 1991 Cost Estimates (millions of 1992 dollars)

| **Cost Category** | May | June | July | August | September |
|---|---|---|---|---|---|
| D&D (WBS 1.4) | | | | | |
| Direct | $4,141 | $3,819 | $3,318 | $3,303 | $3,412 |
| Indirect percentage | 50% | 50% | 50% | 50% | 43% |
| Total | $6,212 | $5,729 | $4,977 | $4,955 | $4,879 |
| **Support facilities (WBS 1.6)** | | | | | |
| Direct | $10,050 | $9,293 | $3,446 | $3,547 | $2,436 |
| Indirect percentage | 50% | 50% | 50% | 50% | 43% |
| Total | $15,075 | $13,940 | $5,169 | $5,321 | $3,483 |
| **Waste management (WBS 1.2)** | | | | | |
| Direct | $1,118 | $808 | $903 | $757 | $689 |
| Indirect percentage | 50% | 50% | 50% | 50% | 43% |
| Total | $1,677 | $1,212 | $1,355 | $1,136 | $985 |
| **Program integration (WBS 1.1)** | | | | | |
| Direct | $5,844 | $2,773 | $2,334 | $2,201 | $1,796 |
| Indirect percentage | 50% | 50% | 50% | 50% | 43% |
| Total | $8,766 | $4,160 | $3,501 | $3,302 | $2,568 |
| Subtotal direct + indirect | $31,730 | $25,041 | $15,002 | $14,714 | $11,915 |
| Contingency (w/o WBS 1.1) | $7,467 | $6,842 | $3,596 | $3,572 | $3,229 |
| Construction Management | $4,574 | $4,167 | $756 | $751 | $468 |
| on all but WBS 1.1 | 15% | 15% | 5% | 5% | 5% |
| M&O fees (5% on all but WBS 1.1) | $1,753 | $1,597 | $794 | $788 | $491 |
| Subtotal rollup | $13,794 | $12,607 | $5,147 | $5,110 | $4,188 |
| Total | $45,524 | $37,648 | $20,149 | $19,824 | $16,103 |

NOTE: WBS, Work Breakdown Structure; M&O, Management and Operations. Some error is introduced because of rounding calculations.

SOURCE: Prompt cost summary table, Case 1, initial estimate, in Ebasco Environmental (1991a); pp. 20, 29 in Murray (1991a); D&D of Gaseous Diffusion Plants, prompt cost summary, all case studies table in Ebasco Environmental (1991b); DOE (1991a).

- The plants will be promptly decontaminated and decommissioned following cessation of operations.
- Where technically and economically feasible, equipment, materials, and structures will be decontaminated for unrestricted release.
- The products of D&D will comply with the criteria referenced in DOE Order 5400.5.
- Standards governing acceptable levels of radioactivity for unrestricted release will be established by the Nuclear Regulatory Commission and the Environmental Protection Agency in time for use in the D&D effort.
- New decontamination facilities will be constructed only at the K-25 site, thus requiring transport of contaminated equipment and materials from the Portsmouth and Paducah sites to the K-25 site for decontamination. The residually contaminated materials will be returned to the originating site for disposal. The decontamination facilities will not be decontaminated or decommissioned at the conclusion of the GDP facilities D&D effort.
- The decontaminated facilities will not be restored to minimum safety standards.
- Existing facilities will be used for administration functions to the extent possible.
- Contaminated solids will be incinerated in the Toxic Substances and Control Act (TSCA) incinerator at the K-25 site, with the ashes returned to the originating site for final disposal.
- The presently classified portions of the GDP facilities will be declassified before commencing D&D of those facilities.
- The Portsmouth and Paducah plants will have any uranium deposits within the process systems removed as part of the plant shutdown process to avoid any criticality problems during D&D and to relax special nuclear materials security requirements.
- All non-D&D related wastes presently stored within the GDP buildings will be returned to the waste generator at no cost to the D&D program.
- Appropriate factors for contractor overhead and profit will be applied to all direct costs.
- A factor of 5 percent for contract management will be applied to all cost elements except Program Integration.
- No restoration of soils near and under the buildings will be included as part of D&D.

### *Ebasco Assumptions*

Additional assumptions were made by Ebasco:

- Assumed uranium concentrations in waste streams will be based on process knowledge because characterization data is not available.
- All uranium waste streams will be sent to the Y-12 plant for uranium recovery.
- A mobile gaseous decontamination unit will be used to remove uranium deposits from within the process systems before disassembly.
- The gaseous decontamination process will remove at least 90 percent of residual uranium in the process equipment, reducing the content to below the special nuclear materials security control limit.
- Construction and operation of two decontamination facilities—the high-assay decontamination facility (HADF) and the low-assay decontamination facility (LADF)—will be required for decontamination and volume-reduction of contaminated components.
- The operational availability of the HADF and LADF will be 65 percent.
- Residual Freon™ will be destroyed using a catalytic burner system.
- Polychlorinated biphenyl (PCB) contamination on duct surfaces will be removed by rinsing.
- All building floors are contaminated with uranium.
- All paint is lead-based and, when removed, will be solidified and disposed as Class I LLW.
- All asbestos-containing materials will be classified as Class I LLW.
- All asbestos-bearing transite siding will be considered nonfriable.
- Selected materials and equipment will be classified as Class III LLW.
- Appropriate criteria will be available for on-site disposal of uranium-contaminated and/or hazardous materials in Class I or Class III disposal facilities at Oak Ridge, Portsmouth, and Paducah.
- Transformers and capacitors are contaminated with PCBs and will require two volume changes of oil to remove the PCBs. The oils will be incinerated in the TSCA incinerator.

- Cooling water and cooling tower sludges will contain uranium contamination but no hexavalent chromium.
- No high-energy sources of gamma radiation are present in the facilities.
- Standard commercial waste containers will be used for waste packaging (i.e. 55-gallon drums and B-25 containers).
- Reduction and expansion of waste volumes will result from the different processes applied to the various waste streams arising from the D&D operations. Detailed assumptions are given in Table 5.1-1 of the Ebasco cost estimate (DOE, 1991a).
- Transportation between GDP sites and to disposal sites will be by truck.
- Disposal locations are within 10 miles of each GDP site.
- Storage costs include a 20-acre paved pad at each GDP site.

## The Assumption of New High- and Low-Assay Decontamination Facilities

The assumption of constructing and operating two large new facilities for equipment decontamination, volume-reduction, and packaging and for assaying the uranium content of the resulting waste packages before shipment to a disposal site has major cost implications. The postulated HADF, which is intended to handle equipment and materials contaminated with uranium enriched to 20 percent uranium-235 ($^{235}$U) or greater, contains 192,000 gross square feet of floor space. The facility is designated as a Special Nuclear Materials Security area, requiring the appropriate security and accountability capabilities. The postulated LADF, which is intended to handle equipment and materials contaminated with uranium enriched to less than 20 percent $^{235}$U, contains 1,241,600 gross square feet of floor space, comparable in size to the K-27 or K-31 gaseous diffusion buildings.

Each facility contains equipment for decontamination and size-reduction of GDP components and waste materials and equipment for assaying packaged wastes to ensure that the residual uranium content of the packages meets disposal site acceptance criteria for uranium contamination before shipment. The postulated decontamination equipment includes gaseous decontamination, high-pressure, water-spray decontamination, and incinerators for liquids and combustibles. Treatment capabilities are provided for stabilization and solidification of sludges, powders, and ashes and for wastewater cleanup. Capabilities for process equipment segmentation and size-reduction before packaging are also provided, including plasma-arc cutting systems and supercompaction. Rinsing capability for components contaminated with PCBs is also provided. The assay systems are postulated to include passive-active neutron interrogation, segmented gamma scanners, and real-time radiography.

The HADF and LADF were assumed to be constructed only at the Oak Ridge GDP. Contaminated materials and equipment from Portsmouth and Paducah are postulated to be transported to Oak Ridge for final decontamination and packaging. However, both Portsmouth and Paducah are postulated to construct a certification facility containing packaging and assay equipment similar to that described previously for the LADF at Oak Ridge.

Estimated construction costs for the HADF and LADF at Oak Ridge are $269 million and $926 million, respectively; the operating costs for 11 years are $228 million and $677 million, respectively (all costs are in 1992 dollars and do not include contingency). The capital costs for the certification facilities at Portsmouth and Paducah are estimated to be $62 million and $59 million, respectively, without contingency. The operating costs for these facilities are estimated to be $740 million (10 years) and $476 million (8 years), respectively, without contingency. Thus, the construction and operation of these facilities contribute nearly $3.437 billion to the total D&D cost, without contingency.

## Analysis of the Ebasco Estimate

There are five cost categories in the Ebasco estimate: (1) Decommissioning and Decontamination (D&D), Work Breakdown Structure (WBS) item 1.4; (2) Support Facilities, WBS 1.6; (3) Radioactive-Hazardous Waste Management, WBS 1.2; (4) Program Integration, WBS 1.1; and (5) Rollups (including contingency and construction management on all but WBS 1.1 and M&O on all but WBS 1.1). The first three cost categories include decontaminating the GDPs and disposing of the resulting waste. The Program Integration and Rollups categories require explanation (see DOE, 1991a, Sec. 3.2.1.1):

> Program Integration includes the costs associated with the project oversight by the M&O Contractor, the Construction Manager, the Remedial Design Engineer, and the costs of an environmental impact study for each of the three sites. The markups for the Construction Manager include subcontract management, field indirects, overhead profit, and contingency. The M&O Contractor markups include surveillance and maintenance, additional security, contractor design and review, contractor construction engineering, health physicists, overhead adders and markups on construction management.

In interpreting these cost estimates, care should be taken to distinguish between "indirects" and rollups. In Table J-1, indirects are represented as a percentage of the direct costs for each WBS category. For estimates May through August, the indirect rate is equal to 50 percent, a value equal to a 30 percent add-on for field indirects, a 3.3 percent add-on for home office overhead (3.3 percent of both direct and field indirects), and a contractor's profit of 12 percent (12 percent of direct and indirect costs and overhead). (A 50 percent addition, or a total of 1.5 times direct cost, is equal to 1.3 × 1.033 × 1.12.) The indirect rate was reduced to 43 percent in the September estimate by lowering the field indirect rate to 26 percent and the contractors profit to 10 percent (1.43 is equal to 1.26 × 1.033 × 1.10).

Other rollups include contingency, construction management (on all but program integration), and the M&O fee (on all but program integration). Contingency, an allowance for unanticipated costs, varied across the three GDPs: for Oak Ridge the contingency rate in the September estimate was 24 percent, for Paducah it was 36 percent, and for Portsmouth it was 39 percent. In the May through August estimates, the contingency allowance was added before calculating construction management and M&O fees. The September estimate adds a contingency allowance after these fees are calculated. The construction management fee on all but program integration, which is in addition to all of the indirects, declined from 15 percent in the May and June estimates to 5 percent in all later estimates. The M&O fees on all but program integration, which is in addition to the construction management fee, is 5 percent in all estimates.

At the bottom of Table J-1, the calculated relationships between direct costs, indirect costs, program integration costs, rollups, and the total cost are presented. Direct costs, not including direct program integration costs, increased as a percent of total costs from 34 to 41 percent from the May estimate to the September estimate. Indirect costs plus program integration costs as a percent of total costs declined from 36 percent to 33 percent from the first to last estimate. Rollups as a percent of total costs declined from 30 to 26 percent. Again, total costs declined from $45.6 to $16.1 billion. Where were cost cuts made?

Much of the change between the May and September estimates resulted from the elimination of the Support Facilities category. The May and June estimates assume that LADFs will be built at each GDP and a single HADF will be built at Oak Ridge. The estimated direct cost for one LADF is $3 billion and for the HADF is $823 million. In the July estimate, full-scale LADFs were eliminated at Paducah and Portsmouth, and metal smelting and refining were eliminated at the HADF. (Note that there is no similarly dramatic decline in the costs of program integration between June and July.) Direct costs decline for these facilities at Oak Ridge in the September estimate to $1.6 billion for the LADF and $497 million for the HADF. Also, the costs of new administration facilities (office buildings) at each site change from the May estimate to the September estimate. At Oak Ridge, the cost of the new office building decreased from $29.7 to $25.4 million. At Paducah and Portsmouth, the cost of the new office buildings decreased from $29.7 to $12.4 million at each site.

Other changes between the estimates include a decline in engineering costs (included in the direct cost estimates) between the May and June estimates; a compression in the time for D&D at Paducah and Portsmouth from 12 years to 6 and 7.5 years, respectively, between May and June; the elimination of soil handling and the decontamination of support facilities between the July and August estimates; and a reduction in the size and operating costs for the support facilities between August and September. Minor changes between the estimates are documented in Murray (1991a).

To summarize, in the 1991 Ebasco cost estimates, the direct cost of D&D and waste management changes little from May to September, remaining in the $4.1 to $5.3 billion range. The direct costs for support facilities decline from $10 to $2.5 billion. Program integration, indirect costs and rollups, including overheads, fees, profits, and contingencies, declined from $30 billion (66 percent of the May total) to $9.5 billion (59 percent of the September total). Although further cost reductions in the direct cost of D&D and waste management would reduce total costs, changes in project management are likely to have a larger impact on these costs.

## Comparison Of The 1988 MMES And 1991 Ebasco Studies

Table J-2 compares the MMES greenfield cost estimate (the MMES cost estimate based on assumptions most like those of the Ebasco estimates) with the Ebasco estimates of May and

TABLE J-2 Comparison of MMES and Ebasco Cost Estimates (millions of dollars)

| | | **Ebasco 1991 (1992 dollars)** | | | |
|---|---|---|---|---|---|
| | | May | | September | |
| Cost Category | MMES (1990 dollars) Oak Ridge GDP | Oak Ridge GDP | All GDPs | Oak Ridge GDP | All GDPs |
| D&D (WBS 1.4) | | | | | |
| Direct | | $1,869 | $4,141 | $1,356 | $3,412 |
| Indirect percentage | | 50% | 50% | 43% | 43% |
| Total | | $2,804 | $6,212 | $1,939 | $4,879 |
| **Support Facilities (WBS 1.6)** | | | | | |
| Direct | | $3,899 | $10,050 | $1,484 | $2,436 |
| Indirect percentage | | 50% | 50% | 43% | 43% |
| Total | | $5,849 | $15,075 | $2,122 | $3,483 |
| **Waste Management (WBS 1.2)** | | | | | |
| Direct | | $472 | $1,118 | $246 | $689 |
| Indirect percentage | | 50% | 50% | 43% | 43% |
| Total | | $708 | $1,677 | $352 | $985 |
| **Program Integration (WBS 1.1)** | | | | | |
| Direct | | $2,312 | $5,844 | $1,009 | $1,796 |
| Indirect percentage | | 50% | 50% | 43% | 43% |
| Total | | $3,468 | $8,766 | $1,443 | $2,568 |
| Subtotal direct + indirect | $5,788 | $12,829 | $31,730 | $5,856 | $11,915 |
| Contingency (w/o WBS 1.1) | $2,315 | $2,828 | $7,467 | $1,169 | $3,229 |
| Construction Management | | $1,832 | $4,574 | $221 | $468 |
| On all but WBS 1.1 | | 15% | 15% | 5% | 5% |
| M&O Fees (5% on all but WBS 1.1) | | $702 | $1,753 | $232 | $491 |
| Subtotal Rollup | | $5,363 | $13,794 | $1,622 | $4,188 |
| Total | $8,103 | $18,192 | $45,524 | $7,478 | $16,103 |
| Ratio of Oak Ridge to Total | | 40% | | 46% | |

NOTE: WBS, Work Breakdown Structure; M&O, Management and Operations.

SOURCE: MMES (1988); Prompt Cost Summary Table, Case 1, Initial Estimate, in Ebasco Environmental (1991a); tables 3.2-1 and 3.2-2 in DOE (1991a).

September of 1991. However, direct comparison of the MMES and Ebasco estimates is not possible. First, the MMES estimate does not identify direct and indirect costs or specify construction management or M&O contractor fees. The MMES estimate does include a contingency of 40 percent for all large facilities. To compare the estimates, indirect costs and rollups are assumed to be included in the MMES labor cost and waste disposal formulas.

Second, $2.751 billion of remedial action activities have been included in the MMES greenfield cost estimate.[1] Remediation costs are not included in the Ebasco D&D cost estimate and should be removed from the MMES estimate for purposes of comparison. Subtracting the cost of such remedial action from the MMES total cost estimate reduces its value from $8.103 to $5.352 billion.

Third, this resulting $5.352 billion estimate was adjusted to 1992 dollars with the GNP implicit price deflator: 1.039 for 1991, and 1.029 for 1992 (see Clinton, 1994, p. 276.) This calculation increases the estimate to $5.722 billion.

Fourth, it must be stressed that these MMES estimates are for Oak Ridge GDP only. The MMES estimate for Oak Ridge GDP has been extrapolated by the committee to arrive at an estimate for all three GDPs. This was done by dividing the MMES cost estimate for D&D of the Oak Ridge GDP by the ratio of the Oak Ridge GDP cost to the total cost for D&D of all sites given in Ebasco's May and September estimates. Those ratios are about 40 percent in the May estimate, and 46 percent in the September estimate (see Table J-2). This increased the MMES estimate to $14.319 billion for a ratio of 40 percent, and to $12.322 billion for a ratio of 46 percent. Of course, this scaling analysis assumes that the MMES-Hanford approach would anticipate a distribution of support facilities and other resources among the sites similar to that assumed by Ebasco.

Although the modified MMES cost projection is much lower than Ebasco's May 1991 estimate, it is similar to Ebasco's September 1991 estimate. These estimates are much larger than MMES's estimate of safe storage: $166 million to implement and $22 million per year, which sum to less than $1 billion for 40 years (assuming a discount rate of zero). The cover letter to the Modernization Study D&D Review concludes:

> In summary, we believe that the estimates for implementing safe storage and maintenance and surveillance of the shutdown facilities are reasonable and form our recommended action over the next decade. The actions implied by "entombment" and "greenfield" [scenarios] require a great deal of further study. Our current feelings are that other strategies will be adopted for the ORGDP [Oak Ridge GDP] facilities. Due to the limited time to prepare these estimates and the need for self-consistent documentation establishing the regulatory position and engineering feasibility, the cost projections should be considered rough order of magnitude only.

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[1] The MMES estimate notes "the following costs for $Cr^{+6}$ [hexavalent chromium] and PCB contaminated soils and foundations have been included for the facilities as listed," but the "inventory of TSCA wastes, sludge fixation, stored wastes in the K-25 Building, and $UF_6$ tails are ***not*** in any of these MTF [Modernization Task Force] D&D summaries."

Therefore, the MMES estimate should not be given as much consideration as later estimates. However, it does provide another approach (i.e., the application of the Hanford formula) to the problem of forecasting D&D costs for the GDPs.

## TLG Cost Estimate

Following completion of the Ebasco cost estimate, DOE contracted with TLG to perform another bottom-up estimate for the GDPs (DOE, 1991b). The TLG estimate used most of the same assumptions and the same inventory of structures and equipment as did the Ebasco estimate.

Several assumptions were made by TLG that are different from or are in addition to the assumptions made by Ebasco:

- Internally contaminated process equipment will be packaged and shipped to the Nevada Test Site (NTS) for disposal after only the required external decontamination. Little or no volume-reduction of the equipment will be done.
- Disposal charge rates at NTS are $8/ft^3$.
- Floors, walls, and ceilings are assumed to be contaminated to varying degrees.
- The empty structures will be decontaminated to unrestricted release levels and demolished. No site restoration will be done.
- Nuclear liability insurance and property taxes are included in the cost estimate.

One of the principal differences in these two sets of estimates was that TLG assumed the converters and associated equipment would not be decontaminated internally but would be sealed and externally decontaminated and shipped intact to the NTS for disposal, at a disposal rate of $8/ft^3$. Another major difference was the duration of the assumed D&D effort: 8 years for TLG, and 11 years for Ebasco. Overall, the cost of D&D for the U.S. GDP complex as estimated by TLG was $13.9 billion. The many smaller differences are discussed in some detail in Chapter 4.

## Saic Review

DOE contracted with SAIC to perform a top-down review of the Ebasco estimate, with a focus on reducing costs (DOE, 1992a,b). The estimate resulting from this review (SAIC's Working Draft Cost Estimate) is compared with the Ebasco September estimate in Table J-3.

TABLE J-3 Comparison of SAIC and Ebasco Cost Estimates (in millions of 1992 dollars)

| **Cost Category** | Ebasco (September) | SAIC |
|---|---|---|
| D&D (WBS 1.4) | | |
| Direct | $3,412 | $3,931 |
| Indirect percentage | 43% | 14% |
| Total | $4,879 | $4,481 |
| **Support Facilities (WBS 1.6)** | | |
| Direct | $2,436 | $359 |
| Indirect percentage | 43% | 14% |
| Total | $3,483 | $409 |
| **Waste Management (WBS 1.2)** | | |
| Direct | $689 | $446 |
| Indirect percentage | 43% | 14% |
| Total | $985 | $508 |
| **Program Integration (WBS 1.1)** | | |
| Direct | $1,796 | $2,251 |
| Indirect percentage | 43% | 0% |
| Total | $2,568 | $2,251 |
| Subtotal Direct+Indirect | $11,915 | $7,649 |
| Construction Management (5% on all but WBS 1.1) | $468 | $269 |
| M&O or Environmental Remediation Management Contractor (ERMC) Fees | $491 | $339 |
| | 5% | 6% |
| Contingency (w/o WBS 1.1) | $3,229 | $1,185 |
| Subtotal Rollup | $4,188 | $1,794 |
| Total | $16,103 | $9,443 |

NOTE: WBS, Work Breakdown Structure; M&O, Management and Operations.

SOURCE: DOE (1991a, 1992a).

### Sensitivity Analysis In The Cost Estimates

How have the earlier cost estimates analyzed the inherent uncertainties in the cost estimating procedure? The Ebasco estimate of 1991 includes an analysis of risk and uncertainty; the TLG 1991 cost estimate includes a discussion of uncertainty,; and the SAIC analysis of 1992 includes a discussion of risk (DOE, 1991a,b, 1992a,b). Each estimate contributes to the general discussion of risk and uncertainty, but none of them provides a sensitivity analysis.

Ebasco focused on the effect of changes in key assumptions on estimated cost, including the following:

- constructing and operating LADFs at Paducah and Portsmouth, which increases costs by 17.2 percent;
- refurbishing buildings undergoing D&D, which increases costs by 3.3 percent;
- constructing new administration buildings at Paducah and Portsmouth instead of refurbishing existing buildings, which increases costs by 0.3 percent;
- incorporating electrorefining capabilities at Oak Ridge, which decreases costs by 1.8 percent;
- providing HADFs at Oak Ridge and Portsmouth and LADFs at all sites, which increases costs by 21.6 percent;
- transporting Portsmouth X-326 equipment (processed highly enriched uranium) to Oak Ridge for processing, which increases costs by 1.8 percent;
- eliminating de minimis waste streams, which increases costs by 0.7 percent;
- transporting all waste to Hanford for disposal, which decreases costs by 2 percent; and
- decontaminating the LADF, HADF, and the assay facilities, which increases costs by 2 percent.

Also, for each of these alternatives, Ebasco examined the effect of increasing the Construction Manager's fee from 5 to 15 percent and the M&O contractor overheads to 42 percent during preconstruction and to 49.5 percent during construction at Oak Ridge, to 60 percent at Portsmouth, and to 70 percent at Paducah. The increase in the Construction Manager's fee to 15 percent reflects Ebasco's assumptions in its May and June 1991 estimates. There was no explanation of why the alternative overhead rates were selected.

Although Ebasco analyzed how its cost estimate changed with changes in these assumptions, it focused on assumptions within the scope of DOE decision making. The analysis did not discuss uncertainty or how it determined a confidence level of from +50 percent to -30 percent for the cost estimate.

TLG was much more explicit in quantifying uncertainty in its analysis. TLG focused on four types of uncertainty:

- pricing uncertainty, which addresses uncertainties in predicting the costs of goods and services before their actual purchase;
- scope omission and error, which is intended to cover miscommunications, miscalculations, and scope mistakes;
- schedule uncertainty, to cover changes in the project schedule duration; and
- expansion of scope, which provides for expansions in the projected scope, owing to unrecognized elements of the work at the time of the estimate.

TLG recognized, but did not incorporate, two other types of uncertainty:

- escalation in the price of materials, equipment, and labor over the life of the project; and
- acts of nature, such as tornadoes, floods, or earthquakes.

TLG performed a Monte Carlo simulation assuming triangular probability distributions for each uncertainty: pricing uncertainty varied between -26 percent and +25 percent for a single line item; scope omission and error varied from -15 percent to +15 percent; schedule uncertainty ranged from -10 percent to +15 percent; and expansion of scope ranged from -15 percent to +15 percent. In the 2,500 Monte Carlo samples, values for these uncertainties were randomly selected from the probability distributions. Levels of confidence were calculated from the resulting cost estimates. Using this approach, under these probability distributions, TLG determined that there was a 50 percent chance that the cost of the project would be below $16.2 billion and a 100 percent chance that the cost would be below $28.7 billion (in 1992 dollars). These figures can be compared to a base estimate of $13.9 billion.

The SAIC estimate contains an interesting discussion of the difference between uncertainty and contingency but does not provide a case analysis, as does Ebasco, or a probability analysis, as does TLG. The SAIC report identifies four key institutional risks:

- lack of Below Regulatory Concern standards;
- lack of declassification of the converters before decommissioning;
- lack of final disposal sites for the wastes generated by the D&D process; and
- lack of a transportation plan from the GDPs to the waste sites.

SAIC does not calculate potential changes in its cost estimate owing to these uncertainties.

Although these estimates hint at an analysis of how uncertainty would influence the cost of the project, none addresses uncertainty in a rigorous way.

## Schedule And Funding Profiles

Schedule and funding profiles can be derived from the cost estimation process. Calculating a funding profile involves assigning time length to each task, organizing tasks in a logical schedule and determining a critical path, assigning costs to each task in each period, and summing the costs for each period and for the length of the project. A more complete analysis also includes discounting to the present or calculating costs using escalated dollars. Only the SAIC estimate included escalating dollar figures.

In this section, the schedule assumptions in Ebasco's September estimate and in the TLG and SAIC estimates are discussed. The MMES estimate (1988) does not discuss scheduling or funding profiles. The Ebasco estimate gives the most complete discussion of the assumptions and methodology underlying its schedule and funding profiles (DOE, 1991a). TLG provides a brief description of the schedule, but does not give a funding profile (DOE, 1991b). SAIC presents detailed figures for the schedule and detailed tables of the funding profile, but the underlying assumptions are scattered throughout the analysis (DOE, 1992a,b). Therefore, the focus is on Ebasco's cost estimate and a comparison of the other estimates with that of Ebasco.

The Ebasco approach is detailed under "Schedule/Resource Cost" (Sec. 5.3) in its cost estimate and is summarized under "Schedule" (Sec. 3.3) of the estimate. To summarize, the Ebasco schedule assumes expenditures of $16 billion (unescalated 1992 dollars) over 37 years, with a peak 9 years into the program at just over $600 million. This peak coincides with the construction of the support facilities at Oak Ridge (HADF and LADF). D&D operations at the three sites are sequential: Oak Ridge is decontaminated between years 9 and 19; Paducah is decontaminated between years 20 and 27; and Portsmouth is decontaminated between years 28 and 37 (year 1 is equal to 1994; year 37 is equal to 2031). These periods are primarily determined by the time required to decontaminate a converter, which is discussed below.

For scheduling purposes, the major phases of the project include the following activities: (1) engineering/design and permitting, including mobilization, site characterization, environmental assessment, environmental impact statements, permits and approvals, and design and engineering; (2) procurement; (3) construction of the support facilities, including design and construction of administration and certification facilities, construction of the HADF, and construction of the LADF; (4) D&D operations; and (5) site preparation and construction of storage facilities, including design and construction of waste disposal facilities and transportation and final disposal of waste.

The schedule was generated:

> Using the cost estimate of workhours developed for the D&D program, durations were developed for each sub-element activity, with each activity then tied to one

> another in their logical sequence of progression to develop logic networks for the program. This logic data was then loaded into a micro-computer based scheduling program (Primavera project planner), which generated the schedule, determined overall project duration and identified critical path. (p. 5-199)

The critical path flows from years 1 to 5 with engineering/design and permitting at Oak Ridge (assumed to be completed in 54 months at Oak Ridge and later, in 48 months, at Paducah and Portsmouth), from years 6 to 9 with the construction of the LADF and HADF (assumed to be constructed only at Oak Ridge), from years 9 to 19 with the D&D of Oak Ridge, from years 20 to 27 with the D&D of Paducah, and from years 28 to 37 with the D&D of Portsmouth.

In the Ebasco cost estimate (DOE, 1991a), the gaseous decontamination of converters is on the critical path for determining the length of the project:

> The overall duration for the D&D effort at Oak Ridge is driven by the gaseous decontamination of the K-25 building converters. The 2,928 converters in K-25 will be decontaminated in the HADF with each requiring an assumed four days (small converter) for sufficient gaseous decontamination given that operations are conducted seven days a week on a continuous basis. This represents a total operations time for the gaseous decontamination in the HADF of 32 years. Utilizing three gaseous decontamination stands simultaneously in the HADF reduces the operating time to roughly 10.7 years. The 2,080 remaining converters at other locations throughout the Oak Ridge Site will be processed through the three gaseous decontamination stands in the LADF. The assumed five days (large converter) decontamination time results in 9.5 years of operation for the LADF. The HADF and LADF will be operated concurrently, therefore, the total schedule for Oak Ridge decontamination process is 11 years. (p. 5-200)

Similar calculations are made for Paducah for its 1,820 large, low-assay converters. With three gaseous decontamination stands in the Oak Ridge LADF, Paducah's converters could be decontaminated in 8 years. At Portsmouth, the 2,880 small, high-assay converters would require 10.5 years in the Oak Ridge HADF, and the 1,140 large, low-assay converters would require 5.2 years to decontaminate in the Oak Ridge LADF. Therefore, the length of the project is driven by the assumption of gaseous decontamination. The Ebasco cost estimate does not consider other decontamination technologies.

The Ebasco cost estimate also includes the cost in each period by determining the work-hours, necessary materials and equipment, and associated indirect costs for each activity. The calculation of labor, materials, and equipment costs is a straightforward multiplication of costs per unit multiplied by the number of units. The calculation of indirect costs was more complicated:

> Direct workhours only represent one component of the total workhours against a given WBS cost account. The other component is the workhours associated with indirect costs which represent management and administrative personnel to oversee contract work. The cost estimate uses a 26% mark-up on top of direct costs to cover indirect costs. The values associated with 18% of the indirects'

> 26% mark-up have been used to project the contractor's staffing costs. Eight percent of the total represents non-staffing overheads (i.e., office space, telephone, reproduction costs, etc.). The estimating team also felt that a unit rate of forty dollars per hour ($40/hour) would be the appropriate factor for establishing the indirect workhours from any dollar estimates. Based on this, the total direct cost associated with a cost account was multiplied by eighteen percent and then divided by the forty dollar per workhour unit rate to establish the indirect workhours against any given cost account (Indirect Hours = Direct Cost X 18% / $40 per hour). It is noted that this was not done for Program Integration, as indirect costs/workhours were considered in the original estimate basis and therefore no additional mark-up was necessary. (DOE, 1991a, p. 5-202)

Therefore, there was no determination of the types of management or administrative personnel required. Implicitly, if materials and equipment are one-third of direct cost (see DOE, 1992a) and unit labor rates are $40 per hour, the cost estimate assumes one indirect manager or administrator for every four direct laborers and supervisors (100 percent-33 percent)/18 percent).

Finally, the Ebasco cost estimate includes calculations of resource requirements during the project and converts there into cost curves. Total personnel is calculated over time to show the maximum personnel requirements. The resulting figures are approximately 6,800 people at Oak Ridge, 4,600 people at Paducah, and 5,700 at Portsmouth (DOE, 1991a, p. 5-202). These figures compare to current employment at Paducah and Portsmouth of 1,758 and 2,581, respectively.[2] Total dollars are plotted to show cash flows in Figure 5.3-17 in the Ebasco cost estimate (DOE, 1991a). However, the axes in the figure appear to be mislabeled. If the right border represents billions of 1992 dollars (not thousands of full-time equivalents), there is a linear cumulative expenditure curve from year 7 to 37 with a $16 billion total. This implies nearly constant annual expenditures of approximately $530 million per year for 30 years. Unfortunately, the Ebasco cost estimate does not detail annual expenditures, so escalated dollars or present value cannot be calculated easily (DOE, 1991a).

The "Schedule Estimate" of the TLG cost estimate (Sec. 5, pp. 38-45) presents a schedule (calculated with Microsoft Project for Windows 1.0, 1990) assuming: (1) all work is performed during an 8-hour workday, 5 days per week with no overtime, (2) "manhour estimates allow for a crew morning and afternoon break of 15 minutes duration each, and time for the crew to transit for lunch and end-of-shift clothing changes," and (3) crews work parallel activities to the maximum extent possible. Because TLG assumes minimal decontamination of the gaseous diffusion equipment (e.g., "the DOE gaseous decontamination process will remove sufficient residual high- and low-enriched uranium from the process systems at all tree sites to render them free of criticality concerns, free of safeguard concerns, and transportable in standard shipping containers for disposal," p. 33), decontamination is completed in 8 years at Oak Ridge from December 1993 to February 2002, in 4 years at Paducah from January 2005 to November

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[2] Based on a fact sheet distributed at the committee's meeting in Paducah, October 20, 1994, and at the Portsmouth plant, August 22, 1994.

2008, and in 4.5 years at Portsmouth from January 2005 to May 2009. No cash flow curves are presented.

The SAIC estimate assumes that the technical approach and the National Environmental Protection Act Record of Decision will be completed in 1995 for Oak Ridge, in 2001 for Paducah, and in 2003 for Portsmouth (DOE, 1992a, b). The estimate also assumes that D&D will begin in 1998 at Oak Ridge, in 2005 at Paducah, and in 2007 at Portsmouth and that documentation and verification will be completed in 2010 at Oak Ridge, in 2014 at Paducah, and in 2016 at Portsmouth. Funding profiles are given in detailed tables for each year, including federal and contractor full-time equivalents (person years), cost of materials, and total costs.

The three estimated schedules discussed in this section project very different end dates and total costs. TLG forecasts a project start in January 1992 and project completion in August 2009; that is, 17.5 years, at a total cost of about $14 billion (in 1992 dollars), or an average spending rate of $800 million per year. SAIC forecasts a project start in 1991 and project completion in 2016; that is, 26 years, at a total cost of about $9.5 billion (in 1992 dollars), or an average spending rate of $365 million per year. Ebasco forecasts a project start in 1994 and project completion in 2031; that is, 38 years, at a total cost of about $16 billion (in 1992 dollars), or an average spending rate of $420 million per year. Without access to the models that generated these projections, the differences between these estimates cannot be reconciled.

## Waste Management

The expected waste volumes and waste management costs estimated by Ebasco and TLG for the gaseous diffusion plants are summarized in Table J-4. Because of different assumptions used for the site characterization, the waste volume of the TLG estimate is approximately 2.9 times higher than that of Ebasco. The total waste management cost (excluding contingency) estimated by Ebasco and TLG amount to roughly $1 and $1.5 billion, respectively (DOE, 1991a,b).

The major elements of waste management costs include the costs for packaging, transportation, and disposal. A fourth element, storage, was assumed by Ebasco to accommodate the temporary storage of packaged waste materials for segregation and staging for disposal.

According to the Ebasco study, the estimated direct costs for packaging and line-haul transportation were primarily based on price quotations from commercial organizations. Estimated direct costs for disposal and storage relied on construction and operations of the waste disposal and storage facilities at each GDP site. Other associated costs include indirect costs, home office overhead costs, and profit, amounting to a total of 43.17 percent, which were added to the direct cost. Under the category of Program Integration in the Ebasco cost estimate, a certain amount of personnel time was also allocated to waste management activities. These program integration costs related to Waste Management (PI-WM) for the three GDP sites are shown in Table J-5 (DOE, 1991a). Considering this cost element, the total waste management cost estimate for the three GDPs is over $1 billion in 1992 dollars. The waste management cost structure is shown in Tables J-6 to J-10. No detailed TLG waste management cost structure by waste type is available at this time for comparison.

TABLE J-4 Ebasco and TLG Waste Volume and Waste Management Cost Comparison

| | **Volume (thousands ft$^3$)** | | Cost (thousands 1992$) | |
|---|---|---|---|---|
| | Ebasco | TLG | Ebasco | TLG |
| Oak Ridge | 10,599 | 32,140 | 383,395 | 633,850 |
| Paducah | 7,102 | 23,393 | 285,846 | 436,572 |
| Portsmouth | 9,060 | 22,252 | 370,679 | 434,837 |
| Total | 26,761 | 77,785 | 1,039,920 | 1,505,259 |

SOURCE: DOE (1991a,b).

TABLE J-5 Ebasco Program Integration (PI) Costs Related to Waste Management (WM) (in 1992 dollars)

| **GDP Site** | Cost |
|---|---|
| Oak Ridge | 31,143,840[a] |
| Paducah | 7,784,180[b] |
| Portsmouth | 15,133,681[c] |
| Total | 54,061,701 |

[a] Includes 13 full-time equivalents (FTEs) for 14 years plus overhead

[b] Includes 5.69 FTEs for 8 years plus overhead

[c] Includes 8.84 FTEs for 10 years plus overhead

SOURCE: Based on DOE (1991a).

## Packaging Cost

Both the Ebasco and TLG estimates relied on the price quotations from U.S. commercial manufacturers and suppliers of currently available drums and containers. To accommodate approximately 26.7 million cubic feet of wastes, Ebasco estimated the types of packaging required as shown in Table J-11.

The purchasing cost of this packaging is estimated at $176.4 million; however, with indirect and overhead costs, the overall packaging cost increases to $267 million (see Table J-10). Packaging unit cost by waste type is shown in Table J-12.

TABLE J-6 Ebasco Waste Management (WM) Cost Summary for the three GDPs (in thousands of 1992 dollars)

| | **Oak Ridge** | Paducah | Portsmouth | Total |
|---|---|---|---|---|
| WM direct cost | 246,030 | 194,213 | 248,331 | 688,574 |
| WM indirect cost (at 43.17%) | 106,221 | 83,849 | 107,214 | 297,284 |
| PI-WM cost | 31,144 | 7,784 | 15,134 | 54,062 |
| Total indirect cost[a] | 137,365 | 91,633 | 122,348 | 351,346 |
| Total WM cost | 383,395 | 285,846 | 370,679 | 1,039,920 |
| "Real" indirect rate applied to WM direct cost[b] | 55.83% | 47.18% | 49.27% | 51.03% |

[a] WM indirect costs + PI-WM cost

[b] Total indirect cost/WM direct cost × 100

SOURCE: Based on DOE (1991a).

## Transportation Cost

The Ebasco cost estimate assumes that two types of transportation will be required: local transportation to local disposal sites; and, for some wastes for the Paducah and Portsmouth GDPs, interstate transportation to decontamination facilities for processing at Oak Ridge and return to originating localities for final disposal. As indicated earlier, transportation costs represent two components: (1) labor and equipment costs associated with loading at each GDP site; and (2) line-haul transportation costs determined by information obtained from commercial motor carriers.

### *Local Transportation to Disposal Facilities (within 10 miles from each GDP)*

All of the waste generated at the Oak Ridge GDP is assumed to be moved directly to local disposal facilities, and approximately two-thirds of the Paducah and Portsmouth wastes will also be shipped as local transportation. A total of 309,909 drums, 111,054 containers, and loose volume of 113,400 tons of waste materials will be transported to local disposal facilities. Table J-13 describes the local transportation cost summary for each GDP site.

### *Interstate Transportation to the Oak Ridge LADF for Processing*

Appropriate Paducah and Portsmouth waste materials will be transported to the Oak Ridge GDP LADF for processing, and the processed wastes will be returned to their originating

TABLE J-7 Ebasco Radioactive and Hazardous Waste Management (WM) Cost Summary for the Oak Ridge GDP (in 1992 dollars)

| **Waste Type** | Volume ($ft^3$) | Packaging ($) | Transport ($) | Disposal ($) | Storage ($) | Total ($) |
|---|---|---|---|---|---|---|
| Level III | 2,068,350 | 32,885,996 | 1,386,561 | 66,573,215 | 761,052 | 101,606,824 |
| Level I | 4,964,068 | 35,400,489 | 3,393,745 | 71,176,769 | 1,826,534 | 111,797,537 |
| Hazardous materials | 2,039,452 | 1,085,370 | 365,855 | 29,242,469 | 750,419 | 31,444,113 |
| Clean | 1,527,168 | 578,000 | 42,194 | 0 | 561,923 | 1,182,117 |
| Total waste volume | 10,599,038 | | | | | |
| Direct cost | | 69,949,855 | 5,188,355 | 166,992,453 | 3,899,928 | 246,030,591 |
| Indirect cost (26%) | | 18,186,962 | 1,348,972 | 43,418,038 | 1,013,981 | 63,967,953 |
| Direct + indirect | | 88,136,817 | 6,537,327 | 210,410,491 | 4,913,909 | 309,998,544 |
| Overhead (3.3%) | | 2,908,515 | 215,732 | 6,943,546 | 162,159 | 10,229,952 |
| Overhead + direct + indirect | | 91,045,332 | 6,753,059 | 217,354,037 | 5,076,068 | 320,228,496 |
| Profit (10%) | | 9,104,533 | 675,306 | 21,735,404 | 507,606 | 32,022,849 |
| WM cost | | 100,149,865 | 7,428,365 | 239,089,441 | 5,583,674 | 352,251,345 |
| Program integration (PI-WM) | | 8,854,194 | 657,135 | 21,137,324 | 495,187 | 31,143,840 |
| Total WM cost | | 109,004,059 | 8,085,500 | 260,226,765 | 6,078,861 | 383,395,185 |
| Percentage of total WM cost | | 28.43% | 2.11% | 67.87% | 1.59% | |

SOURCE: Based on DOE (1991a).

TABLE J-8 Ebasco Radioactive and Hazardous Waste Management (WM) Cost Summary for the Paducah GDP (in 1992 dollars)

| **Waste Type** | Volume ($ft^3$) | Packaging ($) | Transport ($) | Disposal ($) | Storage ($) | Total ($) |
|---|---|---|---|---|---|---|
| Level III | 1,383,898 | 212,361,484 | 9,267,987 | 45,271,988 | 582,592 | 77,484,051 |
| Level I | 3,283,208 | 23,436,673 | 13,766,297 | 47,508,455 | 1,382,161 | 86,093,586 |
| Hazardous materials | 1,345,558 | 707,050 | 4,286,176 | 19,470,403 | 566,451 | 25,030,080 |
| Clean | 1,089,734 | 389,000 | 4,757,299 | 0 | 458,755 | 5,605,054 |
| Total waste volume | 7,102,398 | | | | | |
| Direct cost | | 46,894,207 | 32,077,759 | 112,250,846 | 2,989,959 | 194,212,771 |
| Indirect cost (26%) | | 12,192,494 | 8,340,217 | 29,185,220 | 777,389 | 50,495,320 |
| Direct + indirect | | 59,086,701 | 40,417,976 | 141,436,066 | 3,767,348 | 244,708,091 |
| Overhead (3.3%) | | 1,949,861 | 1,333,793 | 4,667,390 | 124,323 | 8,075,367 |
| Overhead + direct + indirect | | 61,036,562 | 41,751,769 | 146,103,456 | 3,891,671 | 252,783,458 |
| Profit (10%) | | 6,103,656 | 4,175,177 | 14,610,345 | 389,167 | 25,278,345 |
| WM cost | | 67,140,218 | 45,926,946 | 160,713,801 | 4,280,838 | 278,061,803 |
| Program integration (PI-WM) | | 1,879,879 | 1,285,947 | 4,499,256 | 119,098 | 7,784,180 |
| Total WM cost | | 69,020,097 | 47,212,893 | 165,213,057 | 4,399,936 | 285,845,983 |
| Percent of total WM cost | | 24.14% | 16.52% | 57.80% | 1.54% | |

SOURCE: Based on DOE (1991a).

TABLE J-9 Ebasco Radioactive and Hazardous Waste Management (WM) Cost Summary for the Portsmouth GDP (in 1992 dollars)

| **Waste Type** | Volume (ft$^3$) | Packaging ($) | Transport ($) | Disposal ($) | Storage ($) | Total ($) |
|---|---|---|---|---|---|---|
| Level III | 1,729,636 | 28,109,849 | 11,634,013 | 56,574,985 | 618,463 | 96,937,310 |
| Level I | 4,216,618 | 30,067,771 | 18,553,589 | 60,855,960 | 1,507,729 | 110,985,049 |
| Hazardous material | 1,734,506 | 924,650 | 5,959,994 | 25,033,102 | 620,204 | 32,537,950 |
| Clean | 1,378,852 | 492,000 | 6,885,740 | 0 | 493,034 | 7,870,774 |
| Total waste volume | 9,059,612 | | | | | |
| Direct cost | | 59,594,270 | 43,033,336 | 142,464,047 | 3,239,430 | 248,331,083 |
| Indirect cost (26%) | | 15,494,510 | 11,188,667 | 37,040,652 | 842,252 | 64,566,081 |
| Direct + indirect | | 75,088,780 | 54,222,003 | 179,504,699 | 4,081,682 | 312,897,164 |
| Overhead (3.3%) | | 2,477,930 | 1,789,326 | 5,923,655 | 134,695 | 10,325,606 |
| Overhead + direct + indirect | | 77,566,709 | 56,011,329 | 185,428,354 | 4,216,378 | 323,222,770 |
| Profit (10%) | | 7,756,671 | 5,601,133 | 18,542,835 | 421,638 | 32,322,277 |
| WM cost | | 85,323,380 | 61,612,462 | 203,971,189 | 4,638,016 | 355,545,047 |
| Program integration (PI-WM) | | 3,632,083 | 2,622,667 | 8,682,193 | 196,738 | 15,133,681 |
| Total WM cost | | 88,955,463 | 64,235,129 | 212,653,382 | 4,834,754 | 370,678,728 |
| Percentage of total WM cost | | 24.00% | 17.33% | 57.37% | 1.30% | |

SOURCE: Based on DOE (1991a).

TABLE J-10 Ebasco Radioactive and Hazardous Waste Management (WM) Cost Summary for the Three GDP Sites (in 1992 dollars)

| **Waste Type** | Volume ($ft^3$) | Packaging ($) | Transport ($) | Disposal ($) | Storage ($) | Total ($) |
|---|---|---|---|---|---|---|
| Level III | 5,181,884 | 83,367,329 | 22,288,561 | 168,420,188 | 1,962,107 | 276,028,185 |
| Level I | 12,463,894 | 88,904,933 | 35,713,631 | 179,541,184 | 4,716,424 | 308,876,172 |
| Hazardous materials | 5,119,516 | 2,717,070 | 10,612,025 | 73,745,974 | 1,937,074 | 89,012,143 |
| Clean | 3,995,754 | 1,459,000 | 11,685,233 | 0 | 1,513,712 | 14,657,945 |
| Total waste volume | 26,761,048 | | | | | |
| Direct cost | | 176,438,332 | 80,299,450 | 421,707,346 | 10,129,317 | 688,574,445 |
| Indirect cost (26%) | | 45,873,967 | 20,877,857 | 109,643,910 | 2,633,622 | 179,029,356 |
| Direct + indirect | | 222,312,299 | 101,177,307 | 531,351,256 | 12,762,939 | 867,603,801 |
| Overhead (3.3%) | | 7,336,306 | 3,338,851 | 17,534,591 | 421,177 | 28,630,925 |
| Overhead + direct + indirect | | 229,648,605 | 104,516,158 | 548,885,847 | 13,184,116 | 896,234,726 |
| Profit (10%) | | 22,964,860 | 10,451,616 | 54,888,585 | 1,318,412 | 89,628,473 |
| WM cost | | 252,613,465 | 114,967,774 | 603,774,432 | 14,502,528 | 985,863,199 |
| Program integration (PI-WM) (Prorated) | | 14,366,156 | 4,565,749 | 34,318,773 | 811,023 | 54,061,701 |
| Total WM cost | | 266,979,621 | 119,533,523 | 638,093,205 | 15,313,551 | 1,039,919,900 |
| Percent of total WM cost | | 25.67% | 11.50% | 61.36% | 1.47% | |

SOURCE: Based on DOE (1991a).

TABLE J-11 Types of Packaging Assumed in the Ebasco Cost Estimate

| **Type of Packaging** | Number of Units | Purchasing Cost (1992$) |
|---|---|---|
| Drums | 321,396 | 22,497,720 |
| Process containers | 98,502 | 45,310,920 |
| B-25 containers | 90,171 | 59,603,031 |
| 1/4-inch-thick steel containers | 49,026 | 49,026,000 |
| Total | | 176,437,671 |

SOURCE: Based on DOE (1991a).

TABLE J-12 Net Packaging Unit Cost (1992$/ft3)

| Waste Type | Oak Ridge GDP | Paducah GDP | Portsmouth GDP |
|---|---|---|---|
| Low Level I | 7.13 | 7.14 | 7.13 |
| Low Level III | 15.90 | 16.16 | 16.25 |
| RCRA hazardous material | 0.53 | 0.53 | 0.53 |
| Clean/recycle | 0.38 | 0.35 | 0.36 |

SOURCE: Based on DOE (1991a).

cities' disposal facilities for final burial. Transportation costs include loading and line-haul costs. Table J-14 summarizes the round-trip transportation costs between the Paducah and Portsmouth GDPs and the Oak Ridge GDP LADF.

## Disposal Costs

According to the Ebasco estimate, two types of waste disposal facilities will be built at each of the three GDP sites. The first disposal facility will be for LLW I and hazardous materials/RCRA wastes placement, and the second facility will be constructed for LLW III waste disposal, an operation with a higher degree of security and protection needs that must be designed to meet DOE requirements. The waste disposal cost estimate includes site characterization, construction, placement, and operation costs. It is assumed that Oak Ridge

TABLE J-13 Local Transportation Cost Summary for Waste Disposal at the Three GDPs

| | **Oak Ridge** | Paducah | Portsmouth |
|---|---|---|---|
| Waste volume (1,000 ft$^3$) | 9,133,000 | 4,672,000 | 6,017,000 |
| LLW I waste (\$/ft$^3$) | 0.68 | 0.68 | 0.68 |
| LLW III waste (\$/ft$^3$) | 0.67 | 0.64 | 0.64 |
| Hazardous material/RCRA waste (\$/ft$^3$) | 0.69 | 0.69 | 0.69 |
| Clean/recyclable material (\$/ft$^3$) | 0.69 | 0.69 | 0.69 |
| Average unit cost (\$/ft$^3$) | 0.57 | 0.53 | 0.53 |
| Direct cost (\$) | 5,188,000 | 2,498,000 | 3,212,000 |

SOURCE: Based on DOE (1991a).

TABLE J-14 Interstate Transportation Cost Summary for Waste from the Paducah and Portsmouth GDPs

| | **Paducah (Direct Cost)** | Portsmouth (Direct Cost) |
|---|---|---|
| Waste volume (ft$^3$) | 2,430,662 | 3,042,672 |
| LLW I waste (\$/ft$^3$) | 13.72 | 14.37 |
| LLW III waste (\$/ft$^3$) | 13.93 | 14.58 |
| Hazardous material/RCRA Waste (\$/ft$^3$) | 13.86 | 14.51 |
| Clean/recyclable material (\$/ft$^3$) | 9.93 | 11.24 |
| Average unit cost (\$/ft$^3$) | 12.17 | 13.09 |
| Cost to Oak Ridge GDP (\$) | 20,468,232 | 28,431,262 |
| Cost from Oak Ridge GDP (\$) | 9,111,556 | 11,389,804 |
| Total (\$) | 29,579,788 | 39,821,066 |

SOURCE: Based on DOE (1991a).

disposal facilities will operate for 11 years; Paducah operations for 8 years, and Portsmouth operations for 10 years. Clean and recyclable wastes will not be placed in the disposal facility. Disposal costs by GDP site are summarized in Table J-15.

### Storage Costs

The Ebasco cost estimate assumed a 20-acre paved site would be constructed at each GDP site for holding, staging, and scheduling of the packaged wastes to be locally transported for final disposal. Construction costs includes the costs for excavation, subgrade, and pavement for the 20-acre site. The handling cost of drums and containers is also included in the storage cost. Table J-16 summarizes the storage cost for the three GDPs.

### Waste Management Unit Cost Summary

Based on the unit cost component developed by Ebasco, the total direct unit cost by waste type is presented in Table J-17. Tables J-18 to J-21 summarize waste management unit costs by type.

### Summary on Waste Management

In summary, the cost estimates for packaging, transportation, disposal, and storage appear to be high and offer opportunities for cost reduction. Among the waste management cost elements, disposal cost is the major driver, followed by packaging and transportation. Disposal costs and disposal facility locations will dictate the total waste management cost. Packaging, transportation, and disposal elements should be viewed as a single system. Volume-reduction and the recycling of waste material offer the greatest opportunity to affect cost and also to minimize institutional and social risks in transportation of waste material.

TABLE J-15 Disposal Cost Summary by GDP Site

| **Waste Type** | Oak Ridge | Paducah | Portsmouth |
|---|---|---|---|
| LLW I and Hazardous materials waste | | | |
| Volume (ft$^3$) | 7,004,000 | 4,629,000 | 5,951,000 |
| Unit cost (\$/ft$^3$) | 14.34 | 14.47 | 14.43 |
| Direct cost (\$) | 100,437,000 | 66,981,000 | 85,873,000 |
| LLW III waste | | | |
| Volume (ft$^3$) | 2,068,000 | 1,384,000 | 1,730,000 |
| Unit cost (\$/ft$^3$) | 32.19 | 32.71 | 32.70 |
| Direct cost (\$) | 66,567,000 | 45,271,00 | 56,571 |

SOURCE: Based on DOE (1991a).

TABLE J-16 Storage Cost Summary for the Three GDPs

| | **Oak Ridge** | Paducah | Portsmouth |
|---|---|---|---|
| Volume (ft$^3$) | 7,161,000 | 3,370,000 | 4,340,000 |
| Unit cost (\$/ft$^3$) | 0.54 | 0.89 | 0.75 |
| Direct cost (\$) | 3,867,000 | 2,999,000 | 3,255,000 |

TABLE J-17 Waste Management Unit Cost Summary ($/ft3)

| **Waste Type** | Oak Ridge[a] | Paducah[b] | Portsmouth[b] |
|---|---|---|---|
| LLW I waste | 22.69 | 23.18; 36.22 | 22.99; 36.68 |
| LLW III | 49.30 | 50.40; 63.69 | 50.35; 64.29 |
| Hazardous Materials/RCRA Waste | 16.10 | 16.58; 29.75 | 16.40; 30.22 |
| Clean/recyclable materials | 1.61 | 1.93; 11.17 | 1.80; 12.35 |

[a] For the Oak Ridge GDP wastes, only local transportation is required.

[b] For Paducah and Portsmouth, upper figures represent local transportation cost to the disposal facility, and lower figures wastes requiring round-trip transportation to the Oak Ridge LADF for processing.

TABLE J-18 Waste Management Unit Cost Summary for Level I Waste (1992$/ft3)

| | **Packaging** | | Transport[a] | | Disposal | | Storage | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| GDP Site | Net | Gross | Net | Gross | Net | Gross | Net | Gross | Net | Gross |
| Oak Ridge | 7.13 | 11.11 | 0.68 | 1.06 | 14.34 | 22.35 | 0.64 | 0.84 | 22.69 | 35.36 |
| Paducah | 7.14 | 10.51 | 0.68 | 1.00 | 14.47 | 21.30 | 0.89 | 1.31 | 23.18 | 34.12 |
| | 7.14 | 10.51 | 13.72 | 20.19 | 14.47 | 21.30 | 0.89 | 1.31 | 36.22 | 53.31 |
| Portsmouth | 7.13 | 10.64 | 0.68 | 1.02 | 14.43 | 21.54 | 0.75 | 1.12 | 22.99 | 34.32 |
| | 7.13 | 10.64 | 14.37 | 21.45 | 14.43 | 21.54 | 0.75 | 1.12 | 36.68 | 54.75 |

NOTE: Net, direct cost only; gross, including all indirect costs, except contingency.

[a] For the Oak Ridge GDP, local transportation costs to disposal site only. For Paducah and Portsmouth GDPs, upper figures indicate local transportation cost for disposal site and lower figures cover round-trip transportation cost to the Oak Ridge LADF for processing.

SOURCE: Based on DOE (1991a).

TABLE J-19 Waste Management Unit Cost Summary for Level III Waste (1992$/ft3)

| | **Packaging** | | Transport[a] | | Disposal | | Storage | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| GDP Site | Net | Gross | Net | Gross | Net | Gross | Net | Gross | Net | Gross |
| Oak Ridge | 15.90 | 24.78 | 0.67 | 1.04 | 32.19 | 50.16 | 0.54 | 0.84 | 49.30 | 76.82 |
| Paducah | 16.16 | 23.78 | 0.64 | 0.94 | 32.71 | 48.14 | 0.89 | 1.31 | 50.40 | 74.17 |
| | 16.16 | 23.78 | 13.93 | 20.50 | 32.71 | 48.14 | 0.89 | 1.31 | 63.69 | 93.73 |
| Portsmouth | 16.25 | 24.26 | 0.64 | 0.96 | 32.71 | 48.83 | 0.75 | 1.12 | 50.35 | 75.17 |
| | 16.25 | 24.26 | 14.58 | 21.76 | 32.71 | 48.83 | 0.75 | 1.12 | 64.29 | 95.97 |

NOTE: Net, direct cost only; gross, including all indirect costs, except contingency.

[a] For the Oak Ridge GDP, local transportation costs to disposal site only. For Paducah and Portsmouth GDPs, upper figures indicate local transportation cost for disposal site and lower figures cover round-trip transportation cost to the Oak Ridge LADF for processing.

SOURCE: Based on DOE (1991a).

TABLE J-20 Waste Management Unit Cost Summary for Hazardous Material Waste (1992$/ft3)

| | **Packaging** | | Transport[a] | | Disposal | | Storage | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| GDP Site | Net | Gross | Net | Gross | Net | Gross | Net | Gross | Net | Gross |
| Oak Ridge | 0.53 | 0.83 | 0.69[b] | 1.08 | 14.34 | 22.35 | 0.54 | 0.84 | 16.20 | 25.10 |
| Paducah | 0.53 | 0.78 | 0.69[b] | 1.02 | 14.47 | 21.30 | 0.89 | 1.31 | 16.58 | 24.41 |
| | 0.53 | 0.78 | 13.86 | 20.40 | 14.47 | 21.30 | 0.89 | 1.31 | 29.75 | 43.79 |
| Portsmouth | 0.53 | 0.79 | 0.69[b] | 1.03 | 14.43 | 21.54 | 0.75 | 1.12 | 16.40 | 24.48 |
| | 0.53 | 0.79 | 14.51 | 21.66 | 14.43 | 21.54 | 0.75 | 1.12 | 30.22 | 45.11 |

NOTE: Net, direct cost only; gross, including all indirect costs, except contingency.

[a] For the Oak Ridge GDP, local transportation costs to disposal site only. For Paducah and Portsmouth GDPs, upper figures indicate local transportation cost for disposal site and lower figures cover round-trip transportation cost to the Oak Ridge LADF for processing.

[b] Packaged waste only (unit cost for loose pack waste = \$0.16/ft$^3$)

SOURCE: Based on DOE (1991a).

TABLE J-21 Waste Management Unit Cost Summary for Clean/Recycle Material (1992$/ft3)

| | **Packaging** | | Transport[a] | | Disposal | | Storage | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| GDP Site | Net | Gross | Net | Gross | Net | Gross | Net | Gross | Net | Gross |
| Oak Ridge | 0.38 | 0.59 | 0.69 | 1.08 | 0.00 | 0.00 | 0.54 | 0.84 | 1.61 | 2.51 |
| Paducah | 0.35 | 0.52 | 0.69 | 1.02 | 0.00 | 0.00 | 0.89 | 1.31 | 1.93 | 2.58 |
| | 0.35 | 0.52 | 9.93 | 14.61 | 0.00 | 0.00 | 0.89 | 1.31 | 11.17 | 16.44 |
| Portsmouth | 0.36 | 0.54 | 0.69 | 1.03 | 0.00 | 0.00 | 0.75 | 1.12 | 1.80 | 2.69 |
| | 0.36 | 0.54 | 11.24 | 16.78 | 0.00 | 0.00 | 0.75 | 1.12 | 12.35 | 18.44 |

NOTE: Net, direct cost only; gross, including all indirect costs, except contingency.

[a] For the Oak Ridge GDP, local transportation costs to disposal site only. For Paducah and Portsmouth GDPs, upper figures indicate local transportation cost for disposal site and lower figures cover round-trip transportation cost to the Oak Ridge LADF for processing.

SOURCE: Based on DOE (1991a).

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# Glossary

| | |
|---|---|
| **Activity** | Sometimes used for *radioactivity*, particularly when referring to an amount of radioactivity (i.e., the number of nuclear transformations occurring in a given quantity of material per unit of time). |
| **Alpha radiation** | A particle consisting of two protons and two neutrons, given off by the radioactive decay of a number of elements, including uranium, plutonium, and radon. Alpha particles cannot penetrate a sheet of paper. However, alpha-emitting isotopes ingested into the body can be very damaging. |
| **Aqueous decontamination** | As used in this report, removal of radioactive contamination by water-based solutions of acids and other oxidizing agents along with appropriate rinses. Also referred to as chemical decontamination. To be distinguished from dry methods, such as mechanical removal of radioactive contaminants through scraping or vacuuming; and gaseous decontamination involving an agent in the gas phase that reacts with, for example, uranium, for its removal from surfaces. |
| **Asbestosis** | A disease of the lungs caused by inhalation of asbestos particles. |
| **Assay** | Analysis of a material for one or more valuable components. For example, an assay might ascertain the percentage of $^{235}$U isotope in a quantity of natural uranium. |
| **Atomic vapor laser isotope separation (AVLIS)** | An advanced enrichment technology that converts a feed material into product streams in which a selected set of isotopes has been enriched or depleted. Upon electron beam vaporization of the feed stream, desired isotopic vapors in the vapor are selectively photoionized with lasers and electrostatically withdrawn. |
| **Barrier material** | See diffusion barrier. |
| **Becquerel (Bq)** | Like the curie, a measure of the number of disintegrations from a radioactive material. One Bq is equal to 27 picocuries. |
| **Beta radiation** | A particle emitted in the radioactive decay of many radionuclides. A beta particle is identical with an electron. It has a short range in air and a low ability to penetrate other materials. |

| | |
|---|---|
| **Blending** | The combining of materials of different uranium enrichment levels to yield an enrichment level somewhere in between. |
| **Carcinogen(ic)** | A substance that produces or incites cancer. |
| **Cascade** | A connected series of enrichment components (converters), with the material from one being passed to another for further enrichment. |
| **Cell** | A configuration of up to 12 diffusion stages. |
| **Characterization** | An information-gathering process usually involving measurement or sampling and analysis of contaminants present. |
| **Chemical decontamination** | In this report, used synonymously with aqueous decontamination to refer to the decontamination of materials by reaction of radioactive contaminants with chemicals in aqueous solution. |
| **Chlorofluorocarbon (CFC)** | Any of a group of compounds that contain carbon, chlorine, fluorine, and sometimes hydrogen used as refrigerants, cleaning solvents, and aerosol propellants. |
| **Class III low-level waste** | Radioactive waste that will not result in an off-site dose to the public of more than 100 millirem per year. |
| **Class I low-level waste** | Radioactive waste that will not result in an off-site dose to the public of more than 10 millirem per year. |
| **Cleanup** | Actions taken to deal with a release or threatened release of hazardous substances that could affect public health and/or the environment. |
| **Comprehensive Environmental Response, Compensation and Liability Act (CERCLA)** | A federal law, enacted in 1980, that governs the cleanup of hazardous, toxic, and radioactive substances. The act and its amendments created a trust fund, commonly known as Superfund, to finance the investigation and cleanup of abandoned and uncontrolled hazardous waste sites. |
| **Contingency** | In cost estimates, an estimated potential percent increase in cost of a given project resulting from unforeseen events or causes. |
| **Converter** | A cascade component containing the barrier material. Gaseous uranium hexafluoride is pumped into the converters in a cascade via piping and associated compressors and pumps, where it is enriched slightly after passing through the barrier material. |
| **Criticality** | In a nuclear criticality event, an assemblage of enriched uranium results in a self-sustaining chain reaction generating large amounts of heat, radioactive fission products, and gamma and neutron radiation. Usually a nuclear criticality event is self-limiting because the energy release disrupts the geometric configuration of the enriched material |

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| | that caused the criticality. If the assemblage reforms again, another criticality event will occur. Hence, criticality events can be pulsed events. The burst of neutrons that occurs during such an event can be lethal to anyone exposed. |
| **Criticality prevention** | Approaches, either technical or administrative, to prevent the occurrence of criticality events. |
| **Curie (Ci)** | A unit of radioactivity that represents the amount of radioactivity associated with one gram (0.032 ounce) of radium. If a sample of radioactive material exhibits one curie of radioactivity, it is emitting radiation at the rate of 3.7 million times a second or 3.7 million disintegrations per second. One becquerel (Bq) is equal to 27 picocuries (billionths of a curie). |
| **Daughter product, radioactive progeny, decay daughter** | A nuclide formed by the radioactive decay of another nuclide, known in this context as the parent. |
| **Decommissioning** | Retirement of a nuclear facility, including decontamination and/or dismantlement. Often used synonymously with decontamination and decommissioning (D&D). |
| **Decontamination** | Removal of unwanted radioactive or hazardous contamination by a chemical or mechanical process. |
| **Decontamination factor (DF)** | The original amount of radionuclide ($A_o$) divided by the final amount ($A_f$). In some cases, decontamination effectiveness is reported in terms of percentage of contamination removed. |
| **De minimis** | That level of contamination below which regulatory control is not required. |
| **Depleted uranium (hexafluoride)** | The byproduct of the uranium enrichment process. Uranium that in the process of enrichment has been stripped of most of the $^{235}U$ it once contained, so that it has more $^{238}U$ than natural uranium. Depleted uranium is used in some parts of nuclear weapons and as a raw material for plutonium production. Large quantities of depleted uranium hexafluoride ($DUF_6$) are stored at the uranium enrichment sites. |
| **Diffusion barrier** | The porous, tube-like material housed in the converters that is used to separate uranium isotopes of different molecular weights (e.g., $^{235}U$ from $^{238}U$) by virtue of their different diffusion rates. |
| **Electrical raceway** | Localized areas of buildings containing electrical wires and cables. |
| **End state** | In this report, the final state to be achieved at a site through D&D. Also referred to as end point. |
| **Enrichment** | The process of increasing the concentration of one isotope of a given element (in the case of uranium, increasing the concentration of $^{235}U$). |

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| **Entombment** | The encasement of radioactive materials in concrete or other structural materials sufficiently strong and structurally long-lived to ensure retention of the radioactivity until it has decayed to levels that permit restricted release of the site. |
| **Environmental restoration** | The cleanup process for a site designed to ensure that risks to the environment or human health are eliminated or reduced to levels approved by the regulatory agencies. |
| **Federal Facilities Compliance Act of 1992 (FFCA)** | A federal law requiring all federal facilities and installations to adhere to the requirements of environmental protection regulations. |
| **Feed (stream)** | In this report, the uranium hexafluoride gas fed into the gaseous diffusion plant cascades for enrichment. |
| **Fission** | The splitting or breaking apart of the nucleus of a heavy atom like uranium or plutonium, usually caused by the absorption of a neutron. Large amounts of energy and one or more neutrons are released when an atom fissions. |
| **Fixed contamination** | Radioactive contamination that is not easily removed by casual contact or by washing or wiping. |
| **Free release** | Acceptable for use by the public without restriction. |
| **Freon®** | One of a class of chlorinated fluorocarbon heat transfer fluids. |
| **Friable asbestos** | Asbestos that is easily crumbled, thus releasing fibers into the air. Asbestos that is not easily crumbled is referred to as nonfriable. |
| **Fuel reprocessing** | Chemical dissolution and separation of uranium and plutonium from the associated fission products found in irradiated nuclear reactor fuel. |
| **Full-time equivalent (FTE)** | Numeric equivalent, in person hours or salary, of one full-time employee. Concept used for budgetary purposes. |
| **Gamma radiation** | High-energy, penetrating electromagnetic radiation emitted in the radioactive decay of many radionuclides. Gamma rays are thus similar to x rays. |
| **Gas centrifuge process** | A method of isotope separation in which heavy gaseous atoms or molecules are separated from light ones by centrifugal force and an induced counter-current flow in the swirling gas. |
| **Gaseous decontamination** | In this report, removal of uranium deposits by fluorination using chlorine trifluoride gas, often at elevated temperatures. |
| **Gaseous diffusion** | A method of isotope separation based on the fact that gas atoms or molecules with different masses will diffuse through a porous barrier (or membrane) at |

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| | different rates. The method is used to separate $^{235}$U from $^{238}$U. It requires large plants and significant amounts of electric power. |
| **Glovebox** | A sealed box used to handle some radioactive materials with gloves attached to access ports in the wall. Often filled with an inert gas and fitted with a filtered ventilation system. |
| **Greenfield** | Status achieved in returning a formerly contaminated site to free-release conditions, typically to a grassy field devoid of all buildings, former structures, and chemical or radioactive contamination. |
| **Grit blasting** | Decontamination of surfaces with abrasives, such as sand, propelled by high-pressure air. |
| **Half-life** | The time required for half of the original radioactive nuclei in a sample of an isotope to undergo radioactive decay. |
| **Hanford Site** | A 570-square-mile federal government-owned reservation in the desert of southeast Washington State. Established in 1942 as part of the Manhattan Project, the Hanford Site has had the chief mission of producing plutonium for use in nuclear weapons. Hanford is home to nine production reactors and four chemical separation plants. |
| **Hazardous substance/ hazardous waste** | Any material that poses a threat to public health or the environment as defined by the Resource Conservation and Recovery Act and the Comprehensive Environmental Response, Compensation and Liability Act. |
| **High-assay decontamination facility** | The facility assumed to be built in the D&D cost estimates of Ebasco Environmental and TLG Engineering to disassemble and decontaminate equipment contaminated with highly enriched uranium. |
| **High-level radioactive waste** | Highly radioactive material, containing fission products, or traces of uranium, plutonium, or other transuranic elements, which results from chemical reprocessing of spent fuel and irradiated targets. |
| **Highly enriched uranium** | Uranium in which the percentage of $^{235}$U nuclei has been increased from the natural level of 0.71 percent to some level greater than 20 percent. |
| **Indirect costs** | Costs of a project other than direct labor and materials. |
| **Interim storage** | Storage operations for which monitoring and human control are provided and final disposition is expected. Concepts for interim storage include bulk and compartmented storage of solid, liquid, and gaseous wastes. |
| **Ion exchange (resin)** | A chemical process involving the absorption or desorption of various chemical ions in a solution onto a solid material, usually a plastic or resin. The process |

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| | is used to separate and purify chemicals, such as fission products and in adjusting the "hardness" of water (i.e., water softening). |
| **Isotope** | Different forms of an element that have the same atomic number but different atomic weights due to the differences in the number of neutrons contained in the atomic nucleus. Different isotopes of an element may exhibit distinctly different radioactive behaviors or be nonradioactive. |
| **Loose/smearable contamination** | Radioactive contamination that is easily removed on casual contact or by washing or wiping. |
| **Low-assay decontamination facility** | The new decontamination facility assumed to be built in the cost estimates of Ebasco Environmental and TLG Engineering. This facility was postulated to disassemble and decontaminate equipment contaminated with low-enriched uranium. |
| **Low-enriched uranium** | Uranium in which the percentage of $^{235}U$ nuclei has been increased from the natural level of 0.71 percent up to as much as 20 percent, usually to 3 to 5 percent. Low-enriched uranium can sustain a chain reaction when suitably moderated and is used as fuel in light-water reactors. |
| **Low-level radioactive waste** | Radioactive waste not classified as high-level radioactive waste, transuranic waste, spent nuclear fuel or byproduct material, and acceptable for disposal in a licensed land disposal facility. Typically, discarded radioactive materials such as rags, construction rubble, and glass are only slightly or moderately contaminated. |
| **Mechanical decontamination** | Removal of contaminants by physical means, such as scraping, rubbing, or vacuuming. If conducted under dry conditions, the chance of a criticality event in the case of enriched uranium is low. Wet mechanical removal can also be used, such as water jets with an abrasive added. |
| **Melt refining** | Use of high temperature to liquefy metal and separate its contaminants into a slag layer. |
| **Mixed waste** | Waste that contains both chemically hazardous and radioactive materials. |
| **Moderator** | A material (usually water, heavy water, or graphite) that slows neutrons, thereby increasing their chances of fissioning fissile material. |
| **National Priorities List (NPL)** | The Environmental Protection Agency's list of the most serious hazardous waste sites in the country, based on the site's score from the EPA Hazard Ranking System. The list is updated yearly. |
| **National Environmental Policy Act (NEPA)** | A federal law, enacted in 1970, that requires the federal government to consider in its decision-making processes the environmental impacts of, and alternatives to, major proposed actions. |

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| **Natural uranium** | Uranium that has been extracted from natural ore. It is comprised of 99.3 percent $^{238}$U, 0.71 percent $^{235}$U, and traces of $^{234}$U. |
| **Neutron** | A massive, uncharged particle that is part of an atom's nucleus. Uranium and plutonium atoms fission when they absorb neutrons. Human-made elements can be manufactured by bombarding other elements with neutrons in nuclear reactors. |
| **Nevada Test Site (NTS)** | A 1,350-square-mile area of the southern Nevada desert, about 65 miles northwest of Las Vegas, that has been the site of most of the U.S. underground and atmospheric nuclear explosive tests since it opened in 1951. |
| **Nuclide** | A species of atom characterized by its mass number, atomic number, and nuclear energy state, provided that the mean life in that state is long enough to be observable. |
| **Oak Ridge Reservation** | A 58-square-mile reservation near Knoxville, Tennessee. Oak Ridge was established as part of the Manhattan Project in 1942 to produce enriched uranium. Today it is the location of the K-25 site (the shutdown gaseous diffusion plant), the Y-12 plant, and the Oak Ridge National Laboratory. |
| **Permanent storage** | Disposal of radioactive waste so that only negligible risk to the public remains. Typical permanent storage is via land burial. |
| **Prompt dismantlement** | Near-term removal of the equipment, structures, and hazardous and radioactive substances from a site so as not to endanger future occupants. |
| **Purge cascade** | A portion of the enrichment cascade used to remove gaseous contaminants such as low-atomic-weight gases. |
| **Radiological contamination** | The presence of radionuclides in quantities greater than free-release levels. |
| **Radioactive waste** | A solid, liquid, or gaseous material that contains radioactive materials in quantities greater than free-release levels. |
| **Rem (roentgen equivalent man)** | The special unit of any of the quantities expressed as dose equivalent. The dose equivalent in rem is equal to the absorbed dose in rad multiplied by the quantity factor. Typically, guidelines for exposure are given in a number of rems or millirems (mrem) over a given period of time such as a year. |
| **Remedial action, remediation** | The construction or implementation of corrective actions at a site, such as the environmental restoration program at the plant. |
| **Resource Conservation and Recovery Act (RCRA)** | A federal law enacted in 1976 to address the treatment, storage, and disposal of hazardous waste. |
| **Restricted use** | Remediation of a site to other than free-release levels. Restricted release of a site requires engineered and administrative controls to ensure public safety. |

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| **Risk assessment** | An evaluation performed as part of a remedial investigation to assess conditions at a cleanup site and determine the risk posed to public health and/or the environment. |
| **Risk profile** | The spatial and temporal distribution of risk to a particular population group. |
| **Rollup** | Additional costs of a project, such as indirect costs, contingency funds, and profits, which when added to direct costs yield the total cost of a project. |
| **Safeguards** | Technical and inspection measures for verifying that nuclear materials are not being diverted to other inappropriate uses. |
| **Safe storage** | Those actions required to place and maintain a nuclear facility in such a condition that future risk to public safety from the facility is within acceptable bounds and that the facility can be safely stored for as long a time as desired. |
| **Scabbling** | A mechanical, multiple-hammer chipping method of removing layers of contaminated concrete. |
| **Scavenger gas** | A gas, typically chlorine trifluoride, used to react with and remove uranium contamination. |
| **Separative work unit (SWU)** | A measure of the effort required in an enrichment facility to separate uranium of a given $^{235}U$ content into two fractions; one with a higher percentage and one with a lower percentage of $^{235}U$. The unit of separative work is the kilogram separative work unit (kg SWU), or separative work unit (SWU). The initial material is called the feed. The fraction with a higher proportion of $^{235}U$ is called the product; the other is called the tails. Consider a feed of F kilograms to be divided into an enriched stream of P kilograms and a depleted stream of W kilograms. The separative work is given by:<br>$SWU = PV_P - FV_F$<br>where V is the value function, (2x-1) ln[x/(1-x)], with x the mole fraction of $^{235}U$ in the associated product or feed stream. |
| **Special nuclear material (SNM)** | Defined as plutonium, $^{233}U$, or uranium enriched in either $^{233}U$ or $^{235}U$ isotopes. These materials are categorized into "low strategic significance," "moderate strategic significance," and "strategic," depending upon the quantities present and the enrichment levels of the materials, as defined in Chapter 10, Code of Federal Regulations, Part 70 (10 CFR 70). Rules governing the control of such materials are also presented in 10 CFR 70. |
| **Stage** | The basic building block of a gaseous diffusion plant cascade, which is composed of a converter, compressor, motor, control valve, and associated piping. |
| **Stakeholder** | A person or group with a vested interest in the outcome of a decision. |

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| **State and Tribal Government Working Group** | A national stakeholder group representing the interests of state and tribal governments. |
| **Superfund** | A term commonly used to refer to the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA). |
| **Surface contamination** | Radioactive and/or hazardous material above free-release levels adhering to the surface of an object. |
| **Surveillance and maintenance (S&M)** | Those activities necessary to ensure that a site remains in a safe condition, including periodic inspection and monitoring of the site and prevention of access to radioactive materials left on the site. |
| **Switchyard** | A collection of electrical components used to control and condition electrical power (as for the gaseous diffusion plants). |
| **Tails** | The name given to depleted uranium hexafluoride ($UF_6$) after the enrichment process takes place. The depleted $UF_6$, which has an enrichment level less than 0.71 percent, is composed mostly of $^{238}U$ and small amounts of the $^{235}U$ isotopes. |
| **Technetium-99** | A human-made radioactive element produced during nuclear fission. |
| **Toxic Substances Control Act (TSCA)** | A federal law, enacted in 1976 to protect human health and the environment from unreasonable risk caused by exposure to the manufacturing, distribution, use, or disposal of substances containing toxic chemicals. |
| **Toxic(ological)** | Relating to harmful effects of a substance on the human body through physical contact, ingestion, or inhalation. |
| **Transite** | A building material used at the gaseous diffusion plants that is composed of a mixture of cement and asbestos. |
| **Transuranic** | All elements with atomic numbers greater than uranium on the periodic table. All transuranic elements are human made. |
| **Tumulus** | An artificial mound or engineered enclosure. |
| **Unit cost factor** | The cost of labor and materials necessary to perform a given task once. |
| **Unrestricted use** | See free-release. |
| **Uranium hexafluoride ($UF_6$)** | A volatile compound of uranium and fluorine, $UF_6$ is a solid at atmospheric pressure and room temperature but can be transformed into gas by heating. $UF_6$ gas (alone, or in combination with hydrogen or helium) is the feedstock in most uranium enrichment processes and is sometimes produced as an intermediate product in the process of purifying yellowcake (an intermediate product of uranium mining and drilling) to produce uranium oxide. |

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| **Uranium Mill Tailings Radiation Control Act of 1978** | The law requiring the U.S. Department of Energy to remediate some 24 inactive uranium processing sites and 5,000 vicinity properties. |
| **Uranium oxide ($U_3O_8$)** | The most common oxide of uranium found in typical ores. $U_3O_8$ is extracted from the ore during the milling process. The ore typically contains only 0.1 percent $U_3O_8$; yellowcake, the product of the milling process, contains about 80 percent $U_3O_8$. |
| **Volumetric contamination** | Hazardous or radioactive materials that are distributed throughout the volume of otherwise uncontaminated matter. |
| **Weapons-grade** | Uranium containing over 90 percent of the fissile isotope $^{235}U$. |
| **Y-12** | A plant in Oak Ridge, Tennessee, built for the Manhattan Project to enrich uranium using calutrons. Today, this plant produces and stores components made of enriched and depleted uranium and lithium for thermonuclear weapons. |

# Acronyms

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| **ASME** | American Society of Mechanical Engineers |
| **AVLIS** | atomic vapor laser isotope separation |
| **BCST** | Board on Chemical Sciences and Technology (NRC) |
| **BEES** | Board on Energy and Environmental Systems (NRC) |
| **BNFL** | British Nuclear Fuels |
| **Bq** | Becquerel |
| **$CaF_2$** | calcium fluoride |
| **CERCLA** | Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (also called "Superfund") |
| **CFCs** | chlorofluorocarbons |
| **CFR** | Code of Federal Regulations |
| **Ci** | curie |
| **CIP/CUP** | cascade improvement and upgrade programs |
| **$ClF_3$** | chlorine trifluoride |
| **cm** | centimeter |
| **$CO_2$** | carbon dioxide |
| **Cs** | cesium |
| **D&D** | decontamination and decommissioning |
| **D&D Fund** | U.S. Department of Energy's Uranium Enrichment Decontamination and Decommissioning Fund |
| **DOC** | Decommissioning Operations Contractor |
| **DOE** | U.S. Department of Energy |
| **DOT** | U.S. Department of Transportation |
| **dpm** | disintegrations per minute |

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| **$DUF_6$** | depleted uranium hexafluoride |
| **Ebasco** | Ebasco Environmental |
| **EM** | Environmental Management |
| **EPA** | U.S. Environmental Protection Agency |
| **EPACT** | Comprehensive National Energy Policy Act of 1992 |
| **FFCA** | Federal Facility Compliance Act |
| **FTE** | full-time equivalent |
| **g** | gram |
| **GDP** | gaseous diffusion plant |
| **Ge** | germanium |
| **GNP** | gross national product |
| **HADF** | high-assay decontamination facility |
| **HEU** | highly enriched uranium |
| **HF** | hydrogen fluoride |
| **HLW** | high-level radioactive waste |
| **Hp** | horsepower |
| **HVAC** | heating, ventilating, and air conditioning |
| **IAEA** | International Atomic Energy Agency |
| **IOM** | Institute of Medicine |
| **K** | degrees kelvin |
| **kg** | kilogram |
| **Kg U** | kilogram uranium |
| **£** | British pound sterling |
| **LADF** | low-assay decontamination facility |
| **LLW** | low-level radioactive waste |
| **m** | metastable (isotope, as in "$^{234m}Pa$") |
| **m** | meter |
| **M&O** | management and operating |
| **MACS** | Mobile Autonomous Characterization System (Mobile Automated Characterization Systems) |
| **mm** | millimeter |
| **MMES** | Martin Marietta Energy Systems |

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| **MOX** | mixed uranium-plutonium oxide fuel |
| **mrem** | millirem |
| **mSv** | millisievert |
| **MTU** | metric ton uranium |
| **NAE** | National Academy of Engineering |
| **NaI(T1)** | sodium iodide |
| **NAS** | National Academy of Sciences |
| **Np** | neptunium |
| **NRC** | National Research Council |
| **NTS** | Nevada Test Site |
| **OSHA** | Occupational Safety and Health Administration |
| **Pa** | protactinium |
| **PCBs** | polychlorinated biphenyls |
| **pCi** | picocurie |
| **PGDP** | Paducah gaseous diffusion plant |
| **PI** | program integration |
| **ppm** | parts per million |
| **Pu** | plutonium |
| **RCRA** | Resource Conservation and Recovery Act of 1976 |
| **RSM** | radioactive scrap metal |
| **S&M** | surveillance and maintenance |
| **S&S** | safeguards and security |
| **SAIC** | Scientific Applications International Corporation |
| **SSABs** | Site Specific Advisory Boards |
| **Superfund** | see CERCLA |
| **Sv** | sievert |
| **SWU** | separative work unit |
| **$99_{Tc}$** | technetium-99 |
| **TLG** | TLG Engineering |
| **TSCA** | Toxic Substances Control Act of 1979 |
| **U** | uranium |

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| **$U_3O_8$** | uranium oxide |
| **$UF_4$** | uranium tetrafluoride |
| **$UF_6$** | uranium hexafluoride |
| **$UO_2$** | uranium dioxide |
| **$UO_2F_2$** | uranyl fluoride |
| **$UO_2(NO_3)_2$** | uranyl nitrate |
| **USEC** | United States Enrichment Corporation |
| **WBS** | work breakdown structure |
| **WM** | waste management |
| **µg** | microgram |