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LINKING LEGACIES

320361

Connecting the Cold War Nuclear Weapons Production Processes To Their Environmental Consequences

U.S. DEPARTMENT OF ENERGY

OFFICE OF ENVIRONMENTAL MANAGEMENT

This report connects the missions and functions of our nation's nuclear weapons facilities with the inventories of waste and materials remaining at the plants, and the extent and characteristics of contamination in and around the sites.

It aims to provide Congress, DOE program managers, non-governmental analysts, and the public with an explicit picture of the environmental results of each step in the nuclear weapons production and disposition cycle. Such new knowledge from the past can help serve as a guide for the future.

This document was produced by the Environmental Management program's Office of Strategic Planning and Analysis, with assistance from hundreds of people throughout the Department of Energy, as well as from contractors, independent experts, and others.

All of the photographs in ***Linking Legacies*** have been taken by Robert Del Tredici, except those on pages ii (top), 11, 12, 25, 145 (bottom), 179, 197, and back cover.

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Front cover:
Top: Model of the Hiroshima Bomb
on display at Smithsonian Air and Space Museum
in exhibit entitled "The Social Impact of Flight."
Washington, D.C. June 25, 1981.
Bottom: Drums of radioactive waste
in temporary storage
at the Fernald site in Ohio.
December 28, 1993.

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Linking Legacies

Fizeau. This 11-kiloton atmospheric nuclear explosion, code-named "Fizeau," was one of 210 atmospheric nuclear tests conducted by the United States. Of the 1,054 nuclear tests explosions conducted by the U.S., 904 were detonated at the Nevada Test Site. All U.S. nuclear explosions since 1962 have been underground. *Event Fizeau, Operation Plumbbob, Yucca Flat, Nevada Test Site, Nevada. 9:45 A.M., September 14, 1957.*

Barrels of transuranic waste sit on a concrete pad in temporary storage. This waste is contaminated with traces of plutonium. More than 300,000 barrels of such waste from nuclear weapons production are buried or stored around the country. Cleanup efforts throughout the weapons complex will add to the volume of this waste. *Transuranic Waste Storage Pads, E Area Burial Grounds, Savannah River Site, South Carolina. January 7, 1994.*

Linking Legacies

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January 1997

The U.S. Department of Energy
Office of Environmental Management

Underground uranium mine near Grants, New Mexico. Prospectors discovered rich deposits of uranium in the area in 1950, initiating 40 years of mining activity in the region. *Grants, New Mexico. August 19, 1982.*

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A remote monitoring camera inside the Defense Waste Processing Facility allows workers to monitor operations in the world's largest high-level nuclear waste processing facility. This facility fills canisters with high-level nuclear waste solidified in glass. The waste was generated by reprocessing operations, which extracted plutonium for use in nuclear weapons. The waste-filled canisters are stored awaiting the availability of a geologic repository for permanent disposal. *Savannah River Site, South Carolina. June 15, 1993.*

INTRODUCTION

In the aftermath of the Cold War, the United States has begun addressing the environmental consequences of five decades of nuclear weapons production. In support of this effort, the National Defense Authorization Act for Fiscal Year 1995 directed the Department of Energy (DOE) to describe the waste streams generated during each step in the production of nuclear weapons.

Accordingly, this report responds to this mandate, and it is the Department's first comprehensive analysis of the sources of waste and contamination generated by the production of nuclear weapons. The report also contains information on the missions and functions of nuclear weapons facilities, on the inventories of waste and materials remaining at these facilities, as well as on the extent and characteristics of contamination in and around these facilities.

Other DOE reports have provided much of this information separately, but this analysis unites specific environmental impacts of nuclear weapons production with particular production processes. The Department used historical records to connect nuclear weapons production processes with emerging data on waste and contamination. In this way, two of the Department's "legacies"—nuclear weapons manufacturing and environmental management—have become systematically "linked."

In reality, the two legacies were never separate. The secrecy surrounding nuclear weapons made a disconnect between the two seem natural. However, the greater openness within the nuclear weapons complex now makes this new linkage possible, even necessary.

By connecting the Department's inventories of nuclear weapons materials, waste, surplus facilities, and contamination with the processes that generated them, and describing their present status, *Linking Legacies* quantifies the current environmental results of past activities. The goal of this report is to provide Congress, DOE program managers, non-governmental analysts, and the public with an explicit picture of the environmental results of each step in the nuclear weapons production and disposition cycle. This new knowledge from the past can serve as a guide for the future, influencing ongoing activities like waste minimization and pollution prevention and control.

This new knowledge may also encourage us to address two questions during our planning and program implementation: What could we have done differently in the past that would have lightened our burden today? What should we be doing now that can most effectively avoid further environmental problems in the days to come?

Glovebox for handling plutonium is a sealed environment kept under negative pressure and, when necessary, filled with inert gas to keep the plutonium inside from igniting in air. Safety procedures require workers to wear anti-contamination clothing and to handle plutonium through rubber gloves attached to the wall of the box. *Plutonium Finishing Plant, Hanford Site, Washington. December 17, 1993.*

1. Background and Summary of Findings

In 1942, the United States of America began to develop technology capable of producing nuclear weapons under the U.S. Army Corps of Engineers' Manhattan Engineer District (known as the Manhattan Project). Initial efforts resulted in the first atomic bombs used at the end of World War II. With the enactment of the Atomic Energy Act of 1946, nuclear weapons development and production was transferred to the newly-created civilian Atomic Energy Commission (AEC). AEC developed and managed a network of research, manufacturing, and testing sites, focusing the efforts of these sites on stockpiling an arsenal of nuclear weapons. Initially, the nuclear weapons production network was small and scattered, relying on many small, privately owned facilities. In the late 1940s and early 1950s, during a period of great expansion of the nuclear weapons complex, most of these functions were consolidated into a complex of large, centralized, government-owned production facilities.

Congress abolished AEC in 1975. Its nuclear weapons production mission was incorporated into the Energy Research and Development Administration (ERDA), which was subsumed into DOE in 1977.

Stockpiling nuclear materials and weapons required an extensive manufacturing effort that generated large volumes of waste and resulted in considerable environmental contamination. Growing concerns about safety and environmental problems caused various parts of the weapons-producing complex to be shut down in the 1980s. These shutdowns, at first expected to be temporary, became permanent when the Soviet Union dissolved in 1991. Although the nation continues to maintain a reduced arsenal of nuclear weapons and a limited production capability, the Department has largely suspended nuclear weapons production activities and begun to downsize the weapons complex as part of the stockpile stewardship and management program. Production materials and facilities once considered vital to national defense have become excess to the Department's current mission needs. The primary missions of many former nuclear weapons production sites are now environmental restoration, waste management, nuclear material and facility stabilization, and technology development.

In 1989, the Secretary of Energy created the Office of Environmental Restoration and Waste Management (later renamed the Office of Environmental Management) to consolidate budgets and staff devoted to similar environmental tasks within the Department into a single DOE program office. The Office of Environmental Management (EM), through the Department's many field and operations offices, is acting to mitigate the risks and hazards posed by the legacy of nuclear weapons production. Essentially all of the identified legacy waste and environmental damage situations have been, or are being, addressed under the provisions of federal and state law, including the Federal Facility Compliance Act and the agreements made pursuant thereto.

Other DOE Reports on the
Environmental and Potential Human Health Impacts
of Nuclear Weapons Production

- *Closing the Circle on the Splitting of the Atom: The Environmental Legacy of Nuclear Weapons Production and What the Department is Doing About It,* DOE/EM-0266 (1996).
  - Describes the origin and ongoing cleanup of the environmental legacy of nuclear weapons production.
- *Estimating the Cold War Mortgage: The 1995 Baseline Environmental Management Report,* DOE/EM-0232 and 1996 update, DOE/EM-0290.
  - Estimates the life-cycle activities and costs of the DOE Environmental Management Program.
- *Risks and the Risk Debate: Searching for Common Ground,* (1996).
  - Evaluates the risks that the Department's environmental legacy poses to its workers, the public, and the environment.

Surplus facilities. Hanford's B Reactor was the first plutonium-production reactor in the world. Plutonium created in this reactor fueled the first atomic explosion in the Alamogordo desert on July 16, 1945 and it formed the core of the bomb that exploded over Nagasaki on August 9, 1945. Built in less than one year, the B Reactor operated from 1944 until 1968. It has been designated a National Historic Mechanical Engineering Landmark. *100-B Reactor Area, Hanford Site, Washington. July 11, 1994.*

Although the Department is committed to long-term cleanup of the nuclear weapons complex, it is not possible to return all contaminated DOE sites to unrestricted public use. Nuclear material and facility stabilization, remediation, and waste management will be supplemented with monitoring, land-use restrictions, and other institutional controls to protect human health and safety over the long term.

The Four Elements of the Environmental Legacy

Section 3154 of the National Defense Authorization Act for Fiscal Year 1995 directs the Department to describe each step of the complete cycle of production and disposition of nuclear weapons components by the Department of Energy of all waste streams generated before 1992 (See Appendix D). The goal of *Linking Legacies* is to provide Congress with as comprehensive and accurate a picture as possible of the environmental results of each step of the weapons production and disposition cycle. The report broadly applies the term "waste streams" to include four major legacy elements:

- **Waste**, including high-level, transuranic, low-level, and hazardous waste, byproduct material as defined under Section 11e(2) of the Atomic Energy Act of 1954, as amended, and other waste;
- **Contaminated environmental media**, which include soils, groundwater, surface water, sediments, debris, and other materials;
- **Surplus facilities** once used for nuclear weapons production that are no longer needed and are slated to be deactivated and decommissioned; and
- **Materials in Inventory**, which includes all materials not used in the past year and not expected to be used in the upcoming year.

Detailed reports on each element are found in Chapters 3 through 6.

This report analyzes the origins of the Department's current waste inventories. It does not document or recreate historical waste generation, management practices, or releases.

Contaminated environmental media are included in this report because many waste streams were managed in a manner that resulted in releases to the environment. Surplus facilities and materials in inventory are also included because, like waste and contaminated media, they require long-term management even if they are not technically considered "waste."

The Department suspended much of its nuclear weapons production activities prior to 1992. Since that time, a large number of potential release sites, wastes, and facilities have been characterized, and many waste management and cleanup activities have been completed. The data in this report reflect the status of the environmental legacy of the nuclear weapons complex as of mid-1996.

Materials in Inventory. Plutonium is one of the most challenging of the Department of Energy's ten categories of Materials in Inventory. The steel cans shown here have been approved by the U.S. Department of Transportation for shipping plutonium oxide powder and metal across the nation. They are the same kinds of containers used in the commercial food industry. *DOE ZR inner shipping component of a DOT 6M shipping container. Plutonium Finishing Plant, Hanford Site, Washington. December 16, 1993.*

What is Not Covered in this Report

The following subjects are not discussed in this report because they either fall outside the scope of the congressional mandate, are unidentifiable and unquantifiable, or are not under the purview of the Department of Energy:

- Wastewater outfalls, stack emissions, and other releases not in identifiable or quantifiable contaminated environmental media;
- Contaminated facilities in use, including active waste management facilities;[1]

[1] *Although individual facilities that remain in use are excluded, sites at which those facilities are located are included if they contain other legacy elements.*

Complexities of the legacy. This facility at the Oak Ridge National Laboratory blended transuranic and low-level radioactive waste with concrete grout, which it then injected into rock fissures deep underground. This technique is termed "hydrofracture," and it was a standard practice at Oak Ridge for 30 years until it was discontinued in 1983. The Department of Energy plans to install a system to detect and monitor contaminants migrating from the grout into surrounding groundwater, although nothing can be done to remove the radioactive grout itself. One of the Department's surplus facilities, the Old Hydrofracture Facility will be dismantled and its injection wells plugged. The process of dismantlement will generate radioactive waste, but the radioactive scrap metal may be recycled. The large rust spots visible in the photo are the result of hammer blows delivered decades ago to dislodge drying concrete from inside the tank walls. *Old Hydrofracture Facility, Melton Valley, Oak Ridge Reservation, Oak Ridge, Tennessee. January 10, 1994.*

- Materials in use or in strategic reserves;
- Nonradioactive hazardous waste disposed of at commercial facilities;[2]
- Nonhazardous, nontoxic, and nonradioactive waste, e.g., sanitary waste that does not require special management;
- Waste, environmental contamination, surplus facilities, and superfluous materials from the military deployment of nuclear weapons, such as surplus missile silos and contaminated groundwater at bases for strategic bombers;
- Waste, environmental contamination, surplus facilities, and superfluous materials managed by the commercial nuclear industry, (e.g., spent nuclear fuel from nuclear power plants and commercial low-level waste disposal facilities);
- Risk and cost implications of the environmental legacy of nuclear weapons production; and
- Social, economic, and political legacies of nuclear weapons production and the Cold War.

[2] *These materials are presumed to have been treated, stored, and disposed of in a manner that obviates the need for continued management. Any environmental impacts of treatment, storage, and disposal services paid for by DOE would be indistinguishable from the impacts of the management of non-DOE wastes. However, in several cases DOE is a potentially responsible party for hazardous waste sites listed on the EPA National Priorities List, under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), commonly known as Superfund.*

Contaminated environmental media. From 1944 until 1957, untreated liquid low-level radioactive waste from the Oak Ridge National Laboratory was discharged into White Oak Creek, which then flowed directly into the Clinch River. Today, the waters of White Oak Creek carry sediments contaminated with strontium-90, tritium, cesium-137, cobalt-60, and PCBs. These contaminants come from past laboratory discharges and waste storage area seepages. To insure that most of the contaminated particles settle out of the creek water before it flows into the Clinch River, the Department of Energy has constructed a state-of-the-art embayment dam, and, above it, White Oak Lake (pictured here). *White Oak Lake, one mile from Oak Ridge National Laboratory, Oak Ridge, Tennessee. January 11, 1994.*

PROCESSES THAT GENERATED THE LEGACY OF NUCLEAR WEAPONS PRODUCTION

This report describes nuclear weapons production activities in terms of eight general groupings of manufacturing processes; a description of each is essential to gain an understanding of the analyses in this report. The eight general groupings of activities are:

- Uranium Mining, Milling, and Refining
- Isotope Separation (Enrichment)
- Fuel and Target Fabrication
- Reactor Operations
- Chemical Separations
- Weapons Component Fabrication
- Weapons Operations
- Research, Development, and Testing

A brief description of each of these processes is contained in Chapter 2. A more detailed discussion of the processes can be found in Appendix B.

Nonweapons activities also took place at the DOE weapons complex sites. These activities generated waste and contaminated media similar in character and quantity to those resulting from nuclear weapons production. Nonweapons activities are grouped into the following two categories in this report:

- **Support for the Naval Nuclear Propulsion Program.** The Naval Nuclear Propulsion Program is a joint DOE and U.S. Navy program responsible for the design, testing, construction, and operation of nuclear propulsion systems for surface warships and submarines. The Department produced highly-enriched uranium for the Navy at its nuclear weapons complex facilities. DOE continues to accept spent nuclear fuel from Naval nuclear reactors. From 1952 until 1992, Naval reactor fuel was processed to recover enriched uranium for reuse in the weapons programs.
- **Non-defense Research and Development.** A wide variety of non-defense programs have been administered by DOE and its predecessor agencies. Since the beginning of the "Atoms for Peace" program in 1954, the federal agencies charged with administering and regulating the production and uses of atomic power have supported research and development of civilian uses of nuclear energy. These agencies have led the effort to develop nuclear power plants, supplied enriched uranium to civilian reactors, and constructed and operated prototypes and demonstration plants. The Department and its predecessor agencies have also managed many research programs addressing energy supply and basic and applied science and technology.

Summary of Findings

The major findings about the origins and characteristics of each element of the environmental legacy are summarized here. Chapters 3 through 6 present detailed results and conclusions for each element.

This report summarizes the volumes, locations, and radioactivity (where applicable) for each of the four legacy elements. Other measures that assist in explaining the size and scope of the legacy are included. This report quantifies the portion of each legacy element that resulted from nuclear weapons programs, and it allocates the nuclear weapons-related portion of each legacy element among the eight weapons production process steps.

The data in this report support several general conclusions:

The largest portion of the environmental legacy of nuclear weapons production resulted from the production of plutonium and highly-enriched uranium. Assembly of weapons from these fissile materials added relatively little. Fissile materials production encompasses uranium mining, milling, and refining, uranium enrichment, fuel and target fabrication, reactor operations, and chemical separations processes. Fissile materials production for nuclear weapons has been discontinued.

One operation accounted for more waste and contamination than any of the other seven steps in the nuclear weapons production process: chemical separations, which involves dissolving spent nuclear fuel rods and targets in acid and separating out the plutonium and uranium using a chemical process. Waste generated by chemical separations processes accounted for more than 85 percent of the radioactivity generated in the nuclear weapons production process. In addition, chemical separations generated 71 percent of the contaminated water and 33 percent of the contaminated solids (soil, rubble, debris, sludge, etc.). Finally, 24 percent of the contaminated surplus facilities for which the Department is responsible were attributed to chemical separation operations.

These environmental concerns, which have now been quantified in this report, are among the reasons the Department has begun developing alternatives to traditional chemical separations technologies to stabilize spent fuel and targets for long-term safe storage and permanent disposal. Initial results indicate that substantial safety and cost benefits can result from using these alternative technologies. Making this information available and acting on it can help to stabilize irradiated materials, thereby improving nuclear safety, saving money, and promoting nuclear nonproliferation.

The scope of the DOE Environmental Management program is mostly attributed to the nuclear weapons programs of the Department and its predecessor agencies. Weapons production attributed for 68 percent of the waste volume and 89 percent of the waste radioactivity. Also, 81 percent of the volume of contaminated media and 76 percent of the surplus facilities legacy resulted from weapons-related activities. By mass, 49

Major Findings

Waste (Chapter 3):

Waste Type Data 380,000 cubic meters (100 million gallons) of high-level waste, 220,000 cubic meters (50 million gallons) of transuranic waste, 3.3 million cubic meters (870 million gallons) of low-level waste, 32 million cubic meters (8.5 billion gallons) of 11e(2) byproduct material, 146,000 cubic meters (38.5 million gallons) of mixed low-level waste, and 79,000 cubic meters (28 million gallons) of other waste.

- 68 percent of waste by volume is from weapons production.
- 89 percent of waste radioactivity is from weapons production, 11 percent is from nonweapons programs.
- 89 percent of waste by volume is 11e(2) byproduct material from uranium mining, milling, and refining.
- 94 percent of waste radioactivity is in high-level waste from nuclear weapons and nonweapons chemical separation.

Contaminated Environmental Media (Chapter 4):

Contaminated Solid Media 79 million cubic meters (21 billion gallons).

- 95 percent of contaminated solid media is soil.
- 70 percent of contaminated solid media is contaminated with radionuclides, 14 percent with hazardous substances, 16 percent both.
- 93 percent of contaminated solid media by volume is from nuclear weapons production.
- 32 percent of solid media contamination is associated with chemical separation for nuclear weapons production; 37 percent with research, development, and testing nuclear weapons; 11 percent with fuel and target fabrication from nuclear weapons production; and 20 percent with other DOE activities.

Contaminated Water 1,800 million cubic meters (475 billion gallons).

- More than 99 percent of contaminated water is groundwater.
- 14 percent of contaminated water is contaminated with hazardous constituents, 57 percent by radionuclides, 29 percent both.
- 81 percent of contaminated water by volume is from nuclear weapons production.
- 70 percent of water contamination is associated with chemical separation for nuclear weapons production, 19 percent with various nonweapons activities, and 11 percent with other DOE activities.

Surplus Facilities (Chapter 5):

Number of Facilities Approximately 5,100 facilities.

- 76 percent of facilities are weapons-related.

Materials in Inventory (Chapter 6):

Total Mass 820 million kilograms (1,800 million pounds).

- 49 percent of materials in inventory by mass is from weapons production.
- 71 percent of materials in inventory by mass is depleted uranium and 19 percent is scrap metal.
- Enrichment for weapons production produced 38 percent of the material by mass, and enrichment also produced much of the nonweapons material, including much of the depleted uranium, scrap metal, and lithium.

percent of the Department's materials in inventory were procured for, used in, or created by, nuclear weapons programs. The balance of the legacy waste, contamination, materials, and facilities is largely attributable to nuclear energy or energy research programs.

The distinction between the legacy of nuclear weapons and other U.S. government nuclear activities is not always clear. For example:

- The same mines and mills that provided uranium to AEC for nuclear weapons production also provided uranium to AEC for nonweapons programs, including use in naval propulsion reactors, research and test facilities, and commercial power plants.

Methodology

ESTABLISH FRAMEWORK

- Identify universe of legacy materials
- Define eight weapons production process categories:
  - Uranium Mining, Milling, and Refining
  - Isotope Separation (Enrichment)
  - Fuel and Target Fabrication
  - Reactor Operations
  - Chemical Separations
  - Weapons Component Fabrication
  - Weapons Operations
  - Research, Development, and Testing
- Define the four legacy elements:
  - Waste
  - Contaminated Media
  - Surplus Facilities
  - Materials in Inventory
- Peer Review of Analytical Framework

GATHER DATA

- Identify sources of data for each legacy element
- Compile data on historic site missions

ASSIGN MATERIALS TO THE FOUR LEGACY ELEMENTS

- Compare data between sources
- Identify double-counted and unquantified materials
- Eliminate excluded materials

ATTRIBUTE MATERIALS TO WEAPONS AND NONWEAPONS CATEGORIES IN PRODUCTION PROCESSES

- Initial assignment based on site of origin
- Investigate historical operations conducted at sites
- Identify data gaps and develop assumptions
- Revise assignments as necessary based on information about specific historical operations and assumptions

• After 1964, uranium enrichment in the United States was increasingly devoted to naval propulsion reactors, research and test facilities, and commercial nuclear power plants, even though it took place in the same plants that had produced enriched uranium for nuclear weapons. Furthermore, enriched uranium from nonweapons programs was often recycled back to nuclear weapons programs, and enriched uranium produced for the weapons programs was reused in nonweapons programs.

• Nuclear reactors and chemical separation plants constructed and operated primarily to support nuclear weapons production have also produced nuclear materials for nonweapons programs.

METHODOLOGY

To prepare this report, the Department gathered the latest data available for each of the four legacy elements (waste, contaminated environmental media, surplus facilities, and materials in inventory). The data were analyzed to categorize each element of the legacy according to the nuclear weapons process or nonweapons activity from which it resulted. This methodology required assumptions and expert judgment where specific data were not available.

A summary of the methodology used to prepare this report is shown in the text box "Methodology." More detailed information about the methodology used to measure and categorize each legacy element is found in Chapters 3 through 6.

DATA SOURCES AND LIMITATIONS

Most of the data sources used for this report contain information compiled for reasons different from those underlying this report. As a result, some judgments were necessary in interpreting and adapting the existing information to satisfy the requirements of Section 3154 of the National Defense Authorization Act for Fiscal Year 1995.

Specific issues concerning the data for each legacy element are discussed in detail in Chapters 3 through 6. The quantities of waste, contaminated environmental media, surplus facilities, and materials in inventory attributed to the weapons programs and to particular processes are not precise. However, they represent the Department's best judgment based on available data.

While this report covers all four legacy elements in an effort to respond fully to the congressional request, the Department is not able to provide the same level of detail for contaminated environmental media, surplus facilities, and materials in inventory as it does for waste. It was possible to present a detailed

Waste. A painted plastic owl deters birds and mice from nesting among drums of transuranic waste inside a storage dome at the Los Alamos National Laboratory. The drums contain waste contaminated with plutonium and other long-lived radioactive heavy elements. Nuclear weapons research, design, and development generated most waste stored here. *Transuranic Waste Storage Dome, Building 48 East, Technical Area 54, Area G, Los Alamos National Laboratory, New Mexico. February 24, 1994.*

description of volumes, locations, radionuclide content, and hazardous constituents for most waste because mature data are readily available. Data in this report for the other elements are not as complete. Key issues for each legacy element include:

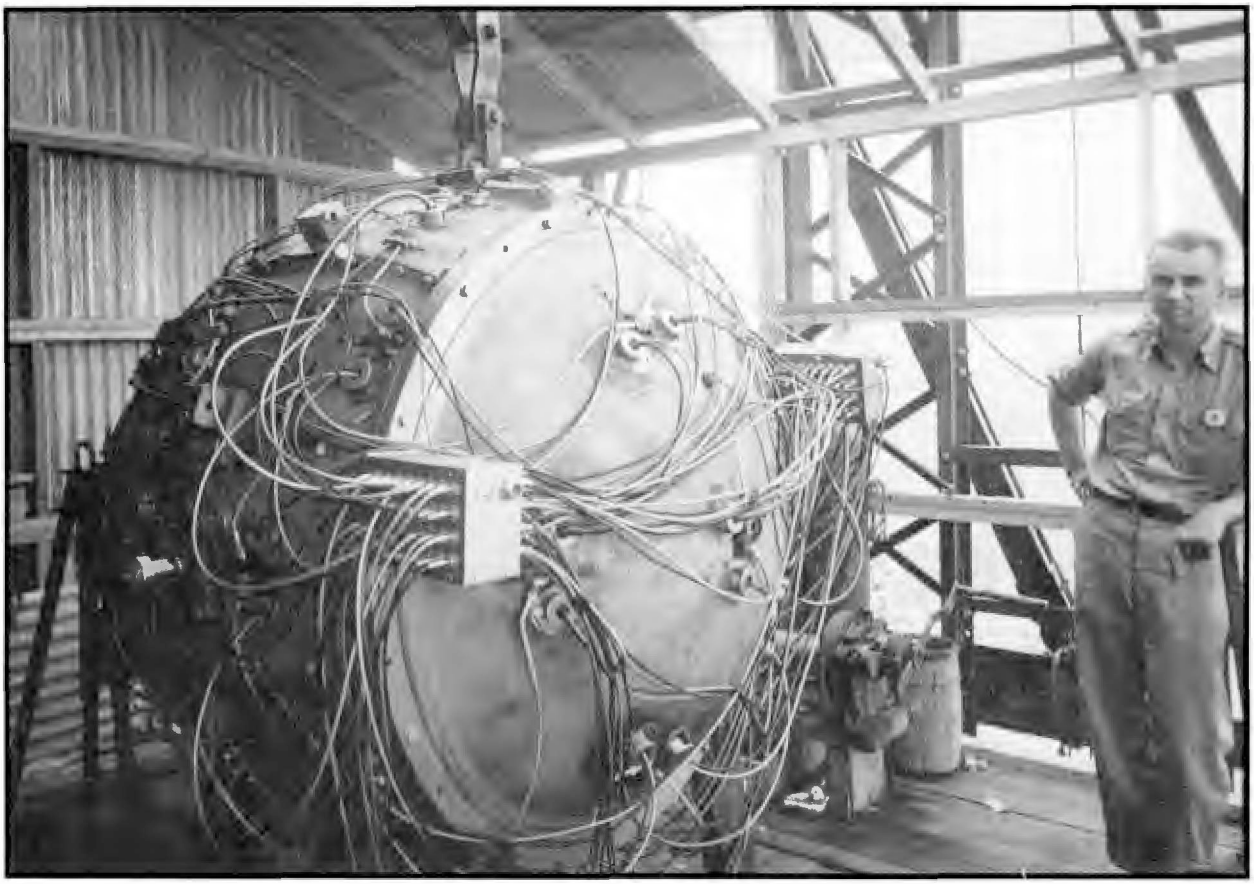
- *Waste* – The Department can provide a reasonably accurate inventory of its waste volumes and characteristics. However, changes between 1942 and 1992 in the definitions of waste categories have caused uncertainty in the categorization of some waste.
- *Contaminated Environmental Media* – Characterization of some potential release sites is not yet complete. The Department is engaged in a multi-year effort to characterize these remaining sites. Additionally, there are different ways to define and quantify contaminated environmental media.
- *Surplus Facilities* – Counting the number of surplus facilities provides only a limited understanding of this element. Size, extent of contamination, condition, type of construction, and other factors vary considerably among the Department's surplus facilities. Some facilities had multiple uses, with each activity responsible for a portion of contamination. With limited information on hand, some judgment was required to attribute certain facilities to the weapons program or to specific processes. Finally, the number of surplus facilities will change in the future when the Department declares additional facilities to be surplus, and as surplus facilities are decommissioned.
- *Materials in Inventory* – The Department began only in the last year to quantify and characterize its materials in inventory. Although the Department has obtained comprehensive, centralized inventory information on ten categories of materials in inventory through the Materials in Inventory Initiative, there are many additional materials at Department-owned facilities that have not been examined.

2. Nuclear Weapons Production Processes and History

Hanford N Reactor opening ceremony. President John F. Kennedy spoke at the opening ceremony for the Hanford N Reactor, which was designed to produce steam for electricity generation in addition to plutonium for the nuclear weapons stockpile. It was Hanford's ninth and last production reactor. The N Reactor was shut down permanently in 1986. *100-N Area, Hanford Site, Washington. September 1963.*

Overview

It is necessary to understand the operation and history of the nuclear weapons complex to properly attribute the resulting waste, contaminated media, surplus facilities, and materials in inventory. Understanding the processes begins with understanding nuclear weapons themselves and the activities that went into making their materials and components. This chapter briefly describes nuclear weapons, their production processes, facility locations, and the history of events that generated today's legacy. Appendix B provides more detailed history and more technical descriptions of key nuclear weapons production processes.



The "Gadget." Dr. Norris E. Bradbury stands next to the world's first nuclear explosive device, code-named the "Gadget," which yielded the equivalent of 21,000 tons of TNT when it detonated at 5:30 AM on July 6, 1945. Dr. Bradbury became the director of the Los Alamos National Laboratory in 1945 and served as head of the lab until 1970. *Jornada Del Muerto Valley, New Mexico. July 1945.*

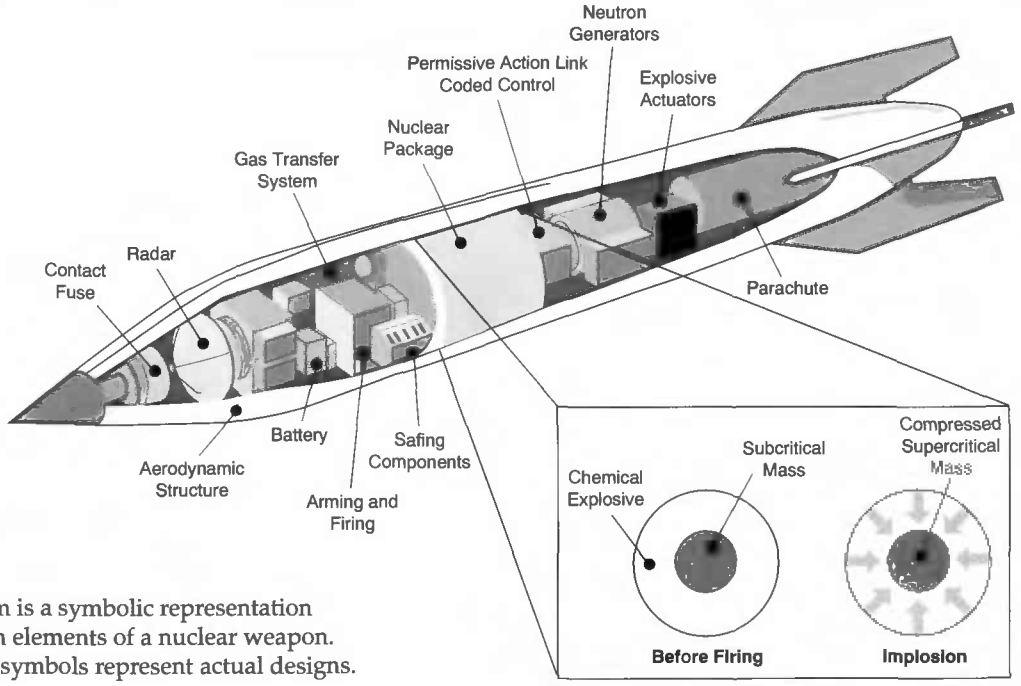
Background

A nuclear weapon is a complex device consisting of many parts. A number of these parts require special materials in their manufacture; all of them have rigorous specifications for assembly. The essential ingredients of all nuclear weapons are fissile materials. Fissile materials are isotopes capable of being split or "fissioned" by a low energy neutron. Fission releases energy and additional neutrons and energy in the process leading to a self-sustaining chain reaction. Figure 2-1 illustrates the generic design elements of a nuclear weapon and explains the basic principles of its operation.

Most of the nuclear weapons complex was devoted to producing fissile and other nuclear materials. Nuclear materials production started with mined and milled uranium. Uranium was either enriched to high uranium-235 levels for direct use in nuclear weapons, or it was used to produce plutonium. In plutonium production, reactor fuel and targets made of uranium were irradiated in nuclear reactors then chemically processed to recover unused uranium and to extract plutonium. Tritium was produced in a similar fashion by separating lithium isotopes, then manufacturing lithium targets which were irradiated in reactors, then chemically processed to recover the tritium. Figure 2-2 illustrates a simplified flow of materials within the nuclear weapons complex.

The numerous activities that went into making nuclear materials and weapons and storing or disposing of the waste were conducted at hundreds of sites across the country. Some of the sites were owned by DOE and its predecessor agencies and operated by contractors; others were privately owned, but worked under contract with DOE; still others provided DOE and its operations contractors with needed services and supplies. Table 2-1 lists the major sites associated with the process categories and Figure 2-3 gives their locations.

Figure 2-1. Generic Design Elements of a Modern Nuclear Weapon



This diagram is a symbolic representation of the design elements of a nuclear weapon. None of the symbols represent actual designs.

Nuclear explosions are produced by initiating and sustaining nuclear chain reactions in highly compressed material which can undergo both fission and fusion. Modern strategic, and most tactical, nuclear weapons use a nuclear package with two assemblies: the "primary," which is used as the initial source of energy; and the "secondary," which provides additional explosive power. The primary contains a central core, called the "pit," typically composed of plutonium-239 and/or highly enriched uranium (HEU), and other materials. Plutonium-239 and HEU are fissile materials, capable of sustaining a chain reaction. HEU contains large fractions of uranium-235. The pit is surrounded by a layer of high explosive.

Primary Detonation

The primary nuclear explosion is initiated by detonating the layer of chemical high explosive that surrounds the "pit" which in turn drives the pit material into a compressed mass at the center of the primary assembly. Compression causes the fissile material to become supercritical. A neutron generator initiates a fission chain reaction in this supercritical mass. The implosion process is illustrated in the inset above.

Boosting

In order to achieve higher explosive yields from primaries with relatively small quantities of pit material, a technique called "boosting" is used. Boosting is accomplished by injecting a mixture of tritium (T) and deuterium (D) gas into the pit. The implosion of the pit along with the onset of the fissioning process heats the D-T mixture to the point that the D-T atoms undergo fusion. The fusion reaction produces large quantities of very high energy neutrons which flow through the compressed pit material and produce additional fission reactions.

Secondary Activation

Radiation from the explosion of the primary can be contained and used to transfer energy to compress and ignite a physically seperate secondary component containing thermonuclear fuel. The secondary assembly may be composed of lithium deuteride, uranium, and other materials. As the secondary implodes, the lithium, in the isotopic form lithium-6, is converted to tritium by neutron interactions, and the tritium product in turn undergoes fusion with the deuterium to create a thermonuclear explosion.

Nonnuclear Components

Nonnuclear components include contact fuses, radar components, aerodynamic structures, arming and firing systems, deuterium and tritium gas transfer systems, permissive action link coded controls, neutron generators, explosive actuators, safing components, batteries, and parachutes.

Figure 2-2. How Nuclear Weapons are Made

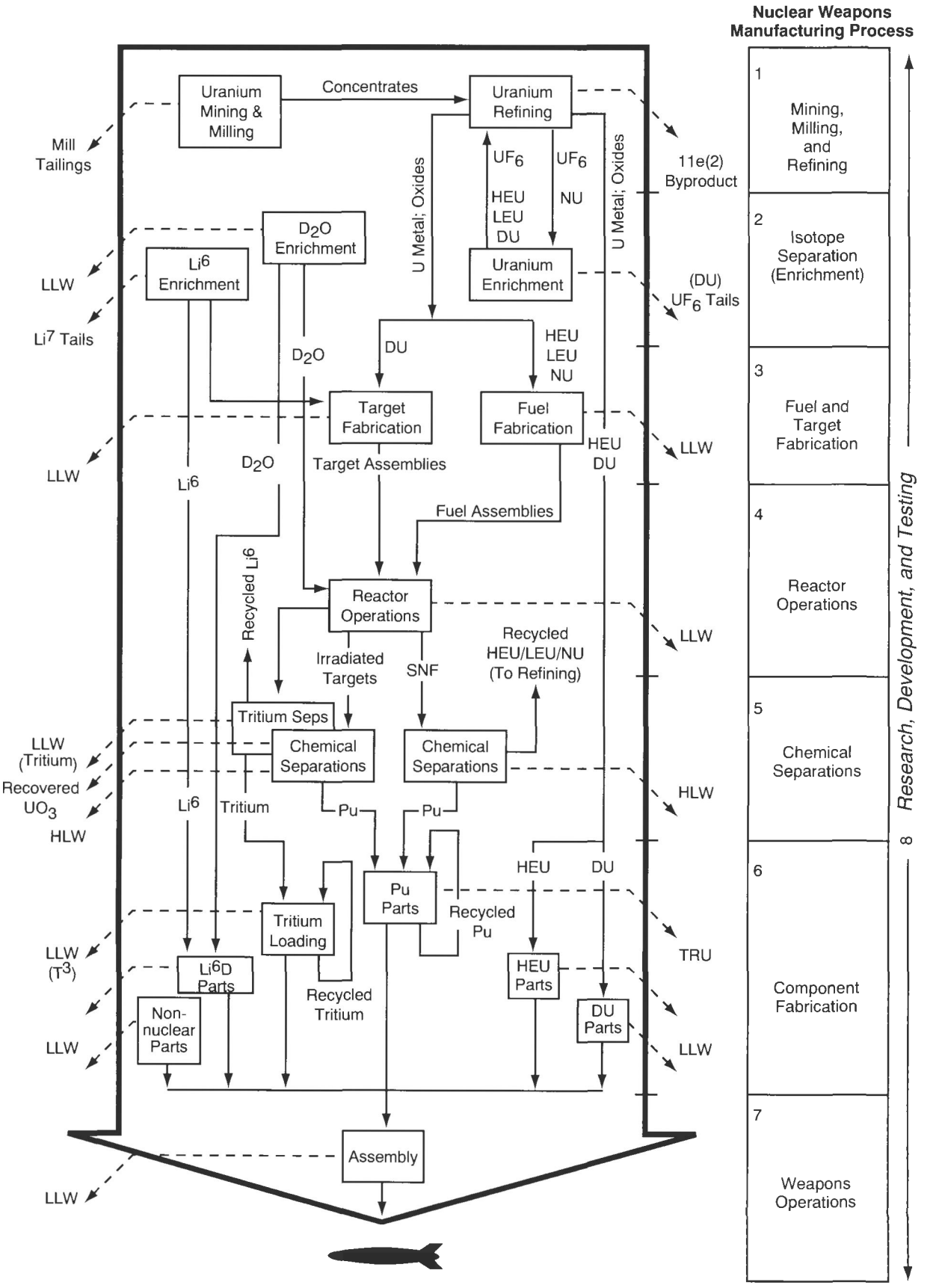
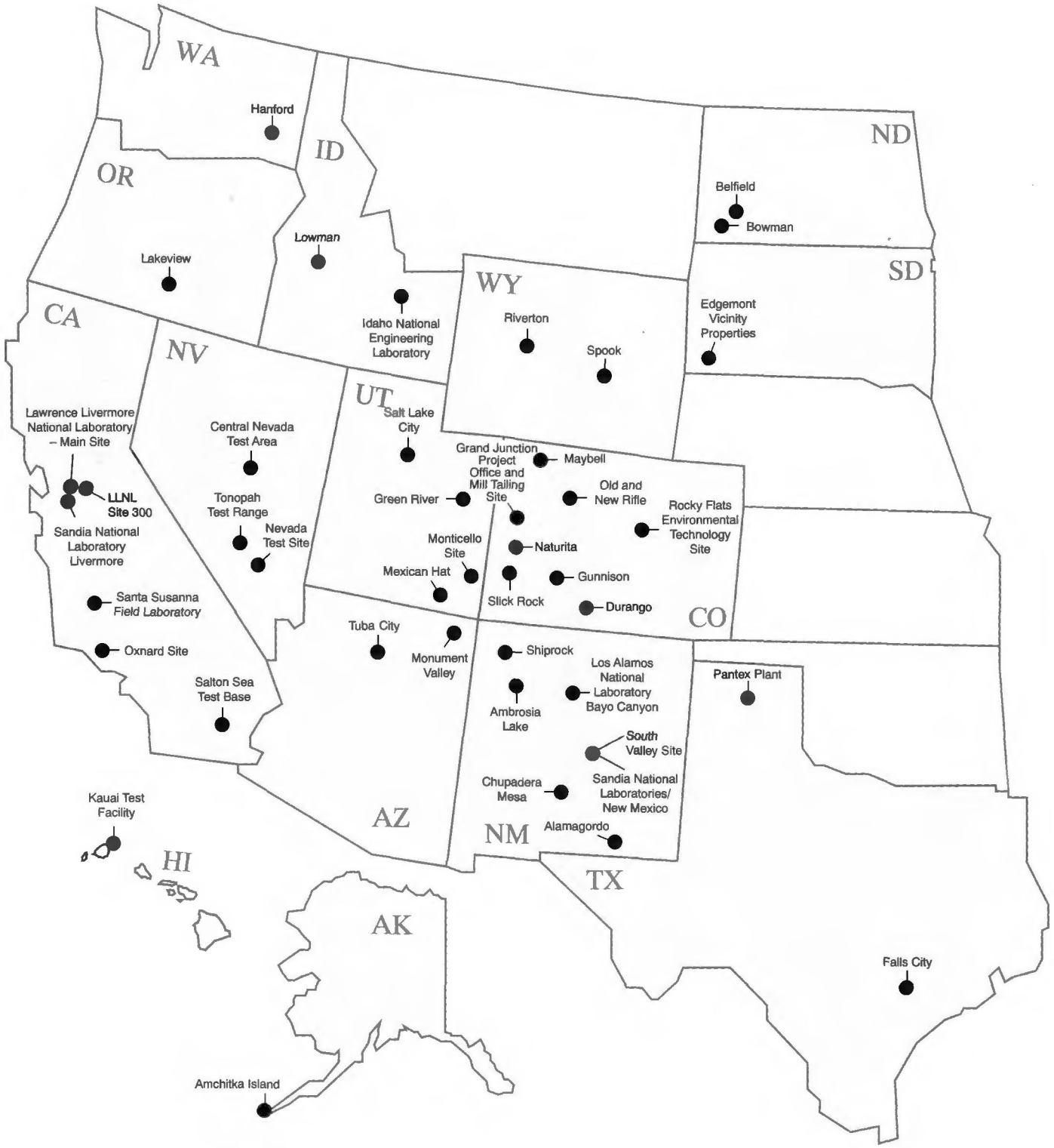
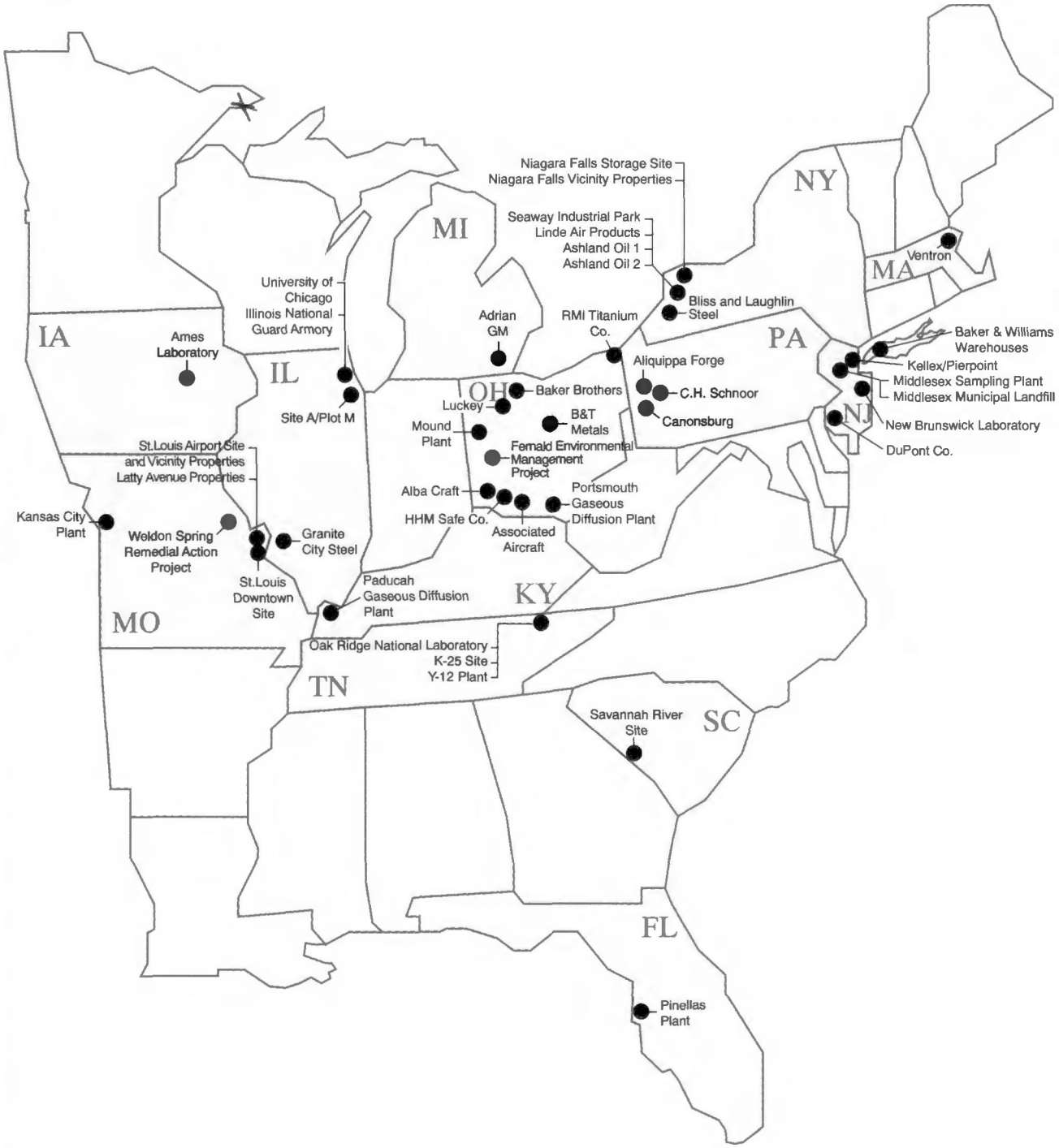


Table 2-1. Functional Processes at the Major Sites

STEP	PROCESS	MAJOR SITES
1	Uranium Mining, Milling, and Refining	Mining & Milling: Uranium Mill Tailing Remedial Action (UMTRA) Project mining and milling sites; other commercially-owned domestic mines; other commercially- and government-owned mills; foreign suppliers Ore Sampling: Fernald and Middlesex Refining: Fernald and Weldon Spring; (natural, depleted, and enriched uranium reactor fuel and targets); Oak Ridge Y-12 (weapon parts and highly enriched reactor fuel); Oak Ridge K-25, Paducah, and Portsmouth Gaseous Diffusion Plants (production of UF_6 feed)
2	Isotope Separation	Uranium: Oak Ridge K-25; Paducah; and Portsmouth Gaseous Diffusion Plants Lithium: Oak Ridge Y-12 COLEX and ELEX Plants Heavy Water: Savannah River Site Heavy Water Plant; Dana Heavy Water Plant
3	Fuel and Target Fabrication	HEU: Savannah River Site 300 M Area Other Uranium: Fernald; Ashtabula; Hanford 300 Area; and Savannah River Site 300 M Area Enriched Lithium: Oak Ridge Y-12 and Savannah River Site M Area
4	Reactor Operations	Hanford: B, D, F, H, DR, C, KW, KE, and N Reactors Savannah River Site: R, P, K, L, and C Reactors
5	Chemical Separations	Weapons Plutonium: Hanford 200 East and West Areas (PUREX, REDOX, T and B Plants, 231-Z Plant); Savannah River Site (F Canyon complex) Uranium Recycling: Hanford (PUREX, UO_3 Plant, REDOX, U Plant); Savannah River Site (H Canyon complex); Idaho National Engineering Laboratory (Idaho Chemical Processing Plant) Tritium: Savannah River Site (Tritium Facility 230H Series)
6	Weapons Component Fabrication	Plutonium: Rocky Flats; Hanford 234-5 Plutonium Finishing Plant; Los Alamos (TA-21 and TA-55) Highly Enriched and Depleted Uranium: Oak Ridge Y-12; Rocky Flats Tritium (Including recovery and recycling): Mound; Savannah River Site (Tritium Facility) Lithium-6 Deuteride (Including recovery and recycling): Oak Ridge Y-12 Plutonium Recycling: Rocky Flats; Los Alamos (TA-55); Hanford Plutonium Finishing Plant
7	Weapons Operations	Other Nonnuclear: Pantex; Oak Ridge Y-12; Mound; Kansas City; Pinellas Assembly and Dismantlement: Sandia; Pantex; Burlington Modifications & Maintenance: Pantex; Burlington; Sandia; Clarksville; Medina Modification Centers
8	Research, Development, and Testing	National Laboratories: Los Alamos; Lawrence Livermore; Sandia (New Mexico and California) Test Sites: Nevada Test Site; Bikini and Enewetak Atolls; Christmas and Johnston Islands; Amchitka Island; Tonopah Test Range; Salton Sea Test Base

Figure 2-3. Department of Energy Nuclear Weapons Sites




Niagara Falls Storage Site
Niagara Falls Vicinity Properties
NY
MI
Seaway Industrial Park
Linde Air Products
Ashland Oil 1
Ashland Oil 2
Ventron
MA
University of Chicago Illinois National Guard Armory
Bliss and Laughlin Steel
Adrian GM
RMI Titanium Co.
IA
Ames Laboratory
PA
Baker & Williams Warehouses
Kellex/Pierpoint
Middlesex Sampling Plant
Middlesex Municipal Landfill
IL
Aliquippa Forge
OH
Baker Brothers
C.H. Schnoor
Luckey
Canonsburg
NJ
New Brunswick Laboratory
Site A/Plot M
B&T Metals
Mound Plant
DuPont Co.
St.Louis Airport Site and Vicinity Properties
Latty Avenue Properties
Fernald Environmental Management Project
Alba Craft
Portsmouth Gaseous Diffusion Plant
Kansas City Plant
HHM Safe Co.
Associated Aircraft
Weldon Spring Remedial Action Project
Granite City Steel
St.Louis Downtown Site
Paducah Gaseous Diffusion Plant
KY
MO
Oak Ridge National Laboratory
K-25 Site
Y-12 Plant
TN
Savannah River Site
SC
FL
Pinellas Plant

Nuclear Weapons Production Process and History

Since the inception of the Manhattan Project in late 1942, the nuclear weapons complex has changed dramatically. The initial phase of its development, beginning during World War II and conducted by the U.S. Army Corps of Engineers Manhattan Engineer District (MED), involved the rapid construction of three sites: one for uranium enrichment (Oak Ridge, Tennessee); one for plutonium production (Hanford, Washington); and one for the research, design, and production of the first wartime atomic weapons (Los Alamos, New Mexico). A large number of private contractors supported these three sites by processing uranium ore into reactor fuel and enrichment feed stock.

After the war, authority over the nuclear weapons complex transferred to the recently-formed Atomic Energy Commission (AEC). Over the next decade, a major expansion coincided with a shift toward government-owned production facilities. Redundant facilities ensured that nuclear weapons production would not be interrupted by a problem at any single site. By the mid-1950s, all of the major weapons complex facilities had been established.

Budgetary considerations and an abundance of formerly scarce nuclear materials resulted in a shift from redundant sites to single-mission sites and a shutdown of some sites and materials production facilities in the mid-1960s. However, in the early 1980s, several of these weapons production facilities were modernized and restarted.

Significant Events: Uranium Mining, Milling, and Refining

- **During WWII**, the United States purchased the uranium content of high-assay uranium ore from the Belgian Congo (now Zaire), supplemented with ore and concentrate from Canada and the Colorado Plateau of the western U.S.
- Imported uranium ores and concentrates were stored at several locations in New York City, upstate New York, and Oak Ridge, Tennessee during **WWII**.
- **WWII** sampling and assaying was accomplished at several sites, including the Middlesex Sampling Plant in New Jersey.
- MED and early AEC uranium refining involved contractors in Tonawanda and Niagara Falls, New York; Cleveland, Ohio; Beverly, Massachusetts; St. Louis, Missouri; Deepwater and Bloomfield, New Jersey; Canonsburg, Pennsylvania; and Ames, Iowa.
- From **1946 until 1971**, AEC bought uranium ore and concentrate from Australia, Canada, Portugal, South Africa, and the Belgian Congo (later Zaire).
- In **1947**, K-25 began refining its own UF_6 feed. UF_6 feed plants were built at the Portsmouth and Paducah enrichment plants in the **early 1950s**.
- In **1948**, AEC instituted an incentive program to stimulate the domestic mining and milling of uranium. The amount of imported uranium was soon matched by domestic supplies. AEC's domestic uranium program was managed by the Grand Junction, Colorado office.
- Post-war refining was consolidated at the Mallinckrodt Chemical Works in St. Louis, Missouri and the government-owned Feed Materials Production Center (FMPC) in Fernald, Ohio, which opened in **1952**.
- In **1956**, the Weldon Spring plant near St. Louis, Missouri was converted from a conventional ordnance production facility and began refining operations. It assumed the functions of the downtown St. Louis uranium refining plant, which shut down in **1958**.
- Sampling was consolidated at Middlesex, New Jersey in the **mid-1940s** and moved to Fernald, Ohio and Weldon Spring, Missouri in the **mid-1950s**.
- The UF_6 production plants at K-25, Portsmouth, and Paducah closed in **1962**. After that time, commercial suppliers in Metropolis, Illinois converted uranium to UF_6 feed. UF_6 tails were also recycled into the enrichment plants as feed.
- The Fernald refinery was on standby from **1962** until the Weldon Spring, Missouri plant was closed in **1966**.
- U.S. government uranium ore purchases ended in **1962**, and uranium concentrate purchases halted in **1971**.
- The Fernald uranium refinery closed in **1972**, although processing of recycled uranium at FMPC continued until **1989**.

America's first uranium refinery. Here and in surrounding buildings, the Mallinckrodt Chemical Works converted raw uranium yellowcake into uranium oxide, green salt, and uranium hexafluoride. The Manhattan Project used uranium processed here as fuel for the world's first nuclear reactors and in the atomic bomb dropped on Hiroshima. After 15 years of operations, the downtown St. Louis uranium refinery closed in 1957. This uranium contaminated building was demolished in 1996. *St. Louis Sash and Door Works Building, St. Louis Downtown Site, St. Louis, Missouri. January 24, 1994.*

In the late 1980s and early 1990s, environmental and safety concerns and the end of the cold war caused many nuclear weapons production sites to shut down. However, a few key nuclear weapons production sites remain in operation at the present time.

The remainder of this chapter describes the eight weapons production process categories, identifies the major sites involved in each category, and briefly describes some of the major events in the history of U.S. nuclear weapons production.

Uranium Mining, Milling, and Refining[1]

Mining and milling involve extracting uranium ore from the earth's crust and chemically processing it to prepare uranium concentrate (U_3O_8), sometimes called uranium octaoxide or "yellowcake." Uranium ores and concentrates are sampled and assayed to determine uranium content, as well as impurities and the existence of other constituents. About half of the uranium used in the U.S. nuclear weapons complex was imported from Canada, Africa, and other areas. The remainder came from the domestic uranium industry that grew rapidly in the 1950s. The first imported uranium, high-grade "pitchblende" ore containing up to 65 percent uranium oxide by weight, was milled in Canada and by domestic contractors. After World War II, imported uranium was purchased in the form of already-milled concentrates and high-grade ores. Domestic uranium was purchased as either ore or concentrate.

[1] *Mining and refining of other materials used in nuclear weapons production, such as iron, aluminum, lead, beryllium, copper, nickel, mercury, lithium, boron, silver, and gold are not covered in this report. Their nuclear weapons program use represents only a small portion of total output.*

Uranium concentrates were refined, or chemically converted, to purified forms suitable as feed materials for the next step in the process. Examples of these feed materials are uranium hexafluoride (UF_6) for enrichment at gaseous diffusion plants, and uranium tetrafluoride (UF_4), or metal, for fuel and target fabrication. Refining, as discussed in this report, also involves the recycling of various production scraps, production residues, and uranium recovered from fuel reprocessing.

Wartime uranium refining was performed by various contractors in several Eastern states. After the war, AEC built government-owned uranium refineries in Fernald, Ohio and Weldon Spring, Missouri.

Most domestic uranium mining and milling that occurred in open-pit or underground mines and at nearby mill sites resulted in very large volumes of slightly radioactive sand-like residues called mill tailings, which typically contain radioactive thorium, radium, radon, and nonradioactive heavy metals in low concentrations. The U.S. government also purchased a small amount of uranium concentrates from in situ solution mining, which produces no tailings. Uranium refining resulted in lesser amounts of tailings and other byproducts than were created through mining and milling. These byproducts are characterized chiefly by the presence of thorium, radium, and radon.

Isotope Separation (Enrichment)

Enrichment is the process of separating naturally occurring isotopes of the same element. The three elements that have been isotopically enriched in large quantities for use in the nuclear weapons complex are uranium, lithium, and hydrogen.[2]

Uranium Enrichment – Uranium enrichment began with natural uranium (NU) and resulted in enriched uranium (EU) and depleted uranium (DU). Uranium found in nature contains approximately 0.71 percent of the isotope uranium-235, the remainder being almost entirely uranium-238. EU is processed uranium containing more than a 0.71 percent concentration of uranium-235; DU, contains less than 0.71 percent uranium-235. Highly enriched uranium (HEU) contains 20 percent or more of uranium-235; it

Significant Events: Uranium Enrichment

- MED initially investigated four processes for the enrichment of uranium: gas centrifuge, thermal diffusion, electromagnetic spectrograph, and gaseous diffusion.
- The U.S. Navy built a pilot scale thermal diffusion plant at the Philadelphia Naval Yard in **1944**.
- During **WWII**, the S-50 thermal diffusion plant and the K-25 gaseous diffusion plant fed the Y-12 electromagnetic separation plant to produce the HEU for the Little Boy bomb. All of these plants were located in Oak Ridge, Tennessee.
- The S-50 and Y-12 enrichment plants shut down in **1945 and 1946**, respectively.
- K-25 was expanded between **1946** and **1954**, and gaseous diffusion plants were built at Paducah, Kentucky and Piketon, Ohio (the Portsmouth Plant) in the **early and mid-1950s**.
- The K-25, Portsmouth, and Paducah plants operated in series, with Paducah as the feed point, and its low enriched product split between K-25, which produced LEU and HEU, and Portsmouth, which produced HEU.
- The K-25, Portsmouth, and Paducah plants ceased producing HEU for weapons purposes in **1964**, dramatically decreasing their output, while production of LEU for production reactor fuel continued.
- K-25, Portsmouth, and Paducah increased their output in the **late 1960s** in response to growing demand for enriched uranium for the U.S. Naval Nuclear Propulsion Program and the nuclear power industry. Portsmouth produced the HEU for the Navy propulsion reactors.
- K-25 was shut down completely in **1987**.
- Under the Energy Policy Act of **1992**, the Portsmouth and Paducah plants were leased by DOE to the newly created United States Enrichment Corporation which continues to operate them.

[2] *Boron isotope separation was also carried out, as were experiments with separating isotopes of plutonium and removing minor isotopes of uranium from irradiated uranium.*

was fashioned into weapons components and also used as a reactor fuel, whereas low enriched uranium (LEU) and NU are used as reactor fuel for the production of plutonium. DU was used in weapon components and as targets for the production of plutonium-239. All of the uranium enriched during the Manhattan Project was HEU for weapons components. However, as early as 1950, LEU was used for reactor fuel.

The first U.S. uranium enrichment facilities were located in Oak Ridge, Tennessee. Additional enrichment plants were later built in Piketon, Ohio and Paducah, Kentucky.

Uranium enrichment has resulted in large amounts of DU in storage, large surplus facilities, uranium-contaminated scrap metal (from facility dismantlement), PCB-contaminated waste and uranium, technetium-99, and organic solvent contamination of soils and groundwater.

Lithium Enrichment – Lithium enriched in the lighter lithium-6 isotope was placed in production reactors to produce tritium and was also chemically compounded with deuterium to be used as a component in nuclear weapons. Natural lithium is about 7.5 percent lithium-6 and 92.5 percent lithium-7. Lithium was enriched at the Y-12 Plant in Oak Ridge, Tennessee using the column exchange (COLEX) and electric exchange (ELEX) processes. Both lithium enrichment processes used large amounts of mercury, and as a result, mercury is a major feature of the contaminated environmental media legacy at Y-12.

Heavy Water Production – Heavy water is used as a source of deuterium for weapons and as a moderator and coolant for nuclear reactors. Natural water contains small amounts of deuterium (0.015 percent), which was concentrated by a combination of hydrogen sulfide-water chemical exchange, water distillation, and electrolytic processes. Heavy water plants were located in Newport, Indiana and at the Savannah River Site in South Carolina.

Significant Events:
Lithium Enrichment

- The Y-12 Plant in Oak Ridge, Tennessee was tasked with the development of lithium isotope separation technology in **1950**.
- Three processes were developed to the pilot plant stage: an organic exchange process (OREX), the ELEX process, and the COLEX process.
- Production-scale lithium enrichment using the ELEX process began at the Y-12 Plant in **1953**. Two large COLEX production plants were built in **1955**.
- The ELEX production plant was shut down in **1956**. One of the COLEX plants was shut down in **1959** and the other continued production until **1963**.
- The Li_6 stockpile is stored at the Y-12 and K-25 Plant. Lithium "tails" depleted in the Li_6 isotope are stored at the K-25 and Portsmouth plants, and a stockpile of unprocessed lithium feed is stored at K-25.

Significant Events:
Heavy Water Production

- **During WWII,** small amounts of heavy water for research came from a variety of sources, including material captured in Germany, a small amount produced domestically by electrolysis and fractional distillation, and from a plant built for the Manhattan Project in Trail, British Columbia, Canada.
- The heavy water plants at the Savannah River Site, South Carolina and Newport, Indiana began operating in **1952** to supply large amounts of heavy water for the Savannah River Site reactors.
- The Dana heavy water plant in Newport, Indiana was shut down in **1957**.
- The Savannah River Site heavy water plant stopped deuterium production in **1982** after a staged shutdown. Re-enrichment of small amounts of degraded, recycled deuterium continues using a moderator rework unit at the Savannah River Site.

Fuel and Target Fabrication

Fuel and target fabrication consists of the foundry and machine shop operations required to convert uranium feed material, principally metal, into fuel and target elements used in nuclear materials production reactors. Some later production reactors used separate fuel and target elements, while early production reactors used the same elements for both fuel and targets. Uranium ingots were extruded, rolled, drawn, swaged, straightened, and outgassed to produce rods and plates. The rods were machined, ground, cleaned, coated, clad, and assembled into finished fuel.

Reactor fuel and target fabrication was initially carried out by private contractors and at the Hanford, Washington and the Savannah River, South Carolina production reactor sites. Within a decade, government-owned plants in Fernald, Ohio and Weldon Spring, Missouri took over part of this mission, supplying the fuel manufacturing plants at Hanford and the Savannah River Site.

Chemical conversion of uranium feed to metal and processing of uranium scrap and residue resulted in low-level waste and environmental contamination with uranium, acids, and solvents. Uranium metallurgy and machining also resulted in facilities becoming contaminated with uranium.

Significant Events: Fuel and Target Fabrication

- During the Manhattan Project, fuel for the Clinton X-10 reactor (later ORNL) and the Hanford B, D, and F production reactors was manufactured by companies in Detroit, Michigan; Columbus, Cleveland, Toledo, Warren, and Hamilton, Ohio; Fort Wayne, Indiana; Reading, New Kensington, and Springdale, Pennsylvania; Bridgeport, Connecticut; and Chicago, Illinois.
- By the **spring of 1945**, Hanford's 300 Area had assumed all of the fuel fabrication responsibilities for the site's reactors except extrusion. Hanford extruded uranium rods onsite from **1946 to 1948**, then shifted to rolled rods supplied by offsite private contractors. Hanford rolled uranium rods from **1950** to **1952**.
- Hanford manufactured lithium targets for tritium production from **1949** to **1952** and again from **1965** to **1967**. The site also made bismuth targets for polonium-210 production and lead-cadmium rods used as a neutron-absorbing "poison" to control reactors.
- The M Area at the Savannah River Site was built in **1952** to clad and assemble fuel elements for the five production reactors located there.
- Facilities at the Savannah River Site M Area manufactured lithium-aluminum targets for tritium production and targets for manufacturing americium, curium, plutonium-238, and other isotopes.
- Uranium slug machining for Hanford and the new Savannah River Site reactors was taken over by FMPC at Fernald, Ohio, which opened in **1952**, and the Weldon Spring plant in Missouri which opened in **1956**. Extrusion was performed by private contractors in Adrian, Michigan, and moved to Ashtabula, Ohio in **1961**. Fernald produced rolled uranium rods onsite.
- To meet the demands of supplying fuel for 13 operating production reactors, private contractors continued to support Fernald and Weldon Spring by machining uranium slugs in the **1950s**.
- In the **1950s**, production reactor fuel changed in several respects: natural uranium was replaced by LEU, solid cylinders were replaced by tubes, and, with the opening of the N Reactor at Hanford in **1963**, aluminum-clad fuel was supplemented by fuel clad with zirconium.
- By the time N Reactor started up at Hanford in **late 1963**, there were sufficient stocks of LEU at Fernald to supply the reactor without requiring additional LEU from the gaseous diffusion plants.
- Weldon Spring shut down in **1966**, and Fernald subsequently assumed all of the fuel fabrication mission.
- In **1968**, the Savannah River Site converted to HEU fuel and DU targets. The HEU was supplied by recycling research, Naval and production reactor spent fuel and recovering the HEU at the Savannah River Site H Canyon and INEL ICPP. Weapons-grade HEU stored at Y-12 was also used to supply some fuel for Savannah River Site reactors. Fernald continued to supply LEU slugs for the N Reactor and the DU targets for the Savannah River Site reactors.
- Hanford's 300 Area made only N Reactor fuel after **1971**. The facilities shut down in **1972** and later resumed production of N Reactor fuel in **1981**.
- Fuel and target fabrication at Hanford's 300 Area ceased permanently in **1987** with the closure of N Reactor. Production at the Savannah River Site M Area and Fernald ended in **1989** with the shutdown of the last Savannah River Site reactor.

Reactor Operations

Reactor operations include fuel and target loading and removal, reactor maintenance, and the operation of the reactor itself. Experimental reactors were built by MED in the Chicago area, Oak Ridge, and Hanford. Nine full-scale production reactors were located at Hanford, Washington, and five others were built at the Savannah River Site in South Carolina.

Almost all of the radioactivity in the environmental legacy of nuclear weapons production was created by reactor operations. Irradiated fuel and targets are highly radioactive. The components of the reactor cores also became highly radioactive over time. However, the waste volume attributed to this activity is primarily composed of low-level waste from reactor support operations. The highly radioactive spent fuel and target materials typically went on to chemical separations, but an inventory of unprocessed spent fuel and targets remain in storage. Cooling the reactors contaminated several large bodies of water including the Columbia River at the Hanford Site and PAR Pond at the Savannah River Site. The reactors also required a large number of support facilities that are now surplus.

Significant Events: Reactor Operations

- Five prototype, test, and research reactors operated in the U.S. during **WWII**—one at the University of Chicago, two in the Palos Forest Preserve outside Chicago, one in Oak Ridge, and one at Hanford. Three full-scale production reactors (B, D, and F) were operating at Hanford by **mid-1945**.
- To limit radiation damage to the reactor's core, the B Reactor at Hanford was shut down in **1946** and restarted in **1948**.
- Between **1948** and **1955**, Hanford built five more production reactors (H, DR, C, KW, and KE). During their life cycles, the original eight Hanford reactors (including B, D, and F), produced weapons-grade plutonium and small quantities of other isotopes (e.g., polonium-210 and tritium).
- AEC established the Savannah River Site near Aiken, South Carolina, in **1951**. Five production reactors (R, P, L, K, and C) at the Savannah River Site manufactured tritium, weapons-grade plutonium, and other isotopes (including uranium-233, neptunium, plutonium-238 and -242, americium, and curium).
- A ninth Hanford reactor, N Reactor, began operating in **late 1963** to make weapons-grade plutonium, fuel-grade plutonium for the experimental breeder reactor program, and steam to generate electric power. N Reactor also made uranium-233 and small amounts of tritium.
- R Reactor at the Savannah River Site was shut down in **1964**.
- All of the original eight Hanford reactors were shut down between **1964** and **1971** as a result of the decreased need for weapons-grade plutonium.
- L Reactor at the Savannah River Site was shut down in **1968** when the Savannah River Site reactors were converted to use HEU fuel and DU targets.
- Beginning in **1981**, DOE began to blend excess fuel-grade plutonium from N Reactor with super-grade plutonium from Savannah River Site to produce weapons-grade plutonium.
- L Reactor at the Savannah River Site was restarted in **1985**.
- N Reactor at Hanford was shut down permanently in **1987**.
- By **1990**, all available N-Reactor-produced fuel-grade plutonium had been blended.
- P, L, K, and C reactors continued to operate at the Savannah River Site until late **1988**.

Significant Events: Chemical Separation

- The bismuth phosphate process for extracting plutonium from irradiated uranium was demonstrated in a pilot plant alongside the Oak Ridge X-10 Reactor in **1944**.
- The T Plant in the Hanford 200 West Area and B Plant in the Hanford 200 East Area opened in **1944** and **1945**, respectively. The plants separated plutonium from spent fuel using the bismuth phosphate process. The B and T Plants at Hanford shut down in **1952** and **1956**, respectively. Together the two plants processed 7,000 metric tons of spent fuel.
- The REDOX process was developed at Hanford in the late 1940s and used in the site's REDOX plant (also known as the S Plant) from **1951** through **1967**. The REDOX Plant at Hanford operated until **June 1967**, processing over 19,000 metric tons of spent fuel during its lifetime.
- The PUREX process was demonstrated at Knolls Atomic Power Laboratory in Schenectady, New York, and used at F and H Canyons at the Savannah River Site and the PUREX Plant at Hanford. The F Canyon began operation in **November 1954**. H Canyon started up in **July 1955**, and Hanford's PUREX Plant started up in the Hanford 200 East Area in **January 1956**.
- The Idaho Chemical Processing Plant (ICPP) at the Idaho National Engineering Laboratory began using variants of PUREX to process spent Navy and experimental reactor fuel for recovery and recycling of the HEU in **1953**. A new "head end" dissolving facility using the fluorinel dissolution process, was built at ICPP in the **mid-1980s**.
- The ICPP shut down in **1992**. During its operation, it recovered a total of 31.5 metric tons of uranium from spent Naval (5.1 metric tons), research, and test reactor fuel.
- The U Plant at Hanford, originally built during WWII to separate plutonium but used instead as a training facility, was modified and used to recover enriched uranium from the site's high-level waste storage tanks from **1952** until **1958**. U Plant employed a process similar to PUREX.
- The PUREX Plant at Hanford was placed on standby in **1972** because of an excess of separated fuel-grade plutonium.
- After the Savannah River Site reactors began using HEU fuel and DU targets in **1968**, the F Canyon was given the mission of processing the irradiated DU targets and producing plutonium-239 as well as americium, curium, and other isotopes; H Canyon was assigned to process the HEU spent fuel and to recover uranium-235, neptunium-237, and plutonium-238.
- At Savannah River Site, plutonium-238 recovery operations shifted to the new HB Line in **1985**.
- The PUREX Plant at Hanford was restarted in **1983**. After restart, a new line at PUREX was used to convert plutonium nitrate solutions to more stable plutonium oxide. The plutonium oxide was transferred to the Plutonium Finishing Plant (PFP) in the Hanford 200 West Area for conversion to metal.
- Hanford's PUREX Plant operated intermittently in the late **1980s** and closed permanently after a short cleanout run in **1990.**
- The first Savannah River Site tritium facility was built in F Area in **1955** to recover tritium from irradiated lithium-6 targets. A new, larger facility in H Area replaced it in **1958**, and the current Savannah River Site tritium facility began operating in **1993**.
- Since **1968**, the Hanford B Plant has been used to remove, encapsulate, and store radioactive cesium and strontium from the Hanford high-level waste tanks.
- In **1953**, the original bulk reduction building of U Plant, 224U Building, was modified and started operating as the UO_3 Plant. The UO_3 Plant solidified recovered uranium from U Plant, REDOX, and PUREX. The plant shut down from **1972** until **1984**, shut down again in **1990**, and operated for a brief period of time in **1994**.
- At the Savannah River Site during the **1980s**, the FA Line solidified recovered DU. HB Line prepared neptunium-237 and plutonium-238 and FB Line produced plutonium-239.
- The FB Line at the Savannah River Site shut down in **December 1989** for maintenance, and the F Canyon shut down in **September 1991** as a result of safety concerns. H Canyon also shut down in **1991** in response to the Secretary of Energy's determination to discontinue spent fuel reprocessing.
- F Canyon restarted in **1996** to stabilize nuclear materials.
- The PFP (234-5 Z Building) at Hanford converted plutonium nitrate into more stable plutonium oxide and metal from **1950** until **1980**, and again from **1984** until **1990**.
- Due to a **1985** accident at the PFP, plutonium oxide from Hanford was sent to LANL TA-55 for conversion to metal for several months.

Chemical Separations

Chemical separation is the process of dissolving spent nuclear fuel and targets and isolating and concentrating the plutonium, uranium, and other nuclear materials they contain. This category also includes the reprocessing of spent nuclear fuel to recover, purify, and recycle uranium for reuse in the nuclear weapons programs and the recovery of uranium from high-level waste at Hanford. Three basic chemical separation processes were used on a production scale in the United States: bismuth phosphate, reduction oxidation (REDOX), and plutonium uranium extraction (PUREX). Chemical separation plants were located at Hanford, Washington; the Savannah River Site, South Carolina; and the Idaho National Engineering Laboratory.

Chemical separation of spent fuel and target elements produced large volumes of highly radioactive, high-level waste, and large quantities of low-level radioactive wastewater, solid low-level waste, and mixed low-level waste. Processing of plutonium and other transuranic isotopes also results in transuranic waste. Waste generation per unit of dissolved heavy metal decreased by a factor of approximately 100 between 1945 and 1960. Very large volumes of water from chemical separation plants[3] —containing low levels of radionuclides and hazardous chemicals—were discharged to the ground, resulting in soil and groundwater contamination.

Hanford workers sit down to dinner at one of eight mess halls at the Hanford Construction Camp, built on the former site of the town founded between 1905 and 1910 by Judge Cornelius Hanford. The construction camp housed 50,000 people at its peak in 1944, and included two movie theaters, a post office, a bank, and a bowling alley. *Hanford Construction Camp, Washington. 1944.*

[3] *The Department has estimated that the Hanford 200 Areas, where the site's chemical separation plants are located, discharged nearly 350 billion gallons of wastewater to the ground between 1945 and 1991.*

Significant Events: Component Fabrication

- Most of the components for the **WWII** Manhattan Project bombs were made at Los Alamos, New Mexico. Some parts were made offsite by ordnance plants, machine shops, and other suppliers.
- Hanford took over the manufacture of plutonium pits at the Plutonium Finishing Plant in **1949**.
- The Y-12 Plant in Oak Ridge, Tennessee began making uranium weapon parts in **1948** and lithium deuteride weapon parts in the **mid-1950s**.
- Although it was no longer the lead site for nuclear component fabrication after **1949**, Los Alamos National Laboratory was a backup production facility and designed, developed, and fabricated these components for test devices. The original plutonium production area built at Los Alamos in late **1945**, DP Site (also known as TA-21), was replaced by TA-55 in **1978**.
- High explosive main charges were produced at the Salt Wells Pilot Plant at China Lake Naval Ordnance Station in California from the fall of **1946** through **1954**.
- The Mound Laboratory in Miamisburg, Ohio was built to manufacture polonium-beryllium initiators and other weapon parts in **1946**.
- The Burlington Army Ordnance Plant in Iowa, primarily a weapons assembly facility, also made high explosive main charges from **1947** until **1975.**
- The Pantex Plant near Amarillo, Texas, was converted from a WWII conventional munitions plant in **1951** to serve primarily as a weapons assembly plant, although Pantex also manufactured high explosive weapons components.
- The Kansas City Plant in Missouri began making nonnuclear weapon parts (electronics, rubber, plastic foams, adhesives, outer casings, and others) in **1949**.
- Steel component fabrication functions were moved from various sites across the nation to the South Albuquerque Works in New Mexico in **1952.**
- Also in **1952**, the Rocky Flats Plant near Golden, Colorado began manufacturing plutonium, HEU, and DU pit parts. Rocky Flats assembled parts from Hanford, Y-12, and the South Albuquerque Works into completed pits.
- The Savannah River Site began loading tritium into weapon components in **1955**.
- The Pinellas Plant was built in Largo, Florida, in **1957** to produce precisely timed neutron generators to initiate chain reactions in nuclear weapons.
- Mound was assigned new production functions beginning in **1955**, including detonators, cable assemblies, and firing sets and stopped producing initiators after the Pinellas Plant began producing accelerator-type neutron generators in **1957**.
- Rocky Flats ceased making HEU components in **1962**, leaving Y-12 Plant as the sole site for these components.
- AEC eliminated Hanford's plutonium component manufacturing mission in **1965**, leaving Rocky Flats the sole source of plutonium components.
- Production of beryllium components became part of normal operations at Rocky Flats in **1958**.
- The South Albuquerque Works closed in **1966**, transferring its stainless steel pit component and tritium reservoir fabrication missions to Rocky Flats.
- Mound began tritium work in **1954** and, in **1969,** began retrieving tritium from retired weapons to be recycled and sent to Savannah River Site for purification and reuse.
- Plutonium scrap and residue recycling operations were performed at the Hanford PFP, Rocky Flats, the Savannah River Site, and Los Alamos National Laboratory.
- From **1968** to **1990**, Y-12 received recovered high-enriched UO_3 from ICPP and uranium nitrate from Savannah River Site H Area and reduced it to HEU metal, which was either stockpiled or used as fuel in the Savannah River Site production reactors.
- Due to the end of the Cold War, the DOE mission to fabricate weapons components was terminated. Rocky Flats production activities ended in late **1989**, and Mound and Pinellas ended their production activities in **1995**. Y-12 now receives and stores nuclear weapon components and processes and stores HEU and lithium-6.

Component Fabrication

Weapons component fabrication includes the manufacturing, assembly, inspection, bench testing, and verification of specialized nuclear and nonnuclear parts and major subassemblies. Also included in this category is chemical processing to recover, purify, and recycle plutonium, uranium, tritium, and lithium from retired warheads, and from component production scrap and residues, as well as the maintenance, recharging, dismantlement, and materials recovery conducted separately on individual components.

The major nuclear component fabrication sites were Los Alamos National Laboratory in New Mexico; the Rocky Flats Plant, near Boulder, Colorado; the Y-12 Plant in Oak Ridge, Tennessee; and the Plutonium Finishing Plant in Hanford, Washington. Nonnuclear components were manufactured chiefly at the Mound Plant in Miamisburg, Ohio; the Kansas City Plant in Missouri, the Pinellas Plant in Largo, Florida; and the Pantex Plant near Amarillo, Texas.

Like many conventional manufacturing processes, nonnuclear component fabrication activities have resulted in hazardous waste and contamination of environmental media and facilities by solvents and heavy metals. High-explosive manufacturing has resulted in facilities and environmental media contaminated with explosives. Fabrication of nuclear components led to the presence of nuclear materials (especially plutonium) in waste, contaminated environmental media and surplus facilities, and created stockpiles of nuclear materials, much of which are no longer needed for the nuclear weapons program.

Weapon Operations

Weapon operations includes the assembly, maintenance, and dismantlement of nuclear weapons. Assembly is the final process of joining together separately-manufactured components and major parts into complete, functional, and certified nuclear weapon warheads for delivery to the Department of Defense (DoD). Maintenance includes the modification and upkeep of a nuclear weapon during its life cycle.[4] Dismantlement involves the reduction of retired warheads to a nonfunctional state and the disposition of their component parts. The dismantlement process yields parts containing special nuclear materials, high explosives, hazardous materials, and other components with hazardous and nonhazardous properties. Some parts are returned to the facility where they were originally produced. Other parts either are maintained in storage (e.g., plutonium pits) or are dispositioned onsite. Disposition processes include

Significant Events: Nuclear Weapons Operations

- In **July 1945**, MED acquired part of Oxnard Field (now Kirtland Air Force Base) in Albuquerque, New Mexico and converted it into a weapons assembly site (Sandia Base).
- Technical Area 2 at Sandia Base assembled nuclear weapons until **1957**.
- The Iowa Army Ordnance Plant in Burlington was converted to a weapons assembly plant in **1947**. Assembly functions performed at Sandia Base were transferred to the Burlington assembly plant by **1949**.
- The Pantex Plant, near Amarillo, Texas was converted to a nuclear weapons assembly plant in **1951**.
- Both the Burlington and Pantex Plants performed assembly activities between **1951** and **1975**, when Burlington functions were transferred to Pantex.
- Until **1962**, AEC stored fissile cores and initiators in separate facilities on military nuclear weapons stockpile storage sites. Maintenance and modification were also done at the bases.
- Two supporting plants were constructed in **1958**, the Clarksville Modification Center on the Fort Campbell Military Reservation in Clarksville, Tennessee and the Medina Modification Center in Medina, Texas. These sites performed tasks such as weapon repair and modification and component modification and testing. Clarksville closed in **1965** and Medina closed in **1966**.
- Final assembly of test devices has been performed at the Nevada Test Site since it opened in **1951** and at the Pacific and other test sites.

[4] *Field replacement of limited-life components by the military is not included in this category.*

crushing, shredding, burning of main high-explosive charges, and firing of small energetic components. DOE is the steward of the weapon until all components have been stabilized, stored, and disposed.

Weapon operations were chiefly done at the Pantex Plant near Amarillo, Texas; the Iowa Army Ordnance Plant in Burlington, Iowa; Technical Area 2 of Sandia National Laboratory; and the Clarksville, Tennessee and Medina, Texas modification centers.

The environmental legacy resulting from assembly and maintenance is relatively small compared to the legacy resulting from the other weapons production steps. This is partly because all the radioactive materials handled in this process are generally in the form of sealed weapons components.

Research, Development, and Testing (RD&T)

Weapons research and development were conducted at MED, AEC, and DOE weapon laboratories and test areas and as a small part of the mission of other laboratories (DoD laboratories are not included in this analysis). As used in this report, nuclear weapons RD&T includes the design, development, and testing of nuclear weapons and their effects. Localized RD&T to support specific site missions (such as fuel fabrication) is generally considered in this report to be part of each site's mission.

The main U.S. nuclear weapons research and development facilities are the Los Alamos, Lawrence Livermore, and Sandia National Laboratories.

Nuclear weapons research and development activities have produced a broad assortment of waste and large volumes of contaminated soil and debris.

Testing – The United States has conducted a total of 1,054 nuclear tests, including 24 joint U.S.-United Kingdom tests. These tests have been conducted for several purposes: 891 detonations were primarily to prove that a weapon or device would function as designed, to advance weapon design, or to verify the reliability of weapons in the stockpile; 100 detonations were chiefly to explore the effects of nuclear weapons; 88 were safety experiments and 4 were storage- and transportation-related experiments; 24 were joint U.S.-United Kingdom detonations; 7 detonations were to develop means of detecting nuclear explosions from a great distance; and 35 detonations explored nonmilitary uses of nuclear explosives. (Some tests comprised multiple detonations.)

Significant Events: Nuclear Weapons Research and Development

- Much of the early theoretical and experimental work leading to development of nuclear weapons was conducted in Europe in the first four decades of the twentieth century.
- American universities made several important contributions to the development of nuclear physics in the **1930s**.
- By **mid-1942**, government support resulted in research becoming concentrated at Columbia University in New York, the University of California in Berkeley, and the University of Chicago Metallurgical Laboratory.
- The U.S. Army Corps of Engineers began construction at Los Alamos in **1942.** Scientists assembled from many research laboratories and universities were tasked with research, design, and engineering of the first nuclear weapons. Many other research institutions and universities also contributed to the development of the atomic bomb.
- On **November 1, 1949**, Sandia Laboratory was formed from the Sandia branch of Los Alamos on the grounds of Oxnard Field (now Kirtland Air Force Base) near Albuquerque, New Mexico. The mission of the new laboratory was the design of nonnuclear components of weapons.
- AEC established the University of California Radiation Laboratory in Livermore, California as a second nuclear design laboratory in **1952**. The facility is now known as the Lawrence Livermore National Laboratory.
- In **1956**, a branch of Sandia National Laboratory was established at Livermore, California.
- Most of the DOE National Laboratories, including Oak Ridge, Brookhaven, Argonne, and Idaho, have performed basic research that has contributed to nuclear weapons development.

U.S. nuclear weapon testing has been carried out principally in the South Pacific and at the Nevada Test Site near Las Vegas, Nevada. However, several tests have been performed at other locations.

Testing has resulted in large areas of contaminated soil and other environmental media, some highly contaminated. Some safety experiments have resulted in significant quantities of plutonium dispersed on the surface. Underground explosions have left underground cavities filled with a vitrified mixture of soil and explosion residues. Surface subsidences have resulted from the collapse of the underground cavities.

U.S., Soviet, British, French, and Chinese atmospheric nuclear weapons tests have collectively increased the current average annual effective radioactive dose equivalent to the population by a fraction of one percent.

Significant Events: Nuclear Weapons Testing

- During **1944** and **1945**, nonnuclear testing for the Manhattan Project was done at four sites: the Salton Sea Test Base, Muroc Air Base and China Lake Naval Ordnance Testing Station in California, and Wendover Field in Utah.
- The first U.S. nuclear weapons test, code-named "Trinity," was near Alamogordo, New Mexico, on **July 16, 1945**.
- Bikini Atoll in the South Pacific was the initial site of MED and AEC weapons testing following the end of World War II. Between **1946** and **1958**, 23 tests took place at Bikini.
- Enewetak Atoll in the South Pacific was used for 43 atmospheric nuclear tests between **1948** and **1958**, including the first thermonuclear test in **1952**.
- Atmospheric nuclear weapon tests have also been carried out in the upper atmosphere or at sea in the Johnston and Christmas Island areas (12 and 24 tests, respectively, at the 2 sites between **1958** and **1962**), the Pacific Ocean (4), and at high altitude over the South Atlantic Ocean (4).
- The Nevada Test Site was established in **1951** and was originally known as the Nevada Proving Grounds. There have been 928 nuclear tests at The Nevada Test Site since it was opened, including 100 atmospheric tests.
- At the Nevada Test Site, test shots Pascal A & B and Rainier were the first attempts to gather data for underground containment, and prepared the way for confining all tests underground in accordance with the Limited Test Ban Treaty.
- Since **1963**, all U.S. nuclear tests have been conducted underground.
- A number of transportation experiments involving the detonation of high-explosive charges without producing a nuclear yield were carried out on the Nellis Air Force Range adjacent to the Nevada Test Site in **1957** and **1963**.
- Weapons-related nuclear Test Faultless was detonated in central Nevada in early **1968**.
- Two megaton-range weapons-related tests were conducted on Amchitka Island, Alaska, in **1969** and **1971**.
- Underground nuclear explosions for the "Vela Uniform" project to improve the capability to detect, identify, and locate underground nuclear explosions were carried out in Fallon, Nevada; Hattiesburg, Mississippi; Amchitka, Alaska; and the Nevada Test Site between **1963** and **1971**.
- Between **1961** and **1973**, 35 nuclear devices were detonated at a number of continental sites (including t2he Nevada Test Site) as part of the "Plowshare" program to investigate the use of nuclear explosives in excavation and natural gas and oil production. These tests are not considered to be part of the nuclear weapons development legacy.
- Salton Sea Test Base in California was used in the **1940s** and **1950s** as a sea level ballistics range to obtain performance data on inert nuclear weapons prototypes. Salton Sea activities were transferred to the Tonopah Test Range in **1961**.
- The Tonopah Test Range in Nye County, Nevada, was established in **1957** for the testing of nonnuclear systems and components of bombs. Typical tests conducted at this site include bomb delivery systems, bomb delivery retardation chutes, and artillery shell trajectories.
- Restoration for Bikini Atoll was performed in **1969** by a joint AEC/DoD/Department of Interior effort organized around a Naval Sea Task Group.
- The Enewetak Proving Ground was placed on standby after Operation Hardtack I in **1958** and officially abandoned in **1960**. It was remediated by a joint DOE/DoD/Department of Interior effort, with the actual cleanup performed by the Army Corps of Engineers between **1978** and **1980** and managed by the Defense Nuclear Agency.

3. Waste

Hanford "Tank Farm." The million-gallon double-walled carbon steel tanks buried here hold high-level nuclear waste from Hanford's plutonium production program. The double-walled tanks have replaced Hanford's older, single-walled tanks which have leaked approximately one million gallons of high-level radioactive waste into Hanford soil. *200 Area, Hanford Site, Washington. July 12, 1994.*

Overview

The term "waste" in this report refers to solids and liquids that are radioactive, hazardous, or both. These materials have, in the past, been disposed of by shallow burial, sea burial, or by deep underground injection.[1] Waste not yet disposed of or which await a decision on their method of disposal, are accumulated in containers, tanks, silos, buildings, and other structures. Also awaiting disposal are previously disposed waste that have been retrieved in site cleanups and are currently in storage.

Waste is measured in terms of its volume (cubic meters) and its radioactivity content (curies).[2] Waste from nuclear weapons production managed by the Department of Energy includes 24 million cubic meters of waste containing about 900 million curies. DOE manages another 12 million cubic meters of waste containing 110 million curies which has resulted from nonweapons activities. The total from both sources is 36 million cubic meters and about one billion curies.[3] Some key information about the waste

[1] *Hydrofracture (an underground injection disposal technology) and sea disposal of radioactive waste have been discontinued.*

[2] *A curie is a unit of radioactivity expressed in terms of nuclear disintegrations per second. It provides a measure of the immediate radioactive emission of the radionuclides in the waste, but it does not take into account the type of particles or amount of energy released per disintegration or the shielding effect of the waste's physical matrix. The number of curies will decrease over time at a rate that depends on the particular isotopes in the waste.*

[3] *By contrast, commercial spent nuclear fuel is estimated to contain 29 billion curies.*

legacy is provided in the text box. The methodology section of this chapter further describes the data sources and documents used in the process to determine the volume, characteristics, and sources of the waste legacy.

Definitions and Categories

This chapter identifies and describes the major categories of waste in the nuclear weapons legacy and provides information on the volume of waste and amount of radioactivity in each category, the location of the waste, and the activities that generated the waste. The waste legacy includes seven major categories:

- High-level waste
- Transuranic waste
- Low-level waste
- Mixed low-level waste
- 11e(2) byproduct material
- Hazardous waste
- Other waste

This categorization takes into account the radioactive and chemically hazardous properties of the waste and is the primary factor used by the Department in determining how a waste should be managed. These categories correspond to distinct waste classes subject to external federal or state requirements or DOE's internal system of orders. Waste is classified as *radioactive* if it contains, or is presumed to contain (based on available data), radioactive source, special nuclear, or byproduct material regulated under the Atomic Energy Act (AEA). Some naturally-occurring and accelerator-produced radioactive materials are also managed as radioactive waste, although they are not subject to the AEA. Waste that does not contain hazardous or radioactive constituents or that contains them at below regulated levels does not appear in this report. This waste does not require long-term monitoring or care and does not pose the same risks as waste in the other categories.

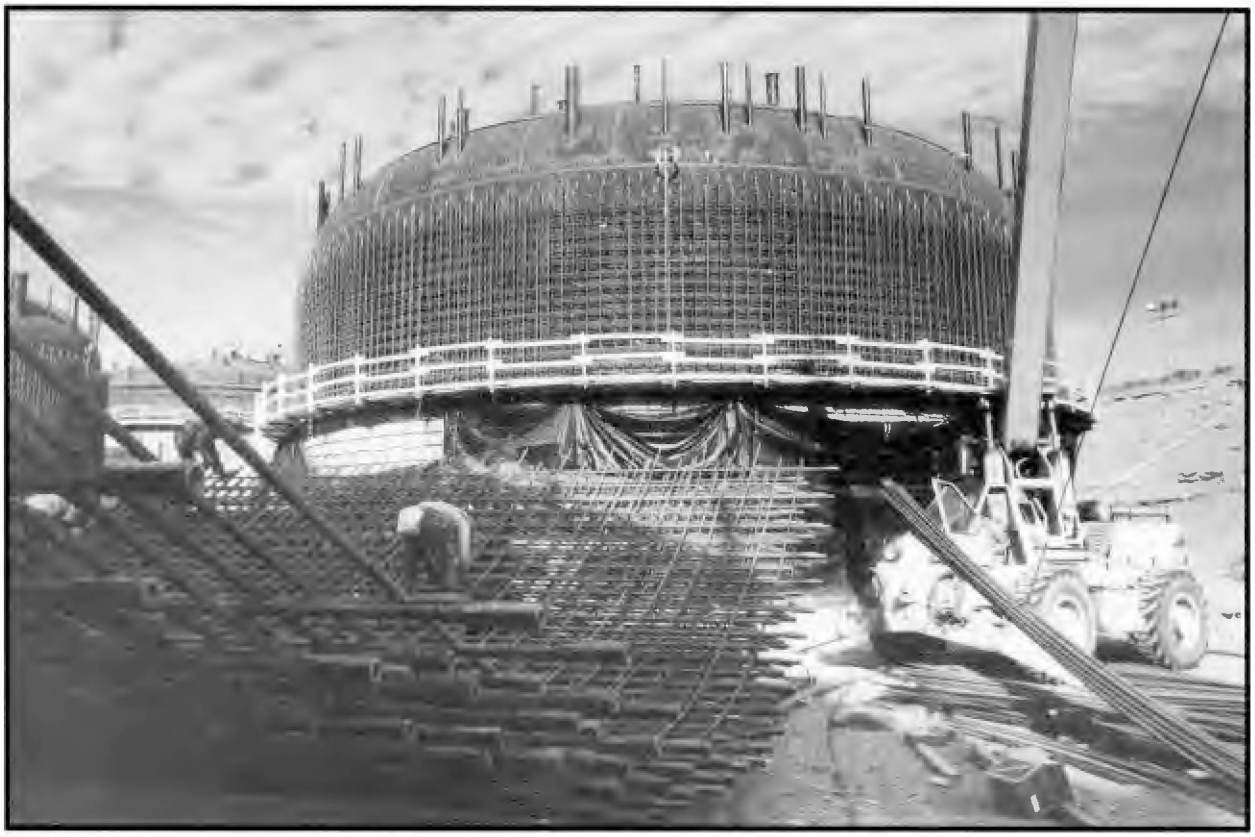
Key Information about the Waste Legacy

- Uranium mining, milling, and refining generated the largest volume of weapons waste (61 percent by volume). The largest volume of this waste is disposed 11e(2) byproduct material (i.e., uranium mill tailings). States with the largest volumes of waste from weapons production are Colorado, Utah, New Mexico, and Texas.
- Weapon operations produced the smallest volume of waste (less than 1%).
- Most of the radioactivity in the waste legacy is contained in high-level waste, attributed to the chemical separation process. All high-level waste remains in storage, except for about one million gallons that has leaked from storage tanks at Hanford, Washington. Most of the high-level waste is located at the three DOE sites performing chemical separation for weapons production located in Idaho, South Carolina, and Washington. Because of differences in the materials processed, the age of the waste, and waste management practices, the radioactive content of the Department's high-level waste (in curies per cubic meter) varies greatly from site to site.
- Radioactivity in waste from uranium mining, milling, and refining; enrichment; and fuel and target fabrication is due generally to natural radioactivity (e.g., uranium, thorium, and their daughter products). Radioactivity in waste from the other processes is due primarily to reactor-generated fission products and transuranic isotopes.
- Portions of all waste categories, except high-level waste, have been disposed. However, much of this waste was originally disposed of under conditions considered inadequate by today's standards.
- The Office of Waste Management oversees much greater quantities of radioactivity than the Office of Environmental Restoration. This radioactivity is contained primarily in high-level waste. The Office of Environmental Restoration, however, manages a larger volume of waste than the Office of Waste Management.

High-level Waste

High-level waste is the highly radioactive waste resulting from the chemical processing of spent nuclear fuel and irradiated target assemblies. It includes liquid waste produced directly, and any solid waste derived from the liquid, that contains a combination of transuranic elements and fission products in concentrations that require permanent isolation.[4] High-level waste also includes some other radioactive waste that is combined with high-level waste from fuel reprocessing. The intense radioactivity primarily

[4] *The definition and management requirements for high-level waste are set forth in DOE Order 5820.2A, the Nuclear Waste Policy Act, and numerous NRC regulations.*



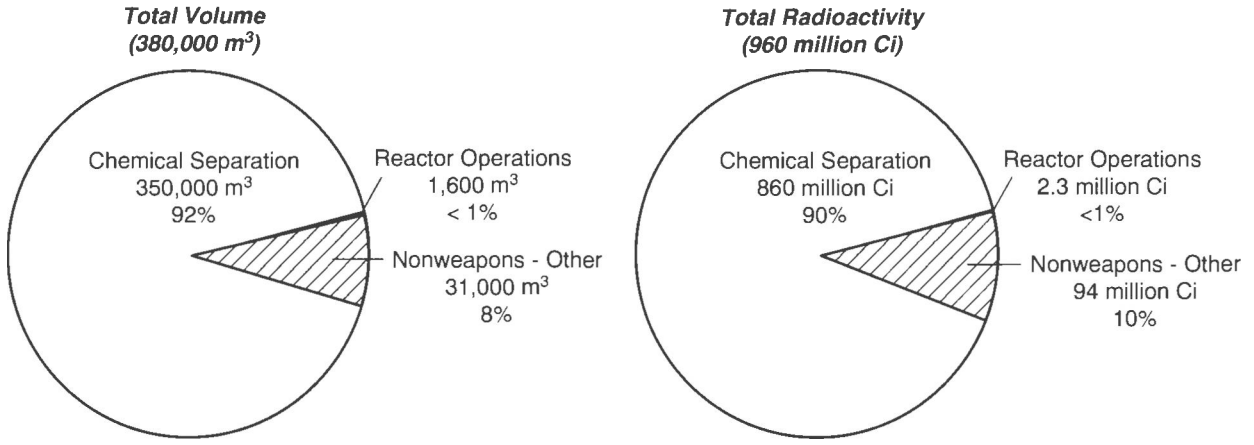
Million-gallon double-walled carbon-steel tank under construction. A total of 149 single-shell tanks and 28 double-shell tanks like this one contain high-level radioactive waste from Hanford's plutonium production operations. This tank design supercedes Hanford's older single-walled tanks, many of which have leaked. Some one million gallons of waste are believed to have leaked from the older single-shell tanks. The new double-walled tanks are expected to last for 50 years. By that time, the Department of Energy anticipates that a sucessful long-term solution for the disposal of high-level waste will have been developed. *200 Area Tank Farm, Hanford Site, Washington. November 16, 1984.*

determines how high-level waste is managed. However, the presence of hazardous constituents and the regulatory status of the waste are also important factors in high-level waste management decisions. Much of the Department's high-level waste also is either known or presumed to contain hazardous constituents subject to regulation under Subtitle C of the Resource Conservation and Recovery Act (RCRA) and is regulated as mixed waste.

High-level waste is formally defined in the Nuclear Waste Policy Act; in Title 10 of the Code of Federal Regulations (CFR), Part 60; and in DOE Order 5820.2A, which governs the Department's management of radioactive waste. By virtue of these definitions, nearly all high-level waste resulting from nuclear weapons production included in the legacy is attributed to chemical separations. Spent fuel from commercial nuclear power reactors is not included in the definition of high-level waste in the Nuclear Waste Policy Act or 10 CFR Part 60. The Department categorizes spent fuel, including fuel and targets from weapons production reactors, research reactors, and some power reactors, as materials in inventory rather than waste. Spent fuel is discussed in Chapter 6 of this report.

The radioactivity in high-level waste comes from fission fragments and their daughter products resulting chiefly from the splitting of uranium-235 in production reactor fuel. These fission fragments and their daughter products are collectively known as "fission products." Although radiation levels and health risks caused by short-lived fission products decrease dramatically in a few hundred years, risks attributable to long-lived isotopes in high-level waste will not change over thousands of years. During most of the initial decay period, most of the radioactivity is caused by cesium-137, strontium-90, and their short-lived daughter products. After the radioactivity from fission products decays to lower levels, radioactiv-

Figure 3-1. High-level Waste Radioactivity Categorized by Process



Notes:
(1) Data compiled from the Integrated Data Base (IDB) Report, Revision 11, September 1995. (See Endnotes a, k, and q).
(2) Waste category assignments are made in accordance with the process set forth in Endnote r.
(3) Nuclear weapons and nonweapons allocations and allocations to individual weapons production process categories are determined subject to the process set forth in Endnote s.

ity from long-lived isotopes, including plutonium, americium, uranium, daughter products from these elements, technetium-99, and carbon-14, becomes the dominant component and will pose the largest long-term potential risk.

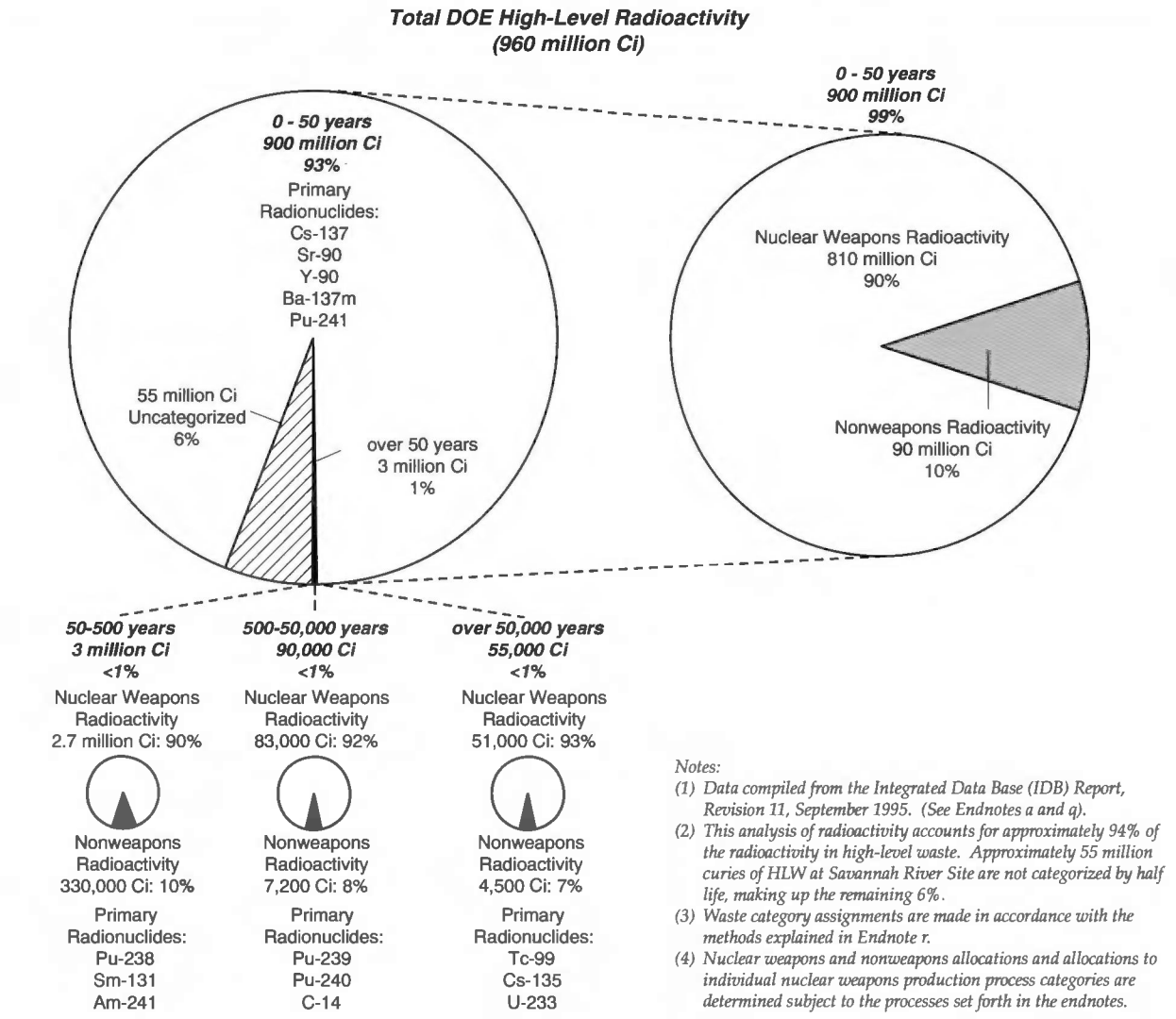
Most of the Department's liquid high-level waste is stored in either a highly acidic or a highly caustic solution, or as a saltcake or sludge. Most of the liquids, sludges, and other forms of high-level waste also contain toxic heavy metals, and some of the high-level waste also contains organic solvents (e.g., hexone, tributyl phosphate) and cyanide compounds.

Of the total volume of 380,000 cubic meters, about 92 percent (350,000 cubic meters) of the Department's high-level waste is the result of weapons production and 8 percent is the result of nonweapons activities. None of the high-level waste is attributed to DOE activities supporting the Naval Nuclear Propulsion Program (NNPP). Of a total radioactive content of 960 million curies, about 90 percent is from weapons production and 10 percent was generated by nonweapons activities (Figure 3-1). Nearly all high-level waste, both weapons and nonweapons, was produced by chemical separation activities, and a small amount of high-level waste is attributed to reactor operation; no high-level waste resulted from the other six weapons production process categories.[5] All high-level waste at Idaho National Engineering Laboratory is attributed to weapons production because it resulted from the reprocessing of spent nuclear fuel to recover highly-enriched uranium for the nuclear weapons program. A portion of the high-level waste at Hanford and the Savannah River Site and all of the high-level waste at West Valley Demonstration Project is attributed to nonweapons activities. Most nonweapons high-level waste resulted from Hanford and West Valley Demonstration Project reprocessing of spent fuel from the Hanford N Reactor to produce fuel grade plutonium for civilian power reactor programs. Additional nonweapons high-level waste was the result of commercial reprocessing of spent fuel from electric utility power reactors conducted at West Valley Demonstration Project.

Over 99 percent of the radioactivity now present in high-level waste is from radionuclides with half-lives of less than 50 years (Figure 3-2). Longer-lived radionuclides make up the remaining fraction of one percent of the current radioactivity. After several hundred years, the short-lived radionuclides will have decayed and will no longer comprise most of the radioactivity.

[5] *High-level waste attributed to reactor operation consists of ion exchange resins used to remove radionuclides from spent nuclear fuel storage basins containing corroded fuel and sludge from the bottom of these pools at Hanford.*

Figure 3-2. High-level Waste Radioactivity Categorized by Half-life



Notes:

(1) Data compiled from the Integrated Data Base (IDB) Report, Revision 11, September 1995. (See Endnotes a and q).

(2) This analysis of radioactivity accounts for approximately 94% of the radioactivity in high-level waste. Approximately 55 million curies of HLW at Savannah River Site are not categorized by half life, making up the remaining 6%.

(3) Waste category assignments are made in accordance with the methods explained in Endnote r.

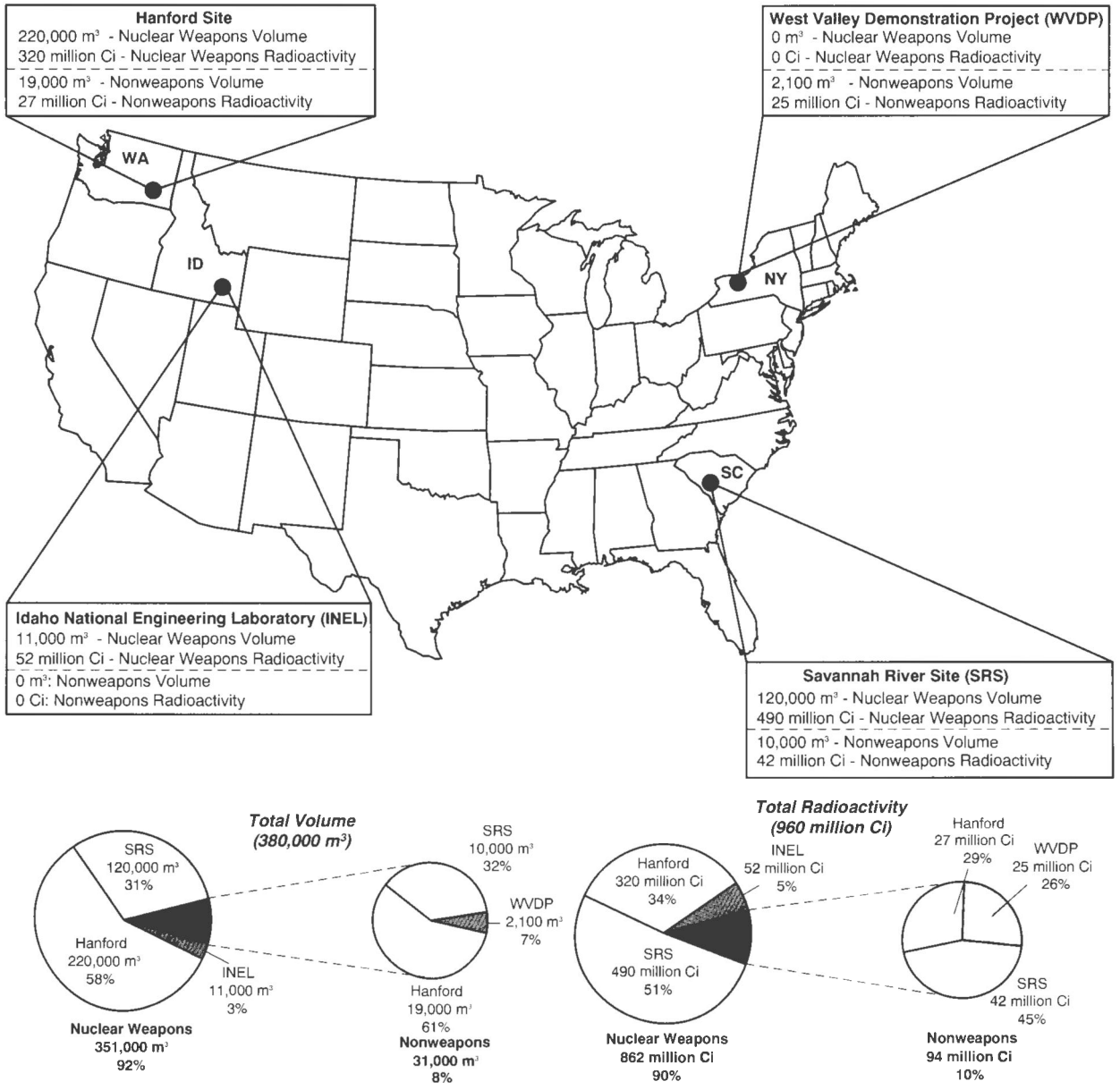
(4) Nuclear weapons and nonweapons allocations and allocations to individual nuclear weapons production process categories are determined subject to the processes set forth in the endnotes.

The Office of Environmental Management manages all of the Department's high-level waste at the four sites where it was originally generated: Hanford Site, Idaho National Engineering Laboratory, the Savannah River Site, and West Valley Demonstration Project.[6] Hanford manages the largest volume of high-level waste; but a larger amount of radioactivity in high-level waste is located at the Savannah River Site (Figure 3-3). The Department has begun to vitrify the high-level waste at the Savannah River Site and West Valley Demonstration Project.

Hanford – At Hanford, high-level waste alkaline liquid, salt cake, and sludge are stored in 149 single-shell underground tanks and 28 double-shell underground tanks. Some transuranic waste and low-level waste is also stored in the tanks but all tank waste is classified at Hanford and managed as high-level waste. The Department is currently processing Hanford tank waste by evaporation to reduce its volume and is transferring pumpable liquids from the single-shell tanks to the double-shell tanks. Some single-shell high-level waste tanks have leaked, releasing approximately one million gallons of waste to the environment. During the 1940s, a relatively small amount of high-level waste was discharged directly to the soil.

[6] *West Valley Demonstration Project is a nonweapons site, owned by New York State and managed by DOE.*

Figure 3-3. Four Sites Managing High-level Waste



Notes:
(1) Data compiled from the Integrated Data Base (IDB) Report, Revision 11, September 1995. (See Endnotes a, k, and q).
(2) Waste Category asssignments are made in accordance with the process explained in Endnote r.
(3) Nuclear weapons and nonweapons allocations and allocations to individual weapons production process categories are determined subject to the process set forth in Endnote s.

Hanford high-level tank waste liquids and solids both contain an average of about 800 curies per cubic meter (Ci/m³).

Hanford also manufactured approximately 2,200 highly radioactive capsules containing concentrated cesium and strontium salts. Some of these high-level waste capsules had been leased for use offsite, and are being returned to Hanford. They are the most highly radioactive high-level waste managed by the Department containing tens of millions of curies per cubic meter. The capsules contain over 40 percent of the high-level waste radioactivity at Hanford, in a volume of less than four cubic meters. Nearly 300

Worker with empty cesium capsule. Between 1968 and 1983, Hanford recovered and encapsulated cesium-137 and strontium-90 from high-level radioactive waste. DOE and its predecessors leased many of these capsules as intense radiation sources for industrial applications. The capsules deteriorated over time, and the last one was returned to DOE in 1996. The capsules are stored in Hanford's B Plant, the World War II chemical separations plant that produced them. *Waste Encapsulation and Storage Facility, B Plant, 200 Area, Hanford, Washington. November 16, 1984.*

capsules have been dismantled, while the remainder are being stored, pending selection of an appropriate stabilization method prior to disposal.

Savannah River Site – High-level waste at the Savannah River Site is composed of alkaline liquid, salt cake, sludge, and precipitate, and is stored in double-shell underground tanks. The volume of high-level tank waste at the Savannah River Site is only about half as large as Hanford tank waste, but it contains about one and one-half times the amount of radioactivity. Hanford tank waste is less radioactive than the tank waste at the Savannah River Site because much of the radioactive cesium and strontium has been removed and concentrated in the capsules, the waste is older and has had more time to decay, and the waste has been mixed with other waste. Savannah River Site high-level tank waste liquids and solids each contain an average of about 4,000 Ci/m^3.

Idaho National Engineering Laboratory – High-level waste at Idaho National Engineering Laboratory is composed of acidic liquid and calcined solids. The acidic liquids are stored in underground tanks and include actual high-level waste as well as sodium-bearing waste that is managed as high-level waste. High-level waste calcine is an interim solid waste form made by processing the liquid waste. The calcine is stored in bins. More than 90 percent of the radioactivity in Idaho National Engineering Laboratory

[7] *Of the 640 tons of spent fuel reprocessed at West Valley Demonstration Project, 380 tons came from the Hanford N Reactor. West Valley Demonstration Project reprocessing produced about 530 kilograms of plutonium from the N Reactor spent fuel. Nearly 900 kilograms of plutonium from commercial spent fuel were sent from West Valley Demonstration Project to Hanford as well. However, nearly all of the plutonium produced was fuel-grade, rather than weapons-grade, and was intended for nonweapons purposes. Most of the plutonium was used in breeder reactor and zero-power reactor programs. Even though most of the spent fuel came from DOE, the commercial reactor fuel generally had a higher "burn up," and as a result, most of the radioactivity in West Valley Demonstration Project high-level waste came from reprocessing commercial fuels.*

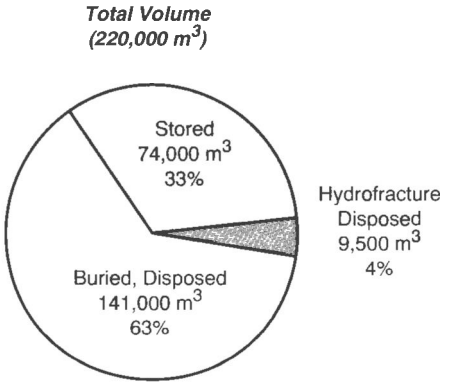
high-level waste is present in the calcine, which contains an average of about 12,000 curies/cubic meter. Liquid high-level waste from Idaho National Engineering Laboratory only contains about 300 Ci/m^3.

West Valley Demonstration Project – Unlike high-level waste managed at Hanford, Idaho National Engineering Laboratory, and the Savannah River Site, the high-level waste at West Valley Demonstration Project was not generated by DOE and is not attributed to weapons production.[7] West Valley Demonstration Project, which operated from 1966 to 1972, was the site of the only commercial nuclear fuel reprocessing plant operated in the United States. In accordance with the 1980 West Valley Demonstration Project Act , DOE is responsible for demonstrating high-level waste solidification at the facility. New York State currently owns both the site and the waste.

In terms of both volume and radioactivity, the amount of high-level waste at West Valley Demonstration Project is much less than that at Hanford, the Savannah River Site, or Idaho National Engineering Laboratory. This high-level waste is stored in tanks and consists of alkaline liquid, sludge, and ion-exchange resin. The high-level waste at West Valley Demonstration Project is similar to that at Idaho National Engineering Laboratory in that the radioactivity in the former's high-level waste is present primarily in the solid high-level waste (i.e., sludge and resin). Although nearly 90 percent of the volume of West Valley Demonstration Project high-level waste is in liquid form (containing about 1,700 Ci/m^3), over 90 percent of its radioactivity is present in the waste that is in solid form (containing 150,000 Ci/m^3).

Under federal law, DOE high-level waste will eventually be disposed of in geologic repositories after it has been treated to produce solid waste forms acceptable for disposal, and repository facilities become available. The DOE Office of Civilian Radioactive Waste Management is responsible for characterizing the Yucca Mountain repository site in Nevada, constructing a repository, and disposing of DOE high-level waste, DOE nuclear spent fuel, and commercial spent nuclear fuel in accordance with the Nuclear Waste Policy Act. The only planned offsite transfers of high-level waste are those from the current storage sites to the repository. At all four sites, the Department is currently pretreating some high-level waste to reduce its volume and produce solid waste forms acceptable for safer long-term storage. At two of these sites, treatment to produce final waste forms for repository disposal is underway. The Defense Waste Processing Facility at the Savannah River Site began producing vitrified final waste forms in May 1996. A facility for vitrifying high-level waste at West Valley Demonstration Project began operations in July 1996. Final treatment of high-level waste at Hanford and Idaho National Engineering Laboratory is now in the planning stage.

Figure 3-4. Transuranic Waste Volume Categorized by Disposition



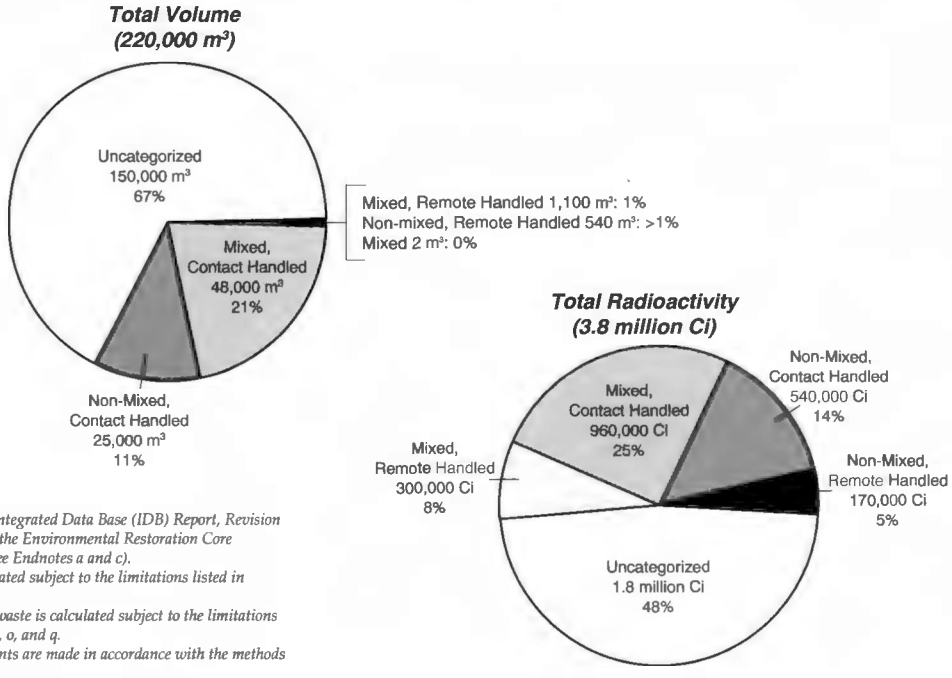
Notes:
(1) Data compiled from the Integrated Data Base (IDB) Report, Revision 11, September 1995, and the Environmental Restoration Core Database, May 1996.
(2) Waste category asssignments are made in accordance with the methods explained in Endnote r.
(3) Waste volumes are calculated subject to the limitations listed in Endnotes f, h, and k.

The Department is currently generating, and expects to generate, relatively small quantities of new high-level waste. Generation of this waste decreased substantially during the late 1980s and early 1990s when the Department stopped reprocessing spent nuclear fuel. In the future, new high-level waste will continue to be generated from several sources, including the maintenance and eventual deactivation and decommissioning of the chemical separation facilities and processing of some nuclear fuel and target elements at the Savannah River Site. However, the quantity of new high-level waste is expected to be small in comparison to the currently stored inventories. In addition, the Department is seeking to develop alternative technologies capable of stabilizing nuclear materials without generating additional waste. Only the new waste from nuclear fuel and target processing (i.e., chemical separation) actually meets the high-level waste definition, but new waste from other sources is managed as high-level waste because it contains very high concentrations of radionuclides.

[8] *Transuranic elements are those with atomic numbers greater than 92, heavier than uranium. All are artificially produced by neutron irradiation, and all are part of the actinide group of elements.*

Transuranic waste storage. A radiological control technician scans the ground for contamination at a transuranic waste storage facility in Idaho. Beneath each concrete plug is a vault for storing three or four drums of remote handled transuranic waste. Most of the vaults are currently empty. Waste stored in these vaults is mostly from nonweapons research at the nearby Argonne National Laboratory-West. *Intermediate Level Transuranic Waste Storage Facility, Radioactive Waste Management Complex, Idaho National Engineering Laboratory, Idaho. March 17, 1994.*

Figure 3-5. Transuranic Waste Volume and Activity Categorized by Handling Type (Nuclear Weapons and Nonweapons Transuranic Waste Combined)



Notes:

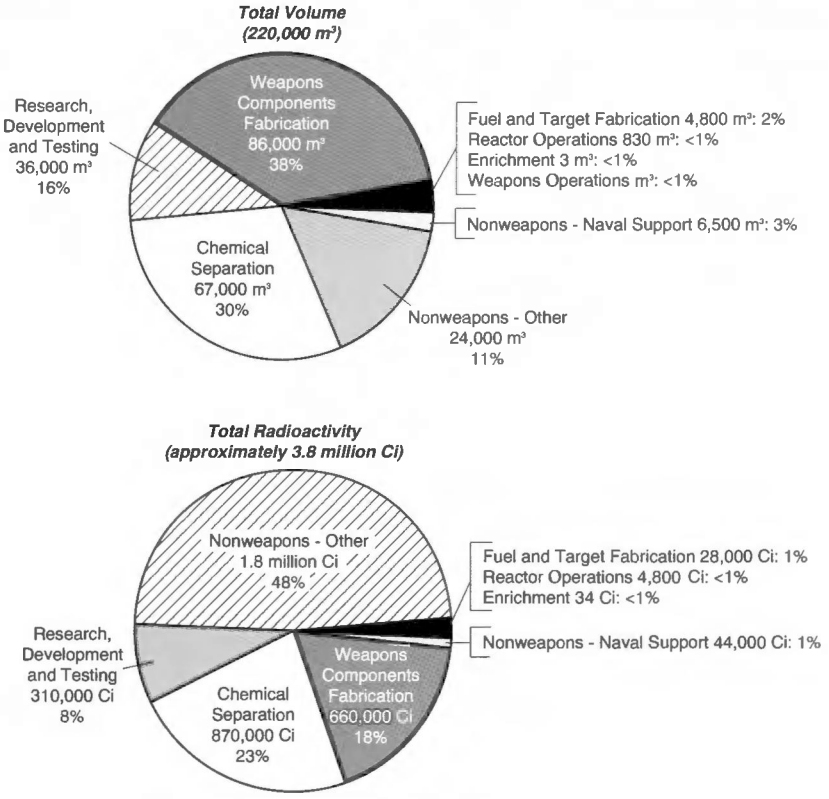
(1) Data compiled from the Integrated Data Base (IDB) Report, Revision 11, September 1995, and the Environmental Restoration Core Database, May 1996. (See Endnotes a and c).

(2) Waste volumes are calculated subject to the limitations listed in Endnotes f, h, and k.

(3) Radioactivity content of waste is calculated subject to the limitations listed in Endnotes l, m, n, o, and q.

(4) Waste category assignments are made in accordance with the methods explained in Endnote r.

Figure 3-6. Transuranic Waste Volume and Radioactivity Categorized by Process



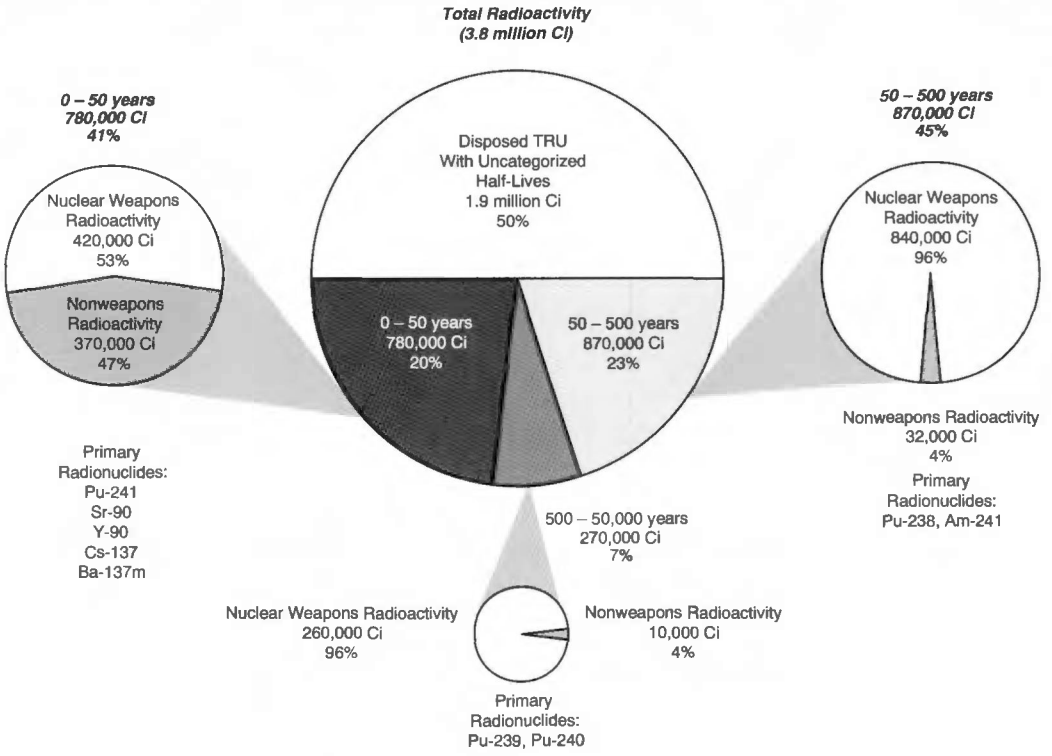
Notes:
(1) Data compiled from the Integrated Data Base (IDB) Report, Revision 11, September 1995, and the Environmental Restoration Core Database, May 1996. (See Endnotes a and c).
(2) Waste volumes are calculated subject to the limitations listed in Endnotes f, h, and k.
(3) Radioactivity content of waste is calculated subject to the limitations listed in Endnotes l, m, n, o, and q.
(4) Waste category assignments are made in accordance with the methods explained in Endnote r.
(5) Nuclear weapons and nonweapons allocations and allocations to individual weapons production process categories are determined subject to the limitations explained in Endnotes t and u.

Transuranic (TRU) Waste

Transuranic (TRU) waste is waste that contains alpha-emitting transuranic elements[8] with half-lives greater than 20 years whose combined activity level is at least 100 nanocuries per gram of waste at the time of assay. Like high-level waste, TRU waste is formally defined in DOE Order 5820.2A. TRU waste is further categorized according to its external surface radiation dose rates. Waste with dose rates exceeding 200 millirem per hour requires special handling and is classified as remote-handled TRU waste. TRU waste below this level is called contact-handled TRU waste. Because of the long half-lives of many TRU isotopes, TRU waste can remain radioactive for hundreds of thousands of years. Some of the common TRU radionuclides present in TRU waste include plutonium-239, -240, -241, -238, and -242; americium-241; and curium-244. Other important radionuclides that can be present in TRU waste, primarily remote-handled TRU waste, are fission products, reactor activation products, and their resulting daughter products, including strontium-90, yttrium-90, cesium-137, barium-137, cobalt-60, and europrium-152, -154, and -155.

Most TRU waste is the result of the weapons production process and contains plutonium. TRU waste from weapons production results almost exclusively from fabrication of plutonium weapons components, recycling plutonium from production scrap, residues, or retired weapons, and chemical separation of plutonium. Considerable amounts of TRU waste also contains hazardous constituents subject to regulation under RCRA (mixed TRU waste), and some contains polychlorinated biphenyls (PCBs) subject to the Toxic Substances Control Act. TRU, mixed-TRU, and PCB-TRU waste have been combined in this analysis because the primary factor used to determine how the waste will be managed is the concentration of TRU radionuclides in the waste rather than the waste's chemical composition. However, the

Figure 3-7. Transuranic Waste Radioactivity Categorized by Half-life (Stored Waste Only)



Notes:

(1) Data compiled from the Integrated Data Base (IDB) Report, Revision 11, September 1995, and the Environmental Restoration Core Database, May 1996. (See Endnotes a and c).
(2) Waste volumes are calculated subject to the limitations listed in Endnotes f, h, and k.
(3) Radioactivity content of waste is calculated subject to the limitations listed in Endnotes l, m, n, o, and q.
(4) Waste category assignments are made in accordance with the methods explained in Endnote r.
(5) Nuclear weapons and nonweapons allocations and allocations to individual weapons production process categories are determined subject to the limitations explained in Endnotes t and u.
(6) Data excludes TRU waste that is buried.

presence of hazardous constituents and the regulatory status of the waste are also important factors that affect TRU waste management decisions.

AEC first managed TRU waste as a separate category of radioactive waste in 1970. Prior to that time, TRU waste and low-level waste were usually combined and managed as a single waste type and were disposed of in shallow burial trenches. Recognizing the need to isolate TRU waste more permanently from the environment, AEC discontinued shallow burial of TRU waste in 1970. Since that time, the Department has placed TRU waste in retrievable storage, typically in metal drums or boxes either on above- or below-grade soil-covered storage pads or in buildings or tanks. Some TRU waste has been disposed of by hydrofracture, which is a form of underground injection used at Oak Ridge National Laboratory. About two-thirds of the TRU waste managed by the Department has been disposed of and the remaining one-third is in storage (Figure 3-4). The Department plans to dispose of stored post-1970 defense TRU waste in a geologic repository. However, TRU waste will continue to be stored until the planned repository, the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico, becomes operational, and the waste is appropriately treated, packaged, and certified for disposal. During transport to the repository, the waste will be packaged in special overpack containers known as TRUPACs.

In 1984, the Department revised the definition for TRU waste, raising the minimum concentration of TRU radionuclides from 10 to 100 nanocuries per gram. Since that time, all newly-generated radioactive waste and a portion of the TRU waste in retrievable storage has been categorized according to the revised standard. However, the concentration of TRU radionuclides in some of the Department's current inventory of TRU waste may be below the revised standard. As the waste is prepared for disposal in WIPP, the Department will reevaluate the TRU content of some of this waste and may reclassify some of it as low-level waste.

Table 3-1. Transuranic Waste Storage and Disposal Sites (Resulting from Nuclear Weapons Production)

Stored TRU Waste

Site	Nuclear Weapons Volume (m^3)	Nuclear Weapons Radioactivity (Ci)	Nonweapons Volume (m^3)	Nonweapons Radioactivity (Ci)
Idaho National Engineering Laboratory, ID	32,000	340,000	2,700	29,000
Savannah River Site, SC	15,000	560,000	0	0
Los Alamos National Laboratories, NM	11,000	210,000	0	0
Hanford, WA	8,100	210,000	1,300	34,000
Rocky Flats Environmental Technology Site, CO	1,100	86,000	0	0
Nevada Test Site, NV	620	3,500	0	0
Mound, OH	260	910	0	0
Lawrence Livermore National Laboratory, CA	220	2,000	0	0
Oak Ridge National Laboratory, TN	53	11,000	1,700	350,000
Sandia National Laboratory, NM	8	0	0	0
Paducah Gaseous Diffusion Plant, KY	3	34	2	22
Pantex, TX	1	0	0	0
Nonweapons Sites	0	0	570	130,000

Buried and Disposed TRU Waste

Site	Nuclear Weapons Volume (m^3)	Nuclear Weapons Radioactivity (Ci)	Nonweapons Volume (m^3)	Nonweapons Radioactivity (Ci)
Hanford, WA	55,000	150,000	8,800	24,000
Idaho National Engineering Laboratory, ID	53,000	230,000	4,500	20,000
Los Alamos National Laboratories, NM	14,000	5,600	0	0
Savannah River Site, SC	4,900	31,000	0	0
Oak Ridge National Laboratory, TN	5	7	170	233
Sandia National Laboratory, NM	1	1	0	0
Nonweapons Sites	0	0	1,350	652,000

Hydrofracture Disposed TRU Waste

Site	Nuclear Weapons Volume (m^3)	Nuclear Weapons Radioactivity (Ci)	Nonweapons Volume (m^3)	Nonweapons Radioactivity (Ci)
Oak Ridge National Laboratory, TN	290	20,000	9,200	660,000

Notes:

(1) Data compiled from the Integrated Data Base (IDB) Report, Revision 11, September 1995, and the Environmental Restoration Core Database, May 1996. (See Endnotes a and c).

(2) Waste volumes are calculated subject to the limitations listed in Endnotes i and k.

(3) Waste category assignments are made in accordance with the process explained in Endnote o.

(4) Nuclear weapons and nonweapons allocations and allocations to individual weapons production process categories are determined subject to the method set forth in Endnotes t and u.

A small percentage of the Department's TRU waste exhibits high direct radiation exposure hazards; it is referred to as "remote-handled" TRU waste. The majority of TRU waste emits low levels of direct radiation, it is referred to as "contact-handled" TRU waste. The handling category of TRU waste that has already been disposed of was not documented at the time of disposal, but the Department believes that much of that waste is contact handled. The chief hazard from contact-handled waste is caused by the alpha-emitting TRU elements they contain. Inhalation and, to a lesser degree, ingestion of these substances is the exposure pathway of concern. Alpha particles emitted by TRU radionuclides cannot penetrate the skin, but they can cause serious localized tissue damage when they are emitted inside the body. When inhaled, TRU elements tend to accumulate in the lungs; soluble TRU materials migrate through the circulatory system and accumulate primarily in the liver and bone marrow. Figure 3-5 shows the volume and radioactivity distribution of stored and disposed TRU waste by handling type. This figure also shows the distribution of TRU waste volume and radioactivity according to whether it contains a hazardous component subject to RCRA. This waste is classified as mixed TRU waste by the Department.

Unlike high-level waste, which is generated from only a few specific processes and has a narrow range of physical matrices and chemical characteristics, TRU waste exists in many forms and can contain a broad spectrum of hazardous chemical constituents. Cleaning, maintenance, and production processes involving plutonium and other transuranic radionuclides generate TRU waste. In the future, deactivation and decommissioning of chemical separations facilities will produce TRU waste. Environmental restoration, and treatment and handling of high-level and low-level waste, also generate TRU waste.

By volume, about 86 percent of TRU waste is the result of weapons production, three percent is the result of DOE activities supporting the NNPP, and 11 percent is the result of other nonweapons activities (Figure 3-6). About 38 percent of all TRU waste is from nuclear weapon component fabrication, including plutonium recycling, 30 percent from chemical separation, and 18 percent from the other weapons production processes. No TRU waste resulted from uranium mining, milling, and refining or from weapon operations. By radioactivity content, about 51 percent of TRU waste came from weapons production, one percent from activities supporting the NNPP, and 48 percent from other nonweapons activities. About 23 percent of the radioactivity in TRU waste is present in waste from chemical separation, 18 percent in waste from component fabrication, and 10 percent in waste from the other weapons production processes. The remaining 48 percent of the radioactivity is in TRU waste from nonweapons activities.

Radionuclides with half-lives of less than 500 years, including plutonium-241 and -238, amiricium-241, and several fission products, 86 percent of the radioactivity in stored transuranic waste. As shown in Figure 3-7, the distribution of radionuclides in transuranic waste from weapons production differs from that from nonweapons activities. Nonweapons TRU waste (primarily from Oak Ridge National Laboratory) contains a much higher proportion of short-lived (less than 50-year half-lives) radionuclides. The stored inventory of transuranic waste contains about 160,000 curies of plutonium-239, equivalent to about 2,600 kilograms of plutonium.

Data on the radioactive content of disposed TRU waste is more limited. However, the Department's Nuclear Materials Management and Safeguards System indicates that a total of about 3,400 kilograms of plutonium are present in combined DOE-stored and -disposed waste, primarily at Hanford, Idaho National Engineering Laboratory, Los Alamos National Laboratory, and the Savannah River Site. This implies that 800 kilograms of plutonium are in the buried TRU waste.

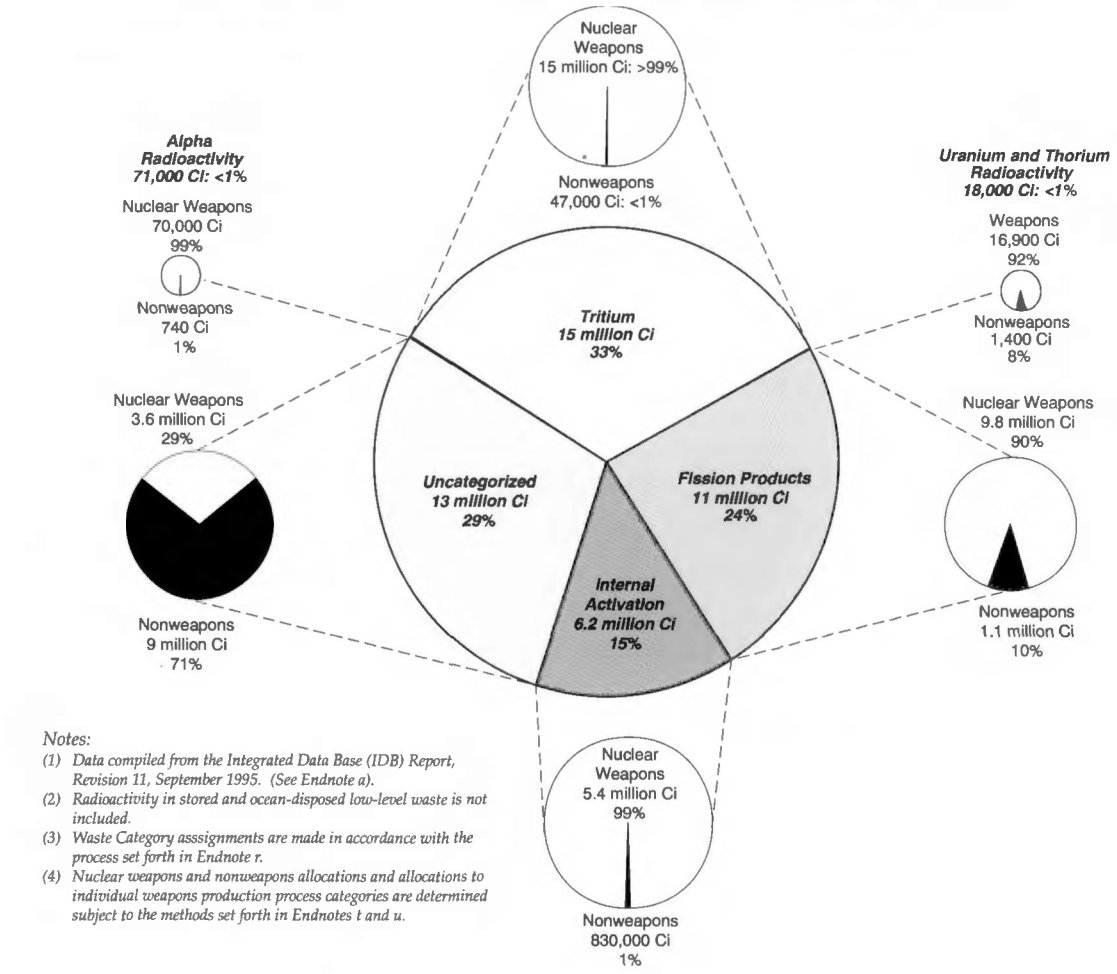
TRU waste includes aqueous and organic solutions, glass, filters, sludges, salts, resins, incinerator ash, leaded rubber gloves, combustibles, ceramics, low-grade oxides, sand, slag, crucibles, alloys, miscellaneous compounds, scrub alloy, and anode heels. Some TRU waste does include organic and halogenated organic solvents, toxic metals, PCBs, acids, and caustics; although, a large portion of TRU waste does not contain chemically hazardous constituents.

Some TRU waste requires special management because it was not produced from weapons production activities or because it cannot be certified for disposal at the planned repository. Nonweapons TRU waste includes filters, resins, neutron sources, reactor vessels, demineralizer systems, and waste from fuel fabrication facilities. Uncertifiable TRU waste includes materials from decontamination and decommissioning of hot cells, waste from nuclear weapons accidents, DoD waste, certain sludges, large metal parts, and remotely-handled items.

TRU waste is managed at 21 sites, including 12 sites where TRU waste from weapons production is managed (Table 3-1). Most stored TRU waste has resulted from weapons production activities at six sites: Hanford, Idaho National Engineering Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, Rocky Flats Plant (now the Rocky Flats Environmental Technology Site), and the Savannah River Site. Smaller amounts of TRU waste are stored or generated at 15 other sites, including a number of sites that produce TRU waste solely from nonweapons activities.

Prior to 1970, TRU waste from weapons production was buried at Hanford, Idaho National Engineering Laboratory, Los Alamos National Laboratories, Oak Ridge National Laboratory, the Savannah River Site, and Sandia National Laboratories/New Mexico (SNL/NM). The largest amounts of stored and disposed TRU waste are at Idaho National Engineering Laboratory. Much of the TRU waste at Idaho National Engineering Laboratory was originally generated by plutonium component fabrication activities at DOE's Rocky Flats Plant, including debris from major fires in 1957 and 1969. Sites at which TRU waste was generated predominantly or entirely by nonweapons activities include nonweapons research sites (Argonne National Laboratory-East and -West, Battelle Columbus Laboratories, Energy Technology Engineering Center, Lawrence Berkeley National Laboratory, and the Missouri University Research

Figure 3-8. Types of Radioactivity in Disposed Low-level Waste



Reactor); NNPP sites (Knolls Atomic Power Laboratory); and sites supporting the commercial nuclear power industry (e.g., Paducah Gaseous Diffusion Plant and West Valley Demonstration Project).

Low-level Waste

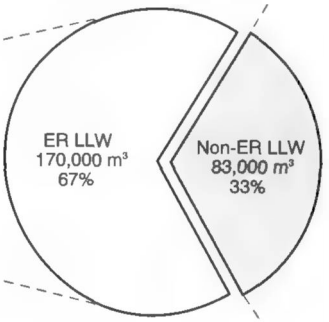
Low-level waste is composed of all radioactive waste not classified as high-level waste, TRU waste, spent nuclear fuel, or natural uranium and thorium byproduct material defined under section 11e(2) of the AEA.

Like high-level waste and TRU waste, low-level waste is defined in DOE Order 5820.2A. It is also defined in the Energy Policy Act of 1992. DOE low-level waste is segregated into remote-handled and contact-handled categories. Some low-level waste contains alpha-emitting transuranic radionuclides in concentrations below the 100 nanocurie per gram minimum concentration established in the TRU waste definition. Low-level waste containing hazardous waste or PCBs is categorized as mixed low-level waste and is presented separately from other low-level waste in this analysis. In addition, the Department manages some naturally-occurring or accelerator-produced radioactive material as low-level waste.

Low-level waste comes from many sources and is present at many DOE sites. The facilities that process, create, or otherwise handle radioactive materials, perform chemical conversions or separations, and fabricate nuclear components, all generate low-level waste. Low-level waste is generated from many of the support activities (e.g., wastewater treatment and equipment maintenance) associated with both weapons production and nonweapons activities. Some low-level waste is also derived from the pretreatment of high-level waste and the management of chemical separation facilities. Finally, low-level waste

Figure 3-9. Physical Matrices of Low-level Waste from Environmental Restoration and Non-Environmental Restoration Activities (Stored Waste Only – Nuclear Weapons and Nonweapons Waste Combined)

Physical Matrix	Volume (m^3)	Percent
Other Solid	140,000	83
Soil	28,000	17
Rubble/Debris	410	<1
Paper/Cloth	370	<1
Residues	180	<1
Sludge	130	<1
Liquid	100	<1
TOTAL	170,000	100



Physical Matrix	Volume (m^3)	Percent
Other	37,000	44
Debris, noncombustible and combustible, mixed	14,000	17
Contaminated metal, equipment, & hardware	11,000	13
Solidified sludges and resins	7,400	9
Debris, combustible	5,700	7
Soil, sediment, and rubble	1,600	2
Other inorganic pariculates	1,600	2
Activated metal, equipment, & hardware	1,600	2
Solidified liquids, chelates, and oils	1,300	2
Biological waste and carcasses	710	1
Filter media	680	1
Debris, noncombustible and compactible	270	<1
Incinerator ash	170	<1
Salt waste	160	<1
Activated carbon	82	<1
Sources (sealed sources, devices, and gauges)	4	<1
Paint waste	1	<1
TOTAL	83,000	100

Notes:
(1) Data compiled from the Integrated Data Base (IDB) Report, Revision 11, September 1995, and the Environmental Restoration Core Database, May 1996. (See Endnotes a and c).
(2) Waste volumes are calculated subject to the limitations listed in Endnotes h, i, and k.
(3) Waste category asssignments are made in accordance with the process explained in Endnote r.

Boxes containing low-level radioactive waste lie in a shallow land burial trench at the Savannah River Site. Alternative methods for the disposal of low-level waste are being developed by the Department. *Savannah River Site, South Carolina. January 7, 1994.*

can be generated from environmental restoration, facility deactivation and decommissioning, and the treatment and handling of TRU waste and mixed low-level waste.

Of the 3.3 million cubic meters of low-level waste managed by DOE, about 85 percent is from weapons production, approximately one percent from activities supporting the NNPP, and 14 percent from other nonweapons activities (Figure 3-10). Low-level waste is attributed to all eight process categories, but most resulted from research, development, and testing (RD&T, 25 percent), fuel and target fabrication (21 percent), chemical separation (17 percent), and uranium mining, milling, and refining (14 percent). By radioactive content, about 72 percent of the Department's low-level waste is from weapons production, less than one percent from activities supporting the NNPP, and 28 percent from other nonweapons activities.

The radioactive content of disposed low-level waste is composed of the following six distinct types of radionuclides that indicate how the radioactivity originated or the level of radioactive hazard: fission products, tritium, internal activation products, alpha radioactivity, uranium and thorium, and uncategorized radioactivity (Figure 3-8). By curie content, more than 99 percent of the tritium, internal activation products, and alpha radioactivity, 90 percent of the fission products, and 92 percent of the uranium and thorium come from weapons production. Nonweapons activities are responsible for 71 percent of the uncategorized radioactivity.

Low-level waste is composed of a wide variety of materials generally similar to those in TRU waste. Recently generated low-level waste (except for low-level waste from environmental restoration activities) is classified into 18 physical forms (Figure 3-9). Low-level waste resulting from environmental restoration activities is classified into categories similar to non-Environmental Restoration low-level waste (Figure 3-9).

Certain low-level waste, known as special case waste, requires special handling and is not suitable for disposal in shallow land burial facilities because of its high radioactive content. This waste includes certain resins, sludges, filter media, radioisotope thermoelectric generators, equipment, demineralizer systems, gauges and dials, waste from hot cells, and other materials.

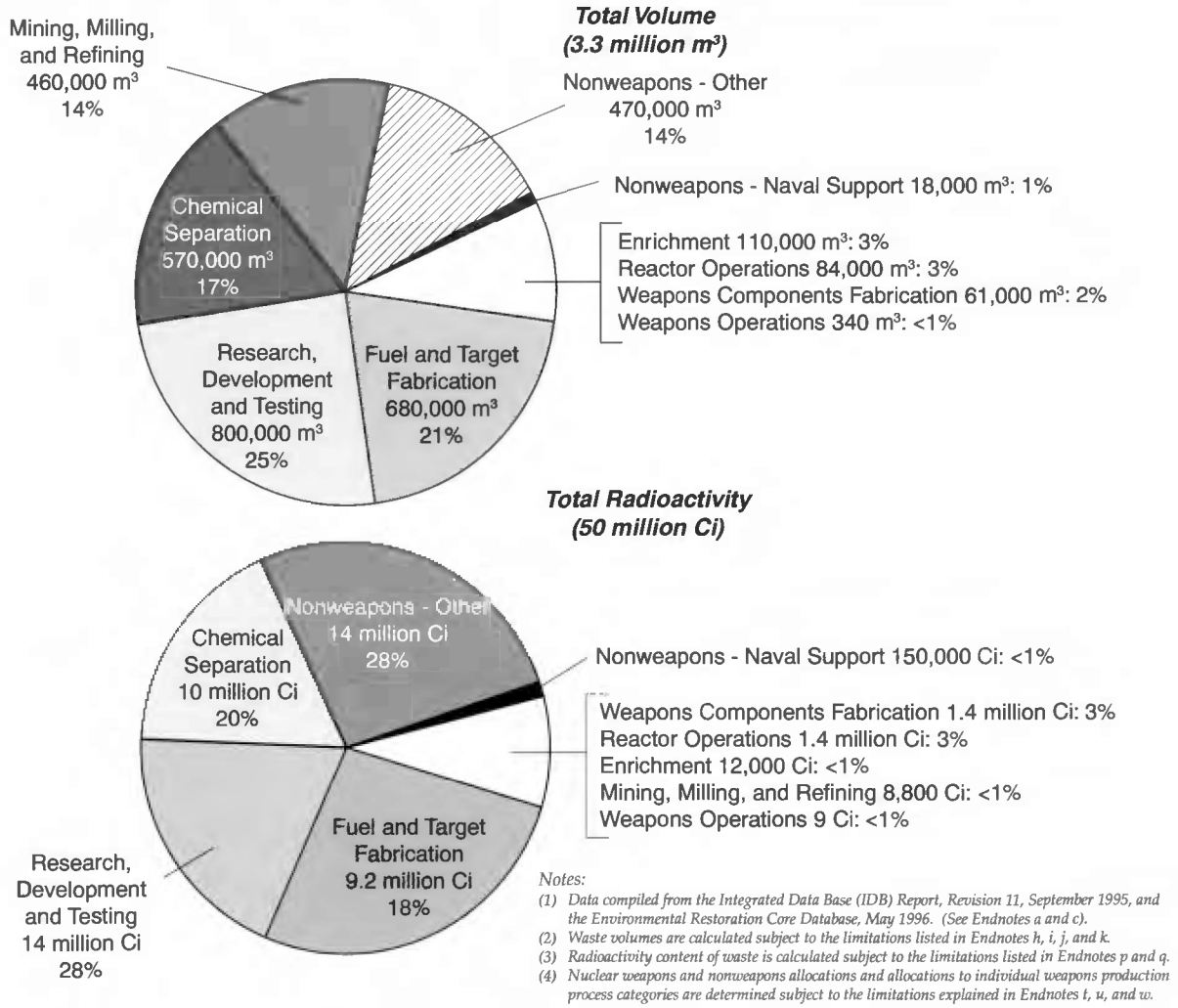
Low-level waste contains a broad spectrum of radionuclides, including nearly all of those found in high-level waste and TRU waste. Most low-level waste contains much lower concentrations of radionuclides than high-level waste and TRU waste, and thus exhibits far lower direct radiation and inhalation/ingestion hazards. A small amount of low-level waste, such as irradiated reactor parts and some of the special-case waste described above, presents much greater radiation hazards and is managed separately from the bulk of low-level waste. Some low-level waste containing uranium enriched in the uranium-235 isotope also can present criticality hazards and must be stored in geometric configurations that are considered criticality safe.

Hazardous constituents generally are not present in waste identified in this report as "low-level waste" since any low-level waste containing RCRA- or TSCA-regulated substances above regulatory levels is classified in this report mixed low-level waste or radioactive PCB waste, respectively. Radioactive asbestos waste has also been classified separately. Low-level waste containing these hazardous constituents has been separated from other low-level waste in this analysis because the presence of RCRA- or TSCA-regulated chemical constituents in the waste is a major factor affecting how the waste will be managed.

The Department did not generally apply RCRA and TSCA standards to low-level waste disposed of the 1980s. An unknown portion of this waste could be classified as mixed low-level waste if current regulatory standards were applied.

At sites that managed both TRU waste and low-level waste before 1970, an unknown amount of the pre-1970 low-level waste was commingled and disposed of with TRU waste. This waste is currently inventoried as TRU waste but some could be considered low-level waste by today's standards. The Department is characterizing some of the buried pre-1970 waste and has made some projections of the TRU, low-

Figure 3-10. Low-level Waste Volume and Radioactivity Categorized by Process



Notes:
(1) Data compiled from the Integrated Data Base (IDB) Report, Revision 11, September 1995, and the Environmental Restoration Core Database, May 1996. (See Endnotes a and c).
(2) Waste volumes are calculated subject to the limitations listed in Endnotes h, i, j, and k.
(3) Radioactivity content of waste is calculated subject to the limitations listed in Endnotes p and q.
(4) Nuclear weapons and nonweapons allocations and allocations to individual weapons production process categories are determined subject to the limitations explained in Endnotes t, u, and w.

Table 3-2. Low-level Waste Resulting from Nuclear Weapons Production

Stored Low-Level Waste (260,000 m³)

Site	Nuclear Weapons Volume (m^3)	Nonweapons Volume (m^3)
Fernald Environmental Management Project (OH)	140,000	0
Latty Avenue Properties (MO)	24,000	0
Portsmouth Gaseous Diffusion Plant (OH)	15,000	10,000
K-25 Site (TN)	9,400	4,700
Mound Plant (OH)	8,800	0
Rocky Flats Environmental Technology Site (CO)	5,300	0
Idaho National Engineering Laboratory (ID)	3,200	9,500
Reactive Metals Incorporated, Ashtabula (OH)	2,900	0
Paducah Gaseous Diffusion Plant (KY)	2,700	1,800
Savannah River Site (SC)	1,600	0
Y-12 Plant (TN)	720	0
Lawrence Livermore National Laboratory (CA)	600	0
Nevada Test Site (NV)	270	0
Pantex Plant (TX)	210	0
Oak Ridge National Laboratory (TN)	110	3,400
Pinellas Plant (FL)	66	0
Hanford (WA)	47	0
Sandia - California (CA)	27	0
Kansas City Plant (MO)	9	0
Nonweapons Sites	0	18,000

Currently Active Low-Level Waste Disposal (2.4 million m³)

Site	Nuclear Weapons Volume (m^3)	Nonweapons Volume (m^3)
Savannah River Site (SC)	680,000	0
Hanford Site (WA)	560,000	53,000
Nevada Test Site (NV)	480,000	0
Los Alamos National Laboratory (NM)	220,000	0
Idaho National Engineering Laboratory (ID)	37,000	110,000
Oak Ridge National Laboratory (TN)	6,800	220,000

Historic Low-Level Waste Disposal (620,000 m³)

Site	Nuclear Weapons Volume (m^3)	Nonweapons Volume (m^3)
Fernald Environmental Management Project (OH)	340,000	0
Y-12 Plant (TN)	150,000	0
K-25 Site (TN)	54,000	27,000
Lawrence Livermore National Laboratory (CA)	9,100	0
Portsmouth Gaseous Diffusion Plant (OH)	7,300	4,800
Paducah Gaseous Diffusion Plant (KY)	4,600	3,000
Sandia National Laboratories/New Mexico (NM)	3,200	0
Pantex Plant (TX)	130	0
Nonweapons Ocean Diposal	0	19,000

Notes:
(1) Data compiled from the Mixed Waste Inventory Report (MWIR) Data System, October 1995.
(2) Waste category asssignments are made in accordance with the methods explained in Endnote r.
(3) Mixed waste inventories not recorded in the MWIR, including some waste resulting from the DOE Environmental Restoration Program, are not included in the physical matrix analysis.

Disposal of DOE Waste at Maxey Flats

Some of the waste legacy from nuclear weapons production is located at the Maxey Flats Disposal Site. This site is included on the Environmental Protection Agency's National Priorities List of hazardous waste sites compiled under the Comprehensive Environmental Response Compensation and Liability Act. DOE has been identified as a potentially responsible party for Maxey Flats.

The Nuclear Engineering Company (now U.S. Ecology) operated Maxey Flats, located in Fleming County, Kentucky, about 65 miles northeast of Lexington, Kentucky, as a low-level radioactive waste disposal site between 1963 and 1977.

A total of 125,000 cubic meters of radioactive waste is estimated to have been buried at the Maxey Flats site during its operation. During its operating period, nearly 54,000 cubic meters of low-level waste from 29 former Atomic Energy Commission contractors was disposed of at Maxey Flats. About 44 percent of this waste came from the Mound Plant, a weapons component fabrication site in southwestern Ohio, and another 1 percent came from other nuclear weapons production sites. The balance of the DOE waste was generated by nonweapons programs, including sites supporting the nuclear navy program.

The commonwealth of Kentucky is managing cleanup of the site. DOE is responsible for funding about 40 percent of the cleanup; the balance is provided by over 800 other responsible parties.

Data on the waste legacy at Maxey Flats is not aggregated with other DOE waste because DOE is not responsible for managing the cleanup of the site.

level, and mixed low-level waste that would be generated from remedial actions at the burial sites. However, these projections are not included in this report.

Similarly, a portion of the Department's waste now classified as TRU waste was placed into storage between 1970 and 1984 and contains between 10 and 100 nanocuries per gram of TRU radionuclides. Upon future recharacterization, some of this TRU waste may be reclassified as low-level waste.

The Department disposes of most solid low-level waste in shallow-land burial facilities. While the Department currently disposes of low-level waste at six sites (Hanford, Idaho National Engineering Laboratory, Los Alamos National Laboratory, Nevada Test Site, Oak Ridge National Laboratory, and the Savannah River Site), buried low-level waste is present at eight other sites that have either conducted onsite disposal in the past or have experienced past radioactive releases resulting in buried low-level waste (Table 3-2).

Much low-level waste is treated prior to disposal to either stabilize the waste form (e.g., by solidifying low-level waste containing free liquid or particulates) or reduce the disposal volume (e.g, by incineration or compaction). Treatment is usually conducted onsite but in some cases waste is transported offsite for treatment and then returned to the Department. The waste is then stored onsite until it is either disposed onsite or transported to another DOE site for disposal. Nineteen sites involved in nuclear weapons production currently store low-level waste, typically in metal drums or metal or plywood boxes. Larger items are wrapped in plastic. Prior to disposal, the waste is certified to ensure that no mixed low-level waste or other prohibited materials (e.g., free liquids that could leak out) are present. Low-level waste emitting high levels of gamma radiation is stored in heavily shielded containers prior to disposal. Low-level waste containing alpha-emitting radionuclides at levels at or above 10 nanocuries per gram are sometimes managed separately from low-level waste containing lower concentrations of alpha-emitters. Because of the potential inhalation hazard, high-alpha low-level waste require special procedures to limit possible inhalation hazards to workers.

In addition to disposing of low-level waste at DOE sites, the Department and its predecessor agencies disposed of some low-level waste at commercial facilities (e.g., Maxey Flats), by underground injection (e.g., hydrofracture at Oak Ridge National Laboratory), or by sea burial. DOE low-level waste recently disposed of at commercial facilities is not included in this report because it is outside the scope of the Department's Environmental Management Program. However, DOE low-level waste disposed of at commercial disposal sites many years ago is included in cases where remedial action is necessary at the disposal site (e.g., at the Maxey Flats, Kentucky, Superfund Site.) Some low-level waste, such as sealed radioactive sources and irradiated reactor parts, is too radioactive for shallow-land disposal; some has been disposed of at greater confine-

[9] *Material at sites managed under DOE's Uranium Mill Tailings Remedial Action (UMTRA) Project and other Environmental Restoration Program sites is defined as residual radioactive material under Title I of the Uranium Mill Tailings Radiation Control Act (UMTRCA). Since this material has the same physical and radioactive properties as 11e(2) byproduct material, it is included with 11e(2) byproduct material for reporting purposes in this document. UMTRCA specifies the requirements under which residual radioactive material at UMTRA sites will be remediated.*

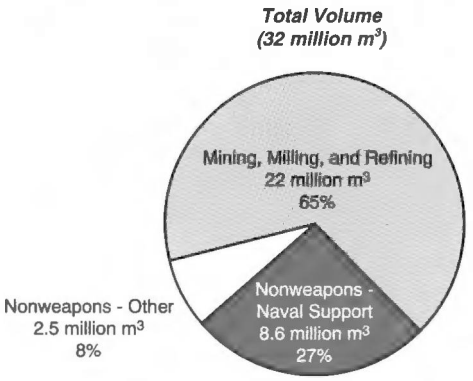
Table 3-3. Commercial Sites Managing 11e(2) Byproduct Material Resulting from AEC Purchases

State	Commercial Site	Volume (m^3)
CO	Cotter Corp., Canon City Mill Site	200,000
CO	UMETCO Mineral Corp., Uravan Mill Site	3,600,000
IL	Kerr-McGee Chemical Corp., West Chicago Thorium Mill Site	20,000
NM	Quivira Mining Company, Ambrosia Lake Mill Site	6,300,000
NM	Homestake Mining Company, Grants Mill Site	880,000
NM	Atlantic Richfield Company, Blue Water Mill Site	5,500,000
SD	Tennessee Valley Authority, Edgemont Mill Site	1,000,000
UT	Atlas Corp., Moab Mill Site	3,700,000
WA	Dawn Mining Company, Ford Mill Site	730,000
WY	Union Carbide Corp., East Gas Hills Mill site	1,300,000
WY	American Nuclear Corp., Gas Hills Mill Site	1,400,000
WY	Western Nuclear, Inc., Split Rock Mill Site	2,100,000
WY	Pathfinder Mines Corp., Lucky MC Mine	1,800,000
WY	Petrotomics Company, Shirley Basin Mill Site	450,000
TOTAL		29,000,000

Source:
Federal Register, May 23, 1994; Reimbursement for Costs of Remedial Action at Active Uranium and Thorium Processing Sites.
Notes:
(1) All sites are former uranium processing facilities except for the West Chicago Thorium Mill.
(2) Volumes only include amount of 11e(2) material resulting from other uranium or thorium sales.
(3) The site owners and operators are responsible for management of all materials at these sites. The sites are not managed by DOE and are not included in the analysis of the waste legacy.
(4) Volumes based on a mass-to-volume conversion of 1.6 dry short tons/cubic meter.

Corroded waste drums. Drums that contain radioactive waste can become radioactive waste themselves, as seen here at the Hazelwood Interim Storage Site outside St. Louis. These 55 gallon steel drums originally held uranium-contaminated 11e(2) byproduct material from the uranium refinery in downtown St. Louis. Once the drums lost their structural integrity, workers transferred their contents and cut up the corroded drums in preparation for disposal. *Hazelwood Interim Storage Site, Latty Avenue, Hazelwood, Missouri. January 29, 1994.*

Figure 3-11. 11e(2) Byproduct Material Volume Categorized by Process



Notes:

(1) Data compiled from the Integrated Data Base (IDB) Report, Revision 11, September 1995, the Environmental Restoration Core Database, May 1996; and GAO/RCED-96-37. (See Endnotes a,c, and d).

(2) Waste volumes are calculated subject to the limitations listed in Endnotes g, i, and k.

(3) Waste category asssignments are made in accordance with the process explained in Endnote r.

(4) Nuclear weapons and nonweapons allociations to individual weapons production process categories are determined subject to the methods set forth in Endnote v.

ment facilities, but most of this waste will remain in storage until treatment and disposal decisions are made and facilities become available.

The Office of Environmental Restoration manages the largest volume of DOE low level waste. Much of the low-level waste generated within the Department is transferred to the Office of Waste Management for further management. In recent years, the quantity of waste resulting from remediation activities (e.g., excavating and treating contaminated soil) and building deactivation and decommissioning has increased. In some cases, this waste is transferred to the Office of Waste Management for further disposition. In other cases, the Office of Environmental Restoration disposes the waste onsite or ships it to commercial disposal facilities.

11e(2) Byproduct Material

11e(2) byproduct material is the Department's term for the tailings or waste produced by the extraction or concentration of uranium or thorium from any ore processed primarily for its source material (i.e., uranium or thorium) content. Like mixed waste, which is defined under RCRA, 11e(2) byproduct material is defined by law, under Section 11e(2) of the AEA as amended by Title II of the Uranium Mill Tailings Radiation Control Act of 1978.[9] (All radioactive materials discussed in this report fall under the definitions of source, special nuclear, or byproduct materials in section 11 of the AEA. There are two types of byproduct material defined in subpart C of Section 11, referred to as 11e(1) byproduct material and 11e(2) byproduct material.)

A few processes associated with the initial milling and refining of uranium ore generate almost all 11e(2) byproduct material. These processes include large-volume ore processing steps to physically separate U_3O_8 from natural ore as well as smaller scale supporting activities such as laboratory analysis and research. The vast majority of 11e(2) byproduct material is composed of homogenous sand- or clay-like particles. After the recoverable uranium is removed from ore, the resulting residues, known as mill tailings, still contain much of their original radioactivity in the form of alpha-emitting uranium, thorium-230, radium-226, and daughter products of radium-226 decay. The total radioactivity levels present in mill tailings can exceed 1,000 picocuries per gram. Radon gas (Rn-222) that is released to the environment as the radium-226 decays causes one hazard associated with the tailings. Because daughter products from radon gas can adhere to dust and other particles in the air, they can present a hazard in enclosed spaces where they can be inhaled, become trapped in the lungs, and cause cell damage as their radioactive decay continues. Toxic heavy metals such as chromium, lead, molybdenum, and vanadium are also present in 11e(2) byproduct material in low concentrations.[10]

DOE manages approximately 32 million cubic meters of 11e(2) byproduct material. Overall, about 65 percent of this amount is attributed to nuclear weapons production, 27 percent is from activities supporting the NNPP, and 8 percent is the result of other nonweapons activities (Figure 3-11). Both the nuclear weapons and nonweapons portions of the 11e(2) byproduct material inventory resulted from mining, milling, and refining. The uranium initially produced at the mines and mills was used for many products, including nuclear weapon components and fuel for plutonium and tritium production reactors,

[10] *The toxic heavy metals and other hazardous constituents in 11e(2) byproduct material are exempt from RCRA. Unlike the other source, special nuclear and byproduct materials under section 11e(1) of the AEA which consist solely of radioactive constituents, 11e(2) byproduct material as defined by the AEA includes both radioactive and nonradioactive components. Thus, 11e(2) material is exempt from RCRA even though it may contain hazardous constituents. When byproduct material is mixed with hazardous waste, however, the mixture becomes a mixed waste subject to RCRA. Data on the relatively small amount of mixed 11e(2) material managed by DOE is presented later in this chapter under the heading of "Other Waste."*

naval reactors, research reactors, and commercial power plants. The apportionment of 11e(2) byproduct material into weapons and nonweapons categories is an estimate based on the amount of uranium used for various nuclear weapons and nonweapons purposes.

The amount of radium-226 present in the 11e(2) byproduct material managed by DOE is about 27,000 curies. Using the allocation method described in the text box, about 73 percent of the radioactivity in the 11e(2) byproduct material resulted from production of uranium for weapons, 21 percent from uranium subsequently used by the NNPP, and 6 percent from uranium used by the government for other nonweapons purposes. Uranium, thorium, radon, and radon daughter products are not included in this total. Detailed data on the inventories of these radionuclides in 11e(2) byproduct material are available at a number of the sites managing the 11e(2) byproduct material, but the data have not been compiled on a nationwide basis.

Mill tailings are typically generated as a slurry and are initially placed in large ponds. The liquid portion of the tailings, which either evaporates or infiltrates out of the ponds, can contain radioactivity levels up to 7,500 pCi/L of radium-226, 22,000 pCi/L of thorium-230, and 0.01 percent uranium. The dry tailings contain about 85 percent of the radioactivity present in unprocessed uranium ore. Dry tailings are periodically removed from the ponds and stored in large aboveground piles. When mill tailings sites are remediated, the dry tailings from ponds and other holding areas, and windblown tailings are typically collected and stabilized in large above grade disposal cells which are capped to prevent future dispersion of the tailings by erosion. This contrasts with the other waste types that, except for unusually large items and environmental restoration waste which is handled in bulk, is typically put in containers for both storage and disposal. Of the 32 million cubic meters of 11e(2) byproduct material managed by DOE, nearly 27 million cubic meters (82 percent)

Three Types of Sites Managing 11e(2) Byproduct Material

- **Sites subject to Title I of the Uranium Mill Tailings Radiation Control Act:** This category is composed of 24 inactive uranium milling sites that had ceased operation by 1978. These sites produced uranium concentrate, the overwhelming majority of which was sold to AEC in support of weapons production, nuclear fuel production for the NNPP, and other AEC programs. Although all of these sites were commercially operated, the law assigns the responsibility for performing environmental restoration at 22 of these sites to the Department. In addition, DOE has designated two more sites, and the vicinity properties of a third site, for restoration under the UMTRA program (Table 3-3). The Department is remediating these sites under the UMTRA Project managed by the Office of Environmental Restoration. Stabilization of the mill tailings has been completed at all but five of the sites. The Department has identified about 8,000 potential vicinity properties associated with these sites. Cleanup has been completed at nearly 97 percent of the 5,275 properties requiring further action.
- **Sites subject to Title II of the UMTRCA and Title X of the Energy Policy Act of 1992:** This category includes 13 commercial uranium mill sites and one commercial thorium mill site that were licensed to operate on or after January 1, 1978 (Table 3-4). For these sites, the *proportion* of uranium (or thorium) sales made to the government to support weapons, naval, and R&D programs is smaller than that for sites in the UMTRCA Title I category. However, most of the sites initially operated to supply uranium to the Atomic Energy Commission and the total amount of uranium provided by these sites is more than that provided by the UMTRCA Title I sites. Beginning in the 1970s, the private sector purchased much of the uranium from these sites to produce fuel for commercial nuclear power reactors and some other applications. For these sites, the mill owners are responsible for cleanup, and the Department is responsible for reimbursing site owners for the portion of decontamination, decommissioning, reclamation, and other remedial action costs determined to be attributable to uranium (and thorium) sales to the Federal Government. Because the Department is not conducting restoration of these sites, the waste (and contaminated media) at these sites is not aggregated with the waste volumes presented in this report. However, the quantities are listed in Table 3-4.
- **Other Sites:** This category is composed of eight sites that stored or processed uranium and thorium ore or concentrates, or were used to store the resulting residues, but that do not fall into the other two categories. This includes six sites that managed uranium for nuclear weapons production (Table 3-3). None of these sites is still active as part of the nuclear weapons production process. Some sites were owned by the AEC and others were owned and operated by AEC contractors during the Manhattan Project and the early part of the Cold War. The Department is responsible for remediating the waste, contaminated media, and facilities at the DOE-owned sites in this category. At the non-DOE-owned sites, the Department is responsible for remediating only some of the waste and contamination attributed to work performed for AEC. The Office of Environmental Restoration is remediating these sites, and several are in the Formerly Used Sites Remedial Action Program (FUSRAP).

Attributing 11e(2) Byproduct Material to Nuclear Weapons Production

Between 1942 and 1971, domestic uranium mines and mill sites supplied about half of the uranium purchased by the Manhattan Project and the Atomic Energy Commission (AEC). Initially, only AEC could legally own processed uranium, or "source material," and nearly all of the uranium it purchased was used for weapons production. Some uranium was enriched to produce weapons components and other enriched and natural uranium was used in reactors to produce plutonium. Later, small amounts of uranium were used in reactors for research, powering naval vessels, and generating electric power. The AEA was amended in 1954 to allow private ownership of nuclear facilities, and again in 1964 to allow private ownership of enriched uranium and plutonium. During the 1960s and 1970s, use of uranium for nonweapons purposes increased, and use of uranium for nuclear weapons production declined. Much uranium also was recycled. For example, uranium used in nuclear weapons production reactors and naval reactors was reprocessed, blended, fabricated into fuel, and reused in the production reactors.

More than 200 pounds of 11e(2) byproduct material are typically produced for each pound of natural (unenriched) uranium product. Because the uranium from the mills was used for both nuclear weapons and nonweapons purposes, the resulting 11e(2) byproduct material is allocated into both nuclear weapons and nonweapons categories. The material is allocated according to how much uranium was used, overall, for various purposes (nuclear weapons program, naval fuel, research reactors or commercial reactors), taking into account all historic AEC uranium purchases (including uranium purchases from sites where DOE is responsible for remediation, other U.S. mill tailing sites, and foreign mill tailing sites). In this analysis, the same allocation is applied to all mill tailing sites, regardless of when the mills operated. This allocation is accurate to within ten percent. It does not take into account that some uranium was recycled for other purposes.

Table 3-4. 11e(2) Byproduct Material Resulting from Nuclear Weapons Production

Remediation Complete

Site	State	Type	Nuclear Weapons (m^3)	Nonweapons (m^3)	Total (m^3)
Falls City	TX	UMTRA	2,900,000	1,500,000	4,400,000
Grand Junction Mill Tailing Site	CO	UMTRA	2,300,000	1,200,000	3,600,000
Old Rifle & New Rifle (2 sites)	CO	UMTRA	2,100,000	1,100,000	3,200,000
Ambrosia Lake	NM	UMTRA	1,900,000	1,000,000	2,900,000
Mexican Hat	UT	UMTRA	1,400,000	750,000	2,100,000
Salt Lake City	UT	UMTRA	1,400,000	720,000	2,100,000
Durango	CO	UMTRA	1,300,000	670,000	1,900,000
Riverton	WY	UMTRA	900,000	480,000	1,400,000
Shiprock	NM	UMTRA	800,000	420,000	1,200,000
Monument Valley	AZ	UMTRA	470,000	250,000	720,000
Lakeview	OR	UMTRA	460,000	250,000	710,000
Tuba City	AZ	UMTRA	390,000	210,000	600,000
Gunnison	CO	UMTRA	360,000	190,000	550,000
Naturita	CO	UMTRA	270,000	150,000	420,000
Green River	UT	UMTRA	190,000	100,000	290,000
Spook	WY	UMTRA	160,000	84,000	240,000
Canonsburg	PA	UMTRA	110,000	60,000	170,000
Lowman	ID	UMTRA	64,000	34,000	98,000

Remediation Not Complete

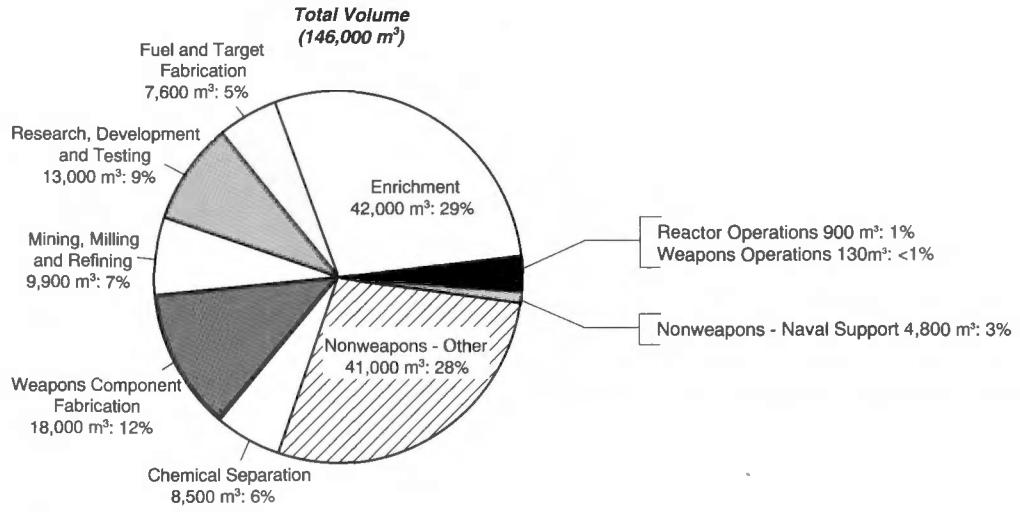
Site	State	Type	Nuclear Weapons (m^3)	Nonweapons (m^3)	Total (m^3)
Maybell	CO	UMTRA	1,700,000	930,000	2,700,000
Monticello Remedial Action Project	UT	Non-UMTRA	1,300,000	690,000	2,000,000
Slick Rock Union Carbide & North Continent (2 sites)	CO	UMTRA	320,000	120,000	440,000
Niagara Falls Storage Site	NY	Non-UMTRA	200,000	0	200,000
Weldon Spring Site	MO	Non-UMTRA	160,000	0	160,000
Bowman	ND	UMTRA	64,000	34,000	98,000
Belfield	ND	UMTRA	29,000	15,000	44,000
Middlesex Sampling Plant	NJ	Non-UMTRA	17,000	9,300	27,000
Edgemont Vicinity Properties *	SD	UMTRA	15,000	8,000	23,000
Fernald Environmental Management Project	OH	Non-UMTRA	11,000	0	11,000
Grand Junction Projects Office	CO	Non-UMTRA	690	370	1,000
Other Nonweapons Sites	N/A	Non-UMTRA	0	56,000	56,000

* *DOE is responsible for vicinity properties only; the Tennessee Valley Authority owns and remediated the former uranium mill site in Edgemont in the late 1980s.*

Notes:

(1) Data compiled from the Environmental Restoration Core Database, May 1996 and GAO/RCED-96-37. (See Endnotes c and d).
(2) Waste volumes are calculated subject to the limitations listed in Endnotes g, i, and k.
(3) Waste category asssignments are made in accordance with the methods explained in Endnote r.
(4) Nuclear weapons and nonweapons allocations and allocations to individual weapons production process categories are determined subject to the process set forth in Endnote v.
(5) Status indicates whether remedial actions at the site have been completed. For UMTRA Project sites, "Complete" signifies only that surface cleanup is finished.

Figure 3-12. Mixed Low-level Waste Volume Categorized by Process



Notes:

(1) Data compiled from the Integrated Data Base (IDB) Report, Revision 11, September 1995; the Environmental Restoration Core Database, May 1996; and GAO/RCED-96-37. (See Endnotes a, c, and d).

(2) Waste volumes are calculated subject to the limitations listed in Endnotes g, i, and k.

(3) Waste category asssignments are made in accordance with the processes explained in Endnote r.

(4) Nuclear weapons and nonweapons allocations and allocations to individual weapons production process categories are determined subject to the methods set forth in Endnote v.

has been stabilized. The remaining 11e(2) byproduct material is scheduled to be stabilized in the next few years.

In the past, uranium mill tailings were considered useful as a construction material and were used extensively on public and private property in many communities near the ore processing sites. These locations where tailings were used for construction purposes or where they were carried by wind or water are known as "vicinity properties."

In addition to mill tailings, 11e(2) byproduct materials resulted from the processing of imported high-grade pitchblende ores. These ores, containing uranium at concentrations 100 times greater than domestic ores, produced a smaller volume of residues. However, these residues contain much higher concentrations of radium-226, thorium-230, radon, and other radionuclides than those from processing domestic ores.

The mining, milling, and refining sites managing 11e(2) byproduct material are typically different from those involved in the other seven weapons process categories. The facilities and processes used are similar to those in other mining operations and involve large-scale outdoor facilities. Most sites managing 11e(2) byproduct material were not originally owned by the Department or its predecessors. Instead, they were owned and operated by companies that processed either government-owned or company-owned uranium and uranium ore. The 11e(2) byproduct materials are present at government and privately-owned uranium and thorium refining plants and ore storage and waste disposal sites in several western states as well as in Ohio, Missouri, New York, New Jersey, and Pennsylvania.

Private companies manage 11e(2) byproduct material at sites subject to Title X of the Energy Policy Act of 1992. Electric companies purchased much of the uranium (and thorium) produced at these sites for commercial nuclear power generation. However, the Atomic Energy Commission (AEC) also purchased some from Title X sites for weapons production and other purposes. DOE established the portion of 11e(2) byproduct material attributed to AEC purchases in accordance with the Energy Policy Act of 1992. This volume of 11e(2) byproduct material is not included in the total volumes presented in Table 3-3 because DOE is not managing it. However, it is comparable in size to the volume managed by DOE (see Table 3-4).

During the active production cycle of the nuclear weapons complex, DOE predecessors purchased between two and three times as much uranium from the Title X sites as was purchased from sites in the UMTRA Project.

Mixed Low-level Waste

Mixed waste is waste that contains both hazardous waste subject to RCRA, and source, special nuclear, or byproduct material subject to the AEA.[11] Although mixed waste was formally defined by statute in 1992, regulators recognized that it required special management many years earlier. The Department first started managing mixed low-level waste as a separate waste type in the 1980s.

Some mixed waste is addressed in the high-level waste and TRU subsections. However, mixed low-level waste is considered separately from other low-level waste because the presence of RCRA-regulated constituents is a major factor in determining how it is managed. In contrast, decisions for treatment and disposal of high-level waste and TRU are based primarily on radiological rather than chemically hazardous characteristics.

Mixed low-level waste is generated during a broad spectrum of processes and activities including equipment maintenance, materials production, cleaning, environmental restoration, facility deactivation and decommissioning, and the treatment or handling of low-level waste and other waste types.

Table 3-5. Mixed Low-level Waste by Matrix

Physical Matrix	Volume (m^3)
Inorganic Sludges	27,000
Solidified Homogeneous Solids	25,000
Soil/Gravel	13,000
Metal Debris	9,000
Organic Debris	9,000
Heterogeneous Debris	7,800
Aqueous Liquids/Slurries	5,100
Inorganic Particulates	3,500
Unknown/Other Solids	3,200
Organic Liquids	2,000
Unknown/Other Debris	2,000
Elemental Hazardous Metals	1,000
Inorganic Nonmetal Debris	900
Unknown/Other Inorganic Homogeneous Solids	820
Lab Packs	480
Reactive Metals	410
Salt Waste	370
Organic Sludges	170
Unknown/Other Inorganic Debris	130
Organic Particulates	120
Batteries	110
Unknown/Other Matrix	100
Paint Waste	86
Unknown/Other Organic Homogenous Solids	64
Final Waste Forms	34
Compressed Gases/Aerosols	31
Elemental Mercury	11
Unknown/Other Liquids	11
Organic Chemicals	4
Beryllium Dust	3
Inorganic Chemicals	2
Unknown/Other Homogeneous Solids	1
Explosives/Propellants	<1

Notes:
(1) Data compiled from the Mixed Waste Inventory Report (MWIR) Data System, October 1995.
(2) Waste category asssignments are made in accordance with the processes explained in Endnote r.
(3) Mixed waste inventories not recorded in the MWIR, including some waste resulting from the DOE Environmental Restoration Program, are not included in the physical matrix analysis.

The Department manages about 146,000 cubic meters of mixed low-level waste. About 69 percent is from weapons production activities, 3 percent from NNPP support activities, and 28 percent from other nonweapons activities (Figure 3-12). The weapons production process categories that produced the most mixed low-level waste are enrichment (29 percent of the Department's mixed low-level waste), component fabrication (12 percent), and weapons RD&T (9 percent). About 20 percent of the Department's mixed low-level waste is attributed to the other five weapons production process categories.

The radioactive component of mixed low-level waste is similar to the component in low-level waste. This waste is generally much less radioactive than high-level and TRU waste and can contain a broad spectrum of radionuclides, depending on the source of the waste. Based on the radioactive content of low-level waste managed at the same sites where mixed low-level waste is managed, it is likely that fewer than 2.4 million curies are present in DOE mixed low-level waste. Although DOE sites generally maintain more detailed data on the radioactive content of the mixed low-level waste inventory, this data has not been compiled at a nationwide level.

DOE tracks the composition of mixed low-level waste by assigning each waste stream to one or more of over 100 treatability groups. The groups take into account the physical matrix of the waste form, the presence of hazardous constituents and characteristics, and the radiological characteristics of the waste.

[11] *Mixed waste is defined in the Federal Facility Compliance Act, a 1992 amendment to RCRA.*

Twenty-eight thousand drums of low-level mixed waste await treatment in a storage yard at the K-25 Plant. These drums contain sludge from settling ponds that received waste from a plating facility that served the uranium enrichment plant. The drums corroded prematurely when a 1987 waste-stabilization project failed to follow guidelines for combining low-level mixed waste with cement. *K-1417 Drum Storage Yards, Pond Waste Management Project, Oak Ridge, Tennessee. January 10, 1994.*

Table 3-6. Mixed Low-level Waste Resulting from Nuclear Weapons Production

Site	State	Nuclear Weapons Volume (m^3)	Nonweapons Volume (m^3)
K-25 Site	TN	26,000	13,000
Rocky Flats Environmental Technology Site	CO	14,000	0
Y-12 Plant	TN	14,000	0
Portsmouth Gaseous Diffusion Plant	OH	11,000	7,000
Savannah River Site	SC	7,300	0
Los Alamos National Laboratory	NM	6,600	0
Paducah Gaseous Diffusion Plant	KY	6,400	0
Idaho National Engineering Laboratory	ID	6,400	19,000
Hanford Site	WA	5,900	490
Fernald Environmental Management Project	OH	3,500	0
Lawrence Livermore National Laboratory	CA	460	0
Nevada Test Site	NV	300	0
Pantex Plant	TX	130	0
Mound Plant	OH	110	0
Oak Ridge National Laboratory	TN	91	2,900
Sandia National Laboratories/New Mexico	NM	75	0
Reactive Metals Incorporated, Ashtabula	OH	67	0
Sandia National Laboratories/California	CA	1	0
Nonweapons Sites	Various	0	900

Notes:

(1) Data compiled from the Integrated Data Base (IDB) Report, Revision 11, September 1995; the Environmental Restoration Core Database, May 1996; and GAO/RCED-96-37. (See Endnotes a, c, and d).

(2) Waste volumes are calculated subject to the limitations listed in Endnotes i and k.

(3) Waste category asssignments are made in accordance with the processes explained in Endnote r.

(4) Nuclear weapons and nonweapons allocations and allocations to individual weapons production process categories are determined subject to the methods set forth in Endnotes t and u.

The major categories of treatability groups, which identify the physical waste matrix, are presented in Table 3-5.

Hazardous constituents present in mixed low-level waste include toxic heavy metals, organic and halogenated organic chemicals, cyanides, inorganic chemicals and elements, explosive compounds, and corrosive chemicals and solutions. Some mixed low-level waste contains both RCRA-regulated hazardous constituents and PCBs regulated under TSCA.

The storage, treatment, and disposal of mixed low-level waste is subject to state and federal RCRA regulations. Mixed low-level waste generally is not disposed of at DOE sites. Instead, DOE stores mixed low-level waste at its sites, and the waste is treated either at DOE or commercial sites. Some mixed low-level waste has been disposed of commercially. (The commercially disposed mixed low-level waste is not included in the totals presented in this report.) Decisions for the future disposal of mixed low-level waste at DOE sites have not yet been made.

In the past several years, mixed low-level waste has been generated or stored at approximately 40 sites. The number of sites varies because some sites sporadically generate small quantities that are promptly treated to render the waste nonhazardous, thereby eliminating the need for storage. Mixed low-level waste from weapons production is managed at 18 sites in 11 states. Six of the weapons production sites also manage mixed low-level waste from nonweapons activities. Nonweapons sites managing mixed low-level waste include ten sites managed under the NNPP, and several small sites and laboratories that play small or no roles in weapons production (Table 3-6).

Hazardous Waste

Hazardous waste is defined under RCRA, its implementing regulations in 40 CFR Parts 260 to 279, and corresponding state regulations. A material is a hazardous waste under RCRA only if it meets the definition of a solid waste. A solid waste is considered to be hazardous if it is either listed in the regulations as a hazardous waste or exhibits a characteristic of corosivity, ignitability, reactivity, or toxicity.

Hazardous waste is managed differently from other waste types handled by DOE. Because hazardous waste does not contain a radioactive component, the Department can more easily release it for private-sector treatment and disposal. After release by DOE, this waste is treated, if necessary, by incineration and other technologies, and the residues, which sometimes are no longer hazardous, are disposed of in landfills. Some DOE hazardous waste is also recycled. This waste is not considered a legacy from nuclear weapons production because no long-term monitoring or management of the waste by the Department is expected.

Prior to offsite release, the Department stores and characterizes hazardous waste to comply with RCRA regulations and to verify that it does not contain radioactive material. The Department also recycles some hazardous waste into usable products. In either case, DOE generally does not store hazardous waste for a long time.

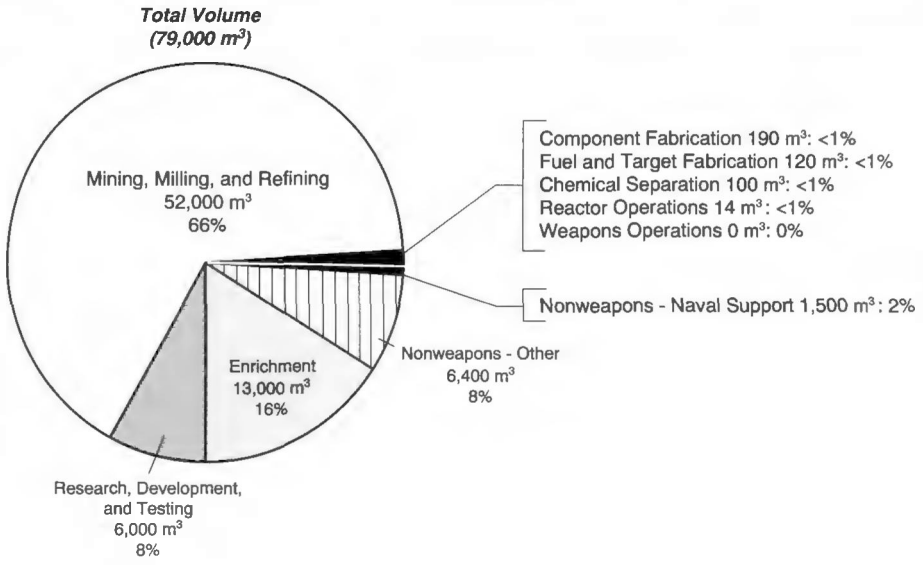
The Department began handling hazardous waste as a distinct waste type in the 1980s. Prior to the regulation of hazardous waste, DOE disposed of some waste at its production sites. Hazardous waste disposal sites are part of the legacy of environmental contamination managed by the Department described in Chapter 4.

Other Waste

Some DOE waste does not fit into one of the previously defined categories because of its chemical and radiological composition. The following waste has been included in this category:

- PCBs and PCBs mixed with radioactive waste, that are subject to TSCA but are not also subject to RCRA. (Some of this waste is classified as mixed low-level waste if it contains other RCRA-regulated hazardous constituents or because it is managed in a state where polychlorinated biphenyls are subject to state RCRA programs.)

Figure 3-13. Other Wastes Managed by DOE Categorized by Process



Notes:

(1) Data compiled from the Integrated Data Base (IDB) Report, Revision 11, September 1995; the Environmental Restoration Core Database, May 1996; and GAO/RCED-96-37. (See Endnotes a, c, and d).

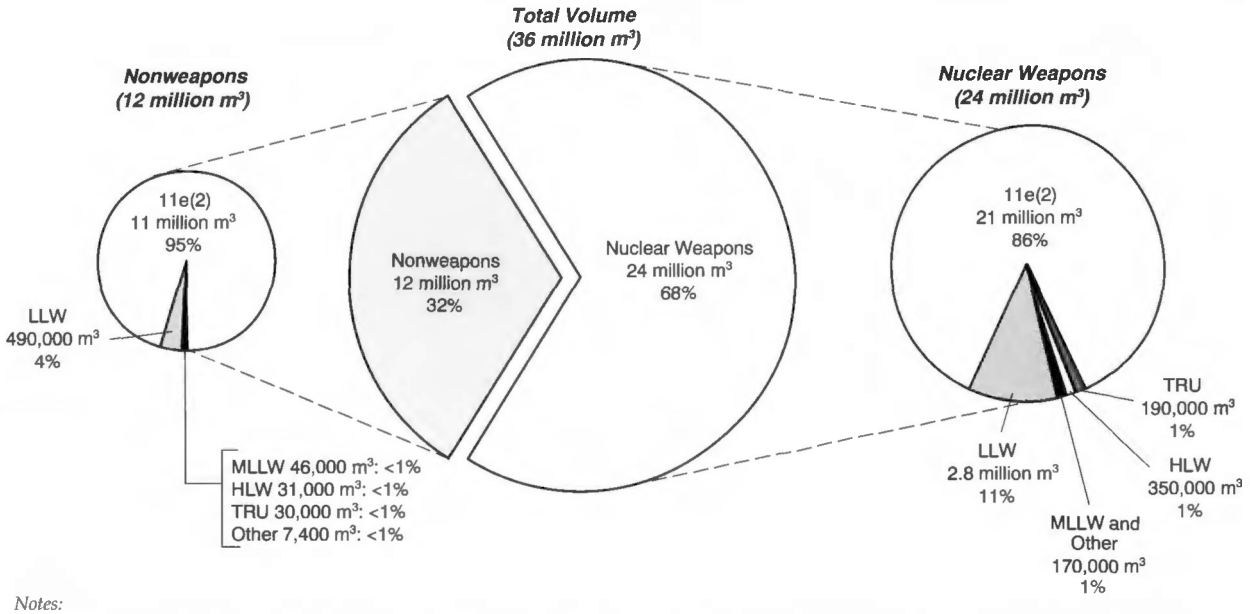
(2) Waste volumes are calculated subject to the limitations listed in Endnotes g, i, and k.

(3) Waste category asssignments are made in accordance with the processes explained in Endnote r.

(4) Nuclear weapons and nonweapons allocations and allocations to individual weapons production process categories are determined subject to the methods set forth in Endnote v.

Radioactively-contaminated asbestos removed from buildings that processed uranium for the Manhattan Project. *Downtown St. Louis FUSRAP site, Missouri. January 29, 1994.*

Figure 3-14. Total DOE Waste Volume Categorized by Waste Type



Notes:

(1) Data compiled from the Integrated Data Base (IDB) Report, Revision 11, September 1995; Mixed Waste Inventory Report (MWIR) Data System, October 1995; Environmental Restoration Core Database, May 1996; GAO/RCED-96-37; and Contaminated Media/Waste Database, 1993. (See Endnotes a, b, c, d, and e).

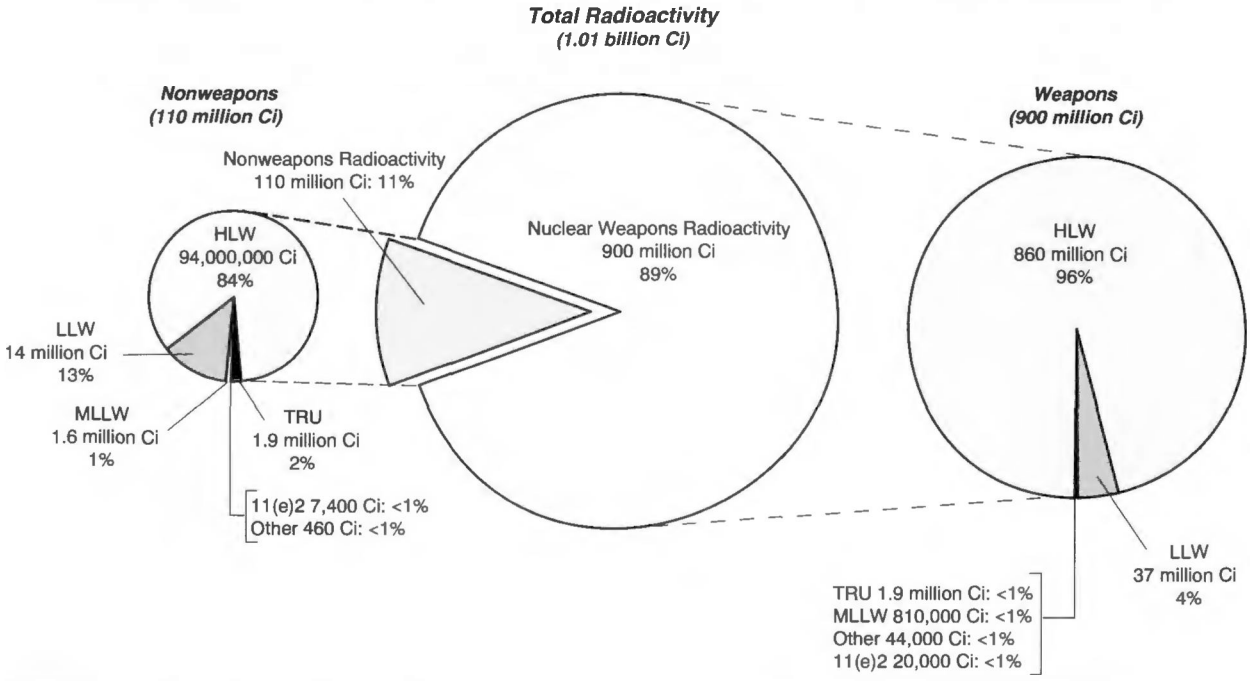
(2) Waste volumes are calculated subject to the limitations listed in Endnotes f, g, h, i, j, and k.

(3) Eadioactivity content of waste is calculated subject to the limitations listed in Endnotes l, m, n, o, p, and q.

(4) Waste category assignments are made in accordance with the methods outlined in Endnote r.

(5) Nuclear weapons and nonweapons allocations and allocations to individual weapons production process categories are determined subject to the process set forth in Endnotes t and u.

Figure 3-15. Total DOE Waste Radioactivity Categorized by Waste Type



Notes:

(1) Data compiled from the Integrated Data Base (IDB) Report, Revision 11, September 1995; Mixed Waste Inventory Report (MWIR) Data System, October 1995; Environmental Restoration Core Database, May 1996; GAO/RCED-96-37; and Contaminated Media/Waste Database, 1993. (See Endnotes a, b, c, d, and e).

(2) Waste volumes are calculated subject to the limitations listed in Endnotes f, g, h, i, j, and k.

(3) Eadioactivity content of waste is calculated subject to the limitations listed in Endnotes l, m, n, o, p, and q.

(4) Waste category assignments are made in accordance with the methods outlined in Endnote r.

(5) Nuclear weapons and nonweapons allocations and allocations to individual weapons production process categories are determined subject to the process set forth in Endnotes t and u.

Table 3-7. Other Category Wastes Resulting from Nuclear Weapons Production

Type	Site	State	Nuclear Weapons Volume (m^3)	Nonweapons Volume (m^3)
Asbestos	Reactive Metals Incorporated, Ashtabula	OH	16	0
Mixed 11e(2)	Middlesex Sampling Plant	NJ	24,000	0
	Weldon Spring Site Remedial Action Project	MO	20,000	0
PCB	Kansas City Plant	MO	24	0
Radioactive Asbestos	Weldon Spring Site Remedial Action Project	MO	7,500	0
	Los Alamos National Laboratory	NM	3,900	0
	K-25 Site	TN	900	450
	Paducah Gaseous Diffusion Plant	KY	260	170
	Savannah River Site	SC	140	0
	Y-12 Plant	TN	110	0
	Portsmouth Gaseous Diffusion Plant	OH	98	64
	Rocky Flats Environmental Technology Site	CO	41	0
	Mound Plant	OH	16	0
	Pantex Plant	TX	3	0
	Lawrence Livermore National Laboratory	CA	1	0
	Sandia National Laboratories/New Mexico	NM	<1	0
	Sandia National Laboratories/California	CA	<1	0
	Nevada Test Site	NV	<1	0
	Nonweapons Sites	Various	0	62
Radioactive PCBs	K-25 Site	TN	5,400	2,700
	Paducah Gaseous Diffusion Plant	KY	4,500	3,000
	Portsmouth Gaseous Diffusion Plant	OH	2,100	1,400
	Los Alamos National Laboratory	NM	2,100	0
	Y-12 Plant	TN	150	0
	Hanford Site	WA	88	8
	Rocky Flats Environmental Technology Site	CO	71	0
	Grand Junction Projects Office	CO	46	0
	Lawrence Livermore National Laboratory	CA	1	0
	Nonweapons Sites	Various	0	87

Notes:
(1) Data compiled from the Integrated Data Base (IDB) Report, Revision 11, September 1995, and the Environmental Restoration Core Database, May 1996. (See Endnotes a and c).
(2) Waste volumes are calculated subject to the limitations listed in Endnotes i and k.
(3) Waste category asssignments are made in accordance with the processes explained in Endnote o.
(4) Nuclear weapons and nonweapons allocations and allocations to individual weapons production process categories are determined subject to the methods set forth in Endnotes t and u.

- Asbestos and low-level waste asbestos that is not subject to RCRA. (Some of this waste is classified as mixed low-level waste if it contains other RCRA-regulated hazardous constituents or because it is managed in a state where asbestos is subject to state RCRA programs.)
- 11e(2) byproduct material that has been mixed with a hazardous waste subject to RCRA (known as mixed 11e(2) byproduct material).

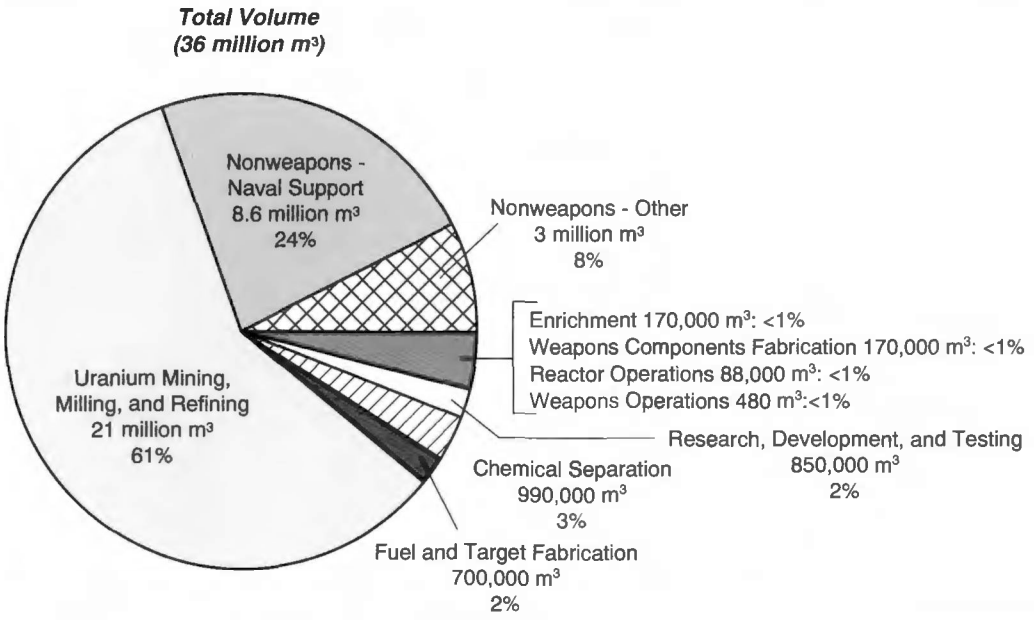
DOE manages about 79,000 cubic meters of these types of waste at about 30 sites, including 19 sites involved in weapons production. This includes 14,000 cubic meters of radioactive asbestos, 22,000 cubic meters of radioactive PCBs, and 44,000 cubic meters of mixed 11e(2) byproduct material.[12] A small amount (40 cubic meters) of nonradioactive asbestos and PCBs also is included in this category. All of the nonradioactive waste and mixed 11e(2) byproduct material is the result of weapons production. The mixed 11e(2) byproduct material is attributed entirely to uranium mining, milling, and refining.

About 94 percent of the radioactive asbestos and 67 percent of the radioactive PCBs also are the result of nuclear weapons production (Table 3-7). When combined, about 16 percent of this waste is the result of enrichment, 66 percent from uranium mining, milling, and refining, eight percent from RD&T, two percent from activities supporting the NNPP, and eight percent from other nonweapons activities (Figure 3-13).

The two sites where mixed 11e(2) material is located are the Middlesex Sampling Plant and Weldon Spring Site (Table 3-7). The radioactive asbestos is located primarily at Weldon Spring Site and Los Alamos National Laboratory. The radioactive PCBs are located primarily at the three uranium enrich-

[12] *See footnote 10.*

Figure 3-16. Total DOE Waste Volume Categorized by Process



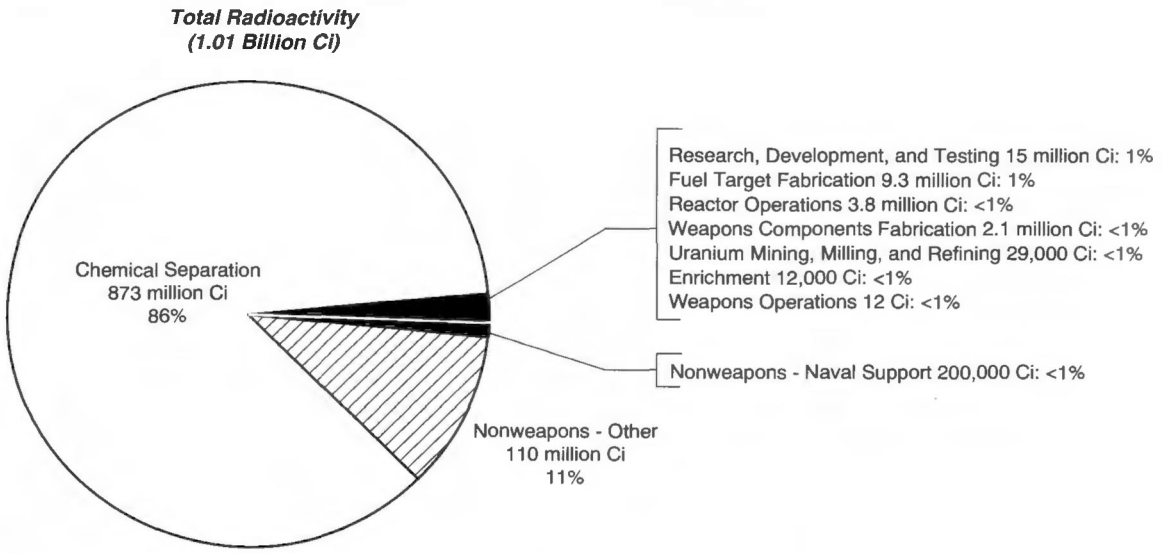
Notes:

(1) Data compiled from the Integrated Data Base (IDB) Report, Revision 11, September 1995; Mixed Waste Inventory Report (MWIR) Data System, October 1995; Environmental Restoration Core Database, May 1996; GAO/RCED-96-37; and Contaminated Media/Waste Database, 1993. (See Endnotes a, b, c, d, and e).

(2) Waste volumes are calculated subject to the limitations listed in Endnotes f, g, h, i, j, and k.

(3) Nuclear weapons and nonweapons allocations and allocations to individual weapons production process categories are determined subject to the process set forth in Endnotes s, t, u, v, and w.

Figure 3-17. Waste Radioactivity Categorized by Process



Notes:

(1) Data compiled from the Integrated Data Base (IDB) Report, Revision 11, September 1995; Mixed Waste Inventory Report (MWIR) Data System, October 1995; Environmental Restoration Core Database, May 1996; GAO/RCED-96-37; and Contaminated Media/Waste Database, 1993. (See Endnotes a, b, c, d, and e).

(2) Radioactivity content of waste is calculated subject to the limitations listed in Endnotes l, m, n, o, p, and q.

(3) Nuclear weapons and nonweapons allocations and allocations to individual weapons production process categories are determined subject to the process set forth in Endnotes s, t, u, v, and w.

ment sites (Paducah, Portsmouth, and K-25) and Los Alamos National Laboratory. The portion of this waste that resulted from nuclear weapons production is presented in Table 3-7.

Results

Figures 3-14 and 3-15 present the relative volumes of the major waste categories and amounts of radioactivity they contain. They show that the largest volume is 11e(2) byproduct material (Figure 3-14), whereas most of the radioactivity is in the high-level waste (Figure 3-15).

The total DOE waste legacy includes 36 million cubic meters of waste. Overall, 89 percent of the volume of the DOE waste legacy is 11e(2) byproduct material and 9 percent is low-level waste; the remaining waste categories only comprise about 2 percent of the waste legacy. The distribution of radioactivity in the waste, however, is very different. Radioactivity in high-level waste is 94 percent, 5 percent in low-level waste, and only about 1 percent of the radioactivity is found in the remaining waste categories.

Approximately two-thirds of the legacy of waste managed by the Department was generated from nuclear weapons production. Some waste has been generated as a result of other DOE programs in basic research, nuclear power research, and other applied research and development activities. Additionally, some waste was generated as a result of producing nuclear fuel for the NNPP (or was directly produced by the NNPP)[13] and commercial nuclear power reactors.

By volume, about 68 percent of the 36 million cubic meter waste legacy is due to nuclear weapons production activities, and the remaining 32 percent to nonweapons activities (Figure 3-16). By volume, 61 percent of the waste legacy came from uranium mining, milling, and refining for weapons production.

Advanced waste water treatment facility under construction. *Fernald Environmental Management Project, Ohio. December 28, 1993.*

[13] *Of the waste attributed to supporting the NNPP program, only a small fraction has actually been generated directly by the NNPP. The majority came from supporting activities, such as uranium mining, milling, refining, and enriching uranium. Most mining and milling occurred at commercially-owned and -operated sites that were later transferred to DOE for cleanup. The enrichment took place at the DOE gaseous diffusion plants.*

Table 3-8. Waste Volume and Radioactivity (Stored and Disposed)

Site Name	State	Nuclear Weapons Volume (m^3)	Nuclear Weapons Radioactivity (Ci)	Nonweapons Volume (m^3)	Nonweapons Radioactivity (Ci)
Falls City	TX	2,900,000	870	1,500,000	460
Grand Junction Mill Tailing Site	CO	2,300,000	2,500	1,200,000	1,300
Old Rifle & New Rifle	CO	2,000,000	1,700	1,100,000	890
Ambrosia Lake	NM	1,900,000	1,600	1,000,000	880
Maybell	CO	1,700,000	310	930,000	160
Mexican Hat	UT	1,400,000	990	746,000	530
Salt Lake City	UT	1,400,000	1,100	720,000	610
Monticello Remedial Action Project	UT	1,300,000	1,300	690,000	710
Durango	CO	1,300,000	1,300	670,000	680
Riverton	WY	900,000	300	480,000	160
Hanford Site	WA	850,000	330,000,000	83,000	28,000,000
Savannah River Site	SC	820,000	500,000,000	10,000	42,000,000
Shiprock	NM	800,000	580	420,000	310
Fernald Environmental Management Project	OH	490,000	8,100	0	0
Nevada Test Site	NV	480,000	9,800,000	0	0
Monument Valley	AZ	470,000	35	250,000	20
Lakeview	OR	460,000	82	250,000	43
Tuba City	AZ	390,000	350	210,000	190
Gunnison	CO	360,000	170	190,000	90
Slick Rock Union Carbide & North Continent	CO	320,000	58	120,000	21
Naturita	CO	270,000	20	150,000	10
Los Alamos National Laboratory	NM	260,000	1,800,000	0	0
Niagara Falls Storage Site	NY	200,000	2,200	0	0
Weldon Spring Site Remedial Action Project	MO	190,000	unavailable	0	0
Green River	UT	190,000	22	100,000	12
Y-12 Plant	TN	170,000	11,000	0	0
Spook	WY	160,000	104	84,000	55
Idaho National Engineering Laboratory	ID	140,000	56,000,000	150,000	11,000,000
Canonsburg	PA	110,000	360	60,000	190
K-25 Site	TN	100,000	69	48,000	34
Bowman	ND	64,000	3	34,000	2
Lowman	ID	64,000	16	34,000	8
Middlesex Sampling Plant	NJ	51,000	unavailable	0	0
Portsmouth Gaseous Diffusion Plant	OH	36,000	64	23,000	42
Belfield	ND	29,000	3	15,000	1
Latty Avenue Properties	MO	24,000	unavailable	0	0
Rocky Flats Environmental Technology Site	CO	20,000	86,000	0	0
Paducah Gaseous Diffusion Plant	KY	16,000	77	10,000	50
Edgemont Vicinity Properties	SD	15,000	unavailable	8,000	unavailable
Lawrence Livermore National Laboratory	CA	10,000	19,000	0	0
Mound Plant	OH	9,200	1,400,000	0	0
Oak Ridge National Laboratory	TN	7,400	130,000	240,000	4,300,000
Sandia National Laboratories/New Mexico	NM	3,300	9,300	0	0
Reactive Metals Incorporated, Ashtabula	OH	2,900	30	0	0
Grand Junction Projects Office	CO	780	unavailable	370	unavailable
Pantex Plant	TX	480	12	0	0
Pinellas Plant	FL	66	30,000	0	0
Kansas City Plant	MO	33	1	0	0
Sandia National Laboratories/California	CA	27	13	0	0
Nonweapons Sites	Various	0	0	98,000	26,000,000
	TOTAL	24,000,000	900,000,000	12,000,000	110,000,000

Notes:

(1) Data compiled from the Integrated Data Base (IDB) Report, Revision 11, September 1995; Mixed Waste Inventory Report (MWIR) Data System, October 1995; Environmental Restoration Core Database, May 1996; GAO/RCED-96-37; and Contaminated Media/Waste Database, 1993. (See Endnotes a, b, c, d, and e).

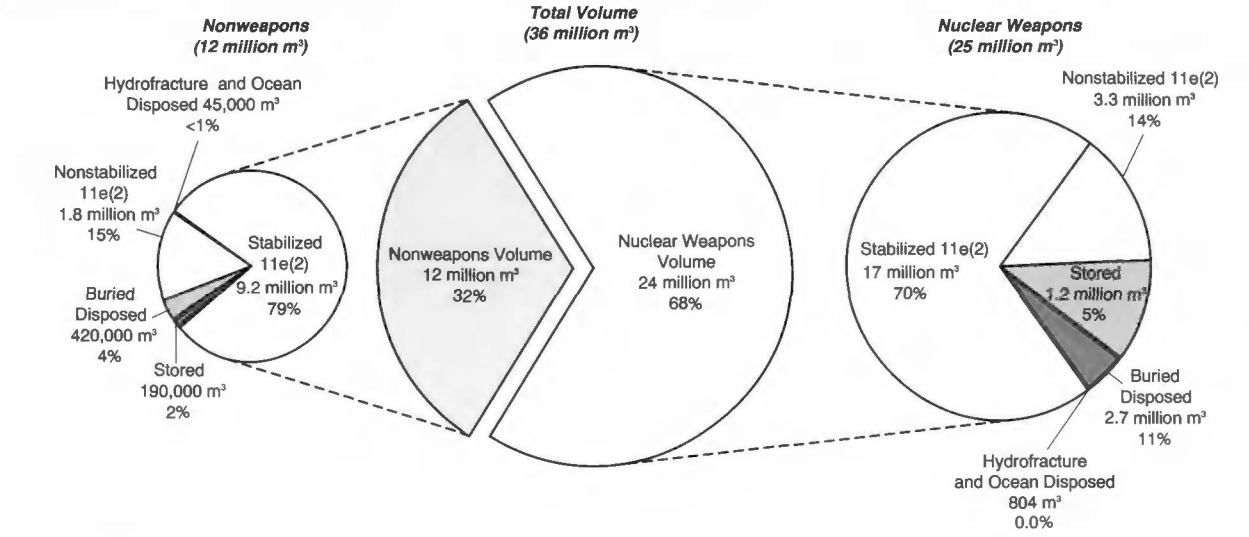
(2) Waste volumes are calculated subject to the limitations listed in Endnotes f, g, h, i, j, and k.

(3) Radioactivity content of waste is calculated subject to the limitations listed in Endnotes j, k, l, m, n, o, p, and q.

(4) Waste category assignments are made in accordance with the process explained in Endnote r.

(5) Nuclear weapons and nonweapons allocations and allocations to individual weapons production process categories are determined subject to the process set forth in Endnotes s, t, u, v, and w.

Figure 3-18. Waste Volume Categorized by Disposition



Notes:

(1) Data compiled from the Integrated Data Base (IDB) Report, Revision 11, September 1995; Mixed Waste Inventory Report (MWIR) Data System, October 1995; Environmental Restoration Core Database, May 1996; GAO/RCED-96-37; and Contaminated Media/Waste Database, 1993. (See Endnotes a, b, c, d, and e).

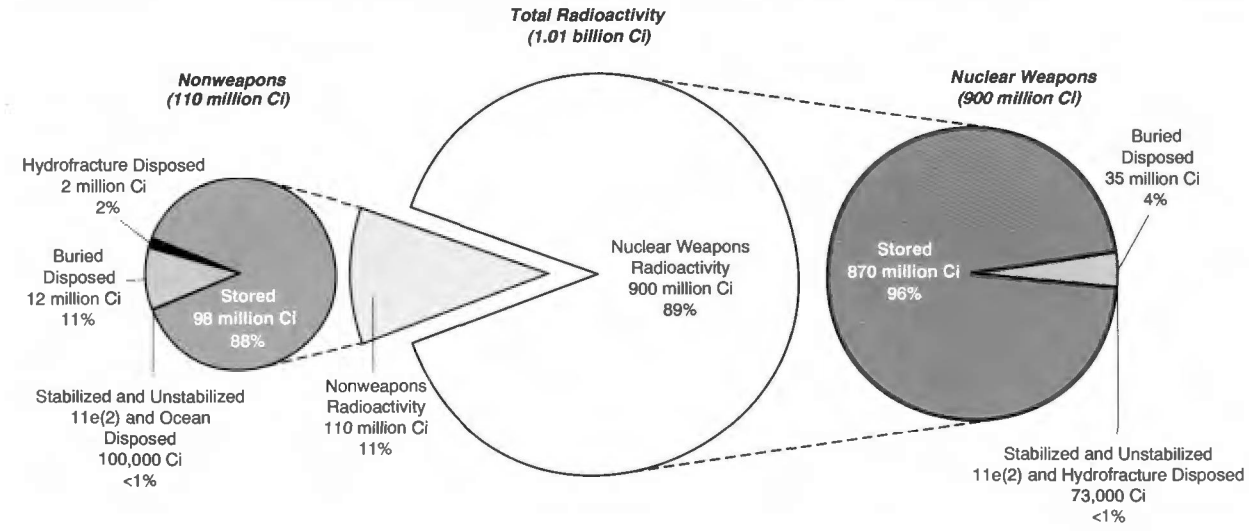
(2) Waste volumes are calculated subject to the limitations listed in Endnotes f, g, h, i, j, and k.

(3) Radioactivity content of waste is calculated subject to the limitations listed in Endnotes l, m, n, o, p, and q.

(4) Waste category assignments are made in accordance with the process explained in Endnote r.

(5) Nuclear weapons and nonweapons allocations and allocations to individual weapons production process categories are determined subject to the methods set forth in Endnotes t and u.

Figure 3-19. Waste Radioactivity Categorized by Disposition



Notes:

(1) Data compiled from the Integrated Data Base (IDB) Report, Revision 11, September 1995; Mixed Waste Inventory Report (MWIR) Data System, October 1995; Environmental Restoration Core Database, May 1996; GAO/RCED-96-37; and Contaminated Media/Waste Database, 1993. (See Endnotes a, b, c, d, and e).

(2) Waste volumes are calculated subject to the limitations listed in Endnotes f, g, h, i, j, and k.

(3) Radioactivity content of waste is calculated subject to the limitations listed in Endnotes l, m, n, o, p, and q.

(4) Waste category assignments are made in accordance with the process explained in Endnote r.

(5) Nuclear weapons and nonweapons allocations and allocations to individual weapons production process categories are determined subject to the methods set forth in Endnotes t and u.

Activities supporting the NNPP attributed for 24 percent. The remaining fifteen percent is attributed to nonweapons activities (8 percent); nuclear weapons production resulted primarily from chemical separation (3 percent), RD&T (2 percent), and fuel and target fabrication (2 percent).

The waste legacy from nuclear weapons production is found at 49 sites in 22 states (Table 3-8). The largest volumes are found in Colorado (35 percent), Utah (18 percent), New Mexico (12 percent), and Texas (12 percent). Nonweapons waste also is managed at 32 of the nuclear weapons sites and 30 additional sites. The sites where the largest waste legacy volumes are located are Falls City, Texas; Grand Junction, Colorado; and Rifle, Colorado. These sites were commercially-owned and -operated uranium mining and milling sites that were closed and later transferred to the Department for cleanup.

Overall, the waste legacy contains 1.01 billion curies. By radioactive content, 89 percent of the waste legacy is due to nuclear weapons production, less than 1 percent to activities supporting the NNPP, and 11 percent is attributed to other nonweapons programs (Figure 3-17). By radioactive content, 86 percent of the waste came from chemical separations for nuclear weapons production. The remaining 3 percent attributed to weapons production resulted primarily from RD&T (1.4 percent), and fuel and target fabrication (0.9 percent).

The largest amounts of radioactivity in the waste legacy are found at the DOE sites that performed chemical separation: 54 percent at Savannah River Site in South Carolina, 35 percent at Hanford site in Washington, seven percent at Idaho National Engineering Laboratory in Idaho and two percent West Valley Demonstration Project in New York. The radioactivity at West Valley Demonstration Project is attributed to nonweapons activities. (Table 3-8).

More than 81 percent of the waste volume has already been disposed or stabilized, and about 18 percent is in storage or is unstabilized (Figure 3-18). In contrast, approximately 96 percent of the radioactivity is contained in stored waste (Figure 3-19).

Methodology and Data

Data Sources

Data on the waste legacy were gathered primarily from previously compiled data sources; new data collection was limited to verifying existing data. The data were collected from the following sources:

- *Integrated Data Base Report – 1994: U.S. Spent Nuclear Fuel and Radioactive Waste Inventories, Projections, and Characteristics*, U.S. Department of Energy, DOE/RW-0006, Rev. 11, September 1995 ("1995 IDB"). The 1995 IDB was used as a basis for determining the volumes and radioactivity levels of all high-level waste, and much of the Department's TRU waste, low-level waste, mixed low-level waste, 11(e)2 byproduct material, and other waste. The IDB is updated annually.
- *1995 National Mixed Waste Inventory Report Data System* (electronic data), October 25, 1995 ("1995 MWIR"). This database was originally issued in a report in response to the Federal Facility Compliance Act, a 1992 amendment to RCRA that granted states the authority to enforce hazardous waste management regulations against federal agencies and required the Department to coordinate mixed waste treatment planning with the states. Since its creation, the database has been updated twice, in May 1994 and October 1995. MWIR data was used as a basis for determining the weapons process category or nonweapons activity for much mixed low-level waste, low-level waste, TRU waste, and high-level waste and was used as a source of some mixed low-level waste volume data not included in the IDB.
- *Uranium Mill Tailings Cleanup Continues but Future Costs are Uncertain*, (GAO/RCED-96-37), U.S. General Accounting Office, December 1995. The Department of Energy provided the data used in this report. It contains estimates of the quantities of 11e(2) byproduct material present at the 24 inactive uranium milling sites managed by DOE under UMTRCA Title I.

Methodology for Attributing Uranium Enrichment Waste

The uranium enrichment plants at K-25, Paducah, and Portsmouth were constructed and initially operated to produce enriched uranium for nuclear weapons. The plants produced highly enriched uranium for weapons components as well as low enriched uranium for use in plutonium production reactors. (Only Portsmouth and K-25 produced highly enriched uranium.) Beginning in the 1950s, small amounts of enriched uranium were used for other purposes such as naval propulsion reactors, research reactors, and nuclear power plants. In the 1960s, production of highly enriched uranium for nuclear weapons was discontinued and production shifted to serve other needs. During the 1970s and 1980s, the vast majority of the enrichment was conducted for commercial nuclear power reactors and smaller amounts were produced for naval reactors and research reactors.

Waste and contamination at the enrichment plants began to accumulate in the 1940s and 1950s and continued into the 1980s when the plants became subject to current environmental standards. However, some waste and contamination resulted from discrete activities over known time periods. Because most waste and contamination at the plants was the result of activities supporting many purposes, but the plants might never have existed if not for the weapons program, the portion of the uranium enrichment environmental legacy attributable to nuclear weapons production is difficult to calculate. Many factors should be considered, and there is no single "correct" approach. The allocation used in this report is only an estimate; it is similar to the approach developed to allocate the costs for decontamination and decommissioning of the plants.

Under this approach, waste or contaminated media that resulted from enrichment or plant support activities performed solely for nuclear weapons purposes are allocated entirely to weapons production. Waste and contamination resulting from activities performed for both nuclear weapons production and nonweapons purposes are divided, and a portion is allocated to each category. The allocation is based on two factors: the amount of separative work units used to enrich the uranium for each purpose (separative work units are a measure of plant output) and the timing of the activity. Timing is accounted for by attributing a larger portion of the waste and contamination legacy to the earlier years of plant operation. This is intended to account for the period during which plant operation is on a "learning curve" and may have more inadvertent waste generation and releases. It also recognizes that the cost to clean up initial waste and contamination is greatest, while the cost to clean up additional waste and contamination is only incremental. The "weighting" of waste and contamination to early operations is determined by assuming a "half-life" of seven years. The seven-year half-life approach allocates 50 percent of the contamination to the first seven years of plant operation, 25 percent to the next seven years, 12.5 percent to the next seven years, etc. (A seven-year period was selected for this analysis because it was the median value used as an example in the enrichment plant decontamination and decommissioning cost allocation study. Other half-life values would result in different allocations, but in most cases, most waste and media would still be allocated to nuclear weapons production.)

This allocation approach has some weaknesses. It considers the output over the entire operating life of the plant. In fact, releases resulting in incremental contamination decreased greatly during the 1980s as the plants became subject to current environmental regulations. Additionally, this approach does not take into account that some releases may have occurred or increased as facilities aged. The effect of incorporating these factors into the approach has not been determined, but they would tend to offset each other. Another weakness of the approach is that some waste or contamination resulted from discrete releases rather than releases over the life of the plant.

While the allocation used in this report has a reasonable basis and is adequate for this analysis, it is only an estimate. Further study or more refined assumptions could improve its accuracy.

- *Environmental Restoration Core Database,* U.S. Department of Energy, revised May 1996 (Core Database). The Department uses this database as an internal management tool. The database contains information on the quantity and composition of stored waste managed by the Office of Environmental Restoration. It also contains information on facility deactivation and decommissioning activities conducted by the Office of Environmental Restoration.

In addition to these sources, some data on the radioactive content of 11e(2) byproduct material at some sites was compiled from DOE's Environmental Restoration Contaminated Media/Waste Database, a precursor to the Core Database currently used to monitor activities in the Environmental Restoration program. To supplement and verify the data from these sources, several other sources were used. However, the 1995 IDB, the MWIR, and Core Database were the primary data sources.

Data Issues and Assumptions

The primary data sources for waste are the IDB, Rev. 11, September 1995; the MWIR, October 1995; the Environmental Restoration Core Database, May 1996; a GAO report on the UMTRA Project (GAO/RCED-96-37), December 1995; and the Environmental Restoration Contaminated Media/Waste Database.

Some volumes of disposed waste are also counted as environmental media. Waste not managed by DOE, including tailings at UMTRCA Title II sites and disposed waste at Maxey Flats, has not been included in the analysis. Remediation waste classified as sanitary, demolition debris, or "NA" also is excluded.

Much of the radioactivity in waste containing relatively low levels of radioactivity was not included in the curie inventory. This waste includes most environmental restoration waste, and some stored low-level waste, mixed low-level waste, 11e(2) byproduct material, and "other" waste. Furthermore, only certain radionuclides have been included for TRU waste and 11e(2) byproduct material. Radioactive decay in disposed TRU waste has not been accounted for. Remote-handled TRU waste mixed with contact-handled mixed waste is classified as remote-handled.

Allocations of high-level waste to nuclear weapons programs are based on the eventual use of the products resulting from the reprocessing.

Allocations of mixed low-level waste, TRU waste, and low-level waste at multipurpose sites production are based on, or extrapolated from, waste stream descriptions in the MWIR.

Allocations of waste from uranium milling and enrichment are estimated based on the various uses of the uranium products. Ocean-disposed waste is assumed to have resulted from nonweapons activities.

Limitations, Uncertainties, and Assumptions

Several important gaps are present in the waste data sources that are currently available. In some cases, these data exist, but the Department has not compiled them in a uniform format at a national level. In other cases, the data have not yet been developed. To fill some of the data gaps, reasonable assumptions were made where possible. In some cases, the quality of data was inadequate even for reasonable assumptions. No attempt was made to quantify such portions of the waste legacy. The assumptions were made in four general areas:

• *Waste Categories* – Criteria used by the Department to categorize waste today are different from criteria used in the past. As criteria changed, the Department and its predecessors recharacterized disposed and stored waste according to the new criteria in only a limited number of cases. In this analysis, the Department classified waste according to how the waste is counted in existing inventory data. That is, no collection or reevaluation of detailed waste characterization data were attempted. For some of these wastes, data on the presence of hazardous constituents are incomplete, and data on the concentrations of TRU radionuclides are often not sufficient to determine whether the total TRU concentration is above or below the current 100 nanocurie per gram threshold. The inventory amounts of stored waste also do not always recognize that some containers are partially empty, and some remote-handled TRU waste is stored in containers combined with contact-handled waste (rendering the entire container remote-handled). Because of the relatively large volume of TRU and low-level waste categorized according to old criteria, the volume of waste that could fall under another category under current categorization criteria also could be large and could affect the results of this analysis.

• *Radioactive Content of Waste* – Data on the radioactive content of much TRU waste, low-level waste, 11e(2) byproduct material, mixed low-level waste, and other waste are incomplete. For TRU waste, some radioactivity data did not take into account radionuclide decay or included only certain isotopes. The radioactive content of some waste, including some low-level waste, mixed low-level waste, and other waste, was not available and was estimated on a site-by-site basis using data on the radioactive content of other low-level waste at the sites. Where comparative data on the radioactive content were not available, the radioactive content of the waste was set at zero. The radioactive content of environmental restoration waste was not estimated except for mill tailings and certain other 11e(2) byproduct materials. For these materials, only data on the radium-226 present was available. Because the vast majority of radionuclides in DOE-managed waste are found in high-level waste, the concentrations assigned to waste in the other categories are relatively small and these assumptions did not significantly affect the results of the analysis.

• *Nuclear Weapons Production Process Categories and Nonweapons Activities* – Only limited data were available to determine whether a given waste was the result of weapons production, NNPP

Waste Isolation Pilot Plant. In southwestern New Mexico, DOE has dug a waste repository deep into a 200-million-year-old rock salt formation. Chambers 2,150 feet below the surface will store transuranic waste from chemical separations, pit manufacturing, and plutonium recycling if the Environmental Protection Agency approves disposal in this repository. *WIPP Site, near Carlsbad, New Mexico. February 25, 1994.*

support, or other DOE activities and, if appropriate, to determine the nuclear weapons production process category responsible for waste generation. The key information used to make weapons-nonweapons determinations and to determine which nuclear weapons production process category resulted in the generation of waste was the historical mission of each site where waste was generated. Since most sites performed activities in only a single process category or a few process categories, information on the site's mission was often adequate to determine, with reasonable certainty, how the waste was generated. However, for those sites performing more than one activity (e.g., Hanford, Savannah River Site, and Y-12 Plant), a more detailed analysis was performed that considered other available information, including the location or building in which the waste was generated and the presence of certain signature chemical and radioactive contaminants, from which information on the waste generating process was inferred. For waste at some sites such as Idaho National Engineering Laboratory and Oak Ridge National Laboratory, a generic sitewide allocation was used. At Idaho National Engineering Laboratory, it was assumed that 75 percent of the low-level waste was from nonweapons activities and at Oak Ridge National Laboratory, 97 percent of the waste was assumed to result from nonweapons activities. Special assumptions were made for waste generated at the uranium mill sites and uranium enrichment sites to attribute the waste to weapons production and nonweapons activities. The same estimate of waste was made for all uranium milling, refining and enrichment sites based on how the uranium products from these sites were used. It was assumed that all low-level waste that was disposed at sea resulted from nonweapons activities.

- *Disposed Waste also Counted as Contaminated Environmental Media* – Some volumes of low-level waste and TRU waste disposed of years ago and the soils that surrounded them are now being assessed under the Department's Environmental Restoration Program. Double-counted materials include much of the disposed TRU waste at Idaho National Engineering Laboratory; low-level waste at

Hanford, Savannah River Site, Fernald Environmental Management Project, Los Alamos National Laboratories and Y-12 Plant; and smaller amounts of waste at other sites. DOE sites maintain information on the amounts of material that have been double-counted, but these data have not been compiled on a nationwide basis. The double-counted materials are further described in Chapter 4 (Contaminated Environmental Media). While much of the low-level and TRU waste historically disposed of at DOE sites is being assessed under the environmental restoration program, this material and the surrounding contaminated environmental media associated with the disposal sites make up only a small portion of all contaminated environmental media being assessed by the Environmental Restoration Program.

Information on these and other assumptions, data sources used in cataloging the waste legacy, and other data issues is presented in the endnotes to this chapter, and is summarized here.

Summary

The Department of Energy's waste legacy includes seven fundamental waste categories: high-level waste, TRU waste, low-level waste, mixed low-level waste, 11e(2) byproduct material, hazardous waste, and "other" waste. The waste legacy was generated at numerous sites throughout the complex, primarily at DOE sites. While much of the waste legacy volume has been disposed of or stabilized, much of the radioactivity still must be addressed. Most of the radioactivity in the waste legacy is in the high-level waste from chemical separation and is managed by the Office of Waste Management. The Office of Environmental Restoration manages most of the waste volume in the form of 11e(2) byproduct material from uranium mining and milling.

Much more is known about the waste legacy than the other legacy elements because the quality of data available to quantify the waste legacy are better than those available to quantify other legacy elements. However, there is uncertainty about the characteristics of waste disposed of many years ago.

Endnotes

a. *Integrated Data Base Report—1994: U.S. Spent Nuclear Fuel and Radioactive Waste Inventories, Projections, and Characteristics* (IDB), Rev.11 (DOE/RW-0006), was used as a source for volume data for high level waste, TRU waste, low-level waste, radioactive PCB waste, and some mixed low-level waste managed by the Office of Waste Management, and radioactivity content data for high level waste, TRU waste, and low-level waste managed by the Office of Waste Management. Data on the volume and activity content of stored and disposed low-level waste was compiled from backup tables for the IDB. The current volume and radioactivity content of waste at most sites has changed, in some cases substantially, since these data were compiled but the total amount across all sites has not changed appreciably.

b. *1995 National Mixed Waste Inventory Report System* (electronic data), October 1995, was used as a source for volume data for some mixed low-level waste.

c. Environmental Restoration Core Database, updated as of May 1996, was used as a source for volume data of TRU waste, low-level waste, radioactive PCB waste, mixed low-level waste, non-UMTRA 11e(2) byproduct material, and mixed 11e(2) byproduct material managed by the Office of Environmental Restoration, and radioactivity content data for some UMTRA Project 11e(2) mill tailings. The volume and waste type data were provided to the Core Database from DOE sites and other field locations. These data are subject to revision as data on environmental restoration wastes continue to be compiled.

d. *Uranium Mill Tailings Cleanup Continues, but Future Costs Are Uncertain* (GAO/RCED-96-37) was used as a source for volume data of 11e(2) byproduct material at UMTRA sites. (The Environmental Restoration Core Database, has been revised to include these data.)

e. Office of Environmental Restoration Contaminated Media/Waste Database was used as a source for radioactivity content of 11e(2) mill tailings at the Monument Valley and Shiprock UMTRA sites, the Monticello Mill Site, and the Grand Junction Project Office Site. (The Environmental Restoration Core Database has been revised to include these data.)

f. Stored TRU waste volume data, as compiled in the IDB, measures the total volume of waste packages, not the volume of waste inside the packages. The difference between package volumes and waste volumes is small compared to the total volume of stored TRU waste.

g. Waste volumes do not include 11e(2) byproduct material at UMTRCA Title II commercial mill tailing sites. Waste resulting from weapons production activities is located at these sites, but the sites and waste are not managed by DOE.

h. Some volumes of historically disposed TRU and low-level waste are double-counted as both waste and contaminated environmental media. The waste volumes come from the IDB and correspond to records on the volume of waste buried; the media volumes (in Chapter 4) come from the Environmental Restoration Core Database. The media volumes are estimates of the amount of contaminated material associated with the buried waste.

i. Waste volumes from the Environmental Restoration Core Database that are classified as sanitary, demolition debris, or "NA" are not included because they do not require special management due to their chemical and radiological content.

j. The volume of low-level waste disposed at sea is estimated based on the approximate number of containers and the assumption that all containers were 55-gallon drums.

k. Waste volume figures are rounded. Because of rounding, some numbers may not appear to add correctly.

l. Radioactivity in waste from environmental restoration activities is not included except for the radium-226 content of mill tailings at UMTRA Project sites and K-65 residues at Fernald Environmental Management Project and Niagara Falls Storage Site. (K-65 residues are a specific type of 11e(2) byproduct material.)

m. Some TRU waste packages classified as remote handled contain a mixture of contact-handled and remote-handled waste. Separating such waste into contact- and remote-handled inventories would reduce the amount of remote-handled waste and increase the volume of contact-handled waste.

n. Radioactivity in disposed TRU waste, as compiled in the Integrated Data Base (IDB), does not include buried TRU at Los Alamos National Laboratories and includes the undecayed amount (i.e., amount prior to disposal) of curies in buried TRU at Idaho National Engineering Laboratory, Oak Ridge National Laboratory, and West Valley Demonstration Project. The radioactivity of TRU waste disposed by hydrofracture at Oak Ridge National Laboratory also is undecayed. The current amount of radioactivity in these wastes is less than the undecayed amount reported.

o. Stored TRU waste radioactivity data, as compiled in the IDB, includes selected isotopes which comprise over 99 percent of the radioactivity. Isotope data for contact-handled TRU waste include uranium-238, -235, and -233; plutonium-239, -240, and -242; and thorium-230. Isotope data for remote-handled TRU waste includes strontium-90; yttrium-90; cesium-137; barium-137; europium-152, -154, and -155; cobalt-60; plutonium-241; and curium-244. Other radioisotopes also are present.

p. Radioactivity content of stored mixed low-level waste and some stored low-level waste managed by the Office of Waste Management are extrapolated from other low-level waste radioactivity content data in the IDB. The radioactivity content of some low-level and waste mixed low-level waste is not included where it could not be extrapolated from other site-specific data.

q. Waste radioactivity inventory values are rounded. Because of rounding, some numbers may not appear to add correctly.

r. Waste categorized as high-level waste includes both mixed high-level waste (i.e., high-level waste that contains a hazardous component subject to RCRA) and non-mixed high-level waste. The TRU waste category includes mixed TRU waste, TRU waste containing polychlorinated biphenyls, and TRU waste whose nonradioactive component is not hazardous. Low-level waste containing asbestos or PCBs is categorized as "other" waste, unless there is a hazardous component present in the waste regulated under RCRA. Material at UMTRA Project sites defined as residual radioactive material under Title I of the Uranium Mill Tailings Radiation Control Act of 1978 has the same physical and chemical properties as 11e(2) byproduct material and is categorized as 11e(2) byproduct material. 11e(2) byproduct material that has been mixed with a RCRA-regulated hazardous waste (mixed 11e(2) byproduct material) is categorized as "other" waste.

s. For high-level waste resulting from fuel reprocessing, allocations are based on the eventual use of the products of reprocessing. For example, high-level waste resulting from reprocessing spent Naval fuel to recycle highly enriched uranium for weapons production is allocated to weapons production. For other waste managed as high-level waste, allocations are based on the process (e.g., decontamination) that generated the waste.

t. For TRU waste, low-level waste, mixed low-level waste, and "other" waste, allocations are based on the mission of the site where the waste was generated. For some multiple purpose sites, allocations of TRU waste and mixed low-level waste are based on waste stream descriptions in the MWIR Data System. Allocations of low-level waste and "other" waste are extrapolated from mixed low-level waste allocations. For much waste at Idaho National Engineering Laboratory and Oak Ridge National Laboratory, generic allocations were applied based on the approximate level of historical activities at the sites. For low-level waste at Idaho National Engineering Laboratory, 25 percent of the waste is attributed to nuclear weapons production and 75 percent is attributed to nonweapons activities. For TRU and low-level waste at Oak Ridge National Laboratory, 3 percent of the waste was attributed to nuclear weapons production and 97 percent to nonweapons activities.

u. Waste at uranium enrichment sites is allocated according to the amounts of enriched uranium produced for various purposes (nuclear weapons program, naval reactor fuel, research reactors, commercial reactors), as measured by separative work units, and taking into account when uranium was enriched. The allocation does not take into account that some uranium was recycled for other purposes. (For example, some uranium initially used as Naval fuel was recycled for weapons production.) Historic records may also be available that would allow waste to be allocated based on the specific causes of waste generation. (The amount of waste generated from uranium enrichment and attributed to supporting the NNPP is managed by DOE at the sites where it was generated, stored, and disposed. The NNPP did not generate or manage this waste.)

v. 11e(2) byproduct material at mill tailings sites is allocated according to how much uranium was used, overall, for various purposes (nuclear weapons program, naval reactor fuel, research reactors, commercial reactors), taking into account all Atomic Energy Commission uranium purchases (including uranium purchases from sites where DOE is responsible for remediation, other U.S. mill tailing sites, and foreign mill tailing sites). The same allocation is applied to all mill tailing sites, regardless of when they operated. This allocation does not take into account that some uranium was recycled for other purposes or that uranium produced at different times at certain sites may have been directed to specific weapons or nonweapons programs. (The amount of waste generated from uranium mining and milling and attributed to supporting the NNPP is managed by DOE at the sites where it was generated, stored, and disposed. The NNPP did not generate or manage this waste.)

w. Waste disposed at sea is assumed to have resulted from nonweapons activities. Ocean disposal has been discontinued.

4. Contaminated Environmental Media

Plant 9 exhaust stack. This exhaust stack was used to control emissions from the Fernald's Plant 9 facility, which processed enriched uranium materials. The malfunctioning of systems like this resulted in releases of several hundred tons of uranium dust to the environment outside the plant buildings over the course of three decades of operations. *Fernald Plant, Ohio. December 30, 1993.*

Overview

Hazardous and radioactive substances from nuclear weapons production, research, development, and testing activities and other Department of Energy (DOE) nuclear and nonnuclear programs have contaminated environmental media (including soil, sediment, groundwater, and surface water) on and around DOE sites. Some waste streams were discharged to the environment with or without prior treatment. These include relatively small, localized releases that may have resulted from accidents; larger planned releases of process effluents; and releases on a much larger scale, such as atmospheric fallout from nuclear weapons tests. In other cases, containment systems such as tanks, drums, or landfills lost their integrity and waste leaked into adjacent soil and water. Contaminated media also resulted from spills and other inadvertent releases during process operations or maintenance.

Contaminated environmental media are primarily water and solids (including soils). Nuclear weapons production activities have resulted in a legacy of 1,500 million cubic meters of contaminated water and 73 million cubic meters of contaminated solid media. Nonweapons activities by the Department and its predecessor agencies have contaminated an additional 350 million cubic meters of water and 5.8 million cubic meters of solid media.

In some cases, a single activity that was performed for both the nuclear weapons and nonweapons programs contaminated environmental media. For example, the same facilities simultaneously enriched

Key Observations of the Contaminated Media Legacy

- The Department of Energy manages about 79 million cubic meters of contaminated solid media (73 million cubic meters from weapons production and about 5.8 million cubic meters from nonweapons activities) and about 1,800 million cubic meters of contaminated water (1,500 million cubic meters from weapons production and 350 million cubic meters from nonweapons activities). Most of the solids are soil and most of the water is groundwater.
- The total of about 1,900 million cubic meters of contaminated media is approximately 50 times larger in volume than the Department's 36 million cubic meters of waste; however, groundwater constitutes approximately 96 percent of the media legacy. The management requirements and options for water differ significantly from those for solid media and waste.
- Contaminated environmental media from nuclear weapons activities are located at 64 DOE environmental management sites in 25 states, including contaminated water at 39 sites and contaminated solids at 40 sites. Contaminated media from nonweapons activities are located at 37 of these sites. Contaminated media from nonweapons activities only are located at an additional 32 sites.
- The Department is assessing the presence of contaminated media or waste at about 9,900 release sites and other units. Work at 2,800 of these sites is complete as of 1996.
- The contaminated media element includes different types of contamination, including widespread but diffuse groundwater and soil contamination and atmospheric fallout, some of which are not included quantitatively in this report. Remediation decisions have not yet been made for some of this contamination. In other cases, remediation is either unnecessary or impractical.

uranium for nuclear weapons, the Naval Nuclear Propulsion Program (NNPP), and commercial nuclear power reactors. The amounts of contaminated environmental media resulting from these multipurpose activities were apportioned in this analysis to determine the volumes attributable to nuclear weapons and nonweapons activities. The methodology section of this chapter lists the data sources and documents the process used to determine the volume, characteristics, and sources of the media legacy.

The Department of Energy is now remediating contaminated environmental media through treatment, removal, and containment-oriented actions. Treatment may remove contaminants from the media or immobilize contaminants within it. In some cases, the media themselves are removed from the environment and treated or stored before final disposal. Given current resources, technology, and priorities, however, the treated media often cannot be returned to the original conditions. If contaminant concentrations and risks are low and regulators concur, DOE often decides not to treat contaminated media. Instead, protection is provided by monitoring contaminant movement and reducing or preventing human exposure through containment or institutional controls. The text box provides observations on the legacy of contaminated environmental media resulting from the activity of DOE and its predecessor agencies.

Definitions and Categories

Contaminated Environmental Media

Contaminated environmental media are naturally occurring materials such as soil, sediment, surface water, groundwater, and other in-place materials (e.g., sludge and rubble/debris that have been disposed of and/or are intermixed with soil) that are contaminated at levels requiring further assessment to determine whether an environmental restoration action is warranted. Contaminated environmental media do not include materials being managed as waste under the Department's Environmental Restoration Program, such as mill tailings, stored waste that have not been disposed of, and waste already sent to commercial facilities or managed under the Department's Waste Management Program. Also excluded are materials that may have economic value, standing structures and equipment, sanitary waste, or construction/demolition debris.

Materials that were previously disposed of but are currently in the Environmental Restoration Program for further assessment with regard to long-term disposition are considered contaminated media. This

status continues unless or until the material is removed, at which time it would be managed as waste.[1] Some waste is very similar to environmental media. For example, 11e(2) byproduct material at a uranium milling site is considered waste; similar material at a non-mill tailing site is considered waste if it is stored but is considered environmental media if it is in place.

The legacy of contaminated environmental media includes media that the Department is managing or is likely to manage actively in the future as well as some media for which no further action is expected. It includes both contaminated media within current DOE site boundaries and some media outside of site boundaries (see text box "Offsite Contamination around DOE Sites").

The Department's Environmental Restoration Core Database maintains most of the information on contaminated media volume used in this report. This database includes data on all contaminated environmental media within the scope of the current Environmental Restoration Program. However, there are additional contaminated media outside the scope of this program, such as areas for which remedial actions have been determined to be unnecessary or infeasible. The Core Database does not include information for such areas. The Department has obtained estimated volumes for most of this category of contaminated environmental media from other sources, but some of the media remain unquantified.

An air-monitoring station at the Fernald plant boundary measures airborne radioactivity exiting the plant property.
Fernald Plant, Ohio. December 29, 1993.

[1] *The Waste Management Program and the Environmental Restoration Program track some materials at waste disposal sites that have been closed and are in line for assessment. This report includes these materials as waste (Chapter 3) and contaminated media (Chapter 4). The Waste Management Program tracks the volume and radioactivity of disposed waste, while Environmental Restoration Program estimates the total volume requiring assessment. (The volume of material to be assessed is typically larger than the disposed waste volume.) Thus, some of these materials are double-counted in this report. The largest volumes of double-counted material include disposed transuranic waste at INEL and disposed low-level waste at Hanford Site, SRS, FEMP, LANL, and Y-12 Plant. Although the exact amount is not known, the double-counted materials constitute no more than a few percent of the contaminated media legacy.*

Equalization pond. *Weldon Spring Quarry, near the Weldon Spring Site, St. Charles County, Missouri. January 29, 1994.*

Categorization and Quantification of Contaminated Environmental Media

In this report, contaminated environmental media are quantified in two ways—by the volume of media and by the number of release sites and other units where contamination is potentially present. Each measure provides a different perspective on the contaminated environmental media legacy.

Offsite Contamination around DOE Sites

Environmental media outside of the boundaries of several DOE sites have been contaminated as a result of onsite activities. At DOE's Paducah Gaseous Diffusion Plant in Kentucky, for example, groundwater has become contaminated by technetium-99, a long-lived radioisotope present in uranium recovered from reprocessed spent fuel, and trichloroethylene, a hazardous cleaning solvent that was once commonly used at the site. The contamination resulted from leaks, waste disposal, and discharges that occurred onsite many years ago. Over time, the contaminants infiltrated to groundwater that flowed northward under the site. After the contaminants reached the groundwater, they began to gradually disperse until several large plumes of contaminated groundwater had formed. DOE has been investigating the contamination for several years to identify the sources and has begun interim removal of the contaminants and control of the groundwater plumes. Until a final decision on remediation of the contamination is reached and implemented, DOE is providing an alternative water supply to the public where the groundwater contamination has reached hazardous levels.

Other sites known to have offsite contaminated media include Fernald, Hanford, Kansas City Plant, Los Alamos National Laboratory, Brookhaven National Laboratory, Lawrence Livermore National Laboratory, Mound, Oak Ridge National Laboratory, Pantex Plant, Rocky Flats Environmental Technology Site, the Savannah River Site, and the Oak Ridge Y-12 Plant.

Media Volume

When measured by volume, contaminated media are categorized according to physical matrix and type of contamination. These two factors, together with site-specific conditions, determine management requirements and alternatives. There are two major categories of physical matrices: water and solid media. Within these two broad categories, the Department tracks 27 specific physical matrices of media as shown in Table 4-1. The vast majority of the Department's contaminated environmental media fall into the categories of groundwater and soil.

A broad range of contaminants is present in media, but they can generally be categorized as radioactive or hazardous.[2] Some media are contaminated by both radioactive and hazardous constituents while others contain only one type of contamination.

Improving waste management to prevent future contamination. Since 1951, more than 200 million gallons of slightly radioactive water from Hanford's high-level waste tanks were routinely discharged into the soil. Such discharges contributed to Hanford's extensive soil and groundwater contamination. To limit further contamination, Hanford began treating this type of wastewater in April 1994 to remove radionuclides and chemicals before discharging it. Prior to treatment, wastewater is stored in these three 6.5 million gallon, double-lined basins with floating covers and a leachate collection system. *Liquid Effluent Storage Facility, 200 Area, Hanford Site, Washington. July 12, 1994.*

Release Sites and Other Units

This report quantifies contaminated media according to five different types of units where contamination is potentially present: (1) release sites; (2) FUSRAP sites; (3) UMTRA surface contamination sites; (4) UMTRA groundwater contamination sites; and (5) facilities.

A release site is a unique location at which a hazardous, radioactive, or mixed waste release has or is suspected to have occurred. A release site is usually associated with an area where waste or substances contaminated with waste have been disposed of, treated, stored, or used. Under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), release sites include both source areas and areas of migration where hazardous and/or radioactive substances have come to be located. A release site typically includes the actual geographic area covered by a source and the extent of

[2] *Although they are not "hazardous" under RCRA, asbestos, and PCBs are considered in the "hazardous" contaminants in this chapter.*

associated contamination as delineated during the characterization process. It may include areas in very close proximity to the contamination that are necessary for implementing a response action. Release sites may include corrective action units, solid waste management units, areas of concern, or other unit categorizations applied under CERCLA or the Resource Conservation and Recovery Act corrective action process. Within this definition, DOE sites may adopt their own site-specific counting methods. There are usually many release sites at an individual DOE site.

FUSRAP and UMTRA manage FUSRAP sites, UMTRA surface contamination sites, and UMTRA groundwater contamination sites. Unlike most DOE sites at which several or many release sites are located, each site in the FUSRAP program is counted as a single site, and each site in the UMTRA Project is counted as one UMTRA surface contamination site and one UMTRA groundwater contamination site (although assessment of the Lowman, Idaho, UMTRA site has determined there is no groundwater contamination at the site).

The final unit is the facility. Although facilities are addressed in Chapter 5, in some cases the contaminated media present around or underneath a facility are considered part of the facility and are not counted as a release site or FUSRAP or UMTRA site. Facilities are included to provide a more complete estimate of the number of units encompassed by this element. (Table 4-2).

Table 4-1. Physical Matrices of Contaminated Media

Water	Solid Media*	
Groundwater**	Asbestos	Rubble/Debris
Liquid	Asphalt	Salts
Surface Water	Concrete/Brick	Sediment
Wastewater	Gas	Sludge
	Metal	Soil**
	Paper/Cloth	Wood
	Residues	Other Solid

* *No inventories are currently assigned to the following subcategories, which are also included in the solid media category: absorbent, compost, filters, kao/wool, personnel protective equipment/filters, resins, solid chemical, solvents/oils, and vapor.*

** *Soil and groundwater comprise 99% of the total volume of contaminated environmental media in the DOE Environmental Management Program.*

Table 4-2. Release Sites and Other Units

Type of Unit	Number of Units
Release Sites	8,727
FUSRAP Sites	46
UMTRA Surface	24
UMTRA Groundwater	24
Facilities	1,077
TOTAL	9,898

The total legacy of contaminated environmental media managed by the Department of Energy includes approximately 7,200 units resulting from nuclear weapons production and 2,700 units from nonweapons activities. Contaminated media are not known to be present at all these units. In some cases only waste is present.

Results

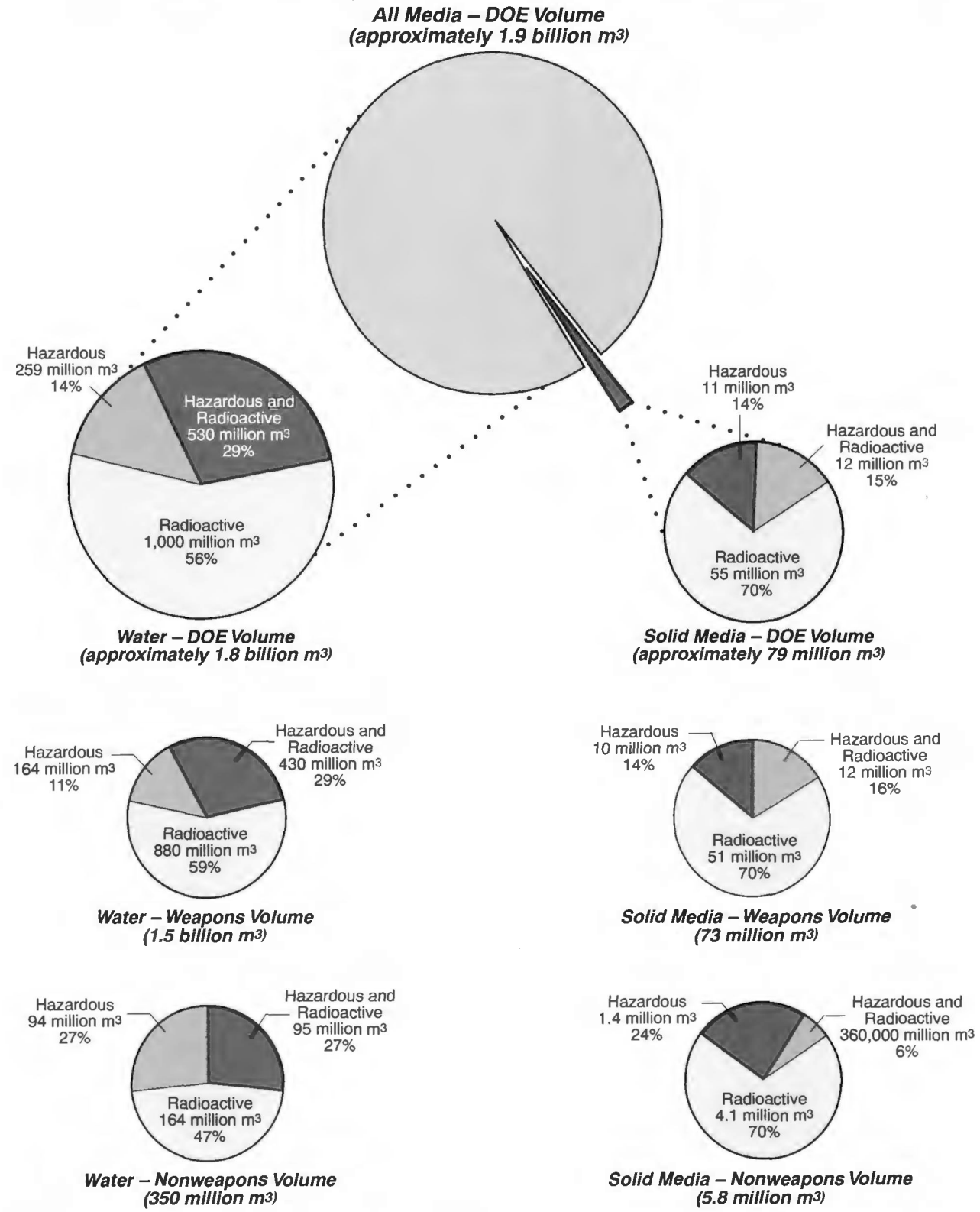
The results in this chapter include a quantitative analysis of the source, composition, and locations of the contaminated environmental media by both volume and number of release sites and other units. This information was obtained from the Department's Environmental Restoration Core Database and was supplemented by information from other sources.

Volume of Water and Solid Media

Figure 4-1 presents the relative volumes of the two major categories of contaminated environmental media that have been quantified. The volume of contaminated water (1,800 million cubic meters) is about twenty-three times the amount of the contaminated solid media (79 million cubic meters).

The contaminated environmental media from nuclear weapons production contains hazardous and radioactive constituents (Table 4-3) .

Figure 4-1. Composition of Contaminated Media



Notes:

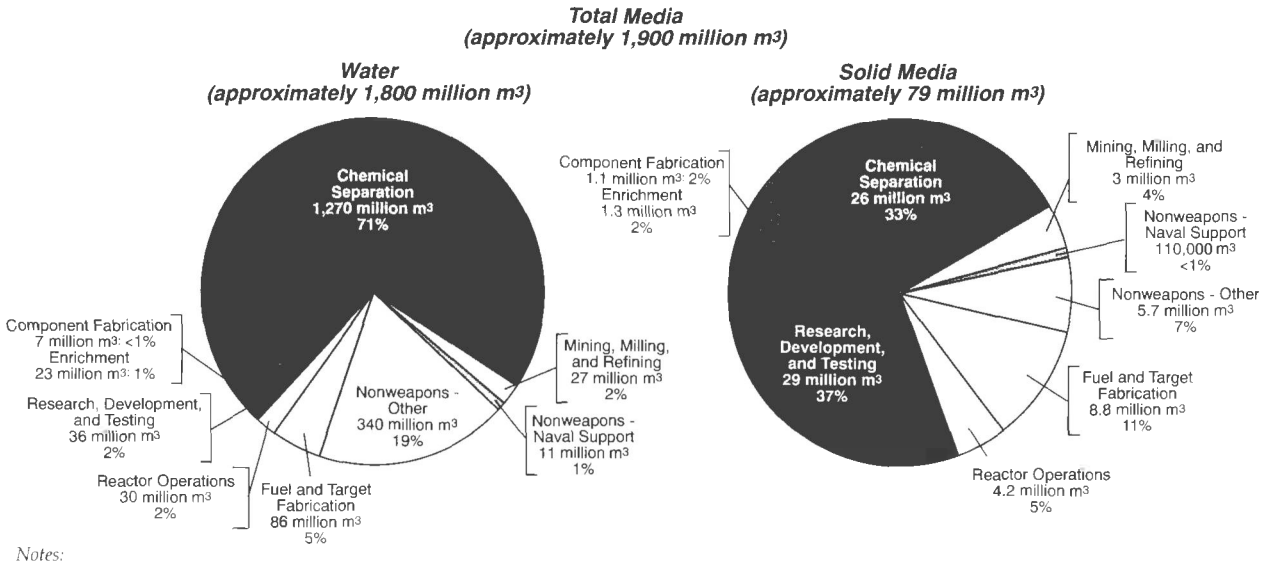
(1) Data compiled from the Environmental Restoration Core Database, May 1996.

(2) Media volume calculations subject to Endnotes a, b, and c.

(3) Weapons allocations are subject to Endnotes e, f, and g.

(4) Includes approximately 1,500 million cubic meters of water and 15 million cubic meters of solid media outside the scope of the current DOE Environmental Restoration Program.

Figure 4-2. Contaminated Environmental Media Categorized by Process



Notes:
(1) Data compiled from the Environmental Restoration Core Database, May 1996.
(2) Media volume calculations subject to Endnotes a, b, and c.
(3) Nuclear weapons allocations are subject to Endnotes e, f, and g.
(4) Includes approximately 1,500 million cubic meters of water and 15 million cubic meters of solid media outside the scope of the Environmental Restoration Program.

Table 4-3. Categorization of Contaminated Media

Category	Volume	Includes:
Hazardous[b]	Liquid: 164 million m^3 Solid: 10 million m^3	Asbestos[a] RCRA Hazardous PCB
Radioactive	Liquid: 880 million m^3 Solid: 51 million m^3	11e(2) Byproduct Material LLW
Radioactive and Hazardous[c]	Liquid: 430 million m^3 Solid: 12 million m^3	TRU MLLW Radioactive Asbestos Radioactive PCB
Neither Radioactive nor Hazardous	Excluded from analysis[c]	Mixed TRU Demolition Sanitary Not Applicable

[a] *"Waste type" as assigned in the Environmental Restoration Core Database.*
[b] *Although they are not "hazardous" under RCRA, asbestos and PCBs are included in these categories.*
[c] *These materials are excluded because they can be managed without special consideration of their hazardous or radioactive characteristics.*

About 84 percent of the water and 91 percent of the solid media were contaminated by weapons production (Figure 4-1). The weapons production process categories that resulted in the most contaminated media are chemical separation (71 percent of the water and 33 percent of the solid media); fuel and target fabrication (5 percent of the water and 11 percent of the solid media); and research, development, and testing (2 percent of the water and 37 percent of the solid media) (Figure 4-2). No contaminated media are attributed to weapons operations.[3]

Contaminated media attributed to nonweapons activities come from a wide range of sources; only a small amount is attributed to support for the Naval Nuclear Propulsion Program (NNPP). (None of the contaminated environmental media volume attributed to supporting the NNPP resulted from operations conducted by or under the purview of the NNPP. Instead, these media resulted from activities managed by other DOE programs.)

Contaminated media from nuclear weapons production are located at 64 environmental management sites in 25 states (Tables 4-4 and 4-5). Sites and states with the largest amounts of contaminated environmental media are Hanford in Washington (1,200 million cubic meters of contaminated water and 20

[3] *While there is evidence of explosive contamination in perched groundwater at Pantex, it is believed to be the result of the site's use as a conventional munitions factory during World War II.*

million cubic meters of contaminated solid media) and the Savannah River Site in South Carolina (200 million cubic meters of contaminated water and 19 million cubic meters of contaminated solid media). Other states with large amounts of contaminated media from nuclear weapons production include California (25 million cubic meters of contaminated water at two sites, primarily at Lawrence Livermore National Laboratory), Kentucky (19 million cubic meters of water at Paducah), New Mexico (10 million cubic meters of solid media at two sites, primarily at Lawrence Livermore), and Colorado (14 million cubic meters of contaminated water at nine sites).[4]

Table 4-4. Contaminated Solid Media Resulting from Weapons Production

Sites	Nuclear Weapons Volume (m^3)	Nonweapons Volume (m^3)	Total
Amchitka Island (AK)	4,600	2,300	6,900
Ashland 1 (NY)	92,000		92,000
Ashland 2 (NY)	40,000		40,000
B&T Metals (OH)	1,700		1,700
Central Nevada Test Site (CNTS) (NV)	6,100		6,100
DuPont (NJ)	6,300		6,300
Fernald (OH)	2,100,000		2,100,000
Hanford (WA)	20,400,000	3,200,000	23,600,000
Idaho National Engineering Site (ID)	510,000	210,000	720,000
K-25 Site (TN)	5,500	2,800	8,300
Kansas City Plant (MO)	28,000		28,000
Kauai Test Facility (HI)	1,400		1,400
Latty Avenue Properties (MO)	140,000		140,000
Lawrence Livermore National Laboratory - Main Site (CA)	2,200,000		2,200,000
Lawrence Livermore National Laboratory - Site 300 (CA)	12,000		12,000
Linde Air Products (NY)	57,000		57,000
Los Alamos National Laboratory (NM)	9,900,000		9,900,000
Luckey (OH)	26,000		26,000
Middlesex Sampling Plant (NJ)	17,000		17,000
Mound (OH)	110,000		110,000
Nevada Test Site (NV)	16,000,000	40,000	16,000,000
New Brunswick Laboratory (NJ)	3,100	340	3,440
Oak Ridge National Laboratory (TN)	380	72,000	73,000
Oak Ridge Reservation (TN)	50,000	7,300	57,300
Oxnard (CA)	76		76
Paducah Gaseous Diffusion Plant (KY)	600,000	390,000	990,000
Pantex (TX)	110,000		110,000
Portsmouth Gaseous Diffusion Plant (OH)	15,000	9,800	24,800
RMI (OH)	29,000		29,000
Rocky Flats Environmental Technology Site (CO)	460,000		460,000
Sandia National Laboratories - Albuquerque (NM)	210,000		210,000
Sandia National Laboratories - Livermore (CA)	11,000		11,000
Savannah River Site (SC)	19,000,000		19,000,000
Seaway Industrial Park (NY)	89,000		89,000
Site A / Plot M (IL)	540		540
St. Louis Airport Site (SLAPS) (MO)	190,000		190,000
St. Louis Airport Site (Vicinity Properties) (MO)	150,000		150,000
St. Louis Downtown Site (SLDS) (MO)	170,000		170,000
Ventron (MA)	1,700		1,700
Weldon Spring Site (MO)	480,000		480,000
Y-12 (TN)	19,000		19,000
TOTAL WEAPONS	58,000,000	3,900,000	62,000,000
TOTAL OTHER NONWEAPONS SITES	0	1,800,000	1,800,000
TOTAL DOE	58,000,000	5,800,000	64,000,000

Notes:
(1) Data compiled from the Environmental Restoration Core Database, May 1996.
(2) Media volume calculations subject to Endnotes a, b, and c.
(3) Weapons allocations are subject to Endnotes e, f, and g.
(4) B&T Metals is complete. Ventron and New Brunswick to be completed Fall of 1996.
(5) Includes approximately 1,500 million cubic meters of water and 15 million cubic meters of solid media outside the scope of the Environmental Restoration Program.

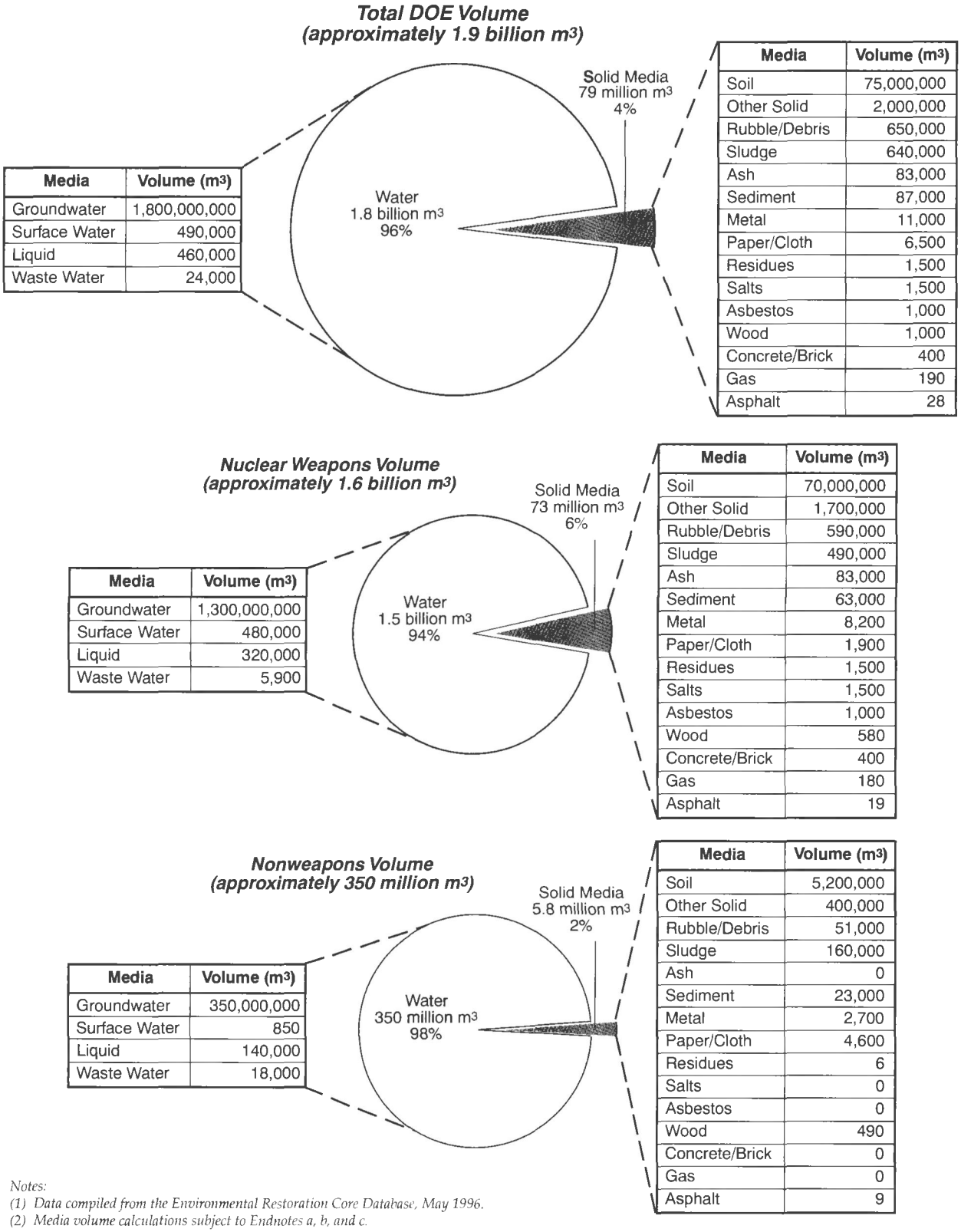
Sites and states with the largest amounts of contaminated environmental media from nonweapons activities include Washington (3.2 million cubic meters of contaminated solid media and 210 million cubic meters of contaminated water at Hanford), Idaho (34 million cubic meters of contaminated water and 210,000 cubic meters of contaminated solid media at INEL), and California (3.0 million cubic meters of contaminated water at two sites and 190,000 cubic meters of contaminated solid media at six sites).[5]

Although the contaminated environmental media legacy from nuclear weapons production is composed of nearly 20 different physical material matrices, 99 percent of the 1,900 million cubic meters are either groundwater or soil (Figure 4-3). Contaminated water from weapons production is over 99 percent

[4] *The nine Colorado sites are the Rocky Flats Environmental Technology Site and eight UMTRA sites.*

[5] *Nonweapons contamination in California is found at Lawrence Berkeley National Laboratory, the General Atomics Site, the Geothermal Test Facility, the Laboratory for Energy-Related Health Research, the Energy Technology Engineering Center, and the Stanford Linear Accelerator Center.*

Figure 4-3. Contaminated Media Volume Categorized by Physical Matrix



Media	Volume (m3)
Groundwater	1,800,000,000
Surface Water	490,000
Liquid	460,000
Waste Water	24,000

Media	Volume (m3)
Soil	75,000,000
Other Solid	2,000,000
Rubble/Debris	650,000
Sludge	640,000
Ash	83,000
Sediment	87,000
Metal	11,000
Paper/Cloth	6,500
Residues	1,500
Salts	1,500
Asbestos	1,000
Wood	1,000
Concrete/Brick	400
Gas	190
Asphalt	28

Media	Volume (m3)
Groundwater	1,300,000,000
Surface Water	480,000
Liquid	320,000
Waste Water	5,900

Media	Volume (m3)
Soil	70,000,000
Other Solid	1,700,000
Rubble/Debris	590,000
Sludge	490,000
Ash	83,000
Sediment	63,000
Metal	8,200
Paper/Cloth	1,900
Residues	1,500
Salts	1,500
Asbestos	1,000
Wood	580
Concrete/Brick	400
Gas	180
Asphalt	19

Media	Volume (m3)
Groundwater	350,000,000
Surface Water	850
Liquid	140,000
Waste Water	18,000

Media	Volume (m3)
Soil	5,200,000
Other Solid	400,000
Rubble/Debris	51,000
Sludge	160,000
Ash	0
Sediment	23,000
Metal	2,700
Paper/Cloth	4,600
Residues	6
Salts	0
Asbestos	0
Wood	490
Concrete/Brick	0
Gas	0
Asphalt	9

Notes:
(1) Data compiled from the Environmental Restoration Core Database, May 1996.
(2) Media volume calculations subject to Endnotes a, b, and c.
(3) Weapons allocations are subject to Endnotes e, f, and g.
(4) Most liquids are groundwater or surface water, but have not been classified as either one.
(5) Includes approximately 1,500 million cubic meters of water and 15 million cubic meters of solid media outside the scope of the Environmental Restoration Program.

M Area settling basin closure site. Metalworking facilities in M Area fabricated fuel and targets for the Savannah River Site's five production reactors. Wastes discharged to the basin from these processes seeped into the groundwater. The wells in the foreground are part of a groundwater treatment system. *M Area Settling Basin, Savannah River Site, South Carolina. June 15, 1993.*

Table 4-5. Contaminated Water Resulting from Nuclear Weapons Production

Site	Nuclear Weapons Volume (m^3)	Nonweapons Volume (m^3)
Ambrosia Lake (NM)	780,000	420,000
Belfield (ND)	160,000	83,000
Canonsburg (PA)	13,000	7,000
Durango (CO)	250,000	140,000
Falls City (TX)	2,900,000	1,500,000
Fernald (OH)	270,000	
GJMTS (CO)	850,000	450,000
GJPO (CO)	90,000	
Green River (UT)	440,000	240,000
Gunnison (CO)	4,600,000	2,400,000
Hanford (WA)	1,200,000,000	210,000,000
INEL (ID)	1	34,000,000
K-25 (TN)	630,000	320,000
Kansas City Plant (MO)	360,000	
Kauai Test Facility (HI)	5,700	
Lakeview (OR)	3,000,000	1,600,000
LLNL (CA)	22,000,000	
LLNL - Site 300 (CA)	3,500,000	
Maybell (CO)	560,000	300,000
Mexican Hat (UT)	280,000	150,000
Monument Valley (AZ)	3,000,000	1,600,000
Mound (OH)	680,000	
Naturita (CO)	250,000	130,000
Nevada Test Site (NV)	8,000	450
ORNL (TN)	260	670,000
Paducah (KY)	19,000,000	1,000
Pantex (TX)	4,200,000	
Portsmouth (OH)	2,400,000	1,600,000
Rifle (CO)	1,700,000	880,000
Riverton (WY)	1,200,000	660,000
Rocky Flats (CO)	1,300,000	
Salt Lake City (UT)	850,000	450,000
Sandia National Laboratory (NM)	400	
Savannah River Site (SC)	200,000,000	
Shiprock (NM)	400,000	210,000
Slick Rock (CO)	98,000	52,000
Spook (WY)	2,500,000	1,400,000
Tuba City (AZ)	2,000,000	1,000,000
Weldon Spring (MO)	710,000	
Y-12 (TN)	930,000	
TOTAL WEAPONS SITES	1,500,000	257,000,000
TOTAL NONWEAPONS SITES	0	93,000,000
TOTAL DOE	1,500,000	350,000,000

Notes:
(1) Data compiled from the Environmental Restoration Core Database, May 1996.
(2) Media volume calculations subject to Endnotes a, b, and c.
(3) Nuclear Weapons allocations are subject to Endnotes e, f, and g.
(4) Includes approximately 1,500 million cubic meters of water and 15 million cubic meters of solid media outside the scope of the Environmental Restoration Program.

groundwater and contaminated solid media are 95 percent soil. The nonweapons media legacy is similar (89 percent of the solid media is soil and over 99 percent of the water is groundwater).

Release Sites and Other Units

The legacy of contaminated environmental media is present at approximately 9,900 release sites and other units. The Department organizes these units into 10 major categories, which are further subdivided into 36 subcategories (Table 4-6).

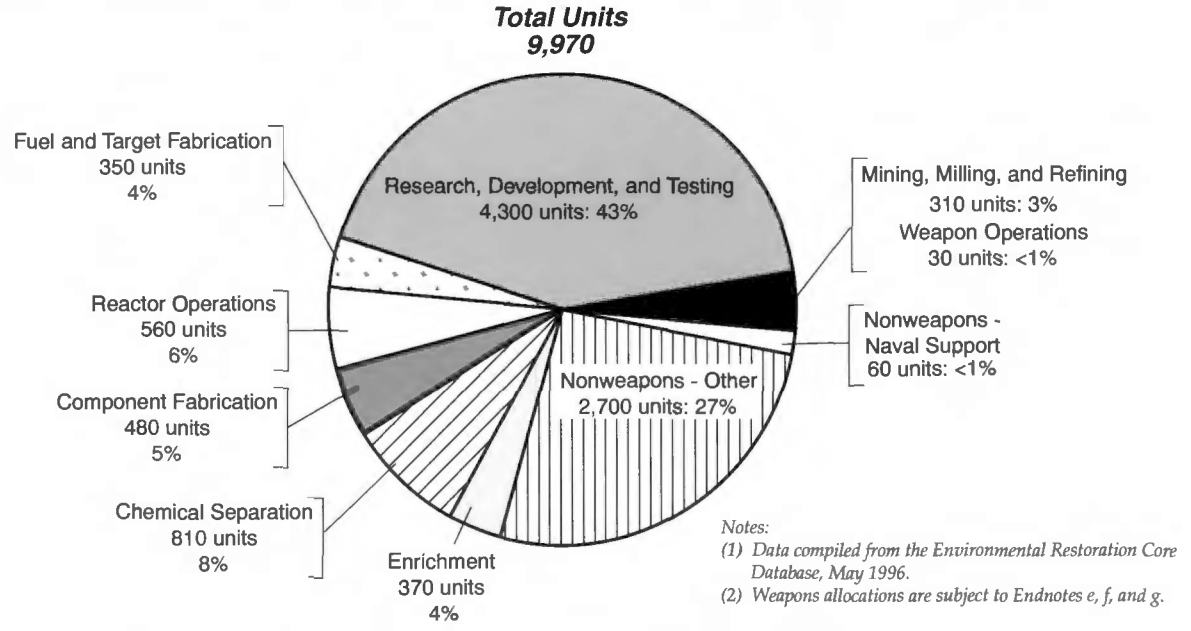
Table 4-6. Categories and Subcategories of Release Sites

Category	Subcategory	Units
Above Ground Material/Waste	Storage Yards and Pads	594
	Debris Piles	143
	Muck Piles	17
	Scrap Yards	49
	TOTAL	803
Surface/Subsurface Material/Waste	Miscellaneous Surface Debris	932
	Landfills	304
	Silos	5
	Trenches/Outfalls	508
	Pits	218
	Burn Pits	126
	Ditches	78
	Fire Training Areas	8
	Wells (Injection, Monitoring, etc.)	78
	TOTAL	2257
Mill Tailings Pile	Uranium Mill Tailings Piles	57
Spills and Leaks	Surface Spills	1079
	Pipeline Leaks	195
	TOTAL	1274
Buildings and Equipment	Buildings or Structures	1389
	Equipment	493
	TOTAL	1882
Tanks	Above Ground Storage Tanks	356
	Underground Storage Tanks	606
	Septic Tanks	250
	TOTAL	1212
Liquid Surface Impoundments	Lagoons	53
	Holding Ponds	109
	Settling and Separation Basins	105
	Seepage Basins	73
	Leach Fields	132
	Sumps	210
	Evaporation Ponds/Pits	82
	TOTAL	764
Underground Test Area Surface and Groundwater	Underground Test Areas	906
	Sediments	45
	Groundwater Plumes	104
	Surface Water	55
	TOTAL	1212
Dispersed Surface Contamination	Land Farms	23
	Above Ground Tests	134
	Firings Ranges/Ordnance	174
	TOTAL	1212
Miscellaneous	Other	204

Of the 9,900 release sites, FUSRAP sites, and UMTRA surface contamination and groundwater sites, and facilities, 73 percent are attributed to weapons production (Figure 4-4). About 43 percent are attributed to weapons research, development, and testing and are located at Los Alamos and the Nevada Test Site (Table 4-7). About 30 percent of the units are attributed to the other seven weapons production activities. Less than 1 percent are attributed to activities supporting the NNPP and about 27 percent are attributed to other nonweapons activities. Most of the nonweapons units are located at Nevada Test Site (primarily from other defense testing activities), Argonne National Laboratory-East, Idaho National Engineering Laboratory, and Oak Ridge Reservation. None of the units attributed to supporting the NNPP are or were operated by or under the purview of the NNPP. Instead, the number of units allocated to supporting the NNPP represents about 27 percent of the units at the uranium mill tailing sites and 7 percent of the units at the uranium enrichment sites.

In addition to Los Alamos and the Nevada Test Site, units attributed to weapons production activities have been identified at 88 other DOE sites in 25 states. Units that were attributed to nonweapons activities are located at 45 of the sites with weapons units, plus another 37 nonweapons sites. The number of sites where these units are found is larger than the number of sites where contaminated media are located because characterization of some units is not complete and, for others, only waste or contaminated structures (not media) may be present at the unit.

Figure 4-4. Release Sites and Other Units Categorized by Process



Notes:
(1) Data compiled from the Environmental Restoration Core Database, May 1996.
(2) Weapons allocations are subject to Endnotes e, f, and g.

Table 4-7. Locations of Environmental Restoration Release Sites and Other Units

State	Nuclear Weapons Units	Nonweapons Units	Total
NM	2,364	11	2,375
NV	1,666	709	2,375
WA	1,173	158	1,331
SC	373	1	374
OH	290	53	343
TN	253	366	619
TX	240	1	241
CA	213	229	441
CO	203	16	219

State	Nuclear Weapons Units	Nonweapons Units	Total
MO	120	0	120
ID	115	454	569
KY	98	63	159
UT	14	8	22
IL	14	521	534
IA	8	3	11
NY	8	73	81
NJ	5	9	14
HI	3	0	3

State	Nuclear Weapons Units	Nonweapons Units	Total
AZ	3	1	4
ND	3	1	4
WY	3	1	4
PA	3	1	4
OR	2	1	3
AK	1	2	3
MA	1	2	3
MI	1	1	1
Nonweapons Sites (Various States)	0	944	944

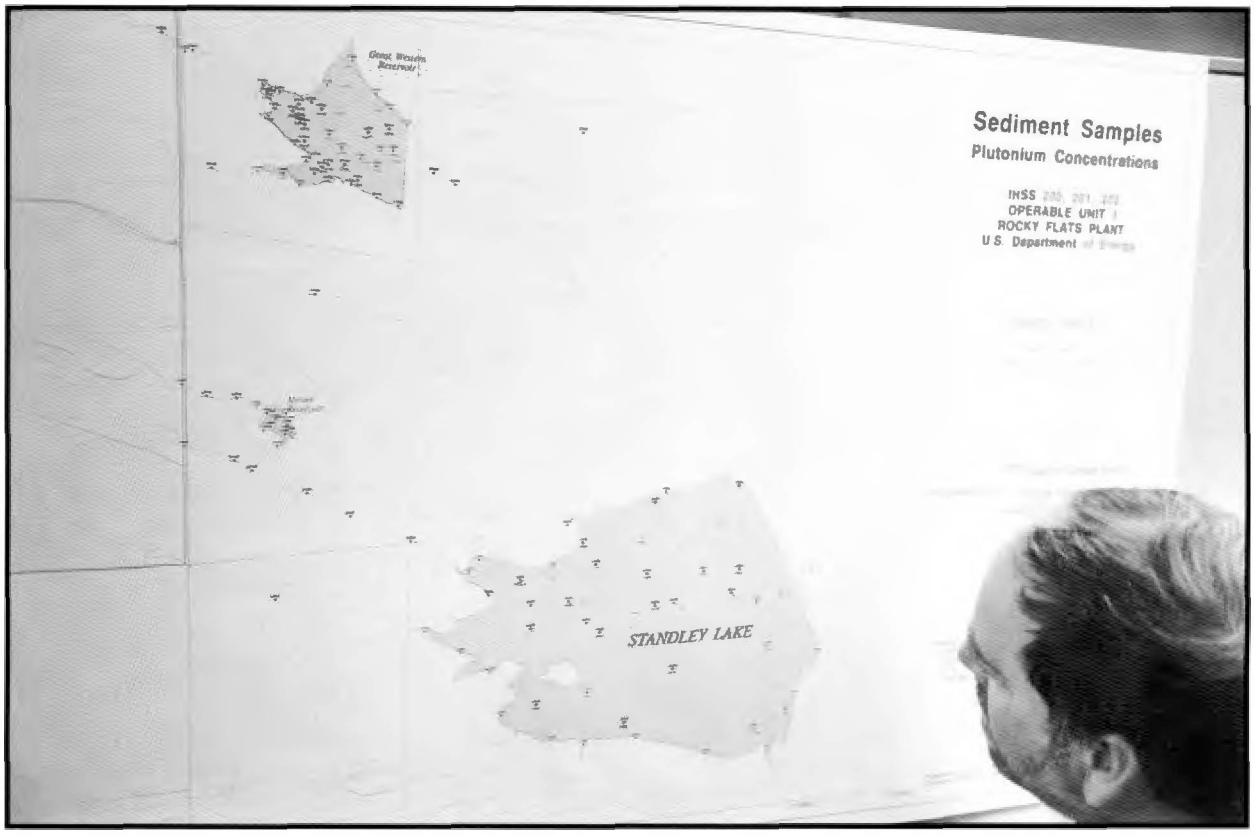
Notes:
(1) Data compiled from the Environmental Restoration Core Database, May 1996 (See Endnote d).
(2) Weapons allocations are subject to Endnotes e, f, and g.

As the Department continues to remediate contaminated environmental media, the total volume and number of release sites and other units will change. Natural decay will decrease the amount of radioactive constituents in the media. Thus, in coming years the legacy of environmental contamination attributable to nuclear weapons production will differ from the quantities identified in this report.

Contamination Not Included in Quantitative Analysis

The volume of some contaminated media resulting from nuclear weapons production and other DOE activities is not tracked in the Core Database. For these media, final decisions about remediation are still pending or cleanup may be impractical or unnecessary. In some cases, the potential human health risks from leaving the contamination unremediated may be less than the risks from remediation. In other cases, removing contamination is impractical or is only possible by destroying the natural habitat that contains it. Examples include:

- Sediments in the East Fork Poplar Creek, the Clinch River, and lower Watts Bar Reservoir contaminated with mercury and other heavy metals, radionuclides and organic chemicals from the Department of Energy sites in Oak Ridge, Tennessee and other industrial, urban, residential, and agricultural sources; and



Characterization and monitoring. A Rocky Flats engineer studies a sediment sampling plan, part of an effort to determine levels of plutonium contamination in the streams, ponds, and reservoirs around the Rocky Flats Site. Sampling plans like this one are used to characterize and monitor environmental contamination throughout the nuclear weapons complex. *Rocky Flats Environmental Technology Site, Colorado. March 19, 1994.*

- Sediments in the 2,640-acre PAR Pond at the Savannah River Site in South Carolina which was contaminated with cesium-137 by releases of reactor cooling water.

In addition to these examples, there have been releases whose results are impossible to locate, fully characterize, or clean up. For example, fallout from over 200 aboveground U.S., Soviet, U.K., French, and Chinese weapons tests is estimated to have raised the current average annual radiation dose by about 0.3 percent (see text box "Radiation from Atmospheric Nuclear Weapons Testing"). There is no practical action that can be taken to locate, remove, or mitigate this contamination, hence no volume estimate is available. Other releases, such as the radioactive releases from early operations at Hanford to the atmosphere and the Columbia River have long ago decayed away (see text box "Radioactive Releases from the Hanford Site"). No contaminated media resulting from these releases exist at the present time.

Some contamination that has already been remediated is not included in the Core Database. One major example is the U.S. nuclear weapons testing sites in the South Pacific. The United States conducted 23 tests on Bikini Atoll and 43 tests on Enewetak Atoll between 1946 and 1958, resulting in substantial contamination to the atolls and nearby areas. Enewetak is located approximately 2,500 miles west of Hawaii and contains 40 named islands, two coral reefs, a small number of inlets, and long stretches of submerged coral reefs. Bikini is located approximately 200 miles east of Enewetak and consists of 25 named islands and unnamed coral heads and islets.

The contamination that resulted from the Pacific tests included high concentrations of cesium-137 and strontium-90 in soils. Neutron activation of steel towers and test device parts led to measurement of high gamma emissions from cobalt-60. Some safety tests also resulted in a measurable localized spread of transuranic elements, including plutonium-239, plutonium-240, and americium-241. Testing on both

Contaminated hillside at Rocky Flats. When drums of plutonium-contaminated oils and solvents corroded and leaked on an outdoor storage pad, this hillside at Rocky Flats became contaminated with plutonium and other toxic substances. Over 5,000 of these drums accumulated while engineers were developing a method to treat the oils for recycling or disposal as non-radioactive waste. The city of Denver, 16 miles away, can be seen in the distance. *Hillside 881, Rocky Flats Environmental Technology Site, Colorado. March 19, 1994.*

atolls also left behind massive reinforced control bunkers, large steel towers used to mount diagnostic equipment, piles of scrap and debris, and much abandoned equipment. The detonations significantly changed the topography of Enewetak—several small islands were totally destroyed.

Table 4-8. Results of Restoration of Bikini and Enewetak Islands

	Bikini	Enewetak
Radioactively Contaminated Debris	500 tons	5,883 cubic yards
Nonradioactive Debris	40,000 tons	253,650 cubic yards
Contaminated Soil		104,097 cubic yards

The Departments of Energy, Defense, and Interior conducted joint cleanup operations at Bikini in 1969 and at Enewetak from 1977 through 1980. As shown in Table 4-8, the restoration generated substantial volumes of debris and soil.

The cleanup at Bikini included the disposal of radioactive scrap metal in the ocean at depths greater than 150 feet at least one mile offshore.[6] Nonradioactive debris was placed in landfills and the U.S. staff built new buildings for Bikini residents. At Enewetak, all radioactive materials were transferred to the island of Runit and entombed in the crater of the Hardtack I Cactus Test conducted in 1958. The tomb was created by sealing the cracks in the crater, mixing plutonium-contaminated soil with cement to form a

[6] *These debris are not included in the ocean-dumped low-level waste discussed in Chapter 3.*

Radiation from Atmospheric Nuclear Weapons Testing

Contamination resulting from atmospheric nuclear explosion is impossible to locate, contain, or remediate. However, because it effects the entire population of the Earth, it is the most significant impact of nuclear weapons on the environment.

Between 1945 and 1962, the United States conducted 210 atmospheric nuclear tests. The former Soviet Union, the United Kingdom, France, and the People's Republic of China have also tested nuclear weapons in the atmosphere. The total yield from all atmospheric nuclear weapons testing was approximately 540 megatons, including 215 megatons from fission. U.S. testing accounts for approximately 30 percent of this total and the former Soviet Union is estimated to be responsible for nearly 60 percent.

Environmental contamination from atmospheric nuclear weapon testing results from (1) fission products, largely beta and gamma radiation emitters such as strontium-90 and cesium-137; (2) neutron activation of weapon materials and materials in the natural environment, such as carbon-14 from activated atmospheric nitrogen and cobalt-60 from steel weapon parts and support towers; and (3) unused nuclear fuel, such as uranium, plutonium, or tritium.

Environmental radiation from atmospheric nuclear weapons tests has declined since atmospheric testing was halted in 1963, and will continue to decline in the future. In 1987, the National Council on Radiation Protection estimated that atmospheric nuclear weapons testing contributed approximately one millirem to the average effective radiation dose of each person in the United States. By comparison, the average annual dose from naturally occurring background radiation is 300 millirem. Actual individual doses may be higher or lower, depending on location, diet, age, and other factors.

Scientists believe radiation health effects to be cumulative over a person's lifetime. Over their lifetime, individuals born before July 1945 will receive an average equivalent radiation from past nuclear weapons testing of 75 millirem from all external sources and from 2 to 65 millirem each to various internal organs (particularly the lungs and bone marrow). With the exception of exposure to carbon-14, most of this dose has already occurred. Younger persons will receive smaller lifetime doses, on average. Again, individual doses may be higher or lower than this average, depending on location, diet, age and other factors.

References:

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Recommendations of the Council on Radiation Protection and Measurements. December 30, 1987. Exposure of the Population of the United States and Canada from Natural Background Radiation. NCRP Report No. 94.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). 1982. Ionizing Radiation: Sources and Biological Effects. 1982 Report to the General Assembly.

slurry, and pumping the slurry into the crater around the contaminated debris. The solid mass was covered by an 18-inch thick concrete cap. Runit remains quarantined and restricted from further use.

Besides the Department of Energy, other organizations are remediating other sites contaminated as a result of the legacy of nuclear weapons production. For example, under an agreement with the Environmental Protection Agency, the General Electric Company is remediating the South Valley Superfund Site in Albuquerque, New Mexico, which was placed on the National Priorities List in 1983. Between 1952 and 1966, the AEC fabricated weapons components at the South Albuquerque Works, a metalworking facility at South Valley. Between 1967 and 1984, the Air Force produced jet engines at the site. General Electric bought the site in 1984. At this site, DOE is providing about 43 percent of the funding for the cleanup, with the balance being provided by six other responsible parties. Contaminated groundwater at South Valley underlies about 74 acres and has an estimated volume of about 330 million cubic meters. However, because DOE is not managing this project, it has not been included in the quantitative results

Radioactive Releases from the Hanford Site

Environmental releases which have long ago decayed away are still a matter of concern to the Department of Energy and its stakeholders. Dose reconstruction studies are a key aspect of the Department's response to these past releases.

The Hanford Environmental Dose Reconstruction Project analyzed radiation releases from the Hanford site and calculated the resulting radiation doses to the surrounding population. Two of the most significant releases of radiation from Hanford are discussed here. Most of the original radionuclides have long since decayed away, although a few of their daughter products may remain in the environment today.

Iodine-131 Releases to the Atmosphere, 1944-1947

When uranium is fissioned in a nuclear reactor, a large variety of radioactive fission products are created. One of the most common of these fission products is iodine-131. Iodine-131, with a half-life of eight days, decays into non-radioactive xenon. Radioactive iodine gas was vented to the plant stacks and dispersed by the wind when spent nuclear fuel from the B, D, and F production reactors at Hanford was dissolved in the T and B plant reprocessing facilities, and to a lesser extent during subsequent steps in the bismuth phosphate separation process. This iodine-131 settled on the ground and rivers, and entered the food chain. The historic iodine-131 releases totaled approximately 685,000 curies between December 1944 and December 1947. After December 1947, irradiated fuel was cooled for a longer period, allowing natural decay to eliminate much of the radioactive iodine. Later on, filters and scrubbers were installed in the exhaust stack system, which further reduced iodine-131 emissions.

Radionuclide Releases to the Columbia River, 1944-1971

Beginning in September 1944 with the initial startup of B Reactor, eight single-pass reactors operated at the Hanford site. The single-pass reactors used Columbia River water to cool the fuel elements in the reactor core. Cooling water flowed around the fuel elements in process tubes in the reactor cores, was stored temporarily in retention basins, and then was released to the river. A ninth reactor, N Reactor, did not discharge directly to the Columbia River. The last single-pass reactor was shut down in 1971. Radionuclides were created when neutrons in the reactor core activated native elements present in the inlet cooling water from the Columbia river, as well as elements that were added by water treatment processes. The reactors also activated elements in the alloys used for process tubes and fuel cladding and materials held in the films deposited on the tube and cladding surfaces. The resulting radionuclides were released in the cooling water discharges to the Columbia River. Uranium fuel element failures caused additional radionuclide releases.

Median estimates of radionuclide releases to the Columbia River, corrected for decay at the time of release, are as follows:

Radionuclide	Half-Life	Total Release 1944 - 1971
sodium-24	15.0 hours	12,600,000 Ci
phosphorus-32	14.3 days	229,000 Ci
scandium-46	83.7 days	120,000 Ci
chromium-51	27.7 days	7,190,000 Ci
manganese-56	2.5 hours	79,600,000 Ci
zinc-65	245 days	491,000 Ci

Radionuclide	Half-Life	Total Release 1944 - 1971
gallium-72	14 hours	3,690,000 Ci
arsenic-76	26.3 hours	2,520,000 Ci
yttrium-90	64 hours	445,000 Ci
iodine-131	8 days	47,900 Ci
neptunium-239	2.4 days	6,310,000 Ci
gross nonvolatile beta emitters*		66,300,000 Ci

Environmental dose reconstructions are underway at the Savannah River Site, Fernald, Idaho National Engineering Laboratory, Rocky Flats, and Oak Ridge.

References:

U.S. Department of Energy, Pacific Northwest Laboratory. October 1992. Iodine-31 Releases from the Hanford Site, 1944 Through 1947, Volume I -Text. PNDWD-2033-HEDR-Vol. 1. DOE Office of Science and Technical Information.

U.S. Department of Energy, Pacific Northwest Laboratory. May 1994. Radionuclide Releases to the Columbia River from Hanford Operations, 1944-1971. PNDWD-2223-HEDR-Vol. 1. DOE Office of Science and Technical Information.

* *The largest contributor to this category (15 to 30 percent) is manganese-56. However, it includes other radionuclides that were never definitively identified. It also does not include volatile beta emitters such as tritium and sulfur-35.*

presented in this report. No estimate of the portion of this contamination attributable to nuclear weapons production is available.

Methodology and Data Sources

Data Sources

The Office of Environmental Restoration Core Database contains most of the volume and media characteristics available for this element of the legacy. This database includes information on contaminated media volumes, site locations, physical matrix of the media, and type of contamination. The database also contains information on individual contaminants present in the media, and the expected future disposition of the contaminated media (e.g., *in situ* treatment, *in situ* disposal, removal and treatment, removal and disposal). It also includes limited data used to infer the weapons production process category or nonweapons activity that resulted in the contamination.

Specifics on the release sites and other units came from a database developed by the Office of Environmental Restoration that is being combined with the Core Database. In the release site database, each release site or unit has a name and the location and type of unit is identified.

Contaminated media volumes and radioactivity figures are rounded to two significant figures because of the uncertainties and approximations discussed here. Because of this rounding, some numbers may not appear to add correctly.

Data Issues and Assumptions

The primary data sources for contaminated environmental media are the Environmental Restoration Core Database and a similar Environmental Restoration program database of release sites and other units.

Some of solid media are also counted as disposed waste. This amount comprises approximately three to four percent of the total volume of contaminated solid media.

Some contaminated media outside the scope of the current Environmental Restoration program are not included in this analysis. Contaminated media managed by organizations other than DOE also are excluded. Therefore, the total amount of contaminated media resulting from DOE activities is underestimated in this analysis. Some of these volumes are very large, however, most of these media are groundwater and sediments.

Volumes of material identified in the Core Database categorized as stored waste, equipment, and structures are excluded from the contaminated media analysis and are accounted for as either waste (Chapter 3) or facilities (Chapter 5). Media to be generated in the future from facility decontamination and decommissioning are also excluded from this analysis (and accounted for in Chapter 5). In addition, media that do not contain contamination requiring special management (sanitary waste or demolition debris) are not included in the analysis.

Limitations, Uncertainties, and Assumptions

Each type of media in the Core Database was examined to determine whether it should be included in the contaminated media analysis. Specifically, it was examined to determine its status, its location, its composition, and whether it resulted from nuclear weapons production.

Evolving Data – Most contaminated media in the DOE Environmental Restoration program are currently undergoing characterization or remediation. For some sites, the Department has already completed interim or final remedial actions. DOE maintains a database of about 9,900 release sites and other units and nearly 6,000 vicinity properties. The Department has been characterizing release sites intensively for the last several years, and now has an understanding of many of the contaminated media at these sites. However, the characterization remains incomplete and existing data has yet to be compiled at a nationwide level. Characterization and data compilation will continue in the coming years, and will further improve the Department's understanding of this legacy element

Categorizing Release Sites and Other Units into Nuclear Weapons and Nonweapons Categories – In the database of release sites and other units, the name and location of the unit determined whether the unit resulted from nuclear weapons or nonweapons activities. Because some sites conducted multiple activities,

fractions of individual release sites are attributed to various activities. The units at mill tailings sites and uranium enrichment sites were categorized in the same manner as contaminated media and waste.

Categorizing Environmental Media – To allocate the media to nuclear weapons or nonweapons activities, individual volumes of media from a single project were often divided among several nuclear weapons processes and nonweapons activities. Site and project descriptions in the Core Database determined whether the media resulted from nuclear weapons production and the weapons production process category. The approach used to categorize contaminated media at mill tailing sites and uranium enrichment sites is the same used to categorize waste at those sites. For media at other sites, allocations were based on the historical operations and nature of contamination at each site.

Excluding Volumes of Material from Contaminated Environmental Media Legacy – Some volumes of material identified in the Core Database were excluded from the analysis of contaminated media because they were included in other elements of the legacy (i.e., 33 million m^3 of stored 11e(2) byproduct material, 6 million m^3 of structures and equipment which are counted as facilities, and 12,000 m^3 of media expected to be generated in the future from facility decontamination and decommissioning). Other volumes are excluded because they did not contain hazardous or radioactive contamination at levels requiring special management (i.e., 215 million m^3 of media categorized as sanitary, demolition, or nonhazardous). For example, some water discharges at Fernald contain levels of uranium contamination low enough that they do not require special management. Media that are not managed by DOE, or for which no volume estimate was available, were also excluded. All other volumes of media were included and were categorized as either hazardous, radioactive, or both hazardous and radioactive.

Ambiguities in Defining and Quantifying the Contaminated Environmental Media Legacy – Interpretations differ as to what constitutes "contaminated environmental media" and what should be tracked as "contaminated environmental media." The portion of contaminated environmental media under active management (e.g., being treated, contained, removed, or subject to institutional controls) is often well established. Data developed by DOE sites and compiled into the Core Database are available on the volumes and characteristics of these media.

The problem resulting from release of a contaminant can be defined in several ways, and each definition can result in a different volume. The definition most often used by DOE in determining the volume of affected media that should be tracked and commonly used by stakeholders and regulatory agencies is the volume of environmental media in which the contaminant is thought to be present above an action level. This approach is subject to some inevitable uncertainties because of shortcomings of the characterization technology, statistical uncertainties introduced in the characterization process itself, and modeling uncertainties in using the data to determine where contaminants are now or to predict where they may migrate in the future.

Other definitions, for example, the volume of the contaminant released to the media, the volume of media containing contaminants above detection levels, the volume of groundwater to be pumped to the surface for treatment, or, in the case of a contaminated aquifer, the entire aquifer which must be specially managed to prevent the spread of contamination, can result in much larger or smaller volumes. Some definitions, such as the volume of the material released, provide results with limited use because they do not consider how the contaminants have affected the environment or the risks they pose to humans.

For example, at the Y-12 Plant in Oak Ridge, Tennessee an estimated 240,000 pounds of mercury metal used in the lithium enrichment process are thought to have been released to the surface water around the site (Table 4-9). In its pure form, this mercury amounts to about 20 cubic meters (5,300 gallons). However, the volume of contaminated sediments resulting from the releases is many thousand cubic meters. Some of the sediments will be cleaned up, and the remainder may be subject to future restrictions. Another example is the Hanford Site, where it is estimated that 346 billion gallons of liquids containing 1.4 million curies of various radionuclides were discharged into the soil between 1944 and 1991. As a result, there are 1.4 billion cubic meters (25 billion gallons) of contaminated water and 23.6 million cubic meters (3.8 billion gallons) of contaminated soil.

Lithium enrichment equipment. An engineer stands before a 20,000 gallon storage tank inside the Oak Ridge Y-12 Plant. This tank once held a lithium solution that was combined with mercury in the COLEX lithium-enrichment process. Enriched lithium is used in thermonuclear weapons; it is also irradiated in reactors to create tritium for nuclear weapons. Mercury in the waste streams from lithium-enrichment in the 1950s and 1960s has contaminated streams and sediments around the Y-12 Plant. *Basement of the Alpha-4 (9201-4) Building, Y-12 Plant, Oak Ridge, Tennessee. January 11, 1994.*

Table 4-9. Results of Y-12 Mercury Release Reconstruction Study

Mercury Lost, Spilled, or Dumped to Environment	Estimated Pounds of Mercury[b]
Lost to air (1950-1963)	51,000
Lost to East Fork Poplar Creek (1950-1982)	239,000
Lost to ground under Y-12	428,000
Lost to sediments in New Hope Pond	15,000
Subtotal Lost	733,000
Additional Mercury Not Accounted For	51,000
Did not receive[a]	500,000
In building structures[a]	60,000
Other specific losses[a]	85,000
Unknown	655,000
Subtotal All Other	1,300,000
TOTAL	2,030,000

[a] *These estimates are speculation and cannot be verified. Source: Mercury at the Y-12 Plant, A Summary of the 1983 UCC-ND Task Force Study, Martin Marietta Energy Systems, Inc., November 1983.*

[b] *One pound (0.45 kg) of metallic mercury would form a cube approximately 1.26 inches (.,2 cm) on a side.*

The Core Database generally identifies the established or expected actions applicable to each volume of media. In some cases, however, decisions have not been made on what, if any, actions should be taken, at what level the site-specific action should exist, or on what volumes of media are subject to the actions. If all media volumes identified in the Core Database as "no further action" were excluded from tis analysis, the volume of contaminated environmental media would be smaller. Additionally, the volume would be larger if other contaminated media volumes not identified in the Core Database were considered (since they are outside the scope of the current Environmental Restoration Program).

Finally, the Department gathers detailed characterization information on media that it believes can and will be remediated. In many cases where decisions are made to monitor so as to ensure that contaminants do not reach receptors, to allow natural attenuation to occur, or to take no action because practical technologies do not exist or risk levels do not justify action, the Department does not collect and maintain the same type of volume information as for actively managed media, and the collected data are not included in the Core Database. Estimates of the volumes of these media have been obtained from other sources when possible.

SUMMARY

The Department's legacy of contaminated environmental media consists of two categories of material: water and solid media. Different management requirements and alternatives exist for each category. Most of the volume of contaminated environmental media is groundwater. These media are present at several thousand specifically-identified release sites and other units across the DOE complex. The greatest uncertainties concerning the volume of contaminated media are the volume of contaminated

RCRA cap. Ten acres of black plastic cover a radioactive waste landfill in Oak Ridge. This high-density polyethylene cap is designed to prevent gases from escaping, reduce erosion, and keep rainwater from leaching contaminants into the groundwater. Installed in 1989, the cap is designed to last 15 to 20 years. *Solid Waste Storage Area 6, Oak Ridge Reservation, Oak Ridge, Tennessee. January 10, 1994.*

media outside the scope of the current Environmental Restoration program. As contaminated media and release sites continue to be characterized and, remediated, new data will become available and estimates will be improve.

ENDNOTES

a. Environmental Restoration Core Database, containing data current as of May 1996, was used as a source for volume data of water and solid media. Volumes of material categorized as stored waste in the database are included in Chapter 3 (Waste); volumes of material categorized as structures/equipment are accounted for in Chapter 5 (Facilities). Some contaminated media volume data are not recorded in the database and are not included in this analysis. Volume estimates of contaminated media at some sites change over time as better data is compiled or as contamination spreads or is cleaned up. Media classified as groundwater, surface water, wastewater, and liquid are categorized as water. All other media are classified as solid media. The volume of contaminated groundwater in the current Core Database likely underestimates the true extent of groundwater contamination since characterization information for this medium is preliminary.

b. Volumes of water and solid media from the Environmental Restoration Core Database that are classified as sanitary, demolition debris, or "NA" are not included. Volumes of water and solid media classified as MTRU, MLLW, 11e(2), RPCB, and RASB in the database are categorized as both radioactive and hazardous/toxic; volumes classified as TRU, LLW, and 11e(2) byproduct material are categorized as radioactive only; volumes classified as HAZ, PCB, and ASB are categorized as hazardous/toxic only. The classifications of contaminated media at some sites may change over time as characterization data continues to improve, regulations change, or as categories are redefined.

c. Media volumes from the Environmental Restoration Core Database that are projected to result from future decontamination and decommissioning activities are not included and are accounted for in Chapter 5 (Facilities), except for soil, sediment, groundwater, surface water, and liquid.

d. Environmental Restoration Release Site Database, containing data current as of April 1996, was used as a source for data on release sites and other units. Contaminated media have not been quantified at all units. Some units contain only stored waste, and characterization is not complete as some units.

e. Allocations are generally based on the processes conducted at the sites where the media or unit is located. For multipurpose sites, allocations are based on media descriptions in the Environmental Restoration Core Database and unit names in the Release Site Database. In cases where the media description or unit name is not adequate to determine the allocation, an estimated sitewide allocation was applied, based on waste allocations used in Chapter 3.

f. For media and units at uranium enrichment sites (K-25 Site and the Paducah and Portsmouth Gaseous Diffusion Plants), allocations are based on the proportions of enriched uranium produced for various purposes (nuclear weapons program, naval fuel, research reactors, nonweapons programs), as measured in separative work units, and taking into account when uranium was enriched. This allocation is only an estimate. Historic records may also be available that would allow media to be allocated based on the specific causes of contamination. For allocations to naval fuel production at these sites, DOE is responsible for the management of all units and media. The NNPP is not currently involved in the management of these sites and has not been involved in the past.

g. For media and units at uranium mill tailing sites, media are allocated based on the uranium purchaser (AEC or non-AEC) and, for AEC-purchased uranium, according to the use of the eventual uranium product (nuclear weapons program, naval fuel, research reactors, nonweapons programs). The same allocation is applied to all mill tailing sites, taking into account all historic AEC uranium purchases including uranium purchases from sites where DOE is responsible for remediation, other U.S. mill tailing sites, and foreign mill tailing sites. This allocation is only an estimate. See the text box in Chapter 3 for a further explanation of this allocation. For allocations to naval fuel production at these sites, DOE is responsible for the management of all units and media. The NNPP is not currently involved in the management of these sites and has not been involved in the past.

5. Surplus Facilities

Savannah River Site heavy water facility. For 30 years, this facility concentrated small fractions of heavy hydrogen in natural water to produce some 300,000 gallons of "heavy water" to cool and moderate the site's five production reactors. Heavy hydrogen extracted at this facility is also used in nuclear weapon components. The facility, built in 1952, has been dismantled. Debris from dismantlement included 180,000 feet of asbestos-covered piping, 150,000 square feet of asbestos-covered equipment, 140 heat exchangers, and 42 towers, each 130 feet tall. *Heavy Water Extraction Facility, Savannah River Site, South Carolina. January 8, 1994.*

Overview

During the course of nuclear weapons production and other activities, DOE and its predecessor agencies built and used more than 20,000 facilities (buildings as well as support structures and equipment). Many of these facilities became contaminated with radionuclides and/or chemical constituents. The change in the Department's mission, and an aging infrastructure, has led DOE to evaluate the status of, and long-term plans for, many of its facilities. The facilities

Key Observations of the Surplus Facilities Legacy

- The Department of Energy has identified approximately 5,000 of its 20,000 facilities as surplus as of 1996.
- Approximately 76 percent of the surplus facilities were part of the Department's nuclear weapons program.
- Approximately 24 percent of the surplus facilities supported chemical separation processes for nuclear weapons programs, 24 percent supported nonweapons activities, 12 percent supported weapons component manufacturing, 11 percent supported reactor fuel and target fabrication, 10 percent supported reactor operations, and of the remaining 19 percent, 9 percent supported nuclear weapons research, development and testing.
- With 1,300 and 1,200 facilities, respectively, Hanford and the Savannah River Site have the largest numbers of facilities identified as surplus. Hanford (250) and Fernald (180) have the most facilities in the decommissioning process.
- Characterization of surplus facilities is not yet complete. However, based on historical information and process knowledge, a large number of the 5,000 facilities are known or suspected to be contaminated with hazardous, toxic, and/or radioactive substances.

Figure 5-1. Surplus Facilities Categorized by Process

Notes:
(1) Data compiled from Office of Nuclear Material and Facility Stabilization database of surplus facilities and Office of Environmental Restoration database of release sites and other units.
(2) Numbers of facilities have been rounded.
(3) Nuclear weapons and nonweapons allocations to individual weapons production process categories are determined according to the methodology described in this chapter.

discussed in this report are those that the Department has identified as "surplus" to its mission. In the future, additional facilities will become surplus as they become obsolete or are no longer needed. The text box "Key Observations of the Surplus Facilities Legacy" summarizes the key observations regarding surplus facilities derived from the existing data.

Surplus facilities are managed by the Office of Environmental Management as well as other DOE program offices. Within the Office of Environmental Management, the Office of Nuclear Material and Facility Stabilization (EM-60) is responsible for stabilizing and storing nuclear materials and deactivating surplus facilities. The Office of Environmental Restoration (EM-40) subsequently manages the Department's decommissioning of these surplus facilities. A summary of the Department's current process for managing surplus facilities is provided in the text box, "Surplus Facilities Management Process."

Surplus Facilities Management Process

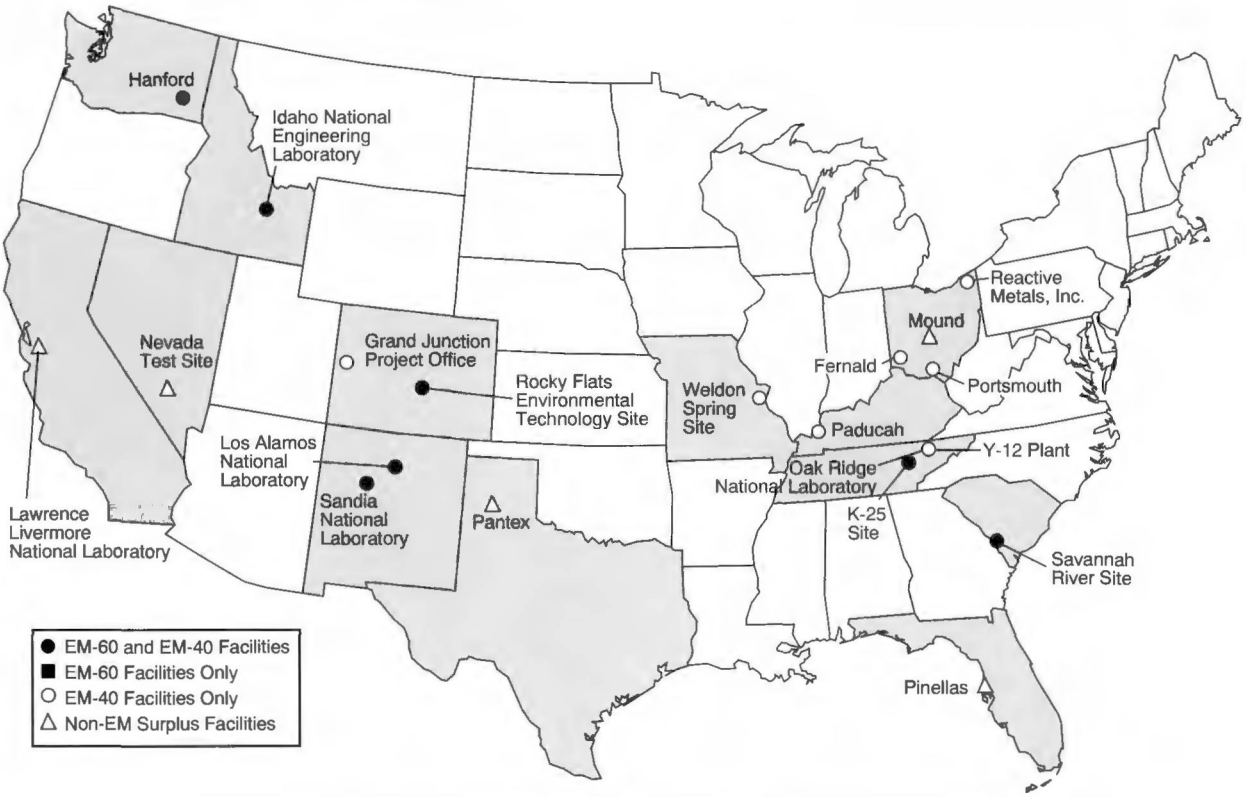
The Department's strategy for addressing surplus facilities has been to transfer responsibility for managing them to the Office of Environmental Management when they are determined to be surplus to the needs of the Department's primary line programs: the Office of Defense Programs, the Office of Nuclear Energy, and the Office of Energy Research. Within the Office of Environmental Management, the Department's strategy has been a two step process: first, to stabilize the facilities to reduce the safety risks and reduce the maintenance costs; and second, to decontaminate and decommission them when it is financially and technically possible and appropriate.

The first step is managed by the Office of Nuclear Material and Facility Stabilization within the Environmental Management program. This office oversees necessary stabilization of any nuclear materials present to reduce short term risk and achieve a condition suitable for long-term storage. Upon completion of stabilization activities, this office undertakes deactivation activities to remove materials, shut down facility systems, and remove or de-energize equipment. Throughout these activities, facilities undergo surveillance and maintenance to provide early warning and prompt remediation of hazardous conditions that may develop. In some cases, where no pre-cleanup stabilization is warranted, facility responsibility may bypass the first step.

In the second step, responsibility for stabilized facilities is subsequently transferred to the Office of Environmental Restoration within the Environmental Management program. This office addresses the contamination inside the buildings and the structures themselves. Decommissioning activities may include removal of contaminated building materials and residual waste, waste treatment, complete destruction, or entombment in place.

From 1989 to 1995, responsibility for most of the largest DOE sites was transferred to the Office of Environmental Management. The Department is now considering whether to continue this process of transferring responsibility for surplus facilities from the primary line programs to these Environmental Management offices for the remaining facilities as they become surplus in the future.

Figure 5-2. Location of Surplus Facilities as of 1996



Site	Number of Facilities		
	Weapons	Nonweapons	Total
Hanford (WA)	1,200	320	1,520
Savannah River Site (SC)	1,100	73	1,173
Rocky Flats Environmental Technology Site (CO)	470	0	470
Nevada Test Site (NV)	260	40	300
Fernald Environmental Management Project (OH)	180	0	180
Mound (OH)	140	0	140
K-25 Site (TN)	88	43	131
Idaho National Engineering Laboratory (ID)	86	190	276
Los Alamos National Laboratory (NM)	58	0	58
Weldon Spring Site Remedial Action Project (MO)	47	0	47
Y-12 Plant (TN)	24	0	24
Oak Ridge National Laboratory (TN)	23	180	203
Reactive Metals, Inc. (OH)	19	0	19
Pantex (TX)	18	0	18
Sandia National Laboratory - NM (NM)	15	1	16
Grand Junction Project Office (CO)	12	7	19
Portsmouth Gaseous Diffusion Plant (OH)	8	6	14
Paducah Baseous Diffusion Plant (KY)	6	4	10
Lawrence Livermore National Laboratory (CA)	3	1	4
Pinellas (FL)	1	0	1
Nonweapons Sites (Various)	0	380	380
TOTAL	3,758	1,245	5,003
Percent	76%	24%	100%

Notes:

(1) Data compiled from Office of Nuclear Material and Facility Stabilization database of surplus facilities and Office of Environmental Restoration database of release sites and other units.

(2) Numbers of facilities have been rounded.

(3) Nuclear weapons and nonweapons allocations to individual weapons production process categories are determined according to the methodology described in this chapter.

(4) Includes a small number of facilities identified as surplus but not yet transferred into the Environmental Management Program.

(5) EM is the acronym for the DOE Office of Environmental Management. EM-40 is the Office of Environmental Restoration which handles the decontamination and dismantlement of facilities. EM-60 is the Office of Nuclear Material and Facility Stabilization which deactivates and maintains surplus facilities.

Results

The total legacy of surplus facilities identified by the Department and managed by the Environmental Management program includes about 5,000 facilities. The Office of Nuclear Material and Facility Stabilization manages approximately 78 percent of them (approximately 4,000 facilities). The Office of Environmental Restoration manages the remaining 22 percent (approximately 1,000 facilities).

Figure 5-1 illustrates the breakdown of the 5,000 surplus facilities into process categories. Approximately 76 percent of them were used for or supported nuclear weapons production activities. Chemical separations processes for nuclear weapons production account for 24 percent of the 5,000 surplus facilities. Each remaining weapons category accounts for between 4 and 12 percent of the total number of surplus facilities except for weapons operations, which accounts for less than 1 percent. Nonweapons activities account for the remaining 24 percent of DOE's surplus facilities.

The distribution of facilities among the process categories generally accounts for all historic and current uses of each facility. Facilities used for both weapons and nonweapons activities are counted fractionally according to how much of the facility was used for each purpose. If a facility was used 50 percent of the time for weapons component fabrication and 50 percent for nonweapons activities, then one-half of the facility was counted in each of those two categories. Similar results were obtained when entire facilities were allocated to single processes based on their initial purpose or their primary historical missions.

Almost 55 percent of DOE's surplus facilities are located at Hanford and the Savannah River Site (see Figure 5-2). These sites played major roles in weapons production and also contributed substantially to nonweapons DOE programs. Almost 40 percent of the surplus facilities at Hanford are attributable to

Storage shed. This mobile barn at the Idaho National Engineering Laboratory functions as a maintenance storage shed. The large cylinders in the background are spent nuclear fuel casks from Germany, Japan, and the United States. *Spent Fuel Storage Cask Testing Pad, Test Area North, Idaho National Engineering Laboratory. March 17, 1994.*

Demolition of surplus facilities. This former uranium processing building at Weldon Spring has been deactivated, decontaminated, decommissioned, and demolished. Surplus facilities at many of the Department's Environmental Restoration sites are being similarly dismantled, reducing the size of this portion of the legacy of nuclear weapons production. *Building 201 (Green Salt Plant), Weldon Spring Plant, St. Charles County, Missouri. January 29, 1994.*

chemical separations and approximately 20 percent resulted from nonweapons research and production activities. Over 55 percent of the surplus facilities legacy at the Savannah River Site resulted from chemical separations and about 5 percent resulted from nonweapons activities. Rocky Flats, Nevada Test Site, and Idaho National Engineering Laboratory also have large numbers of surplus facilities. As a result, approximately 72 percent of the surplus facilities legacy is located in the states of Washington, South Carolina, Colorado, and Idaho.

METHODOLOGY AND DATA

Data Sources

Data on surplus facilities was gathered from two sources: a database of surplus facilities compiled by the Office of Nuclear Material and Facility Stabilization for DOE's 1996 Baseline Environmental Management Report (BEMR) to Congress and a database of release sites, facilities, and other units, called the Environmental Restoration Release Site Database developed by the Office of Environmental Restoration.

The database of surplus facilities compiled by the Office of Nuclear Material and Facility Stabilization evolved from a nationwide inventory of the number and status of DOE facilities across the nation which was conducted in 1993. This inventory, known as the Surplus Facilities Inventory and Assessment (SFIA), identified a nationwide total of over 20,000 facilities, including about 5,000 that were either surplus or expected to become surplus during the next five years. The SFIA provided a foundation for updated analyses conducted by the Office of Nuclear Material and Facility Stabilization for DOE's 1995 and 1996

BEMR efforts. The database containing the results of the most recent assessment identifies about 4,000 surplus facilities and is one of two data sources used to quantify the surplus facilities legacy in this report.

Management of some of the facilities in the 1996 BEMR database has already been transferred to the Office of Nuclear Material and Facility Stabilization. Other facilities are surplus but are still managed by other DOE organizations such as the Office of Defense Programs or the Office of Nuclear Energy.

The second source of data is a database of release sites and other units managed within DOE's Office of Environmental Restoration. The Environmental Restoration Release Site Database identifies approximately 1,100 facilities, including limited descriptive data on each facility. Contaminated environmental media at many of these facilities, are discussed in Chapter 4.

Data Issues and Assumptions

The primary data sources are (1) a database of about 4,000 surplus facilities developed by the Office of Nuclear Material and Facility Stabilization and (2) a database identifying about 1,100 surplus facilities managed by the Office of Environmental Restoration.

All facilities are counted equally in this analysis. Size and extent of contamination were not considered.

Multi-use and general-purpose facilities generally were attributed to more than one process category on the basis of their current and past uses.

Decommissioning of many of the facilities listed in the Office of Environmental Restoration database is underway. Some facilities have already been decommissioned since the currently available data were compiled. In the future, the Office of Environmental Restoration expects to receive additional facilities from the Office of Nuclear Material and Facility Stabilization for decommissioning.

Limitations, Uncertainties, and Assumptions

Of the four legacy elements discussed in this report, surplus facilities are the least well documented. Unlike waste and environmental media, which are stringently regulated, easier to measure, and carefully tracked, surplus facilities have only recently become the focus of centralized planning. Because surplus facilities are subject to fewer regulations or standards, only a limited amount of data has been compiled on a nationwide basis. As a result, the facilities analysis has several notable limitations.

The most important limitation of the facilities analysis used in this report is that all facilities were counted equally in the analysis, regardless of size or level of contamination, and a facility's risk or priority level had no impact on how it was analytically treated. DOE has compiled some data on facility size, contamination, and other characteristics in a database of all DOE facilities, the Facility Inventory Management System, for the purpose of property and asset management. However, this database does not identify which facilities are surplus, and it did not contribute to this analysis.

Another limitation of the facilities data is double-counting. A single facility could appear in both databases depending on which DOE programs are currently responsible for various activities within the facility. DOE developed the two databases for purposes unrelated to this analysis and some overlap occurred in the present analysis since the data were not intended to be aggregated. However, based on spot checks of the facilities named in the databases, DOE believes the number of double-counted facilities is small (on the order of ten) and does not affect the overall results.

The assumptions required to analyze the data came in determining the nuclear weapons process categories and nonweapons activities corresponding to each surplus facility. These determinations were based on the site where each facility is located, the activities conducted at the site and, in some cases, the activities conducted within individual facilities. In general, the assumptions made in the facilities analysis are consistent with those made for related waste and environmental media.

The most important assumption involved fractional allocations of multiple-use or general-purpose facilities. The buildings at the uranium enrichment plants, for example, were partially attributed to both

The Defense Waste Processing Facility at the Savannah River Site and other facilities currently in operation are not included in the inventory of legacy facilities in this report. Nevertheless, by introducing high-level radioactive waste into this facility when it began operating in early 1996, the Department committed itself to decontaminating and decommissioning the facility when it will have completed its mission. That mission is expected to last three decades as the facility converts 34 million gallons of high-level radioactive waste into thousands of glass logs. *Defense Waste Processing Facility, Savannah River Site, South Carolina. January 7, 1994.*

weapons and nonweapons activities, according to the number of separative work units performed for each purpose and the relative length of time each mission was performed (see text box "Methodology for Attributing Uranium Enrichment Wastes" in Chapter 3). As another example, fractions of some administrative and support buildings at Hanford and the Savannah River Site were attributed to several weapons production activities based on the overall general proportion of activities conducted at each site. The total number of facilities allocated to each activity was rounded to the nearest whole number. The approach of allocating a fraction of a facility to each of its historical uses is only one way to determine how much of the surplus facilities legacy resulted from weapons production. This approach was selected because it could be implemented with the limited data available and because it was consistent with similar approaches used to attribute waste, media, and materials in inventory to weapons and nonweapons activities. As noted above, other approaches were explored in the preparation of this report, and were found to give similar results.

SUMMARY

Approximately 5,000 surplus facilities have been identified in this study. These facilities represent the most current estimate available at the time this report was published; however, the number of surplus facilities will fluctuate over time. As operating sites shut down, additional facilities will be declared surplus, and the inventory of legacy facilities will grow; as surplus facilities become decommissioned or other facilities are reused, the inventory of legacy facilities will decrease.

6. Materials in Inventory

Depleted uranium metal billets were once an essential element in the production of weapons-grade plutonium. Today, billets like these are one of the Department of Energy's many types of materials in inventory. Each billet weighs about 1,100 pounds. *Reactive Metals, Inc., Ashtabula, Ohio. June 19, 1984.*

Overview

For 50 years during the Cold War era, the Department of Energy and its predecessor agencies continually acquired, consumed, and produced a wide variety of nuclear and nonnuclear materials to produce weapons and conduct other Department missions. Some of these materials accumulated in significant quantities. When nuclear weapons production was suspended in the early 1990s, the Department had significant inventories of materials on hand. Although the Department still maintains a limited nuclear weapons production capability, the vast majority of these materials are no longer needed to meet current missions. Because of their quantity and characteristics, and the management and disposition challenges they pose, materials in inventory constitute a significant element of the environmental legacy of nuclear weapons production.

In February 1995, DOE launched the Materials in Inventory (MIN) Initiative, a Department-wide effort to improve management, reduce inventories, and reduce costs for materials that no longer have clearly defined or immediate uses. The purpose of this initiative was to assess the Department's inventory, analyze its current management practices, identify its disposition plans, consolidate information on its environmental and safety vulnerabilities, and identify barriers to disposition.[1]

The total amount of materials in inventory is relatively small in comparison with other legacy elements; however, the materials require special management. While some materials in inventory are valuable

[1] *Taking Stock: A Look at the Opportunities and Challenges Posed by Inventories from the Cold War Era, DOE/EM-0275, the report of the MIN Initiative, contains detailed information on the management practices and disposition options for the ten categories of materials in inventory. Taking Stock is the source of the quantitative information provided in this report.*

Categories of Materials in Inventory

NUCLEAR MATERIALS

Natural and enriched uranium includes natural uranium, highly enriched uranium, and low enriched uranium.

Natural uranium is the raw material from which highly enriched uranium and low enriched uranium are produced. It also was formerly used as fuel in some DOE plutonium production reactors.

Highly enriched uranium (HEU) is a form of uranium used as fissile material in nuclear weapons components and in some nuclear reactor fuels.

Low enriched uranium (LEU) is a form of uranium used as fuel for nuclear power reactors, including DOE plutonium-production reactors.

Depleted uranium is a byproduct of the process that produces highly enriched uranium and low enriched uranium. It is used as a raw material to produce plutonium.

Plutonium and Other Nuclear Materials Management and Safeguards System-tracked materials.

Plutonium is a radioactive metal produced from uranium. The isotope plutonium-239 is used as a fissile material in nuclear weapons.

Other NMMSS-tracked materials include nuclear materials such as deuterium, thorium, uranium-233, and americium used for nuclear research and weapons production.

Spent nuclear fuel is fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated. Spent nuclear fuel also includes uranium and neptunium target materials, blanket subassemblies, pieces of fuel, and debris.

Lithium and lithium compounds are used in the manufacture of nuclear weapon systems, and as raw materials for producing tritium, a radioactive material used in nuclear weapons. While lithium is considered a nuclear material, it is not radioactive.

NONNUCLEAR MATERIALS

Scrap Metal and Equipment includes (1) Scrap metal which comprises worn and surplus metal parts and pieces from old buildings, past maintenance, and renovation activities, and other sources; and (2) equipment which is equipment and machinery used for construction, production, or manufacturing, and associated spare parts and hand tools.

Lead is a dense and malleable metal commonly used to shield workers from nuclear radiation.

Sodium is an easily liquefied metal, primarily used as a coolant in nuclear fast breeder reactors.

Chemicals include a wide variety of materials, including acids, bases, solvents, and gases, used for such diverse purpose as scientific research, chemical processing, manufacturing, water treatment, and building and equipment decontamination.

Weapons components include nuclear weapons parts and sub-assemblies, as well as the tooling, testing, and handling equipment used in the production of nuclear weapons.

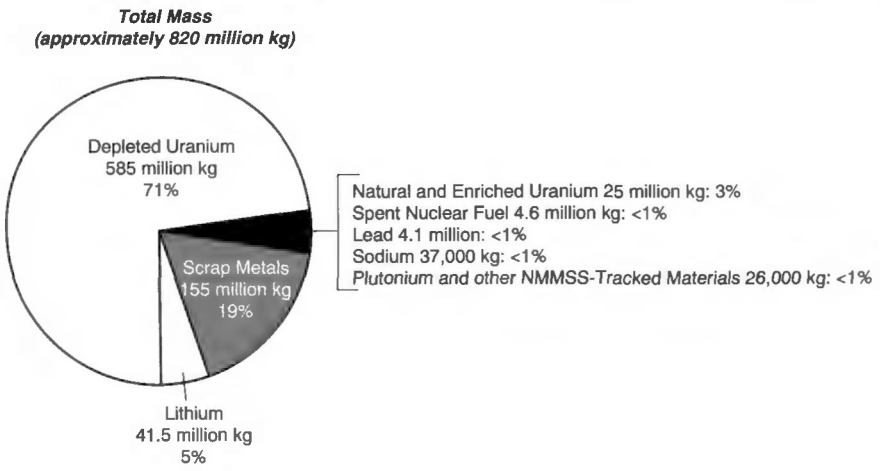
For more detailed information about these materials in inventory, see *Taking Stock: A Look at the Opportunities and Challenges Posed by Inventories from the Cold War Era.*

products, others pose unique risks to human health and the environment or have limited disposition options. Portions of some materials, such as lead, lithium, and scrap metal, have been sold or reused and recycled, but other materials, such as plutonium, can never be released into the public domain.

Definitions and Categories

"Materials in Inventory" are all materials in storage at DOE-owned facilities that are not currently in use, have not been designated as waste, and have not been set aside for national security purposes by the Nuclear Weapons Council (a panel consisting of high level executives from the Departments of Energy and Defense). For nuclear materials tracked by the Nuclear Materials Management and Safeguards System (NMMSS), "in use" is considered to be synonymous with materials in "active" programs, which prescribes use or contemplated use within a two-year period, in accordance with DOE Order 5660.1B, *Nuclear Material Management*. For other materials, "not in use" means the materials have not been used for at least one year and are not expected to be used for the coming year.

Figure 6-1. Summary of Materials in Inventory



Notes:

(1) Data compiled from the Materials in Inventory Report - TAKING STOCK: A LOOK AT THE OPPORTUNITIES AND CHALLENGES POSED BY INVENTORIES FROM THE COLD WAR.

(2) This report does not include quantitative information on chemicals, weapons components, or equipment. In TAKING STOCK chemicals are quantified in various units depending on material; weapons components are quantified in pieces.

(3) SNF quantities are in total mass (kg). The 4,600 metric tons of SNF include about 2,600 metric tons of heavy metal.

(4) Totals may not add due to rounding.

(5) Includes plutonium and HEU from planned nuclear weapon dismantlement at Pantex.

In the MIN Initiative, the Department focused on ten specific categories of both nuclear and nonnuclear materials. These ten categories do not encompass the entire universe of materials in inventory; other materials at DOE-owned facilities fall within this element of the legacy. The ten categories of materials were chosen because they exist in significant quantities; have been the subject of management concerns in the past, or are likely to be of future concern; or are not under a specific DOE program to ensure their comprehensive management. As DOE continues to improve its inventory management systems, it will make further progress in identifying, quantifying and characterizing other materials in inventory.

Key Observations of the Materials in Inventory Legacy

- Over 400 million kilograms of nuclear and nonnuclear materials in inventory have resulted from weapons production. An additional 420 million kilograms of materials in inventory have resulted from nonweapons activities.
- Overall materials in inventory from both weapons and nonweapons activities are present at 44 sites in 19 states.
- Over 85 percent by mass of all materials in inventory is maintained at the Paducah Gaseous Diffusion Plant in Kentucky, the Portsmouth Gaseous Diffusion Plant, in Ohio, and the Oak Ridge K-25 Site, in Tennessee. Almost 80 percent of this material is depleted uranium. When the Fernald site in Ohio and Y-12 site in Tennessee are included, 92 percent (by mass) of all DOE material in inventory mass of this element located within the states of Tennessee, Kentucky, and Ohio.
- Depleted uranium comprises 71 percent of the mass of all materials in inventory; scrap metal makes up 19 percent; lithium represents 5 percent.
- Approximately 38 percent by mass of all materials in inventory is attributable to uranium and lithium enrichment supporting nuclear weapons production. Nearly all of the materials in inventory attributed to nonweapons activities resulted from uranium enrichment.
- Spent nuclear fuel constitutes less than 1 percent of the total mass of DOE's material in inventory; it contains almost all of the radioactivity in the materials in inventory category.

This report incorporated quantitative data from eight of the ten MIN Initiative categories. The two remaining categories, chemicals and weapons components, were quantified in units that could not be converted to mass. The equipment portion of the scrap metal and equipment category also has this limitation.

Maintenance of uranium hexafluoride cylinders. An Oak Ridge worker uses ultrasound to evaluate the effects of corrosion on a steel cylinder containing depleted uranium hexafluoride—the material left over from the uranium enrichment process. The Department of Energy owns over 46,000 cylinders of these enrichment "tails," weighing 10 to 14 tons each. By mass, depleted uranium makes up over 70 percent of the Department's Materials in Inventory. About one-third of the 585,000 metric tons of this material is a result of nuclear weapons production; most of the rest is from enrichment for commercial nuclear power plant fuel. *K-1066-K Cylinder Yard, K-25 Site, Oak Ridge, Tennessee. January 9, 1994.*

Results

Figure 6-1 presents the relative amounts of the eight categories of materials in inventory that have been quantified in terms of their mass. Depleted uranium accounts for about 71 percent of the mass of materials in inventory while scrap metal makes up 19 percent. The other four nuclear materials make up another 9 percent by mass of the materials in inventory, and the remaining two nonnuclear materials make up about 1 percent.

The different categories of materials in inventory contain a variety of radionuclides. As a result, many of the hazards associated with radioactive waste are also present for materials in inventory (e.g., nuclear criticality, radiation and security issues). Four of the materials in inventory categories are inherently radioactive: plutonium and other NMMSS-tracked materials, spent nuclear fuel, natural and enriched uranium, and depleted uranium.

Most of the radioactivity in materials in inventory is in spent nuclear fuel, which contains a broad spectrum of radionuclides with varying half-lives. Materials in the plutonium, natural and enriched uranium, and depleted uranium categories contain a smaller amount of radioactivity and a more limited variety of radionuclides. Radioactivity is also present in some of the nonnuclear materials in inventory due to radiological contamination or activation. For example, some of the lithium shields at Oak Ridge National Laboratory are radioactively contaminated and two have become radioactive as a result of neutron exposure. Large quantities of sodium used for reactor coolant and shielding are also radioactive (approximately 500,000 gallons in DOE inventory, 10 percent of which is classified as MIN). In addition, a

Radioactive scrap metal. Slightly radioactive parts of obsolete uranium enrichment equipment lie in a contaminated scrap-metal yard at Oak Ridge. These 6- and 9-foot wide spun-aluminum disks are categorized as materials in inventory rather than as waste because this metal may be recycled. DOE is recycling some contaminated steel as containers for radioactive waste. Scrap metal constitutes about 20 percent of the Department's Materials in Inventory. *K-770 Contaminated Scrap Metal Yard, K-25 Site, Oak Ridge, Tennessee. January 10, 1994.*

portion of the scrap metal in inventory is radioactively contaminated. In some cases, these radioactively contaminated or activated materials may pose risks to human health and the environment similar to those posed by intrinsically radioactive nuclear materials.

Data on the radioactive content of some materials in inventory are present at the DOE sites that manage the materials. These data have not been compiled at a national level.

Some materials in inventory exhibit hazards due to their chemical properties. For example, uranium hexafluoride, the chemical form of most of the depleted uranium inventory, can produce hydrofluoric acid, a highly corrosive and toxic gas, when exposed to moisture. Materials in inventory with hazardous chemical properties must be stored under special conditions to mitigate these potential hazards.

About half (49 percent) of the materials in inventory legacy has resulted from nuclear weapons production (Figure 6-3). The remaining materials resulted from supplying enriched uranium to the NNPP and commercial nuclear power reactors, various DOE research programs, and other nonweapons activities. About 38 percent of all materials in inventory are attributable to uranium and lithium enrichment for weapons production (Table 6-1). Uranium and lithium enrichment have resulted in nearly all the inventory of depleted uranium (DU), scrap metal, and lithium. Between 5 to 10 kilograms of depleted uranium result for every kilogram of low enriched uranium (LEU) produced, and about 200 kilograms of DU accrue for every kilogram of highly enriched uranium. Similarly, most of the lithium is isotopically depleted in lithium-6, resulting from lithium enrichment, and most of the scrap metal is the result of refurbishment or dismantlement of uranium enrichment plants. Mining, milling, and refining and chemical separation each generated about 4 percent of the materials in inventory.

Table 6-1. Materials in Inventory Categorized by Process

Process	Depleted Uranium (kg)	Low Enriched Uranium (kg)	Natural Uranium (kg)	High Enriched Uranium (kg)	Lithium (kg)	Sodium (kg)	Lead (kg)	Plutonium & Other NMMSS Materials (kg)	Scrap Metal (kg)	Spent Nuclear Fuel (kg)	TOTAL Mass (kg)	Percent
1. Mining, Milling, and Refining	1,600,000	2,680,000	16,700,000			2,780	30,300		9,840,000		31,000,000	4%
2. Enrichment (uranium and lithium)	170,000,000	1,000			41,600,000	320	2,950		97,000,000		310,000,000	38%
3. Fuel and Target Fabrication	4,600,000	3,190,000	406,000	22,000		260	6,270		8,100,000		16,000,000	2%
4. Reactor Operations							525,000		1,600,000	560,000	2,600,000	<1%
5. Chemical Separations	20,000,000	1,400,000	1,500	2,840			77,400	1,710,000	9,400,000		33,000,000	4%
6. Component Fabrication	62,000		68,000	88,000		1,600	5,400	15,000	3,500,000		3,700,000	<1%
7. Weapons Operations				16,700			2,100	21,300	290,000		330,000	<1%
8. Research, Development, and Testing	314,000	17,100	29,000	4,210	1,100	260	939,000	4,000	2,100,000	2,800	3,400,000	<1%
9. Nonweapons - Other	350,000,000	85,500	7,000	18,000	20	566,000	2,400,000	28,700	12,000,000	3,500,000	370,000,000	45%
10. Nonweapons - Naval Support	39,000,000			22,500			127,000		11,000,000	560,000	50,000,000	6%
TOTAL MASS	585,000,000	7,370,000	17,200,000	174,000	41,600,000	571,000	4,110,000	1,780,000	155,000,000	4,650,000	820,000,000	100%
Percent of Total	71%	1%	2%	<1%	5%	<1%	1%	<1%	19%	0%	100%	

Notes:

(1) Data for all materials except SNF compiled from the Materials in Inventory Report – TAKING STOCK: A LOOK AT THE OPPORTUNITIES AND CHALLENGES POSED BY INVENTORIES FROM THE COLD WAR ERA.

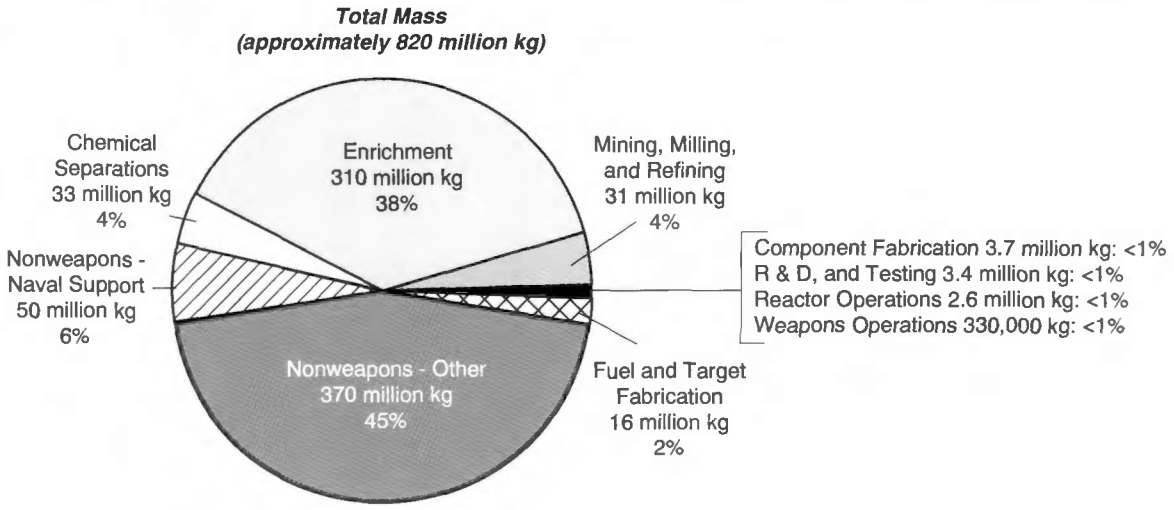
(2) This report does not include quantitative information on chemicals, weapons components, or equipment. In Taking Stock, *chemicals are quantified in various units depending on material; weapons components are quantified in pieces.*

(3) SNF quantities are in total mass (kg). The 4,600 metric tons of SNF include about 2,600 metric tons of heavy metal.

(4) Totals may not add due to rounding.

(5) Includes plutonium and HEU from planned nuclear weapons dismantlement at Pantex.

Figure 6-2. Materials in Inventory Mass Categorized by Process



Each nuclear weapons production process resulted in different categories of materials in inventory (Table 6-1). While uranium and lithium enrichment produced much of the legacy of depleted uranium, scrap metal, and lithium, chemical separation resulted in uranium, lead, and scrap metal, as well most plutonium and other NMMSS-tracked materials. Spent nuclear fuel is the result of reactor operations.

The materials in inventory resulting from nonweapons activities are primarily the result of uranium enrichment for commercial and naval nuclear power reactors. This activity produced most of the inventory of depleted uranium. Nonweapons activities are responsible for most of the Department's lead and sodium, as well as most of the Department's spent fuel, much of which came from the Hanford N Reactor during the period when the reactor produced electricity and fuel-grade plutonium for nonweapons purposes.

The materials in inventory legacy is stored at 44 sites in 19 states (Table 6-2). By mass, over 85 percent of all materials in inventory is maintained at the three gaseous diffusion plants in Paducah, Kentucky; Portsmouth, Ohio; and Oak Ridge, Tennessee. Almost 80 percent of the total mass of materials in inventory at these three sites is depleted uranium. The Y-12 Plant in Tennessee and the Fernald Environmental Management Project in Ohio also store significant amounts of materials in inventory. Consequently, about 92 percent by mass of the materials in inventory are located in Tennessee, Kentucky, and Ohio.

METHODOLOGY AND DATA

Data Sources

Data on materials in inventory came primarily from a single source, *Taking Stock: A Look at the Opportunities and Challenges Posed by Inventories from the Cold War Era* (January 1996) and the accompanying database prepared as part of the MIN Initiative. The database provided information on the amount of each category of material at each site. For several types of materials, the site-specific amount in each category was further subdivided according to material location, subtype, or form. The database provided information on the mass (in kilograms) of each category of material.

Data on nuclear materials in the database developed under the MIN Initiative came from the Department's Nuclear Materials Management Safeguard System (NMMSS) database, which records nuclear material inventories and transactions by location and individual project, including nuclear

Table 6-2. Location and Mass of Materials in Inventory

Site	Weapons (kg)	Nonweapons (kg)
Paducah Gaseous Diffusion Plant (KY)	170,000,000	250,000,000
Portsmouth Gaseous Diffusion Plant (OH)	89,000,000	110,000,000
K-25 Site (TN)	60,000,000	42,000,000
Savannah River Site (SC)	40,000,000	360,000
Y-12 Plant (TN)	11,000,000	
Fernald Environmental Management Project (OH)	11,000,000	
Hanford Site (WA)	7,000,000	2,900,000
Nevada Test Site (NV)	810,000	
Idaho National Engineering Laboratory (ID)	610,000	3,000,000
Lawrence Livermore National Laboratory (CA)	500,000	
Pantex Plant (TX)	330,000	
Los Alamos National Laboratory (NM)	110,000	
Sandia National Laboratories/New Mexico (NM)	110,000	70
Waste Isolation Pilot Plant (NM)	100,000	
Rocky Flats Environmental Technology Site (CO)	77,000	
Oak Ridge National Laboratory (TN)	76,000	2,500,000
Reactive Metals Incorporated (OH)	71,000	
Grand Junction Projects Office (CO)	21,000	
Sandia National Laboratories/California (CA)	330	
Pinellas Plant (FL)	150	
Kansas City Plant (MO)	83	
Mound Site (OH)	57	25
Other Nonweapons Sites (Various)	—	10,000,000
TOTAL	400,000,000	420,000,000

Notes:

(1) Data completed from the Materials in Inventory Report - TAKING STOCK: A LOOK AT THE OPPORTUNITIES AND CHALLENGES POSED BY INVENTORIES FROM THE COLD WAR ERA.

(2) This report does not include quantitative information on chemicals or weapons components. In TAKING STOCK, chemicals are quantified in various units depending on materials; weapons components are quantified in pieces.

(3) SNF quantities are in total mass (kg). The 4,600 metric tons of SNF include about 2,600 metric tons of heavy metal.

(4) Totals may not add due to rounding.

(5) Naval reactor sites are located in Maine, Washington, Hawaii, Virginia, South Carolina, and California.

(6) Includes plutonium and HEU from planned nuclear weapons dismantlements at Pantex.

materials managed by Nuclear Regulatory Commission licensees, nuclear materials present in DOE-managed spent nuclear fuel, and nuclear materials in the Department of Defense nuclear weapons stockpile. For the MIN Initiative, NMMSS data was reviewed and updated at the site level. Spent fuel inventories came from the Department's Integrated Spent Nuclear Fuel Database.

For this report, the determination of whether individual materials were the result of weapons production or nonweapons activities was made primarily by the site where the material was located. Site location was also used to determine the specific weapons process category associated with the material. For materials at sites performing more than one activity, other descriptive data in the database was usually adequate to assign the material to a nuclear weapons process category or a nonweapons activity.

The depleted uranium inventories at the Department's gaseous diffusion plants were allocated to nuclear weapons and nonweapons activities based on enrichment production records. The scrap metal inventories at the gaseous diffusion plants were allocated using a method similar to that used to allocate waste at the enrichment plants. (see text box, "Uranium Enrichment and Weapons Production" contained in Chapter 3), but accounting for the fact that much of the scrap metal came from plant refurbishments and other activities that took place before most of the enrichment occurred for commercial nuclear power plant fuel.

Spent nuclear fuel storage. Corroding spent fuel elements from Hanford's N Reactor are stored in an unlined concrete pool in the 105 K-West area. Steel grates suspended above the surface of the water allow workers to access all areas of the pool. Corrosion of the fuel elements enables radioactive materials to escape into pool water, posing a hazard to workers and the environment. To reduce the danger, the Department is building a new storage facility for this corroding fuel away from the Columbia River. At this new facility, engineers will dry out the spent fuel and store it in special casks to await storage in a geologic repository. *105 K-West Basin, 100 K-Area, Hanford Site, Washington. December 19, 1993.*

Limitations, Uncertainties, and Assumptions

The quality of the data varies among the ten categories of materials addressed by the MIN Initiative. There is a high level of certainty associated with the Department's inventories of nuclear materials. The Department tracks the quantity and location of nuclear materials very closely through NMMSS. Each site verified the quantity and location of nuclear materials no longer needed for DOE national security purposes during the MIN Initiative. However, there is considerably less certainty regarding the quantity of nuclear materials being used for nondefense programs because information on the current use of nuclear materials is not contained in by NMMSS and the information available from other sources is not as detailed.

The data for nonnuclear materials are generally less exact than those for nuclear materials. The level of certainty associated with data for nonnuclear materials varies for several reasons. Inventory data for some materials has not been compiled at the site level. For example, some sites do not maintain sitewide inventory records of scrap metal, lead, and equipment. As a result, the national inventory records of these materials are incomplete. Equipment and chemicals are difficult to identify and quantify for several reasons, such as their heterogeneity and the lack of a uniform unit of measure. Equipment and chemical quantities are measured in a variety of mass, volume, item count (e.g., number of containers or lots), or dollar value units which cannot be easily combined. Weapons components were reported by pieces and warehouse space requirements rather than mass. As a result, the mass of materials in the equipment and weapons components categories has not been determined under the MIN Initiative, and this report does

not include quantitative information on these categories. Also, the MIN Initiative contains data on only a discrete subset of chemicals identified as "Special MIN Chemicals" that includes chemicals of particular stakeholder concern.[2]

SUMMARY

Nuclear weapons production generated a legacy that encompasses significant amounts of a diverse range of materials. Many of these materials fall into five distinct categories of nuclear materials (depleted uranium, natural and enriched uranium, plutonium and other NMMSS-tracked materials, lithium, and spent nuclear fuel) and five categories of nonnuclear materials (scrap metal and equipment, sodium, lead, chemicals, and weapons components). Data on the mass of material in each category is available, except for equipment, some chemicals, and weapons components. The quality of data available varies by category, although most uncertainties are in the data for nonnuclear materials. In terms of mass, most of the materials in inventory legacy is depleted uranium, a byproduct of the uranium enrichment process. However, the greatest portion of depleted uranium resulted from nonweapons activities. Spent nuclear fuel, generated by reactor operations for both weapons and nonweapons purposes, contains most of the radioactivity in the Department's Materials in Inventory.

In addition to the ten categories of materials in inventory identified by DOE, there may be other categories of materials that have not yet been defined or studied. However, most of the materials with major management and disposition concerns appear in the ten identified categories.

Materials in Inventory Data Issues

Mass data on eight categories of materials in inventory are included in this report. Data on the mass of equipment, weapons components, and most chemicals are not included.

In general, data on nonnuclear material categories do not have the same level of certainty as data on nuclear materials.

There may be other materials that meet the definition of materials in inventory in other categories in addition to those studied by the MIN Initiative. Data on the quantities of these materials have not been compiled.

The nuclear and nonnuclear materials covered by this report pose significant management and disposition challenges to the Department because of their quantity and their unique physical, chemical, and radiological characteristics. Current DOE plans include recycling some materials such as lead and scrap metal, and selling some uranium scrap metal and lithium to commercial industries. DOE plans to dispose of spent fuel in a geologic repository pursuant to the Nuclear Waste Policy Act. For other materials, particularly plutonium, disposition is being determined through the National Environmental Policy Act process.

[2] *The MIN Initiative obtained information on the masses of all reported "Special MIN Chemicals," a subset of this MIN category which includes chemicals of particular stakeholder concern. This report does not include this inventory data as it does not give a complete picture of this category. For more information, see* TAKING STOCK.

APPENDICES

APPENDIX A

HISTORY OF THE ADMINISTRATION OF UNITED STATES NUCLEAR WEAPONS PROGRAMS

The nuclear weapons program of the United States began with an August 1939 letter from Albert Einstein to President Franklin D. Roosevelt informing him of the recent research on nuclear chain reactions in uranium. Two German physicists, Otto Hahn and Fritz Strassman, had discovered the process of fission in December 1938. After Einstein alerted him to the possibility of harnessing this phenomenon to produce extremely powerful bombs, Roosevelt established a joint Army-Navy committee to further study this question. In November 1939, this "Uranium Committee" recommended that the military begin funding fission chain reaction research, already being conducted at several American universities.

By the time the Uranium Committee made its recommendation, Europe was at war, commencing with the German invasion of Poland on September 1, 1939. As the war in Europe intensified, Roosevelt established the National Defense Research Committee to oversee the work of the Uranium Committee and other Government scientific research projects, including those on radar and anti-submarine warfare. Even before the United States' entry into the War, the Uranium Committee continued to recommend government funding of chain reaction and isotope separation research. Concurrently, American universities continued their research, including the discovery, in early 1941 at the University of California in Berkeley, of an artificially-produced fissile element, soon named "plutonium."

In June 1941, the National Defense Research Committee re-formed into an advisory board to the Office of Scientific Research and Development and the S-1 Committee replaced the Uranium Committee. A series of reports by the National Academy of Sciences as well as the British MAUD committee[1] report in 1941 emphasized the feasibility of the atomic bomb and the need for further research. In January 1942, a month after the Japanese attack on Pearl Harbor and the entry of the United States into the war, President Roosevelt approved the development of the atomic bomb. The project was established under the U.S. Army Corps of Engineers Manhattan Engineer District (MED) in August 1942.[2]

The Manhattan Engineer District, commanded by General Leslie R. Groves, oversaw all aspects of the wartime atomic bomb program, including scientific research, the acquisition of raw materials, the construction and operation of facilities, and the development, manufacturing, and testing of the first atomic weapons.

Security and secrecy were also the responsibility of the MED. The existence of the Manhattan Project and the atomic bomb was not revealed to the public until August 6, 1945, after the destruction of Hiroshima.

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[1] *"MAUD" is a code name for the committee, not an acronym. Rhodes, Richard,* The Making of the Atomic Bomb *(New York: Simon & Schuster, 1986), pg. 341.*

[2] *A brief history of the Manhattan project and the events that led up to it can be found in F. G. Gosling,* The Manhattan Project: Making the Atomic Bomb, *DOE/HR-0096 (Washington, D.C.: U.S. Government Printing Office, September 1994.) More detailed historical information can be found in: Hewlett, Richard G. and Oscar Anderson, Jr.,* The New World, 1939-1946, *Volume I of* A History of the United States Atomic Energy Commission *(University Park: Pennsylvania State University Press, 1962); Jones, Vincent C.,* Manhattan: The Army and the Atomic Bomb *(Washington, D.C.: U.S. Government Printing Office, 1985); Rhodes, Richard,* The Making of the Atomic Bomb *(New York: Simon & Schuster, 1986); and Smyth, Henry D.,* A General Account of the Development of Methods of Using Atomic Energy for Military Purposes Under the Auspices of the United States Government, 1940-1945 *(Washington, D.C.: U.S. Government Printing Office, 1945).*

The Atomic Energy Commission

After intense debate, Congress decided to transfer the United States' atomic energy programs from the Army to a civilian agency. The MED was superseded on January 1, 1947 by the United States Atomic Energy Commission (AEC) [3] established by the Atomic Energy Act of 1946. AEC was responsible for all aspects of the development and regulation of nuclear technology, but chiefly the management of the nuclear weapons complex. The AEC expanded and centralized the weapons complex into a network of Government-owned, contractor-operated facilities by the mid 1950s.

The AEA has been amended several times, but most significantly in 1954 to encourage the peaceful use of atomic energy. After 1954, the AEC established numerous civilian atomic energy programs. Basic physics research and the development and commercialization of nuclear power and other industrial uses of nuclear technology were the main focus of the "Atoms for Peace" program.

ERDA and the Department of Energy[4]

Following the energy crisis of the early 1970s, the executive and legislative branches began a series of reorganizations in an effort to better coordinate the federal government's energy policies and programs, including the atomic energy programs of the AEC. AEC was abolished by the Energy Reorganization Act in 1974. Regulatory authority was transferred to the newly-formed Nuclear Regulatory Commission (NRC) while the AEC's research and development activities, including the nuclear weapons complex, were given to the newly-created Energy Research and Development Administration (ERDA).

In 1977, the Department of Energy Organization Act created a cabinet level agency, the Department of Energy (DOE) and transferred ERDA's responsibilities to this new entity. To this date, the Department of Energy continues to oversee the nuclear weapons complex. To manage the Department's waste management, environmental remediation, and environmental compliance activities, the Secretary of Energy consolidated these functions in 1989 into the Office of Environmental Management. The Office of Environmental Management assumed a majority of these responsibilities, and the budgets to implement them, from functions previously exercised by the Office of Defense Programs, and, to a lesser degree, from the Offices of Nuclear Energy and Energy Research.

[3] *A comprehensive history of the AEC can be found in Hewlett, Richard G. and Francis Duncan. Atomic Shield, 1947-1952, Volume II of A History of the United States Atomic Energy Commission (University Park: Pennsylvania State University Press, 1969); and Hewlett, Richard G. And Jack M. Holl, Atoms for Peace and War, 1953-1961, Volume III of A History of the United States Atomic Energy Commission (Berkeley: University of California Press, 1989).*

[4] *The history of the DOE is described in Fehner, Terence K. And Jack M. Holl, Department of Energy, 1977-1994: A Summary History, DOE/HR-0098 (U.S. Government Printing Office, 1994). The events leading up to the establishment of the Environmental Management program are described in Gosling, F.G., Closing the Circle: The Department of Energy and Environmental Management, 1942-1994, DOE History Division, Draft, March 1994.*

Appendix B

The Eight Major Processes of the Nuclear Weapons Complex

Nuclear weapons production in the United States was a complex series of integrated manufacturing activities executed at multiple sites across the country. These activities have been grouped into eight major processes:

- *mining, milling, and refining* of uranium;
- *isotope separation* of uranium, lithium, boron and heavy water;
- *fuel and target fabrication* for production reactors;
- *reactor operations* to irradiate fuel and targets to produce nuclear materials;
- *chemical separations* of plutonium, uranium, and tritium from irradiated fuel and target elements;
- *component fabrication* of both nuclear and nonnuclear components;
- *weapon operations*, including assembly, maintenance, modification, and dismantlement of nuclear weapons; and
- *research, development, and testing.*[1]

Figure B-1 illustrates the major design elements of modern nuclear weapons in a generic manner, and explains how the weapons work. Figure B-2, "How Nuclear Weapons Are Made," illustrates the interrelationship among the eight processes.

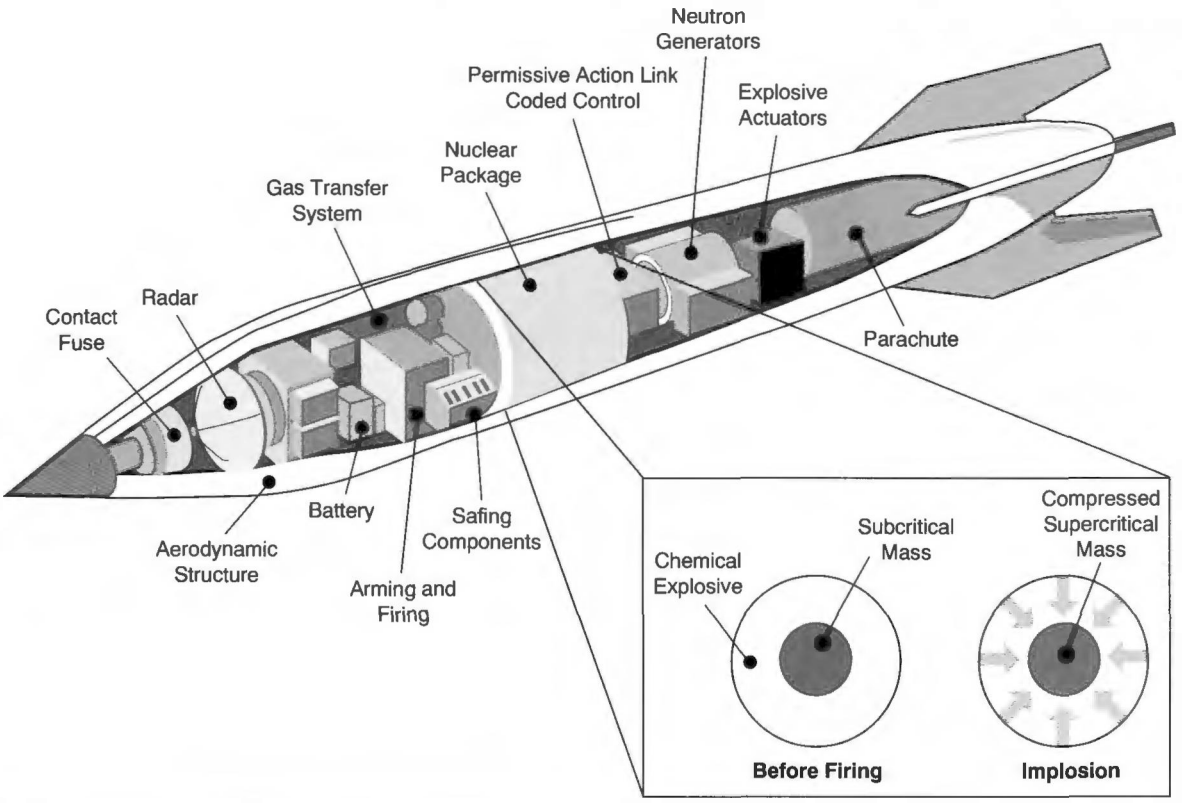
Weapons complex configuration and weapons design and manufacturing processes in the U.S. have changed substantially from the Manhattan Project era. Laboratories and production plants developed better technologies to increase their capabilities, output, and efficiency. The weapons themselves have evolved considerably, becoming smaller, lighter, more powerful and versatile, safer, and more reliable. The federal government centralized the weapons complex in the early 1950s. By the mid-1960s, stockpiles of some key weapons materials became plentiful enough that the complex ceased producing them.

This appendix traces the evolution of each of the eight functional processes. It is important to note that the sites and processes changed over time as weapons designs, stockpile requirements, and technology evolved. Figure B-3 is comprised of four charts that illustrate the flow of materials through the nuclear weapons complex during four key stages in its history. Detailed discussions of the historical evolution of each of the eight nuclear weapons complex production processes are to be found in the sections following these charts.

In addition, this appendix examines the flow of nuclear and radioactive materials and suppliers of special materials, components and equipment. Due to the large scope of the nuclear weapons complex operation over the past fifty years, however, it is not possible to catalogue all the sites and contractors that contributed to it; nor is it possible to discuss every waste stream or release of contaminants.

[1] *Nuclear weapons research, development, and testing take place concurrent with the other seven processes. Research and development are mostly complete before component fabrication begins, but testing may continue until a weapon system is retired from the stockpile.*

Figure B-1. Generic Design Elements of a Modern Nuclear Weapon



Nuclear explosions are produced by initiating and sustaining nuclear chain reactions in highly compressed material which can undergo both fission and fusion reactions. Modern strategic, and most tactical, nuclear weapons use a nuclear package with two assemblies: the primary assembly, which is used as the initial source of energy, and the secondary assembly, which provides additional explosive release. The primary assembly contains a central core, called the "pit," which is surrounded by a layer of high explosive. The "pit" is typically composed of plutonium-239 and/or highly enriched uranium (HEU), and other materials. HEU contains large fractions of the isotope uranium-235.

Primary Detonation

The primary nuclear explosion is initiated by detonating the layer of chemical high explosive that surrounds the "pit" which in turn drives the pit material into a compressed mass at the center of the primary assembly. Compression causes the fissile material to become supercritical. A neutron generator initiates a fission chain reaction in this supercritical mass. The implosion process is illustrated in the inset.

Boosting

In order to achieve higher explosive yields from primaries with relatively small quantities of pit material, a technique called "boosting" is used. Boosting is accomplished by injecting a mixture of tritium (T) and deuterium (D) gas into the pit. The implosion of the pit along with the onset of the fissioning process heats the D-T mixture to the point that the D-T atoms undergo fusion. The fusion reaction produces large quantities of very high-energy neutrons which flow through the compressed pit material and produce additional fission reactions.

Secondary Activation

Radiation from the explosion of the primary is contained and used to transfer energy to compress and ignite a physically seperate secondary component containing thermonuclear fuel. The secondary assembly is composed of lithium deuteride uranium and other materials. As the secondary implodes, the lithium, in the isotopic form lithium-6, is converted to tritium by neutron interactions, and the tritium product in turn undergoes fusion with the deuterium to create a thermonuclear explosion.

Nonnuclear Components

Nonnuclear components include contact fuses, radar components, aerodynamic structures, arming and firing systems, gas transfer systems, permissive action link coded controls, neutron generators, explosive actuators, safing components, batteries, and parachutes.

Figure B-2. How Nuclear Weapons are Made

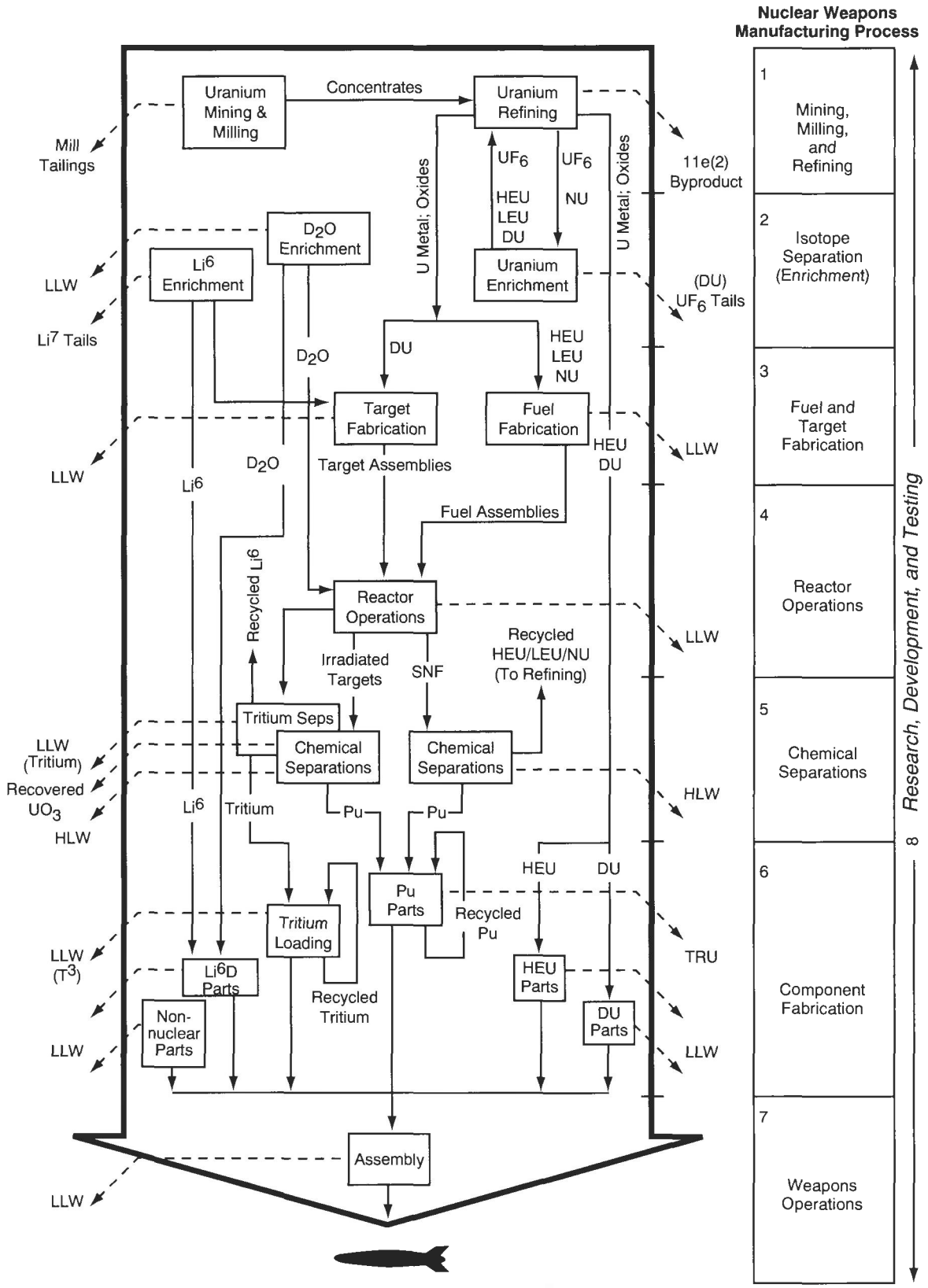


Figure B-3. Flow of Materials Through the Nuclear Weapons Complex *(one of four)*

The four following diagrams illustrate the flow of materials in the US nuclear weapons complex during the four major phases of its evolution. They do not depict any single point in time. Some simplification was necessary to bring out the major features of each time period.

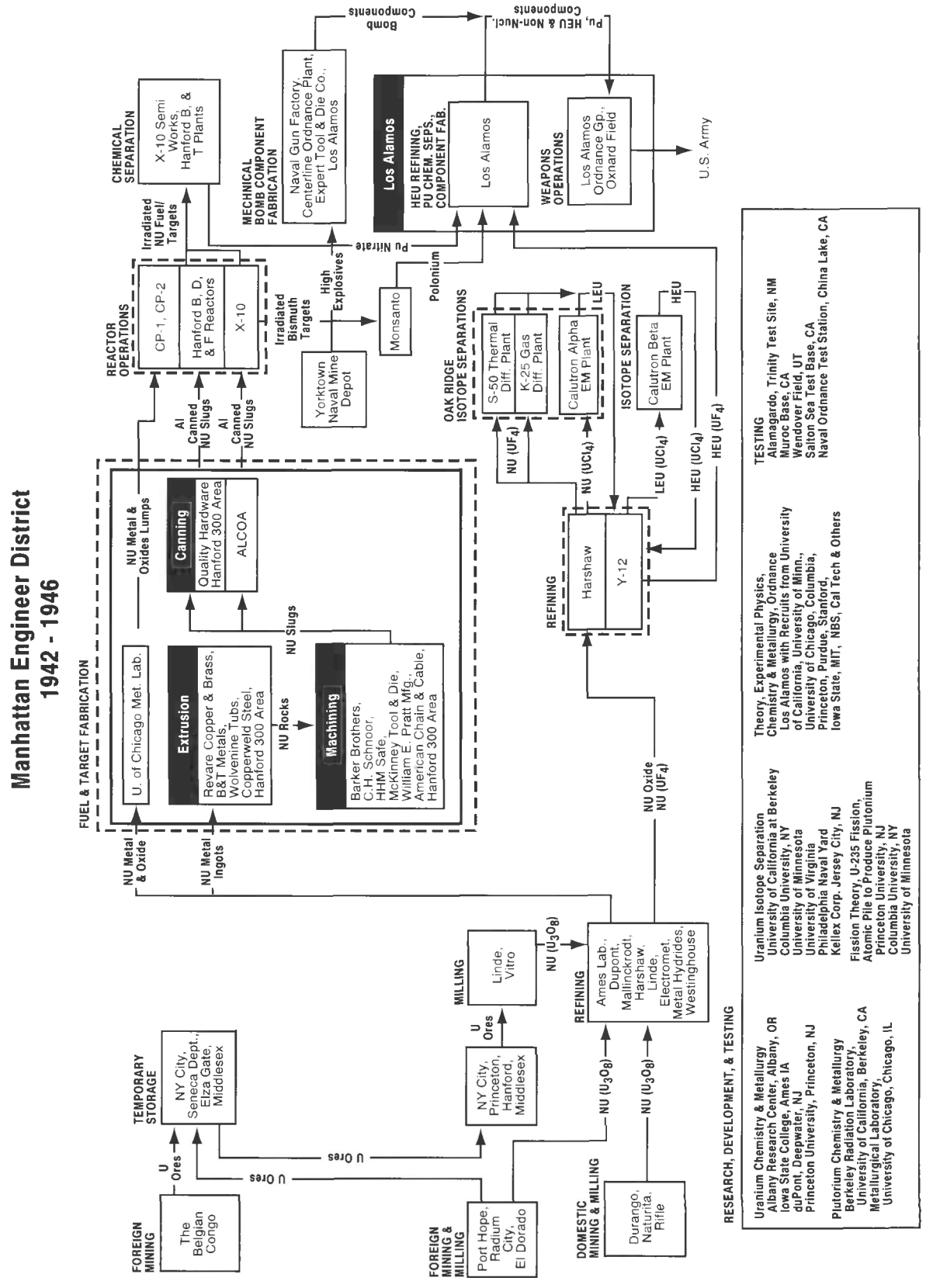
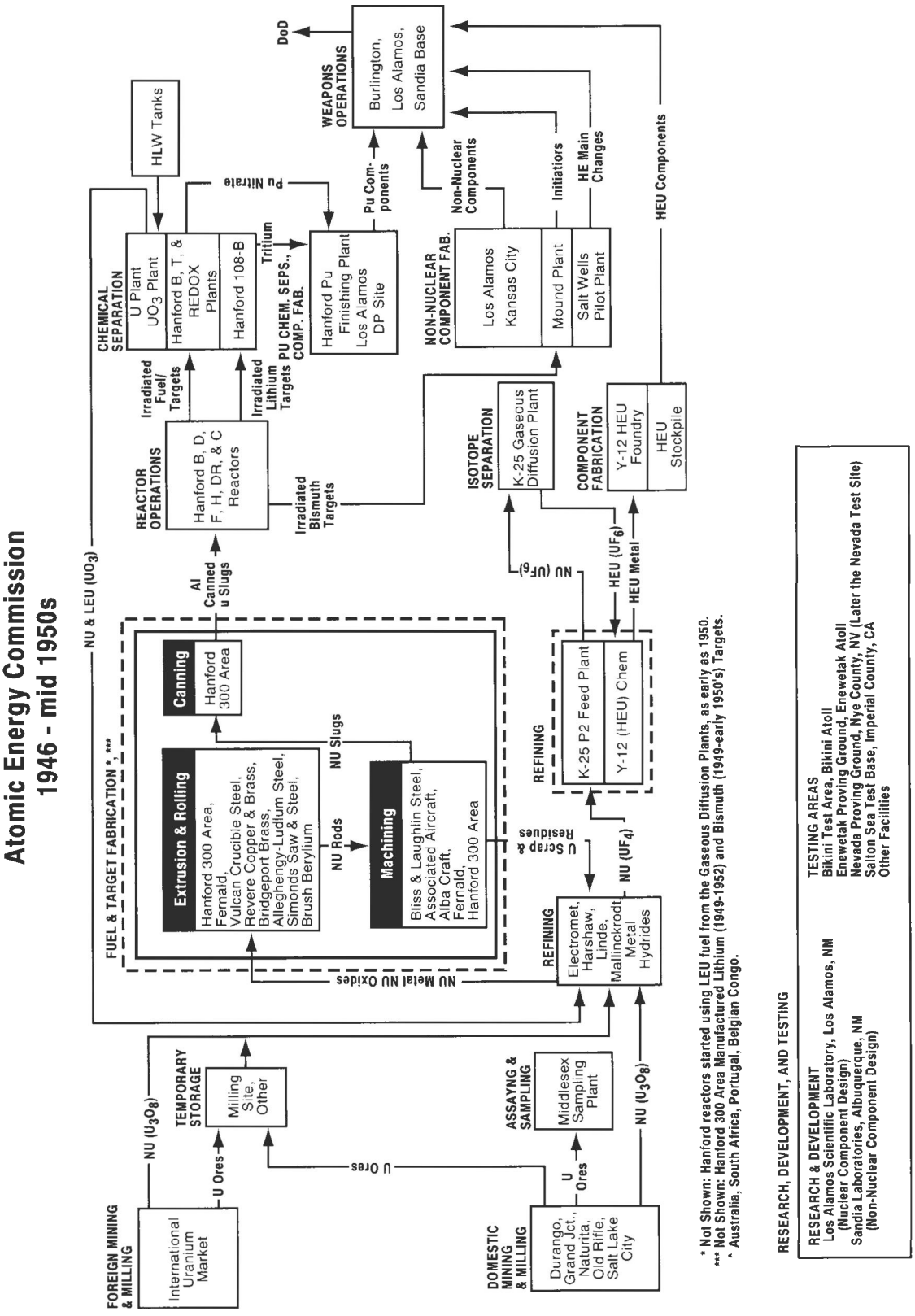


Figure B-3. Flow of Materials Through the Nuclear Weapons Complex *(two of four)*



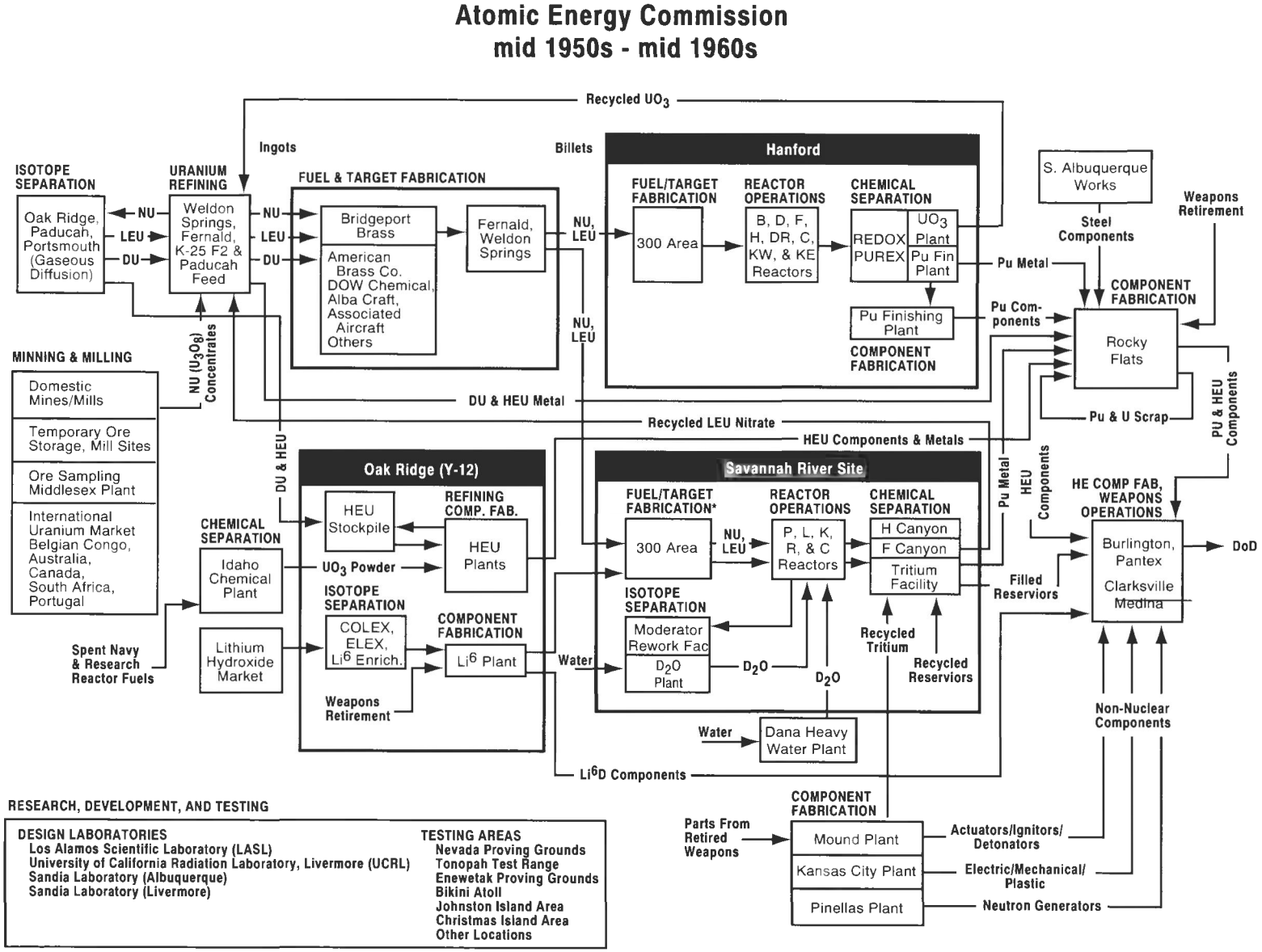
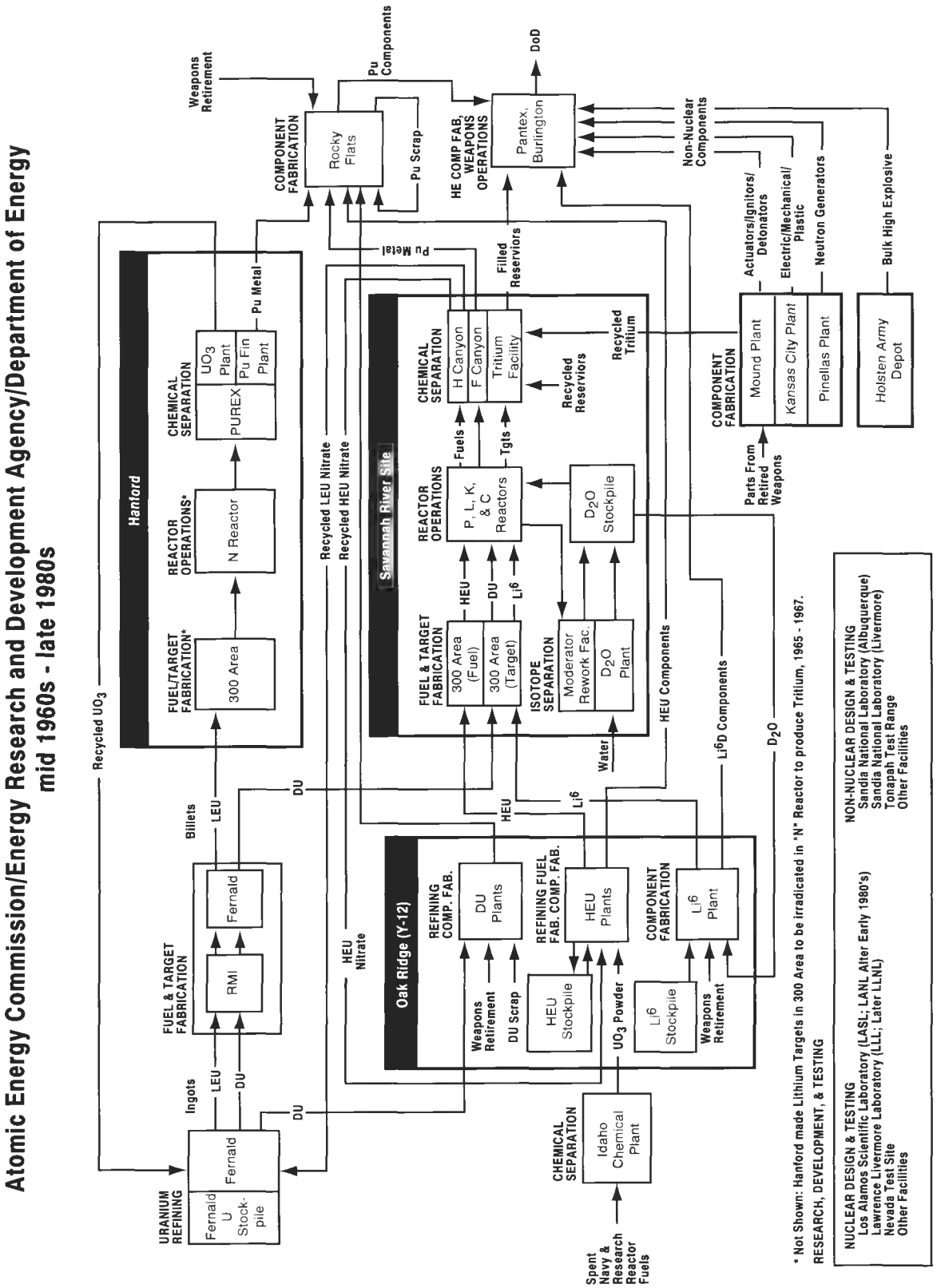


Figure B-3. Flow of Materials Through the Nuclear Weapons Complex *(three of four)*

Figure B-3. Flow of Materials Through the Nuclear Weapons Complex *(four of four)*



Mining, Milling, and Refining Uranium

Uranium *mining and milling* is the extraction of ore from the earth's crust and the physical and chemical processing of that ore to isolate uranium concentrate, also called uranium octaoxide, yellowcake, and U_3O_8. Mining and milling also includes ore assaying and sampling functions. High-grade "pitchblende" ores, in situ solution mining, and uranium recovery from phosphate and vanadium mining byproducts have also provided uranium for the U.S. nuclear weapons program.

Uranium *refining* consists of chemical processing to change uranium concentrate into feed material suitable for further processing, e.g., uranium hexafluoride (UF_6) for enrichment at the gaseous diffusion plants as well as uranium oxide or metal for fuel and target fabrication and weapons component manufacturing. In this report, refining includes the chemical conversions required for the reuse of uranium recovered from production scraps and irradiated nuclear fuels.

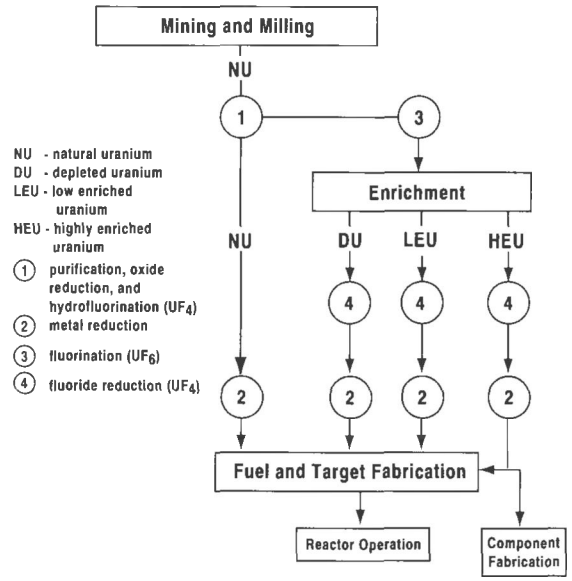
The refining steps and the wastes produced depended on the intended use of the product. Figure B-4 shows refining options commonly selected beginning in the early 1950s.

All of the U_3O_8 produced through the mining and milling process was natural uranium (NU) and was generally purified, reduced to an oxide, and hydrofluorinated to UF_4. Unenriched uranium that was to become reactor fuel was then reduced to metal (or converted to oxide) for further fabrication into reactor fuel elements. Uranium to be enriched was converted into UF_6 by fluorination. To be usable, the products of enrichment — highly-enriched uranium (HEU), low-enriched uranium (LEU), and depleted uranium (DU) — were converted from UF_6 back to UF_4, then reduced to metal for further fabrication into reactor targets (DU), fuel elements (LEU and HEU), and weapons parts (DU and HEU).

Manhattan Project Uranium Acquisitions

The initial purchases of uranium by the United States government took place

Figure B-4. Uranium Refining Processes



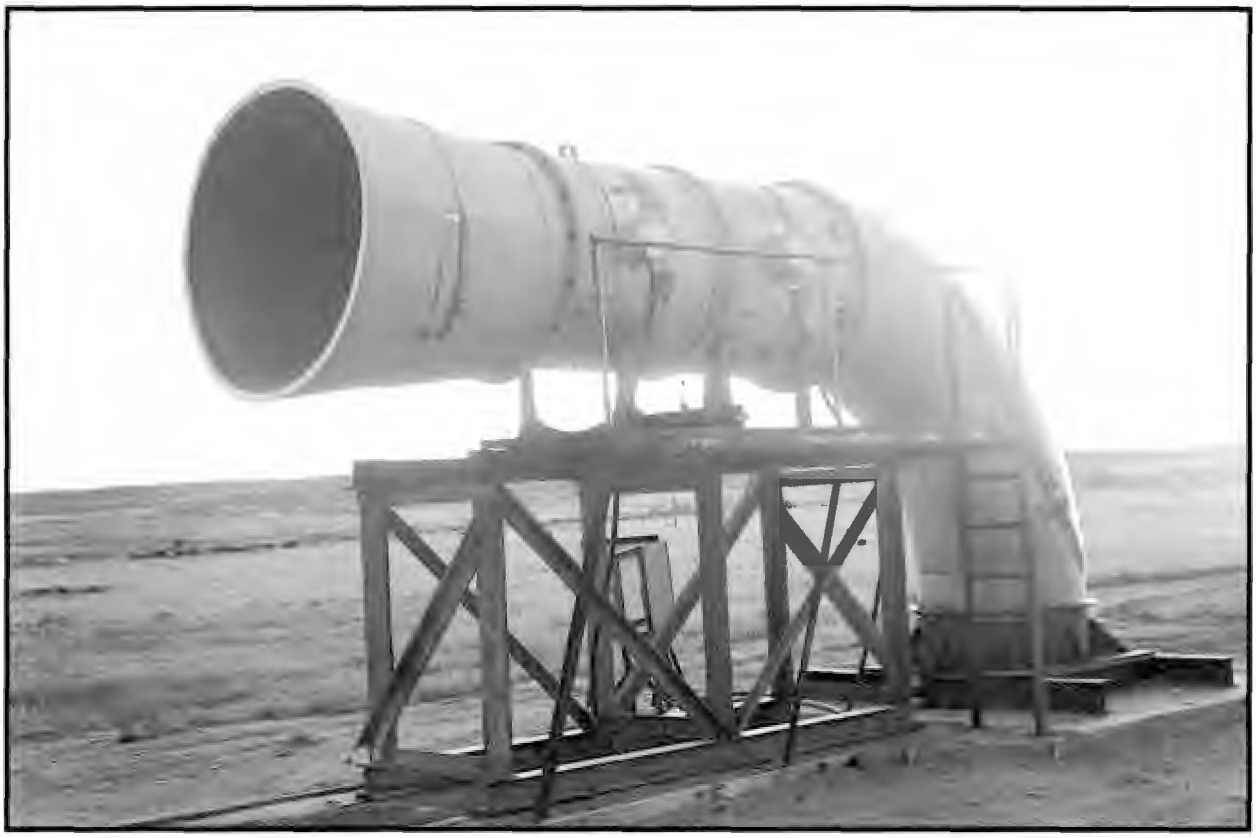
Uranium Refining

There were primarily two processes that emerged in the United States for refining U_3O_8 concentrate into other forms of uranium: the dry process and the wet process.

The dry process converted U_3O_8, through a series of steps, into uranium hexaflouride (UF_6) and then purified the UF_6 by fractional distillation. Wet process purification involved a chemical solvent extraction process to prepare a high-purity UO_3 compound from U_3O_8 concentrate; this material was further processed using the same chemical steps as the dry process. The wet process eventually became the procedure of choice because it produced purified uranium compounds earlier in the process, resulting in either high-purity UF_6 feed for the uranium enrichment plants or high-purity feed of other forms to be used as fuel and targets in production reactors.

Summary of the Wet Process:

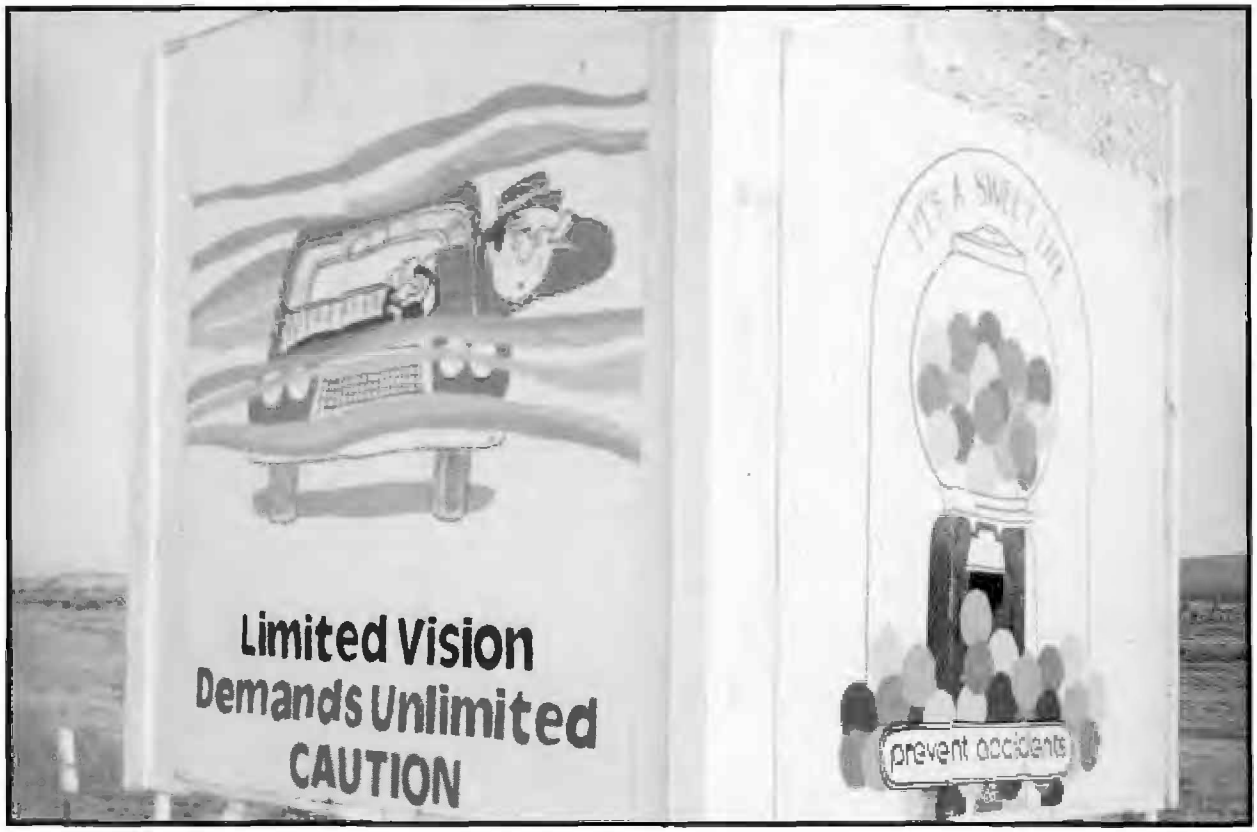
- Purification and oxide reduction, which involved: (i) digestion (dissolution) and removal of uranium with nitric acid; (ii) solvent extraction using an organic solvent process followed by a stripping process for purification; (iii) denitration by thermal decomposition to UO_3, known as "orange oxide"; and (iv) reduction with hydrogen to UO_2, known as "brown oxide."
- Hydrofluorination by reacting UO_2 with anhydrous hydrogen fluoride gas (HF) to produce UF_4, known as "green salt."
- Either fluorination or reduction to metal, depending on the intended form of the end product. Fluorination converted UF_4 to UF_6 to be used as feed for the gaseous diffusion uranium-enrichment process. Alternatively, UF_4 was reduced to uranium metal to be used as fuel and targets in production reactors or directly as weapons components.



Radon gas vent. Radon is an odorless, colorless, radioactive gas, produced by uranium as it decays. It is a carcinogen. Vents like this one disperse radon gas from inside underground uranium mines, reducing miners' exposures. *Ambrosia Lake uranium mining district near Grants, New Mexico. August 18, 1982.*

The Jackpile open-pit uranium mine. This is one of the largest open-pit uranium mines in the United States. *Near Grants, New Mexico. August 19, 1982.*

The Durango uranium mill tailings pile on the banks of the Animas River is the mound on the left. Since this photograph was taken, these tailings have been stabilized. *Durango, Colorado. August 17, 1992.*



Industrial safety sign near a uranium mill in the Ambrosia Lake region. *Near Grants, New Mexico. August 19, 1982.*

between 1942 and 1944. The Manhattan Engineer District (MED) purchased uranium contained in pitchblende ores from the Belgian Congo (containing up to 65 percent uranium oxide by weight) from private radium suppliers. The suppliers retained ownership of the residues, which contained radium and other precious metals. Ores and U_3O_8 concentrate from the Great Bear Lake area of Canada (Radium City, Northwest Territories) and Port Hope, Ontario supplemented the African uranium. In addition, domestic uranium and vanadium mines and mills in Uravan, Durango, Grand Junction, and Naturita, Colorado; and Monticello, Utah on the Colorado Plateau supplied ores and lower grade concentrate.

The importation of these ores occurred at various locations. African ores entered the country primarily at ports along the northeast coast of the United States while the Canadian ores and concentrates moved primarily through ports along the great lakes in western New York and northern Ohio. Both the African ores and Canadian ores and concentrates were temporarily stored in New York City, at the Seneca Army Depot, in New York; in the Elza Gate area of Oak Ridge, Tennessee; or in Middlesex, New Jersey, prior to their transport to domestic milling and refining operations. Some of the concentrates received from Port Hope were temporarily stored in the Baker and Williams Warehouses on the west side of Manhattan in New York City.

Ore Sampling – The majority of the African ores were sampled and assayed at the Middlesex Sampling Plant in Middlesex, New Jersey established in 1943. Miscellaneous sampling activities were also conducted on site in the New York temporary storage areas, at Princeton University in New Jersey, and at the Hanford Site in Washington.

Manhattan Project Milling and Refining

Before the Manhattan Project began, the major use of uranium was as a coloring agent for ceramics. Developing the technology to produce pure uranium metal became a priority for the Manhattan Project. Universities and private companies with experience in related chemical processes participated in the task, and, as a result, Manhattan Project uranium refining was widespread.

During World War II, the African and Canadian ores were milled to black oxides, a form of U_3O_8 concentrate, by Linde in Tonawanda, New York, and at the Eldorado facilities in Port Hope, Ontario, Canada. Vitro, located in Canonsburg, Pennsylvania, chemically converted uranium ores to sodium diuranate. Mallinckrodt Chemical Works also produced black oxide at its Destrehan Street Plant in downtown St. Louis, Missouri.

Several sites refined black oxide and sodium diuranate to orange oxide (UO_3) and then to brown oxide (UO_2). Mallinckrodt produced about two thirds of the UO_2 while DuPont produced most of the remaining one third in its Deepwater, New Jersey plant–the Chambers Dye Works. Linde and Harshaw Chemical in Cleveland, Ohio also produced UO_2. In July 1942, Mallinckrodt began using ether to purify uranium in a solvent extraction process and DuPont followed suit. However, more than half of the DuPont product came from uranium peroxide obtained by processing uranium-bearing scrap. UO_3 and UO_2 were, in turn, refined into green salt (UF_4) by DuPont, Harshaw, Mallinckrodt, and Linde. Mallinckrodt was the major producer.

Several organizations developed processes to produce pure uranium metal. Westinghouse Electric in Bloomfield, New Jersey; Metal Hydrides in Beverly, Massachusetts; and Iowa State College in Ames, Iowa, produced the uranium metal used in the Stagg Field reactor. Westinghouse used a photochemical process while Metal Hydrides and Iowa State employed a calcium reduction process starting with UF_4. Metal Hydrides and Westinghouse continued uranium metal production through the summer of 1943. However, the Metal Hydrides product was impure and pyrophoric, and the throughput of the Westinghouse process was insufficient to meet the project's needs.

Researchers at Iowa State soon perfected a magnesium reduction process (also investigated by Brush Beryllium Co. of Cleveland, Ohio) which quickly became the standard. Electro Metallurgical Company in Niagra Falls, New York, also known as "Electromet," built the largest metal reduction plant.

The Port Hope uranium refinery in Ontario, Canada, refined uranium for the Manhattan Project, and for the next 20 years it refined uranium for the U.S. nuclear weapons program. *Eldorado Uranium Refinery, Blind River, Ontario, Canada. August 25, 1986.*

Mallinckrodt in St. Louis, Missouri; DuPont in Deepwater, New Jersey; and Iowa State University also produced uranium metal using the magnesium process. Metal Hydrides, DuPont, and Iowa State recycled scarce uranium scrap. Quality control was provided by the University of Chicago Metallurgical Laboratory (the "MetLab"), Princeton University, the Massachusetts Institute of Technology, and the National Bureau of Standards in Washington, D.C.

Beginning in 1944, the Oak Ridge Y-12 Plant converted UO_3 to uranium tetrachloride (UCl_4) feed for the Calutron electromagnetic spectrograph. Harshaw and DuPont produced hexafluoride (UF_6) from UF_4 as feed for the S-50 Thermal Diffusion and K-25 Gaseous Diffusion projects in Oak Ridge. By early 1945, the S-50 and K-25 plants were supplying low-enriched UF_6, which was also converted to UCl_4 at Y-12 to be further enriched in Calutrons.

In 1945, the HEU (also called "Oralloy," for Oak Ridge Alloy) from the Calutrons was converted at Y-12 into UF_4 and sent to Los Alamos. The Los Alamos Chemistry and Metallurgy Division further purified the HEU and reduced it to metal for the "Little Boy" atomic bomb. Refining highly enriched uranium (HEU) required special considerations because of criticality and security concerns.

Post-War Uranium Purchases

After the War, the United States continued to import uranium from Canada and the Belgian Congo. Australia, South Africa, Portugal, and other nations also exported uranium to the United States. The Atomic Energy Commission (AEC) began a program to stimulate the domestic mining and milling of uranium in 1948; as a result, the domestic uranium mining and milling industry grew rapidly. Hundreds of uranium mines in New Mexico, Colorado, Arizona, Utah, Oregon, Texas, Wyoming, and Washington

Soil contaminated with uranium residues at the Middlesex Sampling Plant. From 1943 until 1955, most of the uranium purchased by AEC was assayed and sampled at Middlesex. These uranium residues continuously release radon gas. To contain the gas, the soil is covered with an impermeable barrier. *Middlesex Sampling Plant, Middlesex, New Jersey. December 10, 1993.*

produced uranium ore which was also milled at plants in those and other states.[2] Phosphate mining plants in Florida, Louisiana, and Texas produced uranium as a byproduct, while two plants in the Dakotas extracted uranium from lignite coal ashes.

All ore sampling activities were centralized at Middlesex in the mid-1940s. The Middlesex Sampling Plant discontinued its sampling activities in 1955. The ore sampling function was transferred to the Feed Materials Production Center in Fernald, Ohio. After the Weldon Spring Plant was constructed in 1957, domestic uranium concentrates were shipped there for sampling as well.

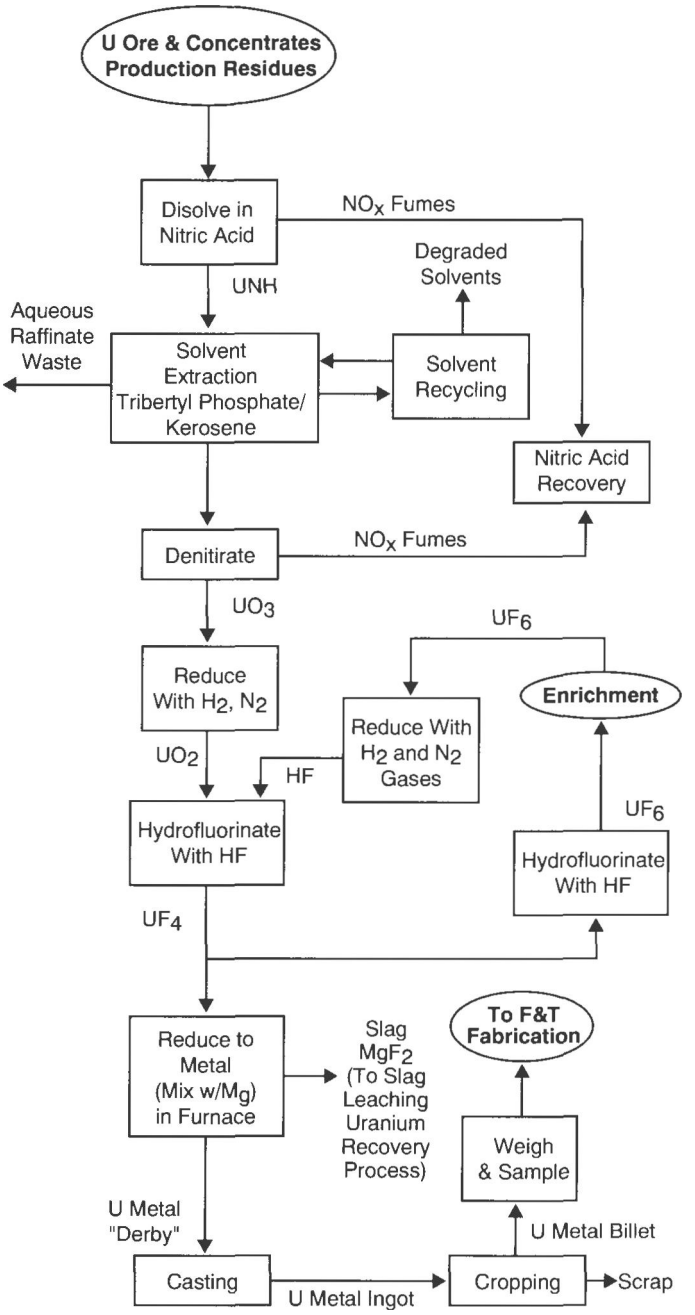
Until March of 1962, when AEC's Domestic Uranium Program and ore purchases for weapons programs terminated, AEC purchased and held uranium ore and then gradually sold it back to the mills as their capacity increased. In total, MED and AEC purchased over 3.6 million tons of domestic uranium ore, equivalent to 11,373 tons of U_3O_8 concentrate. AEC's Grand Junction, Colorado office managed the ore purchasing program. By the end of 1966, AEC had no unprocessed ore remaining in storage. AEC domestic and foreign concentrate purchases continued until 1971 and totaled 325,000 tons, consisting of 175,000 tons from domestic sources and 150,000 tons from foreign sources.

Besides uranium, AEC also purchased thorium, another naturally occurring radioactive source material. The Middlesex Sampling Plant was used primarily for sampling and storage of thorium materials and residues from 1955 until September 1967. Maywood Chemical Works (Maywood, New Jersey), Rare Earths, Inc. (Wayne, New Jersey), and W.R. Grace (Curtis Bay, Maryland) milled thorium for AEC.

[2] *A total of 24 uranium processing sites that sold ore to AEC and thousands of "vicinity properties" where uranium mill tailings were used as landfill or construction material are presently being remediated under the Uranium Mill Tailings Remedial Action project (UMTRA). UMTRA was established by Title I of the Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978. Uranium and thorium mills licensed to operate as of January 1, 1978 are remediated under Title II of UMTRCA. DOE reimburses the mill owners for a portion of the costs of this work based on the amount of concentrates purchased from the mill by the Department and its predecessors.*

Post-War Uranium Refining

Figure B-5. Uranium Refining (Fernald)



After the war ended, Mallinckrodt Chemical Works continued to convert U_3O_8 to UO_3 and UO_2 in a new plant on Destrehan Street in St. Louis. Harshaw Chemical Company also produced UO_2 until 1951. Electromet produced UF_4 that was reduced to metallic uranium either on site in Niagra Falls, New York or by Mallinckrodt in St. Louis, Missouri. Electromet continued to produce UF_4 and uranium metal until 1949. Harshaw and Mallinckrodt produced green salt (UF_4) as well, shutting down in 1951 and 1957 respectively.

In the early 1950s, AEC built two new feed materials plants, the Weldon Spring Plant in St. Charles County, Missouri and the Fernald Plant near Cincinnati, Ohio to expand and centralize AEC's uranium refining functions. Fernald and Weldon Spring assumes almost all of the functions previously carried out by Mallinckrodt, Harshaw and Electronet. Weldon Spring produced UO_3 and UO_2 from 1956 to 1966, and Fernald from 1952 through 1962, when the site's uranium refinery was placed on standby. The Fernald refinery was reactivated with the shutdown of the Weldon Spring plant in 1966. Government purchases of uranium concentrate ended in 1971. Refining of recycled uranium at Fernald continued until the plant was closed in July 1989. Fernald also processed thorium periodically between 1954 and 1975, albeit in smaller amounts than uranium.

Harshaw Chemical continued to produce most of the UF_6 feed for the K-25 uranium enrichment plant at its Cleveland, Ohio plant after the war. However, in December 1947, the F2 Plant at K-25 became operational, allowing the plant to produce its own feed by initially converting UO_3 to UO_2 to UF_4 to UF_6 and later UO_2 to UF_6. Harshaw expanded its UF_6 production in 1947, and was placed on standby by May 1953. When the Paducah and Portsmouth Gaseous Diffusion Plants were built and started up in 1954 and 1956, they included feed operations similar to that at K-25. The Oak Ridge, Portsmouth and Paducah feed plants were shut down in 1962, and the conversion of U_3O_8 to UF_6 for gaseous diffusion plant feed was taken over by the privately-owned Allied Chemical Co. Plant in Metropolis, Illinois. Thereafter, UF_6 feed came from commercial sources, existing stocks, and partially-depleted UF_6 tails stored at the enrichment plants.

Natural, low-enriched and depleted uranium were reduced to metal at the Weldon Spring and Fernald plants after the early 1950s. These plants also recycled uranium from scraps and residues such as slag, machining chips, and cleaning solvents. Highly-enriched uranium processing has been centralized at the

Vitro Properties. Uranium ore for the Manhattan Project was milled at this site. Today, the site is part of the Uranium Mill Tailings Remedial Action project. *Canonsburg, Pennsylvania. June 13, 1984.*

Inside Building 51 of the Mallinckrodt Chemical Works, 40 tons of purified uranium were produced for Fermi's Chicago pile. This site processed uranium for AEC until 1957. *Downtown St. Louis FUSRAP Site, Missouri. January 29, 1994.*

St. Louis Airport Storage Site (SLAPSS). In 1946, the Manhattan Engineer District condemned 22 acres of farmland to store uranium-, radium-, and thorium-contaminated wastes generated at the downtown St. Louis uranium refinery. Because of contamination, this site is now part of the Formerly Utilized Sites Remedial Action Program. The man in the photo is measuring radiation levels outside the site fence line. *St. Louis Airport Storage Site, St. Louis, Missouri. January 30, 1994.*

Weldon Spring Raffinate Pit 4. The Weldon Spring Plant processed uranium for AEC from 1957 until 1966. Four lagoons, called "raffinate pits," and a nearby quarry received uranium-redium-, and thorium-contained residues and wastes from the plant's uranium refinery and reactor fuel factory. Contaminated rubble and soil from the demolition of a uranium processing facility in downtown St. Louis and debris from the adjacent Army munitions factory and chemical plant have also been dumped here. DOE plans to remove sludge from the pits, treat it, and entomb it onsite by September, 2001. *Raffinate Pit 4, Weldon Spring Plant, St. Charles County, Missouri. January 29, 1994.*

Oak Ridge Y-12 Plant since 1947, when the Y-12 plant took over from Los Alamos the mission of reducing highly-enriched UF_6 to metal. The Y-12 metal reduction plant shut down in 1964 when sufficient HEU reserves for weapons had accumulated and the gaseous diffusion plants stopped producing HEU for weapons. Y-12 also purified and recycled HEU from production scraps and residues and returned weapon parts. This mission is still carried out at the Y-12 Plant at the present time.

Environmental Legacies of Uranium Mining, Milling, and Refining

The residues from refining the African ores which contain a considerable amount of radium and other valuable materials, were initially stored at the Lake Ontario Ordnance Works in Lewiston, New York. The ore supplier, African Metals Corporation, retained ownership of the radium and precious metal content of these residues until 1983. Some of the residues were moved to the K-65 silos at the Feed Materials Production Center in Fernald, Ohio in the early 1950s. Additional residues from refining at Fernald and the Mallinckrodt Chemical Works in St. Louis were stored in the same silos. African Metals exported a portion of the residues to their facility in Belgium.

Off site disposal of uranium refining residues from the early MED and AEC refining operations took place near St. Louis, Missouri; at Lewiston and Tonawanda, New York; and Canonsburg, Pennsylvania. Residues from the Mallinckrodt Chemical Works operations were deposited at the current St. Louis Airport Site. In 1967, a private firm purchased these residues and stored and processed them at what is now known as the Latty Avenue Properties.

The former Haist property, now known as Ashland Oil #1 (Tonawanda) was used to store residual material from the Linde refining operations. Some of these residues were later moved to the adjacent Ashland Oil #2 and Seaway Landfill. Vitro deposited wastes from its Canonsburg works at the Pennsylvania Railroad Landfill Site (Burrell Township, Pennsylvania). Uranium- and radium-contaminated building rubble from the demolition of the Mallinckrodt uranium ore processing facility in St. Louis was disposed of at the Weldon Spring Quarry and Raffinate Pits. The Middlesex Municipal Landfill in New Jersey received construction debris from the Middlesex Sampling Plant.

Fernald – The Fernald plant produced approximately 2.2 pounds of waste for each of the 400 million pounds of uranium metal it processed. Solid hazardous and low-level wastes were disposed on site in a series of six waste pits, the Burn Pit, and the "Clearwell." Two fly ash piles on site also received construction rubble and ash from electrostatic precipitators used to control uranium dust emissions. See Table B-1 for a description of the waste pits at Fernald. Waste Pit 3 is known to have leaked into the aquifer underlying the site. Laboratory chemicals and low-level combustible materials were disposed of in the Burn Pit beginning in 1957. The Clearwell received surface runoff from the waste pit area and, until 1987, was used as a final settling basin before runoff was discharged to the Great Miami River. After 1987, the Clearwell received only decanted water from Waste Pit 5, some of which was pumped there from Waste Pit 6. Waste Pits 2, 4, and 6 have the highest levels of uranium-238 while Pits 3 and 5 contain higher levels of thoriam-230 and mercury. The Clearwell and Pit 5 contain the highest concentrations of radium-226. The pits also contain elevated levels of aluminum, calcium, iron, magnesium, and PCBs. The Burn Pit has been found to contain high levels of silver and lead. Uranium, thorium, organic chemicals, and PCBs have migrated from the waste pits into the surrounding environment.

Fernald treated liquid effluents and discharged them to the Great Miami River and Paddy's Run, a stream running along the plant boundary. Processing wastes from Plant 1 (the Sampling Plant, which also reconditioned steel drums used to store and transport uranium salts, oxides and residues) containing mixed wastes including uranium, thorium, barium salts, and waste oils contaminated with lead were stored on a concrete pad in drums beginning in 1952. By July 1990, 45,000 drums had accumulated. DOE shipped these wastes to the Nevada Test Site for disposal beginning in 1985.

The Feed Materials Production Center processed uranium "feed" for the U.S. nuclear weapons complex from 1951 until 1989. Its main tasks were refining uranium and manufacturing reactor fuel and targets. Today, the site no longer produces uranium feed materials. It has been renamed the "Fernald Environmental Management Project." *Fernald, 20 miles outside Cincinnati, Ohio. May 22, 1984.*

Table B-1. Description of the Waste Pits at the FMPC (Fernald, OH)

Waste Pit	Date opened	Date closed	Volume of waste	Description of waste
Pit 1	1952	1959	33,672 cubic yards	Solid LLW; 52,000 kg U
Pit 2	1957	1964	18,478 cubic yards	Solid LLW; 1.2 million kg U, 400 kg Th
Pit 3	1959	1977	237,053 cubic yards	Primarily concentrated, lime-neutralized radioactive nitrate raffinates; 129,000kg U, 400 kg Th
Pit 4	1960	1986	60,000 cubic yards	Concentrated, lime-neutralized radioactive nitrate raffinates; LLW containing barium chloride, 5/81-4/83; 3 million kg U, 61,800 kg Th
Pit 5	1968	1987	98,841 cubic yards	Liquid waste slurries from the refinery and recovery plant until 1983; clear decant, filtrate and nonradioactive slurries
Pit 6	1979	1987	11,556 cubic yards	Fine-grained wastes, including green salt (UF_4), filter cakes and process residues; 845,000 kg U

Weldon Spring – The Weldon Spring Plant used a nearby quarry and four waste lagoons (called " Raffinate Pits") to store contaminated residue from uranium processing. Workers disposed of contaminated rubble from the demolition of the downtown St. Louis uranium processing plant in these pits as well. The quarry was also used to dispose of contaminated wastes from the plant and from the Army ordnance plant formerly located at the site. Wastes and contaminated soils from Weldon Spring are being consolidated into a disposal cell on the former site of the chemical plant.

The K-65 Silo. This underground silo at Fernald contains residues from African pitchblende ore refined in upstate New York for the Manhattan Project. The Fernald Plant also placed in this silo wastes from its own uranium processing. Radon gas from this silo and another adjacent to it was the major source of radiation exposure to people in the surrounding area. *K-65 Silo, Fernald Environmental Management Project, Ohio. January 29, 1994.*

Isotope Separation

Isotope Separation, also commonly known as "enrichment," is the process of concentrating one or more isotopes of the same element. Three elements that have been isotopically separated in large quantities in the U.S. nuclear weapons complex are uranium, lithium, and hydrogen. Smaller amounts of various other materials, including boron, have also been isotopically enriched for use in the nuclear weapons programs.

Uranium – Uranium enrichment begins with natural uranium (NU) and results in enriched uranium (EU) and depleted uranium (DU). NU contains 0.711 percent of the isotope uranium-235, the remainder being almost entirely uranium-238. EU is uranium that has been processed so that it contains more than a 0.711 percent concentration of uranium-235. DU contains less than 0.711 percent uranium-235. EU and NU are made into reactor fuel elements which sustain the chain reaction while absorbing neutrons to produce plutonium-239. DU is used in weapon components and in reactor targets to be irradiated for the production of plutonium-239. Highly enriched uranium (HEU) contains more that 20 percent of the uranium-235 isotope. HEU is used in weapons components and is also used as a reactor fuel, depending on the enrichment level.

Lithium – Natural lithium consists of 7.5 percent lithium 6 and 92.5 percent lithium-7. Lithium enriched in the lighter lithium-6 isotope is irradiated in reactors to produce tritium, which is used in nuclear weapons. Some weapons components are made from Li-6 which has been chemically combined with deuterium to form a ceramic material, lithium deuteride.

Hydrogen – Naturally occurring hydrogen contains 0.015 percent of the deuterium isotope (H^2 or D). "Heavy water" is produced by enriching water in deuterium. The resulting liquid, D_2O, is used as a coolant and moderator for some of the Department's nuclear materials production reactors. Deuterium separated from heavy water is also used in components of nuclear weapons.

Boron – Boron-10 was produced for the weapons complex because it is a powerful neutron absorber used to control neutron fluxes in reactors and nuclear weapons.

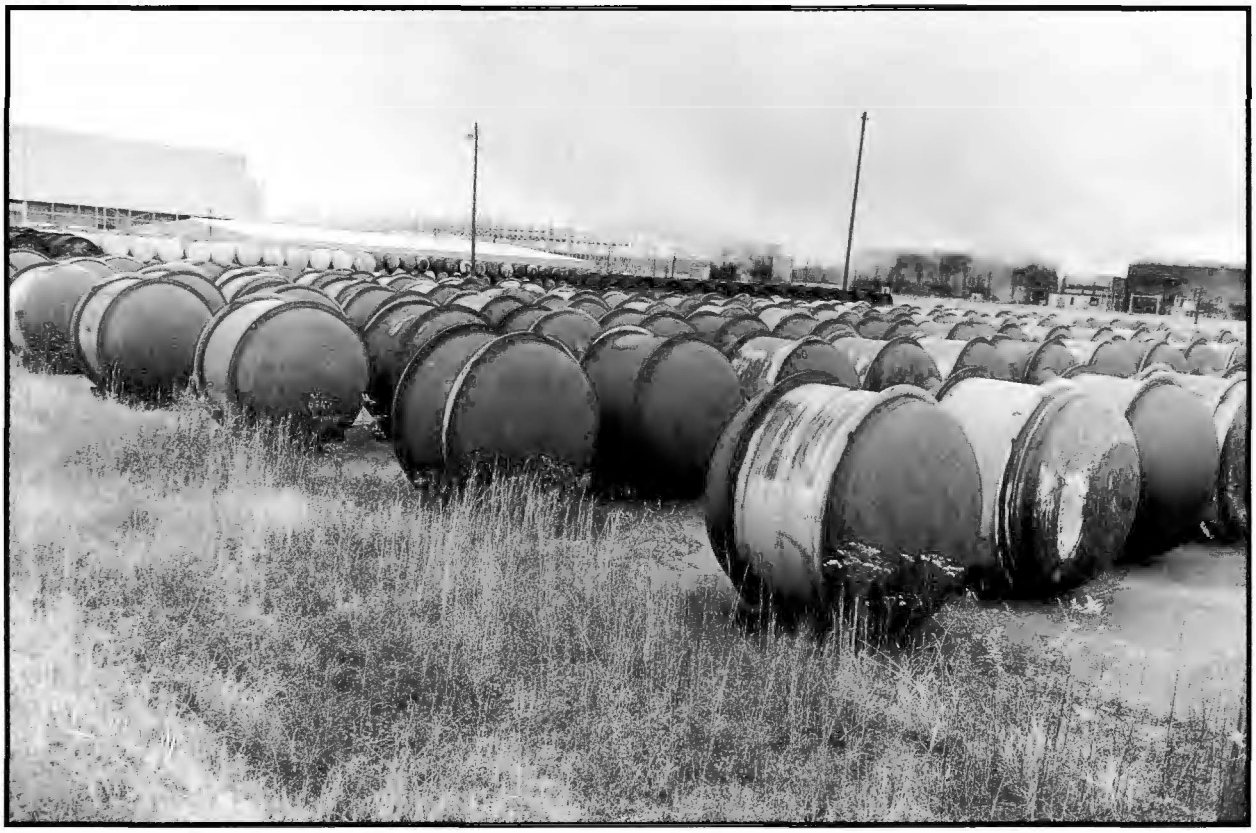
Uranium Enrichment

Uranium Enrichment in the Manhattan Project, – The Manhattan Project simultaneously pursued plutonium and highly enriched uranium as fissile materials for atomic weapons. Thus, one of the key challenges in the initial development of the nuclear weapons program was separating the isotopes of uranium. Because uranium isotopes have almost identical chemical properties, they cannot be separated using chemical processes. Uranium-235 and uranium-238 must be separated physically, by exploiting the small difference in the atomic masses of the two isotopes. Because of the small difference in the weights of the two isotopes, even physical separation is difficult. Uranium's complex chemistry and the corrosive and reactive nature of some of the important uranium compounds complicate handling of large quantities of uranium.

The pre-war Office of Scientific Research and Development and MED initially investigated four processes for the isotopic enrichment of uranium: gas centrifuge, thermal diffusion, electromagnetic spectrograph, and gaseous diffusion. MED developed these four processes through the pilot plant stage. An explanation of each process is provided in the text box "Uranium Enrichment Processes."

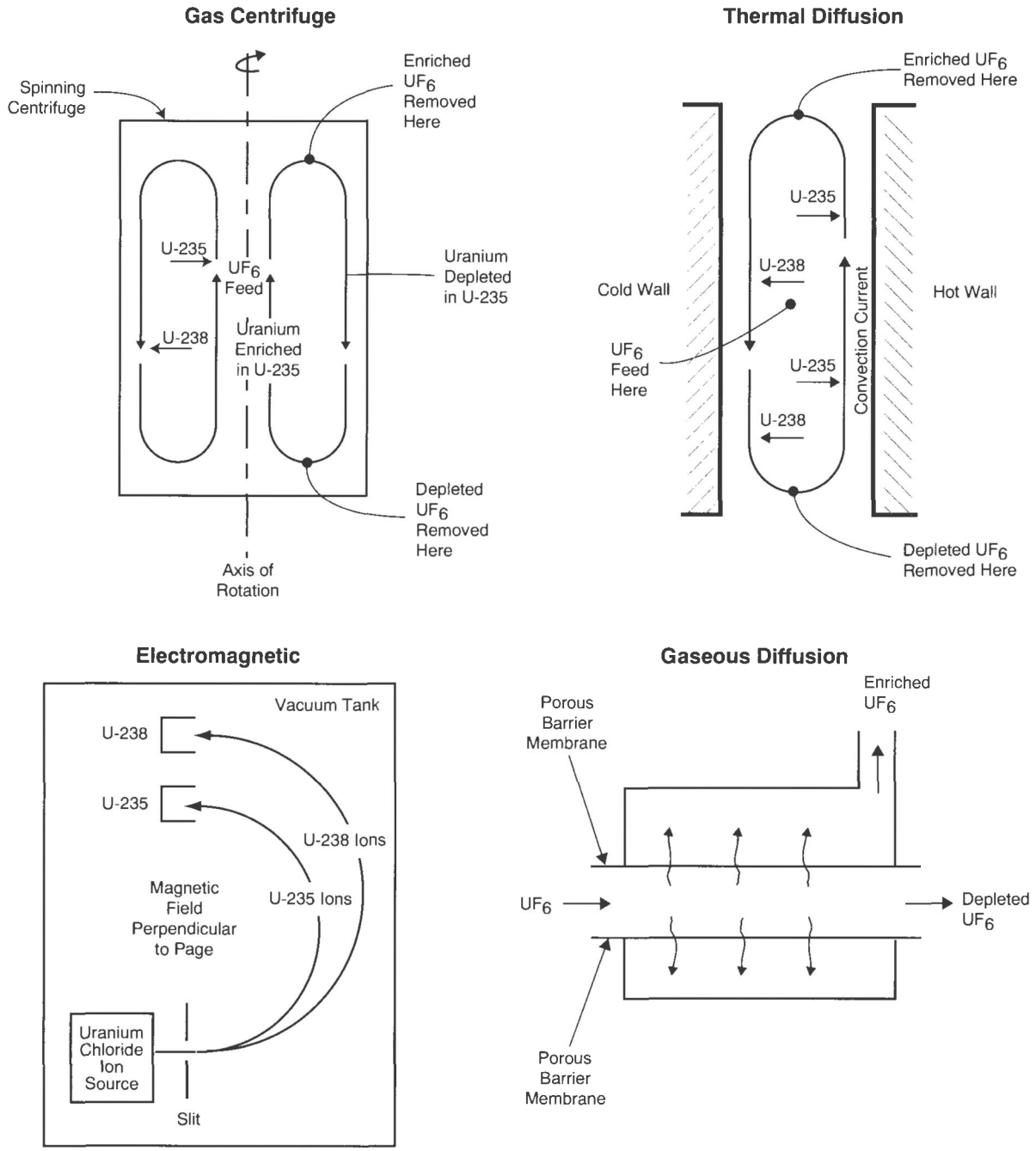
The electromagnetic, thermal diffusion, and gaseous diffusion processes all contributed to the production of enriched uranium during the Manhattan project. Technical difficulties prevented the successful use of gas centrifuge during World War II. Two stages of electromagnetic "Calutrons" at the Y-12 Plant (grouped into "racetracks," named for their oval shape) produced all of the HEU for "Little Boy," the atomic bomb detonated over Hiroshima, Japan. Y-12 featured nine first-stage "alpha" racetracks and four second-stage "beta" racetracks.

Portsmouth Gaseous Diffusion Plant. Built between 1952 and 1956 during AEC's expansion of its uranium enrichment capacity, the Portsmouth plant enriched uranium up to 97 percent uranium-235. The facility is currently operated by the United States Enrichment Corporation under a lease from DOE; it now enriches uranium for commercial reactor fuel. *Portsmouth Gaseous Diffusion Plant, Piketon, Ohio. June 20, 1982.*



Gaseous diffusion "tails." These cylinders contain depleted uranium hexofluoride left over from the uranium enrichment process. They are stored on the grounds of the Paducah, Kentucky uranium enrichment plant. *Paducah Gaseous Diffusion Plant, Kentucky. December 18, 1985.*

Figure B-6. Processes for Enriching Uranium



The Y-12 plant calutrons were created by various firms located in many different regions of the country. Tennessee Eastman coordinated the construction and procurement effort and Stone & Webster of Boston, Massachusetts designed the Y-12 Plant. Westinghouse Electric produced vacuum tanks, liners, ion sources, and collectors in their Pittsburgh factories. General Electric of Schenectady, New York supplied the high-voltage electrical equipment. Allis-Chalmers, located in Milwaukee, Wisconsin made vacuum pumps, and the Chapman Valve Company of Indian Orchard, Massachusetts manufactured vacuum valves. Due to wartime copper shortages, the magnetic coils for the calutrons were wound with silver borrowed from the U.S. Treasury depository in West Point, New York. It was cast into billets by the

Defense Plant Corporation in Carteret, New Jersey, extruded and rolled into strips by Phelps Dodge Copper products in Bayway, New Jersey, and finally wound onto coils by Allis-Chalmers in Milwaukee, Wisconsin.

To increase their efficiency and output, the calutrons were fed with low-enriched uranium from the S-50 and, later, the K-25 Plant, both at Oak Ridge. A scaled-up version of the thermal diffusion pilot plant operated by the U.S. Navy at the Philadelphia Naval Yard, the S-50 Plant was built to take advantage of the excess steam produced by the K-25 Plant powerhouse. S-50 used concentric hot and cold pipes to provide the temperature difference needed to separate uranium isotopes. Built in nine months, S-50 fed low-enriched uranium to the Y-12 Plant Calutrons from March 1945 through September 1945.

Once technology problems relating to the development of an effective diffusion barrier material were overcome, the K-25 gaseous diffusion plant also produced LEU to feed the Calutrons at Y-12 beginning in March 1945. After the K-25 plant began to produce weapons-grade uranium in August 1945, the Y-12 electromagnetic plant was shut down.

Construction of the K-25 Plant was a major industrial effort. The Kellex corporation, of Jersey City, New Jersey, a subsidiary of the M. W. Kellogg Company designed the plant. Construction was managed by the J.A. Jones Construction Co. out of Charlotte, North Carolina, with the assistance of Ford, Bacon & Davis. The plant and equipment were created by companies from all areas of the country. The original K-25 converters (the corrosion-resistant tanks enclosing the diffusion barriers) were manufactured and assembled by the Chrysler Corporation in Detroit, Michigan. Half a million specialized valves were supplied by Crane Manufacturing Company while compressors designed to handle uranium hexafluoride were developed and supplied by the Allis-Chalmers Company based in Milwaukee, Wisconsin.

Uranium Enrichment Processes

Gas Centrifuge – The lighter uranium-235 isotope concentrates near the center of a spinning centrifuge of gaseous uranium UF_6, hexafluoride from which it can be removed. Using this method, the first gram quantities of enriched uranium were produced at the University of Virginia in 1941. An improved device was operated by Standard Oil at the Bayway Refinery, New Jersey in 1944. Westinghouse Electric manufactured the centrifuges in East Pittsburgh, Pennsylvania, and built a small centrifuge pilot plant in Bayonne, New Jersey. Engineering difficulties during WW II led to a decision to concentrate efforts on the other processes, although a pilot plant in Oak Ridge and a full-scale plant in Piketon, Ohio were built in the 1970s.

Thermal Diffusion – In the presence of a temperature difference, the lighter uranium-235 isotope will diffuse toward a hot area faster than the heavier uranium-238 isotope. Initially developed at the Naval Research Laboratory in the Anacostia section of Washington, DC, the Navy built a thermal diffusion pilot plant using concentric hot and cold pipes at the Philadelphia Naval Yard in 1944. Thermal diffusion was employed on a production scale at the S-50 plant in Oak Ridge, Tennessee, in 1945. The process provided LEU feed to the Y-12 electromagnetic process plant until the S-50 plant was closed in August 1945.

Electromagnetic Spectrograph – Scientists working at the University of California in Berkeley developed the electromagnetic enrichment process that was installed and operated at the Y-12 Plant in Oak Ridge, Tennessee, from late 1943 through the end of 1946. The process is based on the fact that ions of the heavier uranium-238 atoms are deflected less than the ions of the lighter uranium-235 atoms as they travel through a magnetic field. Electromagnetic enrichment was done in a device called a "Calutron," a modification of an early cyclotron. Uranium chloride salt was used for this purpose. Unlike the other uranium enrichment processes, the electromagnetic process is a batch process. The electromagnetic enrichment plant produced the first gram quantities of HEU in 1944. Using LEU feed from S-50 and K-25 in early 1945, the Calutrons supplied all the HEU for the "Little Boy" bomb detonated over Hiroshima, Japan.

Gaseous Diffusion – The gaseous diffusion process is based on the difference in rates at which uranium isotopes in the form of gaseous UF_6 diffuse through a porous barrier. Development of this barrier was the most significant obstacle to success. A small pilot cascade was operated in Pupin Hall at Columbia University in New York City. The Kellex Corporation of Jersey City, New Jersey designed the first gaseous diffusion plant. The full-scale K-25 gaseous diffusion plant (2,996 diffusion steps or stages) was completed and operational at Oak Ridge in August 1945. Before its completion, K-25 supplied some low-enriched feed for the Y-12 Calutron devices of the electromagnetic process. Large amounts of electricity are required to pump the UF_6 through the diffusion cascade and to remove the heat of compression.

The K-25 Gaseous Diffusion Plant enriched uranium for nuclear weapons and commercial reactor fuel from 1945 until 1987. When first built, the U-shaped K-25 building was one of the largest roofed structures in the world, covering nearly 43 acres. *K-25 Gaseous Diffusion Plant, Oak Ridge, Tennessee. June 12, 1982.*

The K-25 Gaseous Diffusion Process Building is half a mile long and 1,000 feet wide. It is comprised of fifty buildings four stories tall and arrayed in a U-shape. The lower floor, which once housed electrical equipment and process control panels, now stores hazardous and radioactive wastes and part of the DOE's stockpile of virgin and enriched lithium. *K-25 Process Building, K-25 Gaseous Diffusion Plant, Oak Ridge, Tennessee. January 9, 1994.*

Converter vessels in a gaseous-diffusion plant contain porous barriers that enrich uranium in gaseous form by separating out the atoms of uranium-235 from more-abundant uranium-238. Each of these vessels is a stage in the enrichment process, and there are a total of 5,122 stages at this plant. The more stages uranium hexafluoride gas passes through, the higher its enrichment becomes. *Unit 7, Cell 2, K-33 Demonstration Cell, K-25 Site, Oak Ridge, Tennessee. June 21, 1993.*

Partially-dismantled converter vessels used in the gaseous diffusion uranium enrichment process. *K-25 Building, Oak Ridge, Tennessee. January 12, 1994.*

Houdaille-Hershey Co. manufactured diffusion barriers at their Oakes Products Plant located in Decatur, Illinois. These diffusion barriers were made using nickel powder supplied by the International Nickel Co. plant in Huntington, West Virginia. Heat exchangers to remove the heat of compression were built by A.O. Smith Company in Milwaukee, Wisconsin and by Whitlock Manufacturing Company. Bart Laboratories, International Nickel, and Midwest Piping and Supply produced three million feet of special piping that could resist the corrosive effects of UF_6. Many other firms supplied pumps, instruments, gauges and other parts.

Post War Expansion of Uranium Enrichment – In September 1945, the Y-12 Calutrons and the S-50 thermal diffusion plant were shut down. Although they had proved effective during the war, the electromagnetic and thermal diffusion processes had several disadvantages. Calutron enrichment was a batch process, limiting its output and requiring considerable maintenance. The collectors had to be removed regularly so the enriched uranium product could be scraped out of them. The Calutron tanks and other equipment were periodically washed and cleaned to recover accumulated uranium from their surfaces. The Calutrons processed uranium in the form of uranium chloride salt, UCl_4. This salt oxidizes readily when exposed to air, which creates chemical processing problems in the Calutron feed and product material. Thermal diffusion was also inefficient. These difficulties contributed to the decision after the War to rely on gaseous diffusion, which allowed a continuous flow of uranium through the process.

To meet the projected demand for enriched uranium, AEC expanded the K-25 Gaseous Diffusion Plant beginning in 1946. Between January 1946 and June 1954, buildings K-27, K-29, K-31, and K-33—another 1,540 stages—were added to K-25, greatly increasing the plant's capacity. Expansion continued with the construction of two more gaseous diffusion plants. Peter Kiewit Sons' Company constructed the Portsmouth Gaseous Diffusion Plant, located in Piketon, Ohio, beginning in 1952. The plant, which features 4,080 stages in three buildings, was completed between November 1955 and February 1956. The Paducah Gaseous Diffusion Plant, in Paducah, Kentucky, was constructed between January 1953 and December 1954. F. H. McGraw and Company of Hartford, Connecticut was the general contractor. The Paducah Plant has 1,812 enrichment stages, housed in five buildings.

The three gaseous diffusion plants' output was nearly all highly-enriched uranium for the weapons program between 1946 and 1964. The plants also produced low-enriched uranium to be used as production reactor fuel during this period. Paducah was the feed point for the three plants and the low enriched Paducah product was split between the K-25 plant and the Portsmouth plant, which produced a variety of enrichments up to 97 percent. In addition to the functions of the diffusion cascade and the feed plant, K-25, Portsmouth and Paducah also cleaned and reconditioned the diffusion converters and other equipment.

The End of Weapons HEU Production and the Growth of Civilian Uranium Enrichment – AEC discontinued HEU production for weapons in 1964 because it had accumulated sufficient stocks. The K-25 and K-27 buildings at Oak Ridge were placed on standby at that time, and the remainder of K-25 was used to produce LEU. The gaseous diffusion plants continued to produce HEU after 1964 for other AEC programs, including civilian nuclear power research and the U.S. Navy nuclear power program. However, gaseous diffusion plant output dropped drastically for several years.

Gaseous Diffusion Plant output gradually increased again in the late 1960s to meet growing demand for enriched uranium for the commercial nuclear power industry. AEC and DOE sold uranium enrichment services to the commercial nuclear power industry. By the early 1970s, uranium enrichment plant output had risen back to its pre-1964 levels.

In the 1970s, DOE revived the development of the gas centrifuge enrichment process, and built a pilot plant at K-25 in Oak Ridge. The success of this project led to the construction of a full-size gas centrifuge plant at the Portsmouth Plant in 1977. However, to this date, the Portsmouth centrifuge plant has not operated at full scale. K-25 also supported the development of the Atomic Vapor Laser Isotope Separation (AVLIS) technology for uranium enrichment.

In 1992, Congress passed the Energy Policy Act and, under its provisions, uranium enrichment operations at the Portsmouth and Paducah Plants were leased by DOE to the newly-created United States Enrichment Corporation (USEC). The K-25 Plant was shut down in 1987, before the creation of USEC. At this time, USEC continues to operate the plants, although DOE has retained the responsibility for managing the environmental legacy left from prior operations.

Environmental Legacy of Uranium Enrichment – The three gaseous diffusion plants created a tremendous quantity of waste. Organic solvents, such as trichloroethylene (TCE), were used chiefly in the cleaning and maintenance of the enrichment plant equipment. Polychlorinated biphenyls (PCBs) were used as dielectric materials in the large electric power systems that powered the gaseous diffusion plant and in various gaskets and seals in plant equipment. From 1946 through 1987, estimated uranium releases from K-25 included 10,500 kg to the air, 16,700 kg to surface water, and 33,000 kg to on site land disposal. In addition, tens to hundreds of gallons or pounds of various volatile chemicals, like methylene chloride and fluorine, were released to the atmosphere though normal use.

The K-25 Site includes the K-1070-A contaminated burial grounds, where materials contaminated with uranium, thorium and their chemical compounds, UF_6, beryllium chips, boron, radioactively contaminated sodium fluoride, oil, plutonium, and arsenic were placed in unlined trenches, pits, and diked drum storage pads for waste oils and PCB wastes between the late 1940s and 1976. Also located at K-25 is the K-1070-C/D classified burial grounds, a 22-acre tract; the 1.3 acre K-1407-B holding pond, an unlined hazardous waste lagoon, used from the 1940s until the early 1980s for settling metal hydroxide precipitates from neutralized solutions; the K-1413 treatment facility, where groundwater was contaminated with solvents, radionuclides, and acid waste in the 1950s; and a number of contaminated scrap metal yards. Seventy thousand drums of sludge from the settling ponds have been solidified and removed.

Uranium enrichment is the largest contributor to the Department of Energy's materials in inventory. The Department stores depleted uranium enrichment "tails" at all three gaseous diffusion plants. Enrichment is also the major source of the Department's scrap metal inventory, including large amounts of steel, aluminum and nickel. This material results from the replacement and removal of enrichment process equipment.

Uranium enrichment plants have also resulted in some of the largest of the Department's surplus facilities. Although not as numerous as the facilities involved in other production processes, the gaseous diffusion plant buildings are very large, with many acres of floor space. Contamination in these facilities includes enriched uranium, PCBs, and asbestos.

Lithium Enrichment

Lithium enriched in the lighter lithium-6 isotope is used as a raw material for the production of tritium, and in weapons components in the form of lithium deuteride, a material which resembles a ceramic. The Oak Ridge Y-12 Plant began the initial effort to develop lithium isotope separation processes in 1950. Three processes were explored: COLEX, ELEX, and OREX.

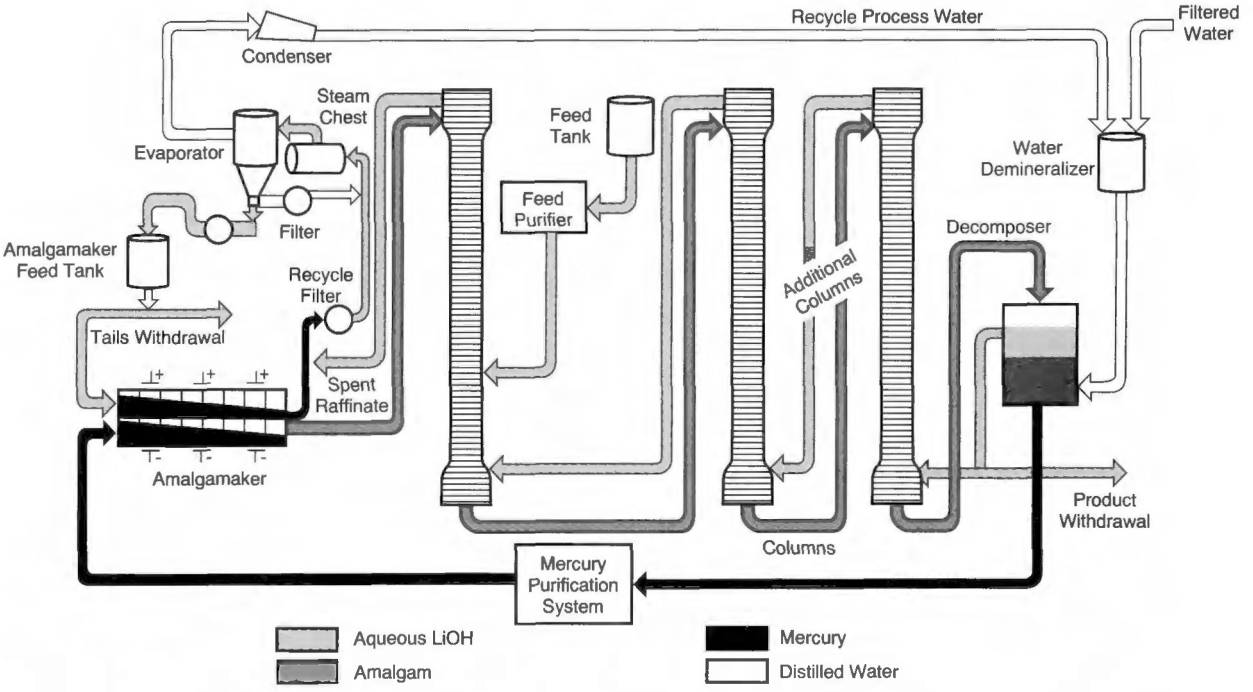
The first successful laboratory separation was achieved with the ELEX process—an electrically driven chemical exchange process similar to that used in chlor-alkali plants for the manufacture of chlorine gas and sodium hydroxide. The ELEX pilot plant was built at Y-12 in 1951. Y-12 operated a production scale ELEX plant in building 9204-4 ("Beta 4") from 1953 until 1956. This plant was cleaned out and dismantled by 1959.

The OREX process, in which an organic solution of lithium was exchanged with a solution of lithium in mercury (called an "amalgam") never advanced further than the pilot plant stage. The OREX pilot plant in Y-12 Building 9202 was built in 1952 and subsequently dismantled between 1957 and 1959.

The COLEX process (the name is a contraction of "column exchange") is based on the fact that isotopes of lithium are partially separated when transferring between an aqueous solution of lithium hydroxide and

a lithium-mercury amalgam. The COLEX process supplied most of the enriched lithium needed for the weapons complex. AEC built two large COLEX facilities, called Alpha 4 and Alpha 5, in Buildings 9201-4 and 9201-5 at the Y-12 Plant. Alpha 4 operated from January 1955 until 1963. The unit was placed on standby until it was dismantled in the late 1980s. Alpha 5 began operating in 1955. It was shut down in 1959 and restarted in 1963 for a six-month campaign. Y-12 Plant engineers dismantled and disposed of the Alpha 5 COLEX process equipment in 1965 and 1966. Site contractors operated an open-air mercury receiving operation, where mercury flasks were emptied into a pipe leading to the COLEX plants, at the

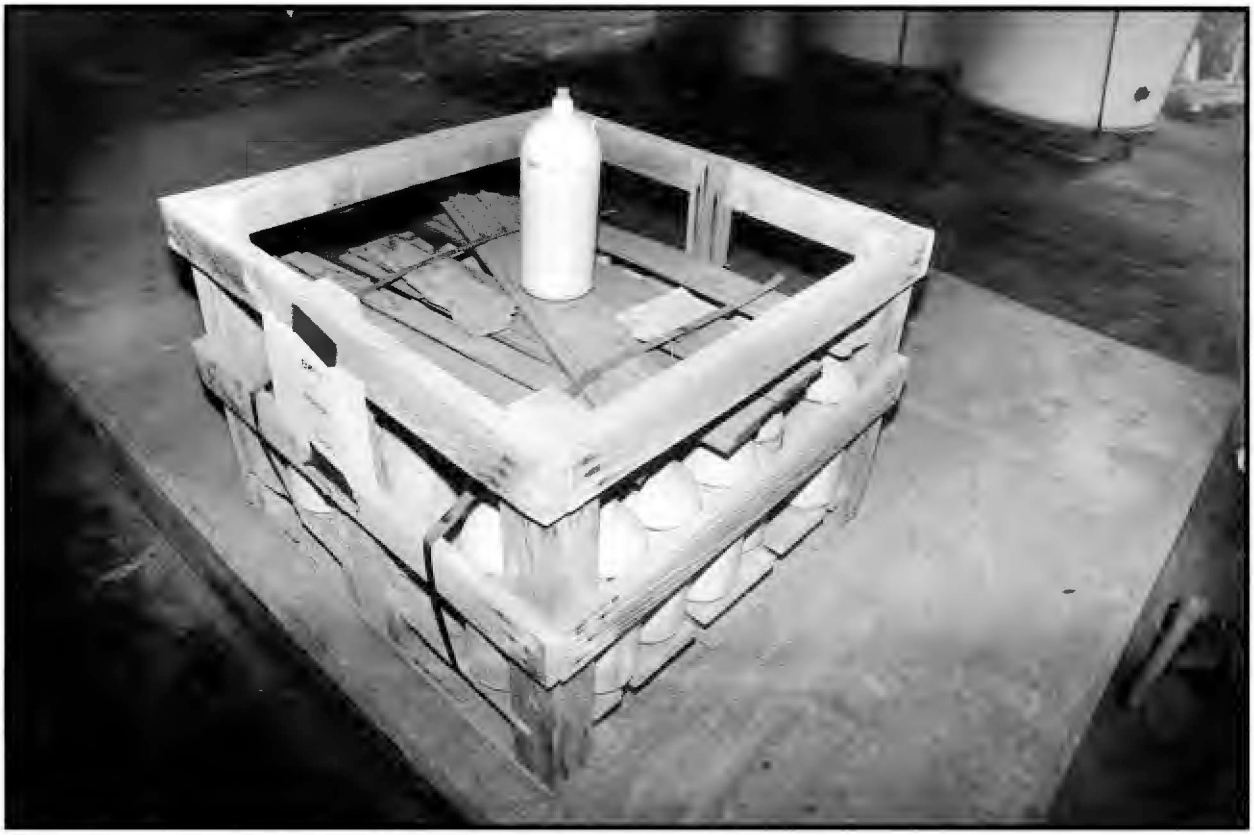
Figure B-7. COLEX Process for Lithium Isotope Separation



site of the current Building 9103. They used a furnace in a shed at the location of Building 81-10 to roast sludges, wastes and other materials for mercury recovery.

Lithium enrichment has created a considerable amount of materials in inventory. DOE stores the lithium enrichment "tails," depleted in the lithium-6 isotope, at the Portsmouth Plant and the K-25 Site. K-25 also stores a stockpile of unprocessed lithium. Y-12 and K-25 both store the Department's stockpile of enriched lithium.

The COLEX process employed approximately 24 million pounds of mercury. Most of the mercury used in the COLEX and ELEX processes was returned to the General Services Administration (GSA) once it was no longer needed. However, a great deal of mercury was lost in wastes, spills, and through evaporation. A mercury-nitric acid purification system utilized in the COLEX process between 1955 and 1960 was the source of the major mercury-bearing waste stream at Y-12. This system discharged a diluted, neutralized acid waste containing mercuric nitrate to East Fork Poplar Creek. Mercury vapor from the plant was exhausted to the environment by the building ventilation systems. Mercury from spills also contaminated basement sumps which were pumped through three concrete sedimentation tanks into the storm sewer and from there were pumped directly into East Fork Poplar Creek. DOE believes that small amounts of residual mercury are still present in the Y-12 Plant sewers. Inorganic mercury compounds of the type released at Y-12 plant were not initially believed to be toxic unless inhaled. It was not until 1970



Flasks of mercury used for lithium enrichment at Y-12. Between 1951 and 1963, a significant fraction of the available world supply of mercury was used in this process. Approximately 730,000 pounds of that mercury is known to have been lost, spilled, or dumped into the environment around Oak Ridge, and for which an additional 1.3 million pounds are unaccounted. *Alpha 4 Building, Y-12 Plant, Oak Ridge, Tennessee. January 11, 1994.*

Lithium enrichment "tails," a byproduct of lithium enrichment at Oak Ridge, are stored at the Portsmouth and K-25 plants. The 30.8 million kilograms of lithium tails stored at Portsmouth are stacked from wall to wall and floor to ceiling in a series of "barns." DOE repackaged these materials in the 1980s after their original cardboard containers deteriorated. This lithium was sold to commercial buyers in 1996, and is gradually being shipped off site for use in batteries and other industrial applications. *Portsmouth Gaseous Diffusion Plant, Piketon, Ohio. 1986.*

COLEX lithium-enrichment equipment. This plant was shut down in 1963. *Alpha 4 Building, Y-12 Plant, Oak Ridge, Tennessee. January 11, 1994.*

Reality Lake, originally named New Hope Pond, is located at the eastern end of the Y-12 Plant. Engineers created the lake in 1963 to alter the flow of East Fork Poplar Creek, which runs through the Y-12 site. Their aim was to reduce variations in the alkalinity of the creek water and limit the spread of chemical spills. Sediments containing mercury from Y-12 settled at the bottom of the lake rather than washing downstream into the Clinch River. Although this reduced the severity of contamination in the Clinch River system, it poses problems for the environment at Y-12, as the sediments of the creek and lake are severely contaminated. *Reality Lake, Y-12 Plant, Oak Ridge, Tennessee. June 15, 1993.*

that scientists discovered the biological methylation of inorganic mercury in the environment, which raised concerns over mercury discharges to surface water.

Approximately two million pounds of mercury used in the lithium enrichment processes have still not been accounted for. Approximately 730,000 pounds (about 4,000 gallons) of this material is believed to have been lost in waste streams, evaporation, and spills. A study done in 1983 estimated that evaporation during maintenance operations, seepage from pumps and other equipment, the venting of mercury vapors, and the smelting of mercury-contaminated scrap released 51,300 pounds of mercury into the air. The COLEX process discharged 239,000 pounds of mercury to East Fork Poplar Creek in the process waste stream, some of which is now in sediments at the bottom of New Hope Pond. DOE believes that these waste discharges are also the source of some of the mercury contamination in Watts Barr Lake, Poplar Creek and the Clinch River. However, these bodies of water are also downstream from a commercial chlor-alkali plant. Residual mercury contamination at Y-12 includes sludges and mercury residue in building sewers and drain systems. The 1983 study also estimated that approximately 425,000 pounds of mercury were lost to the soil in eight accidental spills at the Y-12 Plant.

Boron-10 Production

Boron-10 is a powerful neutron absorber with many uses in the nuclear weapons complex. The boron-10 production process uses a dimethyl ether-boron trifluoride complex. The complex is fed into a distillation system. When the complex is boiled, part of the vapor phase breaks down into boron trifluoride and dimethyl ether. Boron triflouride vapor molecules containing lighter boron-10 atoms reassociate into the liquid phase more rapidly than molecules containing the heavier boron-11 isotope. As a result, the heavier isotope is concentrated in the vapor phase and the lighter isotope in the liquid phase.

To supply boron-10, AEC built a plant in Model City, New York, near Niagra Falls. The plant operated from September 1954 until 1958, when AEC placed it on standby. The Model City plant was rehabilitated in mid-1964 and restarted. First, the restarted plant converted the remaining inventory of boron-10 from potassium fluoborate (KBF_4) to elemental boron to meet immediate weapon and reactor program demands. The plant continued to produce boron-10, until it was placed on standby again in March 1971 Since that time, the government has relied on commercial nuclear industry suppliers to convert its inventory of enriched boron-10 to a powder form, and to supply additional boron-10.

Heavy Water Production

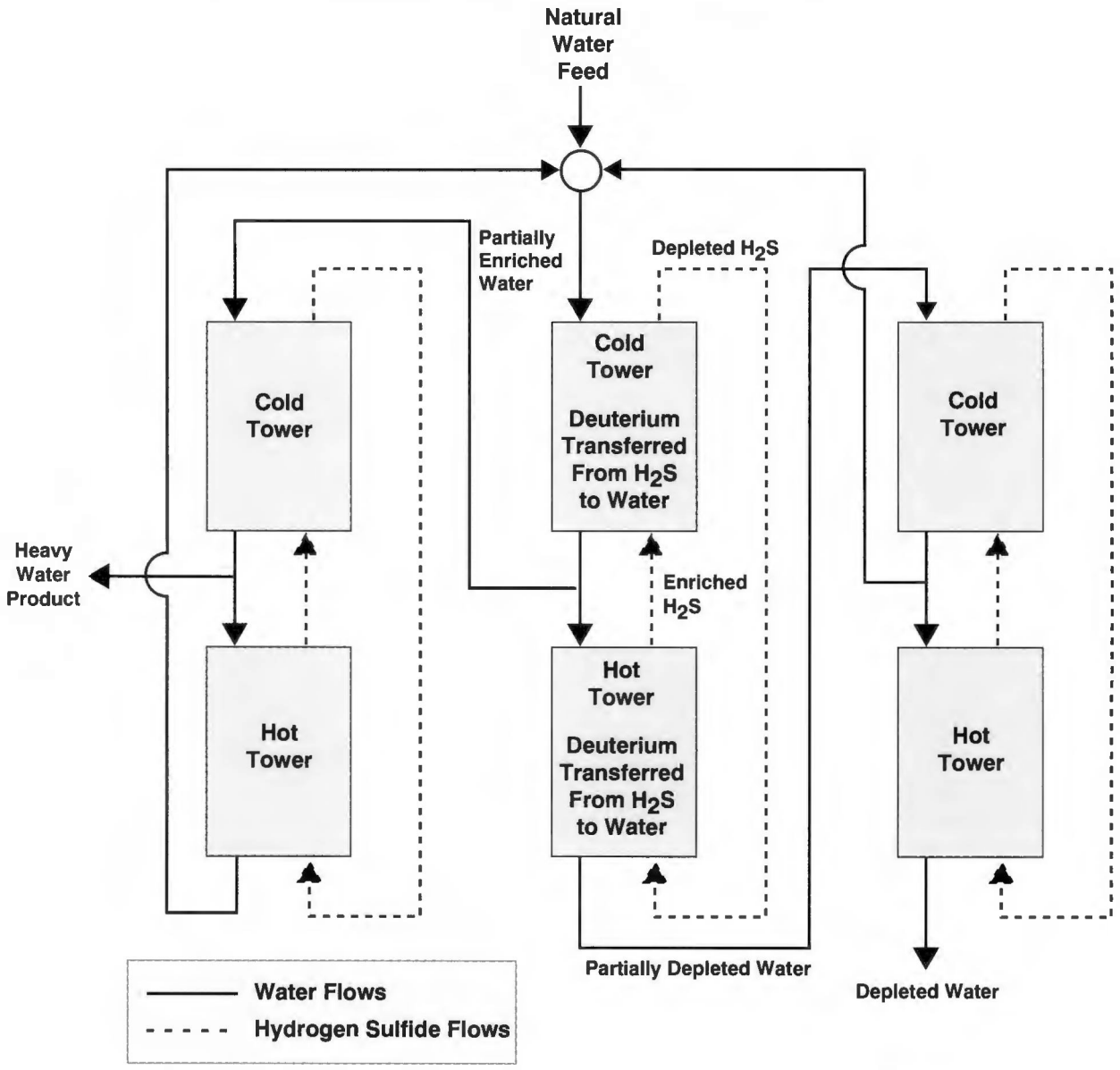
Deuterium occurs naturally at a concentration of about 0.015 percent in the element hydrogen. This naturally occurring isotope was concentrated to produce pure deuterium in the form of "heavy water." Deuterium, has three major uses in the nuclear weapons complex due to its low neutron absorption and ability to undergo fusion to create heaver elements. Heavy water was used as a coolant and moderator in nuclear materials production reactors at the Savannah River Site. Deuterium separated from heavy water is combined with enriched lithium-6 to make ceramic-like lithium-6 deuteride parts for the secondary stages of thermonuclear weapons. Finally, a mixture of deuterium and tritium gases is injected into the "pit" of the primary (fission) stage of modern U.S. nuclear weapons to "boost" nuclear explosive yield.

Heavy water can be made using hydrogen sulfide-water chemical exchange, water distillation, or (in the earlier years) electrolysis. A description of the hydrogen sulfide process is contained in Figure B-8.

A small amount of heavy water was produced by electrolysis in the United States prior World War II. A plant operated by Norsk Hydro in Vemork, Norway was the world's major source of heavy water in the early 1940s. The first large heavy water plant in North America was built for the Manhattan Project by Standard Oil Co. at the Consolidated Mining & Smelting Company plant in Trail, British Columbia, Canada.

Most of the heavy water for the U.S. nuclear weapons programs was made at two sites. The Dana Heavy Water Plant in Newport, Indiana operated from April 1952 until May 1957, and remained on standby

Figure B-8. Heavy Water Enrichment Using the Hydrogen Sulfide Process



until July 1959. The Savannah River Site Heavy Water Plant in South Carolina began operating in October 1952, and after a staged shutdown, terminated heavy water production in 1982. Savannah River Site engineers finished dismantling the production plant in 1996. Both sites used a combination of hydrogen sulfide-water chemical exchange, water distillation, and electrolysis processes. Degraded "half-heavy water" from dismantled weapons was recycled through the Savannah River Site Heavy Water Plant for re-enrichment. The Savannah River Heavy Water Plant continues to produce deuterium gas for nuclear weapons from existing heavy water stocks using an electrolytic process.

Savannah River Heavy Water Plant being dismantled. The plant seperated and concentrated the small fraction of deuterium found in ordinary water to produce "heavy water." Heavy water produced here between 1952 and 1982 was used in plutonium and tritium production reactor on the site and in nuclear weapons. *Heavy Water Extraction Facility, Savannah River Site, South Carolina. January 8, 1994.*

Heavy Water Production

Deuterium, which occurs naturally at a concentration of 0.015% in water, can be concentrated by several methods, all of which exploit the differences in chemical properties that result from the difference in the masses of the two isotopes.

Hydrogen Sulfide-Water Exchange – In a mixture of hydrogen sulfide (H_2S) and water at chemical equilibrium, the concentration of deuterium in water is greater than the concentration in H_2S. The difference in these concentrations depends on the temperature of the mixture. In practice, water and hydrogen sulfide gas are made to flow in opposite directions at two different temperatures. Deuterium is transferred from the gas to the water in the cold section. The depleted gas is recirculated to the hot section, where deuterium is transferred back into the gas from the water. Several stages of this process allow deuterium enrichments of up to 20-30%.

Fractional Distillation – Water molecules containing deuterium atoms vaporize at a higher temperature than those without deuterium, so the boiling point of heavy water is slightly higher than that of normal water. Water vapor above a mixture of normal and heavy water will be slightly depleted in deuterium as a result, while the liquid will be slightly enriched. Enrichment results from successively boiling off and removing vapor containing normal hydrogen.

Electrolysis – Water containing normal hydrogen is more easily disassociated into hydrogen and oxygen gases by an electric current than water containing deuterium. This allows the isotopes to be separated.

The Savannah River Site heavy water plant used the hydrogen sulfide-water exchange process to partially enrich heavy water. Deuterium was further concentrated by fractional distillation, and then by electrolysis. The moderator rework unit at SRS used fractional distillation to re-enrich reactor moderator that had become depleted in deuterium.

Fuel and Target Fabrication

Fuel and target fabrication consists of the foundry and machine shop operations necessary for the conversion of uranium feed material into the fuel and target elements used in nuclear materials production reactors. Included are the casting, extrusion, alloying, plating, cladding, machining, etching, cleaning, degreasing, and grinding to produce the finished elements.

Three basic types of production reactor fuel and targets were manufactured. Some of the production reactors used natural or low-enriched uranium as fuel. The uranium-235 in the fuel sustained the chain reaction while the uranium-238 in the fuel captured neutrons to produce plutonium. Other reactors used "driver fuel" (made with highly-enriched uranium) and separate targets (made of depleted uranium) for the same purposes.

In addition to uranium, various materials placed in the reactor cores ("targets") or around them ("blankets") absorbed neutrons to produce useful isotopes. Targets and blankets of lithium-6 were used to make tritium. Targets of thorium-232, neptunium-237, and bismuth-209 have been used to produce, respectively, uranium-233, plutonium-238, and polonium-210. DOE and its predecessors have irradiated many more target materials in small amounts to produce special isotopes, including thulium-170, iridium-192, lanthanum, plutonium-242, americium, curium, and californium.

Manhattan Project Reactor Fuel Manufacturing

The first nuclear reactors, including the three Chicago piles, the Oak Ridge X-10 reactor, and the Hanford B, D and F production reactors and 305 test pile, were built and operated by the Manhattan Engineer District of the U.S. Army Corps of Engineers. Because enriched uranium was not available in large quantities until 1945, and enrichment focused on producing highly-enriched uranium for weapons, Manhattan Project reactors used fuel made of unenriched natural uranium (NU) metal.

Metallurgical properties of uranium were unknown before the Manhattan Project. Most of the early uranium metallurgical research was accomplished from 1942 to 1943 at various research facilities including the University of Chicago Metallurgical Laboratory (known as the "Met Lab"), Iowa State College (now the Iowa State University) in Ames, Iowa, DuPont's Chambers Dye Works in Deepwater, New Jersey, Princeton University in New Jersey, and the Albany Research Center in Albany, Oregon.

The first self-sustaining chain reaction was achieved in a "pile" called CP-1 ("Chicago Pile 1) built by Enrico Fermi and his Met Lab colleagues under a squash court at the University of Chicago. "Fuel" for the pile consisted of lumps of uranium oxide and metal. Westinghouse Electric of Bloomfield, New Jersey, Metal Hydrides of Beverly, Massachusetts, and the Iowa State College supplied metallic uranium. Laboratory workers at the University of Chicago pressed uranium oxide, supplied by the Mallinckrodt Chemical Works in St. Louis, Missouri, into solid lumps. CP-1 was disassembled and rebuilt at the Palos Forest Preserve outside Chicago as CP-2; the uranium was reused.

Unlike the Chicago reactors, the Oak Ridge X-10 and Hanford reactors required cooling to dissipate the heat generated by their much greater power output. The X-10 reactor used air as a coolant, while the Hanford reactors, although originally designed to be helium cooled, were built to use cooling water from the Columbia River. Uranium fuel for these reactors had to be "canned" to prevent the release of highly radioactive fission products into the coolant and prevent corrosion of the uranium by the coolant. The high power levels of the Hanford reactors called for uranium slugs to be "bonded" to aluminum cans to improve heat conduction from the slug to the cooling water, however, fuel for the Oak Ridge reactor was "unbonded." Due to problems with slug canning, MED manufactured "unbonded" Hanford slugs as a backup. These slugs later proved to be unsatisfactory.

Beginning in 1943, 14 private contractors and vendors produced fuel for the X-10 pilot plant reactor and the full-scale Hanford production reactors. Several contractors extruded, rolled, or drew uranium ingots into long rods that were subsequently straightened and outgassed (heated in an inert atmosphere).

Another group of contractors machined these finished rods into short slugs and ground, coated, bonded and canned them into finished uranium slugs. Hanford eventually manufactured its own fuel rods on site.

Engineers selected extrusion over rolling, drawing, forging, and other uranium rod fabrication methods. At the start of the extrusion process, workers preheated uranium billets in a rotary electric resistance furnace for about an hour. They quickly placed the hot billet into the extrusion container after brushing or flattening it as necessary to remove rough or swollen spots. A hydraulic ram pushing against a block at the back of the billet forced the hot metal through a die at high pressure. In about ten seconds, the extrusion press formed a 20 inch long, 200 pound billet into a 14 foot long rod. Workers quickly straightened and quenched the finished rod in water. They removed the unextruded "butt" end of the billet from the press and recycled it as scrap.

Between 1943 and 1946, the Revere Copper and Brass Company extruded uranium rods in its Detroit, Michigan plant. B&T Metals of Columbus, Ohio extruded a large quantity of uranium metal rods for Hanford from April through August 1943. Wolverine Tube in Detroit, Michigan extruded uranium for MED starting June 1943. As an alternative to extrusion, the Carpenter Steel Company of Reading, Pennsylvania experimented with rolled uranium rods in July 1944, but these proved to be inferior to the extruded product. Joslyn Manufacturing & Supply Company of Fort Wayne, Indiana also rolled uranium rods from billets starting in 1944 and continued until 1949. Uranium ingots began arriving at Hanford in November of 1944, however, extrusion there did not commence until January 1945.

A specialized machine tool performed the final straightening of uranium rods. Subsequently, workers heated the rods for several hours in an inert atmosphere to drive off gases (especially hydrogen) that are dissolved, combined or included in the metal. This process is called "outgassing." The Copperweld Steel Company of Warren, Ohio outgassed and straightened a large quantity of uranium rods for the Hanford and Oak Ridge reactors between May and August 1943. Revere Copper & Brass also outgassed and straightened rods in Detroit. Hanford began outgassing and straightening its own uranium fuel rods in September 1944.

Extruded or rolled uranium rods, 5 to 6 feet long and 1.425 to 1.475 inches in diameter, had to be cut and finished into eight inch long, 1.36 inch diameter slugs with tight tolerances. The slug machining process is straightforward. A machinist finishes one rough end of a straightened, outgassed uranium rod on a lathe. The machinist uses the lathe to reduce the rod to the proper diameter, cut off a slug, finish the cut end of the slug, and round off the corners. During this process, a large flow of coolant (a water and oil mixture) prevents the uranium chips and turnings from igniting.

Before 1942, nobody had ever machined metallic uranium. Summerville Tubing Co., Wycoff Drawn Steel Co., International Register Co., and Globe Steel (locations unknown) initially developed uranium machining techniques in 1942 and 1943.

Hanford began machining uranium rods in December of 1943. Baker Brothers of Toledo, Ohio machined 130 tons of uranium rods from Revere Copper and Brass into slugs, filling most of the initial fuel requirement for the Oak Ridge graphite reactor between June and October 1943. Baker Brothers also manufactured unbonded uranium slugs for Hanford from early 1944 until July of that year. C.H. Schnoor (Springdale, Pennsylvania) machined unbonded Hanford slugs from metal rods between May and July 1944. The Herring-Hall-Marvin Safe Company in Hamilton, Ohio machined uranium slugs from rolled rods in the 1940s to the early 1950s. American Chain & Cable Co. in Bridgeport, Connecticut swaged uranium rods (i.e., reduced their diameter) in 1944. The William E. Pratt Manufacturing Co. (a subsidiary of Joslyn Manufacturing & Supply) machined slugs for CP-1 in the spring of 1943 and, in the spring of 1944, turned and ground unbonded Hanford slugs. Subsequently, between May and August of 1944, McKinney Tool & Manufacturing in Cleveland, Ohio turned and ground unbonded Hanford slugs.

Development of sealed cans that would allow sufficient cooling of the uranium slugs was a difficult task. Alcoa in New Kensington, Pennsylvania sealed the slugs for the X-10 reactor into unbonded aluminum

cans. Experimental, unbonded Hanford slugs were canned by the Quality Hardware & Machine Corporation of Chicago, Illinois in the summer of 1944.

The slug canning process for Hanford was developed by DuPont at the Grasselli Laboratory in Cleveland, Ohio. Hanford's "triple dip" slug coating and canning process for bonding the uranium slugs to the cans started in March 1944. The original fuel elements for the Hanford reactors were solid uranium cylinders encased in aluminum cans. Uranium slugs were cleaned with nitric acid, then successively bathed in molten bronze, tin and an aluminum-silicon mixture. After water quenching, the sleeve was removed from the element, the aluminum end cap was machined and brazed on, and the finished element was etched in nitric acid. Steel sleeves surrounding each can were cleaned in sodium hydroxide. Aluminum caps and cans were cleaned in a sodium dichromate solution, followed by a methanol dip and air drying. Three tests followed. First the element was sprayed with acenaphtelene mixed with carbon tetrachloride and heated to test the bond between the core and can. Next the acenapthelene was removed with trichloroethylene and the canned element was heated in a steam autoclave in Building 314 to test for leaks. Finally, the element was radiographed (x-rayed) to check the porosity of the weld.

Fuel manufacturing produced scrap in the form of chips and turnings from the lathes, rejected fuel slugs, the "butts" from the extrusion process, uranium oxide, and acids and sludges from the slug, cap, sleeve, and can pickling, cleaning, and recovery processes. Uranium scrap processing was initially centered at the Metal Hydrides plant in Beverly, Massachusetts, which recast uranium scrap from 1943 until 1947.

Uranium metal reduction. A Fernald metals worker guides a cylindrical steel reaction vessel containing new uranium metal away from a bank of furnaces toward a cooling area. To convert into a metal, workers mixed green uranium salt crystals with magnesium granules in these reaction vessels, then heated them in a vacuum induction furnace for several hours until molten uranium metal was formed. Once the cylinder cooled, workers would remove the solidified uranium metal, re-melt it, and cast it into a cylindrical ingot. *Plant 5, Metals Production Plant, Feed Materials Production Center, Fernald, Ohio. December 16, 1985.*

Sampling the Derby. A Fernald metals worker collects metal shavings from a new uranium derby. She will send them to an onsite laboratory which confirms the isotopic content and purity of the metal. *Plant 5, Metals Production Plant, Feed Materials Production Center, Fernald, Ohio. December 17, 1985.*

Fernald Laundry. At the Fernald site, over 1,000 pairs of cotton work suits were laundered daily to rid the clothing of uranium dust. Laundry water was treated as low-level radioactive waste because of its uranium content. *Feed Materials Production Center, Fernald, Ohio. December 16, 1985.*

Post-War Development of Fuel Fabrication

After the end of the war, Hanford manufactured its own reactor fuel for a few years using uranium metal ingots supplied from off site. However, slug manufacturing shifted off site again in the late 1940s and early 1950s. Hanford stopped extruding uranium rods in 1948, switching to rolled rods from off-site suppliers. In 1950, Hanford began making rolled uranium rods on site, but AEC shifted the rolling work to the Fernald, Ohio Feed Materials Production Center and its supporting contractors in 1952. During the late 1940s and early 1950s, uranium rods were rolled or extruded by Vulcan Crucible Steel Company in Aliquippa, Pennsylvania, Revere Copper and Brass, and the Brush Beryllium Company in Detroit, Joslyn Manufacturing & Supply Company in Fort Wayne, Indiana, Allegheny-Ludlum Steel Corporation in Watervliet, New York, and Simonds Saw & Steel Co. of Lockport, New York.

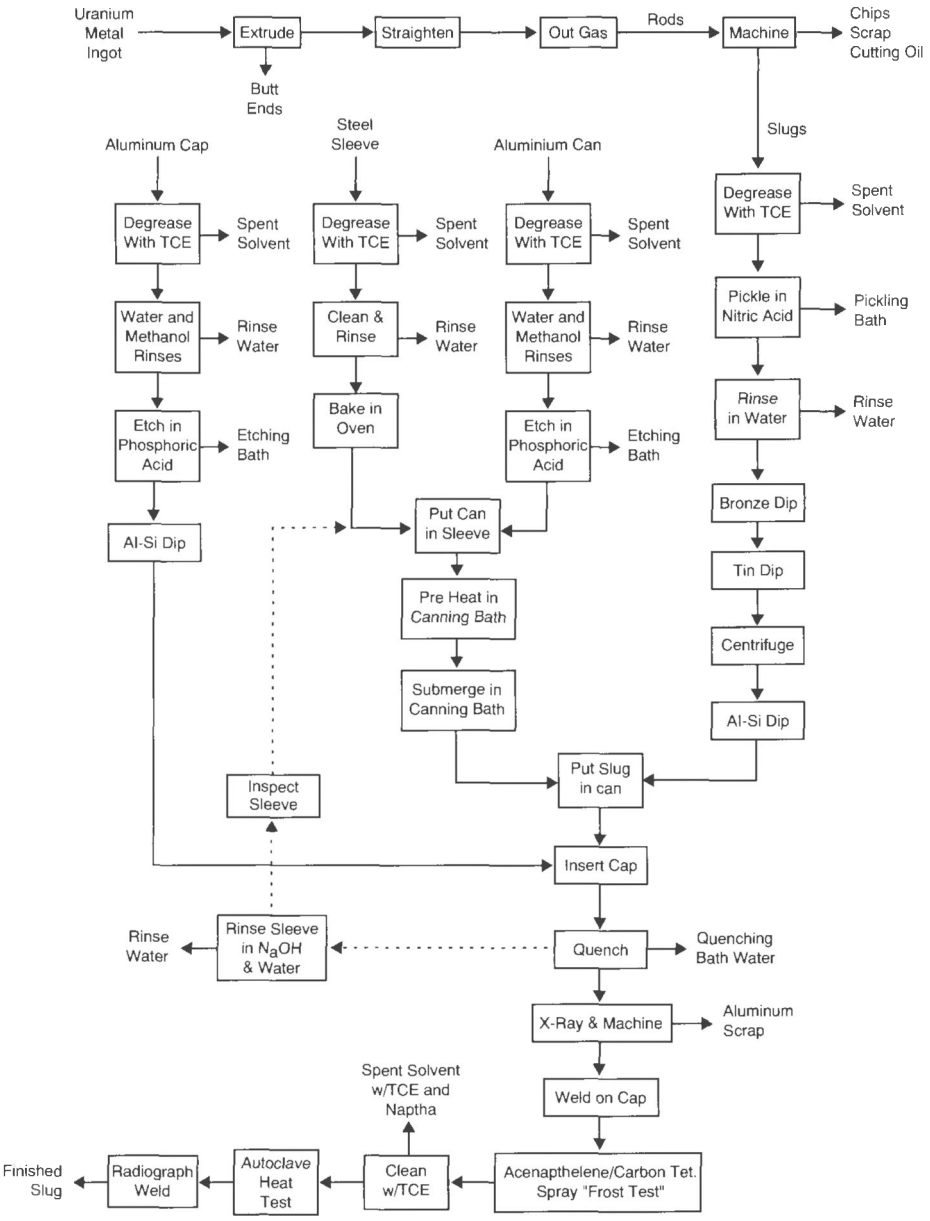
Uranium ingots were machined into billets on a lathe at Fernald. The shiny ingots have been machined while the dull ones have not. *Fernald Feed Materials Production Center, Ohio. December 17, 1985.*

To increase plutonium production capacity, Hanford began adding low-enriched uranium fuel slugs to its reactors as early as 1950. Enriched uranium fuel also allowed Hanford engineers to even out the reactor's temperature and power distribution, reducing problems caused by uneven thermal expansion and radiation-induced swelling of the graphite core. Neutron absorbing "poison" slugs, also made on site, also helped to even out the reactor's power distribution. Most of these enriched uranium slugs were manufactured using the same techniques as the natural uranium slugs. However, some of the fuel elements were made of highly-enriched uranium alloyed with aluminum, which required special fabrication techniques to prevent accidental criticalities. These "driver" elements were often used in combination with special targets such as the lithium targets used to make tritium. Improvements in fuel slug design gradually reduced the tendency of the fuel slugs to become misaligned inside the reactor.

Fernald and Weldon Spring

AEC greatly expanded the number of production reactors in the weapons complex in the late 1940s and early 1950s. By 1955, a total of thirteen AEC production reactors were in operation: eight at Hanford and five at Savannah River. To supply fuel for these new reactors, AEC established the Feed Materials Production Center in Fernald, Ohio, in 1951. Fernald's sister facility, the Weldon Spring Plant near St. Louis, Missouri, opened in 1956. In addition, commercial contractors continued to support AEC's fuel fabrication needs throughout the 1950s.

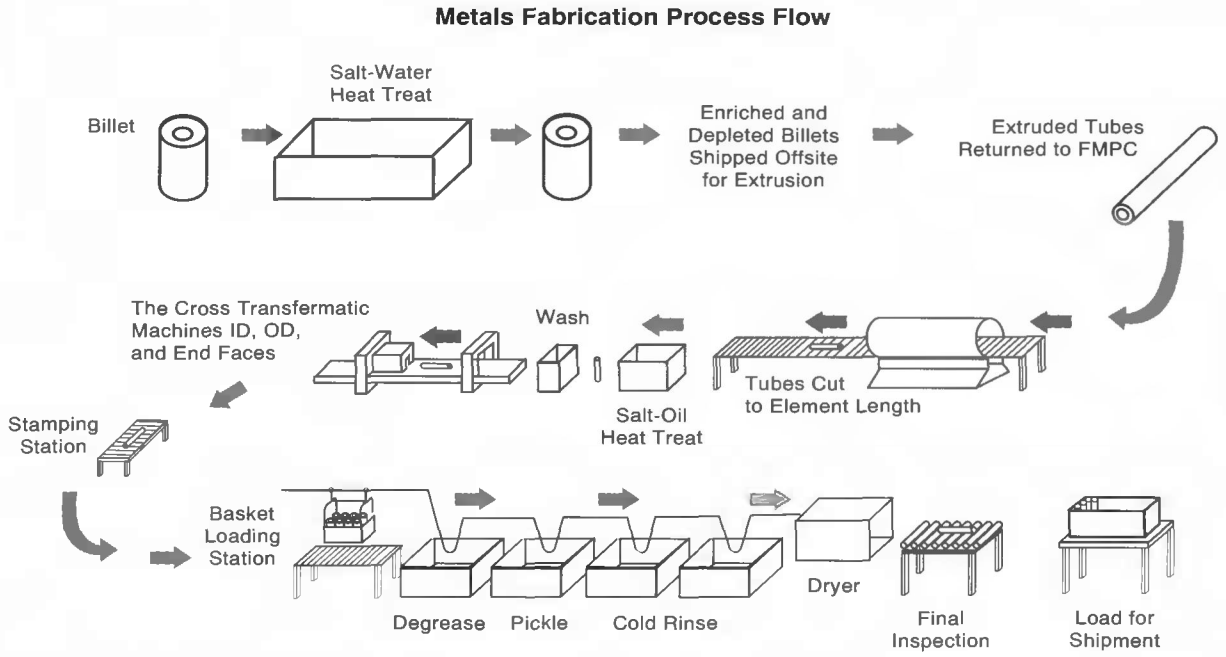
Figure B-9. Fabrication Process for Hanford Reactor Fuel, 1945 to 1954



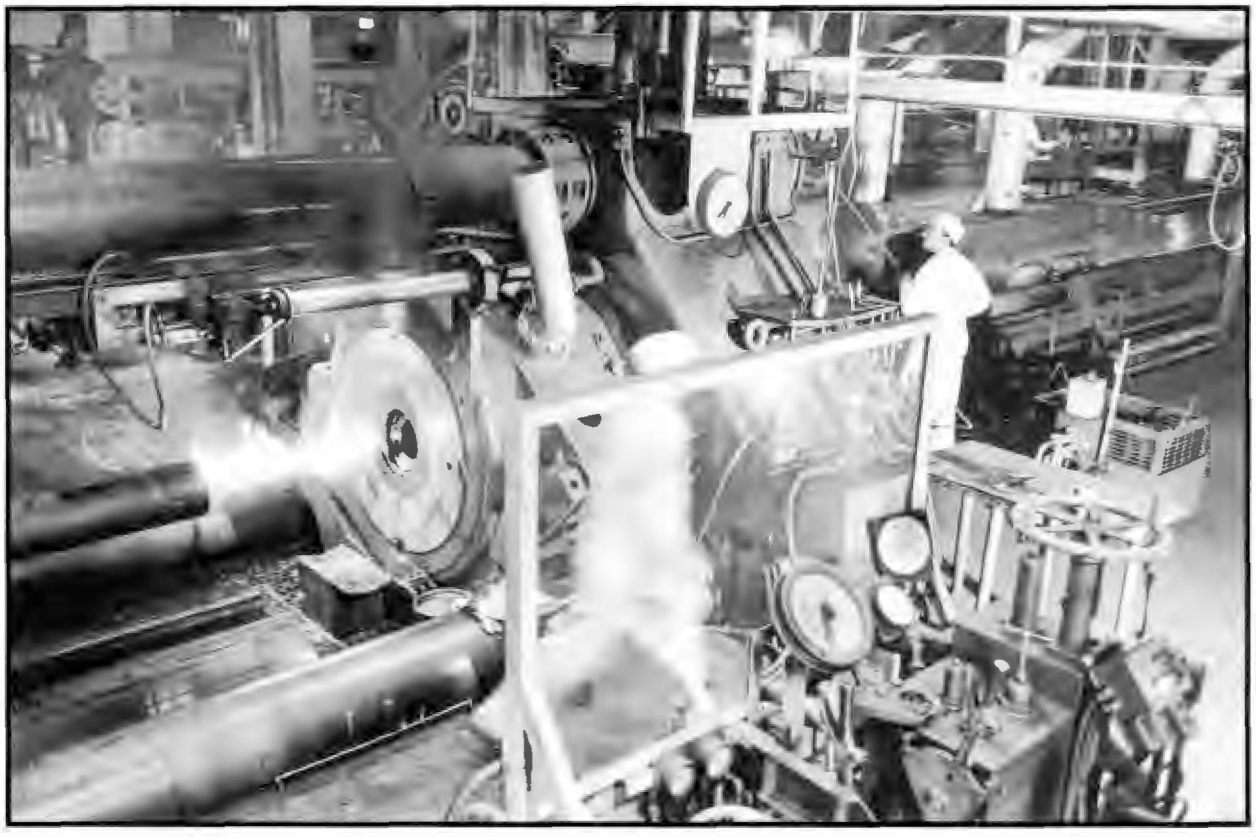
AEC improved its reactor fuel manufacturing technology with the help of several contractors. Bethlehem Steel, in Lackawanna, New York, developed improved rolling mill pass schedules in 1949 to be used at the Fernald plant. Developmental work using rolling mills to make uranium rods was also done by Allegheny-Ludlum Steel in Dunkirk, New York between 1950 and 1952. Starting in 1954, Bridgeport Brass Company in Bridgeport, Connecticut (at a facility known as the Havens Laboratory) and Adrian, Michigan, worked to improve the extrusion process. In 1961 and 1962, the large extrusion press used for semi-production work at Adrian was dismantled and transported to the Ashtabula, Ohio Reactive Metals, Inc. plant where it was permanently installed. Work at the Bridgeport laboratory continued, moving to Seymour, Connecticut in 1962.

Extrusion and Machining – FMPC and Weldon Spring produced ingots of natural, low-enriched and depleted uranium to be extruded off site into tubes and billets for further machining into the uranium cores and shipment to the Hanford and Savannah River sites for cladding and assembly. The extrusion was performed by Bridgeport Brass Co. in Adrian, Michigan from 1954 to 1961 and then by its corporate successor, Reactive Metals, Inc., in Ashtabula, Ohio. Fernald also housed its own rolling mill. Figure B-10 provides a schematic of the production processes as they were performed at Fernald in the 1980s.

Figure B-10. 1980s Extrusion and Machining Production Process at Fernald



Note: Chips and lathe turnings from machining are crushed, pickled, rinsed, dried, formed into briquettes, and re-cast.



Ashtabula uranium metal extrusion press. This press extrudes red hot uranium ingots into long tubes. The uranium tubes were shipped back to Fernald where they were cut into fourteen inch lengths. These segments were then sent to South Carolina where they will be bombarded with neutrons and transformed into plutonium. *Reactive Metals, Inc., Ashtabula, Ohio, June 19, 1984.*

Along with many of the extrusion plants and rolling mills mentioned above, American Brass Co. of Waterbury, Connecticut, extruded copper-clad uranium billets for the Savannah River Site in the late 1950s, using copper-plated billets supplied by Nuclear Metals, Inc. Granite City Steel, located in Granite City, Illinois, x-rayed uranium ingots to detect metallurgical flaws for Weldon Spring from 1958 until 1966. Dow Chemical in Madison, Illinois, researched and developed extrusion techniques in 1957 and straightened uranium rods for Weldon Spring in 1959 and 1960. A number of contractors provided uranium slug machining services: Bliss & Laughlin Steel of Buffalo, New York; Alba Craft Laboratory of Oxford, Ohio; and Associated Aircraft and Tool Manufacturing, Inc. of Fairfield, Ohio.

Slug Cladding and Assembly – Except for the periods from 1944-1948 and 1950-51, Hanford received all of its uranium slugs from off site suppliers. With the exception of the experimental (and unsatisfactory) unbonded slugs produced in 1944, slug cladding and fuel element assembly have always been a mission of Hanford's 300 Area. Similarly, the Savannah River Site always received uranium slugs from off site suppliers, but cladded and assembled them to produce completed fuel elements in the M Area.

Hanford Fuel Improvements – Beginning in 1954, the solid cylindrical fuel rods were replaced with "cored" fuel rods, in which the uranium cylinder was drilled lengthwise to allow for expansion during irradiation and sealed into aluminum cans with closed ends. Also in 1954, Hanford switched to a new, lead-dip process for canning the fuel. The process consisted of immersing the uranium fuel cores in a bath of molten lead covered with molten aluminum, followed by a molten aluminum-silicon bath. At about the same time, the bonding test was changed, eliminating the use of acenapthelene and carbon tetrachloride. Between 1955 and 1964, about 30,000 single-pass reactor fuel elements were canned each week. A "hot die size" process involving nickel plating which incorporated nickel sulfate, nickel chloride, and boric acid was developed in the early 1960s, but never implemented on a large scale.

By 1957, the cored fuel rods were supplanted by tubular "I&E" fuel rods which allowed cooling water to run down the middle as well as around the outside. Various fuel slug improvements were tested, including changes in end designs, cladding materials and processes, and end cap welding. Eventually Hanford adopted "tru line" fuel elements with male and female ends to prevent misalignment of the fuel elements in the reactor.

N Reactor Fuel Fabrication at Hanford – The Hanford N Reactor used slightly enriched uranium fuel. Fernald and Weldon Spring produced the enriched uranium ingots and sent them to Ashtabula to be extruded into tubular billets. Fernald then shipped the billets to Hanford, where they were clad with zirconium into finished fuel assemblies using the coextrusion process. By the time of the start-up of the N Reactor at Hanford in late 1963, there were sufficient stocks of enriched uranium at FMPC to supply it without additional uranium from the gaseous diffusion plants. Hanford also chemically recycled enriched uranium from its own fuel, and enriched "mined" uranium for reactor fuel from the high-level waste tanks on site, using the U Plant. Enriched uranium from the gaseous diffusion plants was not needed for Hanford until 1985, shortly before N Reactor was shut down.

The coextrusion process for fabricating N Reactor fuel was developed in Building 306 (known locally as the "Met Semi-Works") and implemented in the 333 Fuels Manufacturing Building. Copper and copper-silicon preshapes and backing plates were inspected and cleaned with nitric, nitric hydrofluoric, and chromium nitric sulfuric acid. Next, zircaloy-2 cladding materials (an alloy of zirconium with nickel, tin, chromium and iron) were degreased in an organic solvent, rinsed with nitric and hydrofluoric acid, and air dried. The uranium billets were degreased with perchloroethylene, etched with nitric acid, rinsed with water, dried, and inspected. The uranium, copper, and zirconium parts were assembled and welded, tested, heated and extruded together. The extruded elements were cooled, cut, and machined. Nitric acid rinses removed copper and silicon residues and nitric sulfuric acid chemically milled away excess uranium on the ends of the slugs. A final nitric and nitric hydrofluoric acid etching preceded the brazing on of the end caps. The end caps were degreased and etched as well. After additional finishing, the parts were given a final etching in nitric hydrofluoric acid, tested, and assembled. This process reached a peak volume of 250 fuel elements per week in the mid-1980s.

Miscellaneous Target Fabrication at Hanford – Hanford made lithium-aluminum alloy targets between 1949 and 1952 as part of the P-10 tritium production project. (Tritium was called "coproduct" at Hanford.) From 1965 to 1967 the site again manufactured lithium aluminum target inserts, this time for the N Reactor. To make polonium-210, Hanford's 300 Area manufactured lead-bismuth alloy targets (called "B Metal") and welded them into unbonded aluminum cans, from 1944 to the early 1950s. The site's reactors used lead-cadmium fuel elements in nonbonded aluminum cans, made on site, as "poison" elements until 1971. In the1940s engineers at Hanford investigated thorium poison slugs (called, "myrnalloy") and thorium targets reappeared in the 1950s for experimental uranium-233 production. Hanford also manufactured a variety of aluminum spacers used to hold the fuel rods in position inside the cooling water tubes from the late 1950s to 1971. The spacers were electrolytically anodized to create a protective aluminum oxide coating. Beginning in the mid-1960s, Hanford made passivated steel spacers for the N Reactor.

Savannah River Site M Area – M Area at the Savannah River Site manufactured fuel for the Savannah River Site reactors beginning in 1954. The five SRS reactors originally were fueled with aluminum-clad NU slugs which served as both fuel and targets. These slugs, and the manufacturing processes, were similar to those at Hanford.

To increase production capacity and operational flexibility, SRS converted in 1968 to HEU fuel using recycled enriched uranium. HEU metal from Y-12 was received at the SRS M Area, alloyed with aluminum, and extruded into aluminum-clad assemblies. After 1968, the SRS M Area also received depleted uranium metal slugs from FMPC and bonded them into tubular metal cans to be used as plutonium production targets. Enriched lithium (Li-6) received from Y-12 in sealed aluminum cans was alloyed and clad with aluminum for use as tritium production targets.

Shutdown of DOE Fuel Fabrication

Weldon Spring shut down in 1966 after losing a direct competition with Fernald. Buildings 313 and 314 at Hanford, which made fuel for the eight single pass reactors, shut down in 1971, and the equipment was removed from the mid-1970s to the mid-1980s. The N Reactor coextrusion process was discontinued in December 1986 when N Reactor shut down.

Fernald and the Savannah River Site M Area continued to manufacture reactor fuel after Hanford's reactors closed. However, they too shut down in 1989, when the Savannah River Site's reactors ceased operating for environmental and safety upgrades. With the exception of a brief restart of one reactor, SRS never resumed production, and the temporary shutdowns of Fernald and the Savannah River Site M Area became permanent.

Post-War Uranium Scrap Processing and Recycling

Uranium was scarce and expensive during the Manhattan Project and enriched uranium, even more so. Even after considerable domestic and world supplies of uranium were discovered in the mid-1950s, enriched uranium remained a precious commodity. Hence, recovery of uranium from process effluents, scrap, and other waste was a priority in the nuclear weapons complex.

Hanford began recycling uranium scrap on site in 1946. Chips of uranium metal from slug machining were sorted, washed, and pressed into briquettes. Uranium metal chip fires were a common problem. At first, the briquettes (and presumably other materials) were sent to Metal Hydrides in Beverly, Massachusetts, to be recast, but in May 1946, the briquetting was halted. In 1947, a "melt plant" was set up in the Hanford 300 Area. The melt plant melted the scrap metal with new uranium metal and recast the metal into ingots to feed the fuel manufacturing process. Another plant at Hanford began oxidizing various solid uranium-bearing materials and shipping them off site in five gallon buckets. Both the melting and oxidizing operations at Hanford were phased out between 1952 and 1954.

Crates of depleted uranium Mark 31 Target cores await shipment to the Savannah River Site where they would be bombarded with neutrons and partially transformed into plutonium. *Fernald Feed Materials Production Center, Fernald, Ohio. December 17, 1985.*

Fernald eventually began to receive and recycle unirradiated uranium scrap from fuel fabrication. After 1954, the scraps and residues from the Hanford fuel fabrication processes were filtered, slurried into sodium diuranate, and shipped to the Fernald plant.

A number of private contractors processed unirradiated uranium scrap for AEC in the 1960s, including the Davidson Chemical Company division of W.R. Grace and Company (later part of Nuclear Fuel Services, Inc.) in Erwin, Tennessee; Nuclear Materials and Equipment Corporation (NUMEC) of Apollo, Pennsylvania; United Nuclear Corporation in Hematite, Missouri and New Haven, Connecticut; National Lead Company in Albany, New York; Kerr-McGee Corporation located in Guthrie, Oklahoma; and General Atomics of La Jolla, California.

Fuel Fabrication Waste Management

Fernald and Weldon Spring – Waste from fuel and target fabrication and scrap recycling at the Fernald and Weldon Spring plants was managed in the same manner as the waste from uranium refining. Fernald disposed of solid and slurried waste in seven pits, a clearwell, two lime sludge ponds, and a sanitary landfill. Treated liquid waste flowed into the Great Miami River. Weldon Spring used a nearby quarry and four waste lagoons (called "raffinate pits") to store contaminated residue and waste from the plant.

Hanford 300 Area – Fuel fabrication at Hanford generated a considerable amount of waste, particularly acidic liquid waste from fuel slug can, cap and sleeve cleaning and testing, and uranium scrap processing. From the beginning of its operations, Hanford 300 Area discharged waste acids (nitric, sulfuric, hydrofluoric, and chromic nitric sulfuric) containing uranium, zirconium, copper, beryllium, and other materials, to an underground tank containing limestone, then to percolation ponds through a process sewer. Radioactivity levels in the original process pond, which covered 490,000 square feet to a depth of five feet,

rose by three orders of magnitude been 1945 and 1948, including a September 1947 spike from a large release of uranyl nitrate hexahydrate.[3]

The original process pond dike broke on October 25, 1948, spilling most of the pond's contents into the Columbia River. Following this accident, a new process pond was built to the north of the original pond, and the two ponds were used in tandem. Periodically, sludge from the ponds was dredged to recover uranium. In 1955, 10,300 pounds of uranium were recovered from a 9-inch deep swath of sludge taken from the bottom of the North Process Pond. The 300 North cribs were built in 1948 to allow UNH, ammonium nitrate, hexone, and other solvent wastes to percolate into the ground. These cribs received liquids containing 2,070 pounds of uranium by 1956. The Process Ponds were phased out in 1974 and 1975, and replaced by the 300 Area Process Trenches and the Waste Acid Treatment System.

In 1973, the Waste Acid Treatment System began operation at Hanford. This facility neutralized waste acids (approximately 210,000 gallons annually) with sodium hydroxide, and it centrifuged and filtered them to remove the resulting solids. Solids were then drummed and disposed of at the Hanford site. Tanks held the remaining liquid effluents, which were trucked to large, open solar evaporation basins in the 100-H reactor area until 1975. From 1975 until 1985, the effluents were disposed in the 300 Area Process Trenches. After 1985, Hanford took these liquids to the 200 Areas or shipped them off site for disposal. Rinse water, process water, cooling water, and steam condensate continued to be discharged to the process sewer. Several spills and leaks of process water occurred, including a June 1978 spill of 19,000 gallons of waste etching acid. At least six solid waste burial grounds were used in the Hanford 300 Area.

Savannah River Site M Area – From 1954 until 1958, waste effluents from metal-forming, electroplating and cladding activities, which contained metal degreasing solvents, acids, caustics, and metals, were discharged to the Tims Branch stream. In 1958, AEC authorized the construction of the M Area settling basin for waste streams containing enriched uranium. Some additional effluents were diverted from the Tims Branch outfall to the settling basin in 1973. After the Tims Branch stream outfall was closed in May 1982, all M Area effluents were diverted to the settling basin. However, in November 1982, most process effluents which did not directly contact the uranium and other radioactive materials (such as cooling water and surface drainage) were diverted back to the Tims Branch outfall. The Savannah River Site discontinued usage of the M Area Settling Basin in July 1985 when the Liquid Effluent Treatment Facility became available. Areas contaminated by wastes from the Settling Basin include the basin itself, the overflow ditch, the natural seepage area, a bay known as Lost Lake, and the inlet process sewer line.

[3] *Uranyl nitrate hexahydrate, chemical formula $UO_2(NO_3)_2*6H_2O$, is usually abbreviated as UNH*

REACTOR OPERATIONS

Reactor operations include fuel and target loading and removal, reactor maintenance and modification, and the control and cooling of the reactor as it operates. Large production reactors provide the neutrons needed to produce nuclear materials in large quantities. Smaller reactors are used to test materials and perform experiments.

Operating a nuclear reactor creates highly radioactive materials—spent nuclear fuel and irradiated targets. The structures of the reactor core and the reactor coolant also become radioactive. Most of the radioactivity in the DOE weapons complex was created in production reactors.

Manhattan Engineer District Reactor Operations

Seven nuclear reactors operated in the United States before and during World War II for the purpose of reactor research and nuclear materials production. Under contract to the U.S. Army and in cooperation with the University of Chicago, the E. I. du Pont de Nemours Corporation of Wilmington, Delaware, designed the Manhattan Project reactors and managed the procurement of the materials they required.

The Chicago Piles – The first reactor, which proved that a self-sustaining nuclear fission chain reaction was possible, was the Chicago Pile (CP-1) built by Enrico Fermi and his associates at the University of Chicago. CP-1 began operating on December 2, 1942. The reactor was fueled with lumps of natural uranium metal and oxide in a moderator matrix of graphite blocks. Forty tons of graphite for the reactor were supplied by the United States Graphite Company and machined at the MetLab. Denser, purer graphite came from the National Carbon Company. CP-1 had no cooling system and produced only a few

L-Reactor, Savannah River Site. Mark 31 target cores from Fernald were loaded into this reactor and bombarded with neutrons, which transformed some of the depleted uranium metal into plutonium. In front of the reactor are three reservoirs of cooling water. The Savannah River Site had a total of five plutonium production reactors. *L Area, Savannah River Site, South Carolina. August 6, 1983.*

watts of power. Recovery of any plutonium produced in the reactor was possible only after complete dismantlement.

By March 1943, CP-1 had been dismantled and rebuilt with modifications as CP-2 at the Palos Forest Preserve outside of Chicago. This location was code-named "Site A." CP-2 was larger than CP-1 and featured five feet of shielding to protect the scientists from radiation exposure. A heavy-water reactor, built for research on reactor physics, started up at Site A in May 1944. This reactor was called "CP-3."

After the war, reactor research in Chicago continued. The newly organized Argonne Laboratory was relocated its present site southwest of Chicago in January 1947. Today, Argonne National Laboratory is one of the Department of Energy's multi-program research laboratories. In 1956, AEC directed the shutdown of CP-2 and CP-3, still operating at Site A. Uranium, graphite, and heavy water were removed from these reactors, and the remaining shells were buried in a nearby area known as "Plot M."

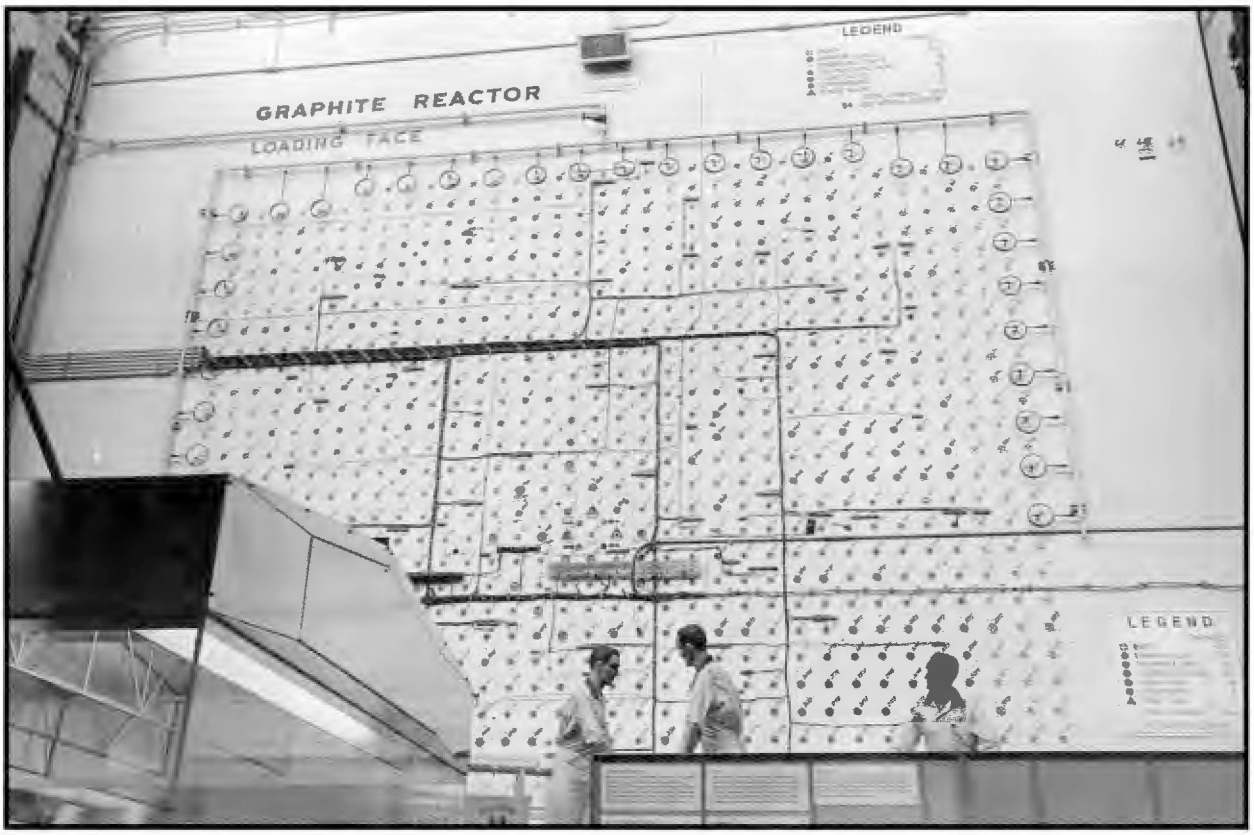
Clinton Pile (X-10) – To test the principles of reactor operation and plutonium separation, the Manhattan Engineer District built a "semi-works," code-named "X-10." Originally planned for the Chicago area, MED relocated the semi-works to the more isolated area of eastern Tennessee known then as Clinton, now called Oak Ridge, for safety and security reasons. The X-10 reactor (also called the Clinton Pile or the "Graphite Reactor") was the pilot plant for large plutonium production reactors soon to be built at Hanford, Washington.

X-10 consisted of a cube of graphite moderator 24 feet on each side, fueled by aluminum-clad natural uranium cylinders fed and discharged through 1,239 horizontal cylindrical holes. A charging machine inserted fresh slugs through the front face of the reactor, and pushed spent slugs out through the rear, where they fell into a water-filled channel. Workers transferred buckets of these irradiated slugs to the neighboring separation plant using an underwater monorail. Exhaust fans pulled cooling air through the pile, keeping it under a slight vacuum to prevent an escape of contamination. Air-cooling was selected for its simplicity, even though engineers had abandoned gas-cooling in favor of water-cooling for the full-scale Hanford reactors in February 1943. Seven feet of concrete shielding protected reactor operators from radiation. Controls included four horizontal "shim" rods, two horizontal regulating rods, six vertical safety rods, and a backup system using boron steel shot suspended over the reactor core. Designers provided various openings in the reactor to facilitate the insertion and removal of experimental samples. Initially, X-10 had a power output of 1,000 kilowatts; this output was soon quadrupled.

The X-10 reactor became operational on November 4, 1943. The Clinton Pile focused on plutonium production, research on shielding, and the biological effects of radiation. By February 1944, X-10 was producing several grams of plutonium per month. The high neutron background from this material greatly influenced the design of the plutonium bomb being developed at Los Alamos. X-10 also produced radioactive lanthanum, for use as a tracer in high-explosives experiments, and irradiated bismuth targets to produce polonium-210 for weapon initiators.

After the war, Oak Ridge scientists continued to use the X-10 reactor for reactor research nuclear physics, and isotope production for medical, industrial and agricultural applications. Oak Ridge produced radioactive lanthanum ("Rala") until 1956. The X-10 site became Oak Ridge National Laboratory in 1948. The Oak Ridge Graphite Reactor, as it is known today, was decommissioned in 1963. It is now a national historic landmark, open to visitors.

Hanford 305 Test Pile – To test materials for the full-sized production reactors at Hanford, Manhattan Project engineers used the 305 Test Pile. The reactor's air cooled, natural uranium fueled, 16-foot graphite cube was shielded by five feet of concrete. Horizontal regulating and shim rods controlled the reactor power, with vertical and horizontal safety rods and a steel-shot-filled vertical safety tube in case of emergencies. Uranium metal slugs fueled the reactor, but because of the low power output, they were not designed to be easily removable. Twenty horizontal openings accommodated test stringers for irradiating samples.



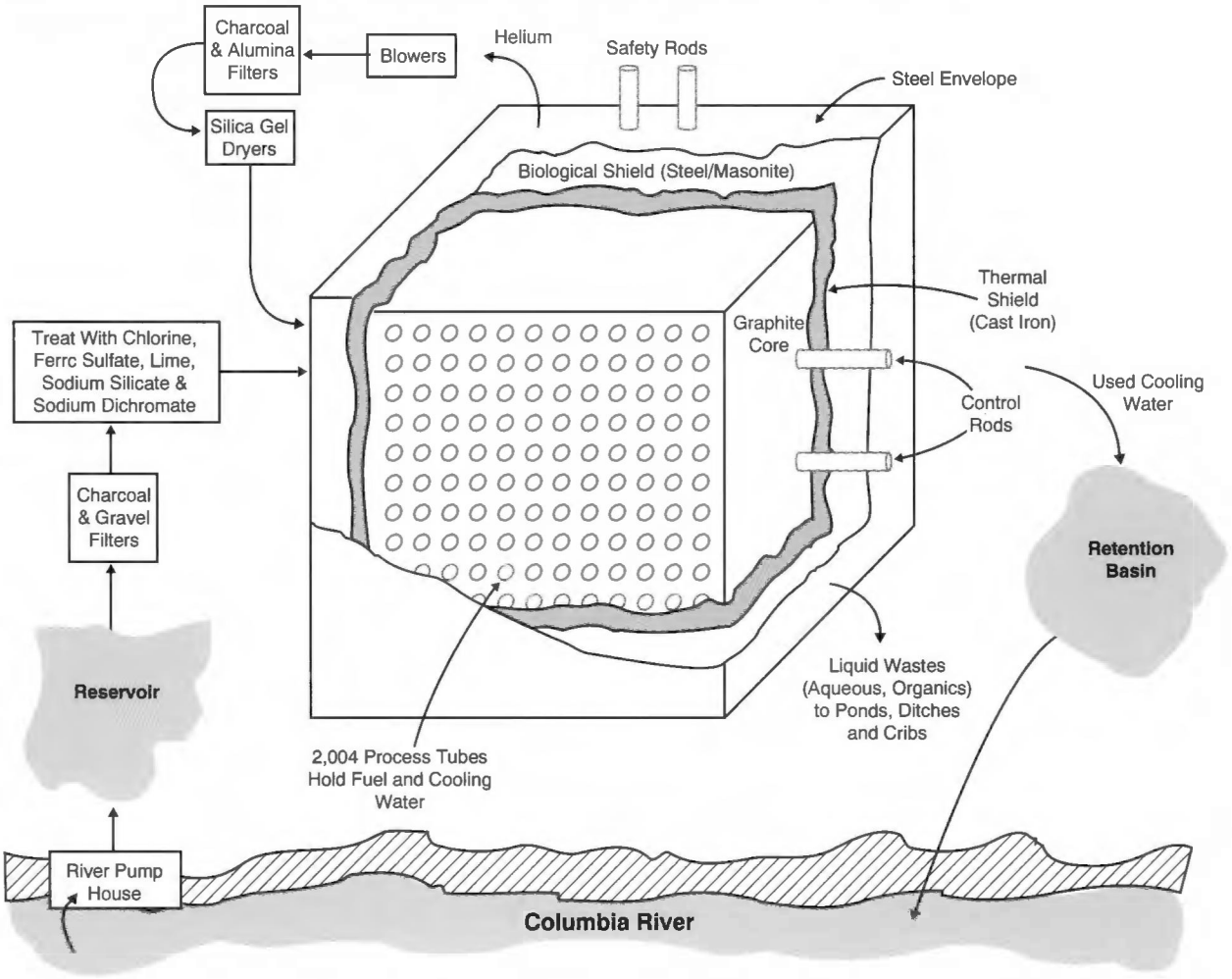
The Oak Ridge Graphite Reactor, code-named "X-10," produced the world's first gram quantities of plutonium. It was the pilot plant for Hanford's full-size plutonium production reactors. X-10's core is a graphite block 24 feet on each side. A charging machine inserted fresh uranium metal slugs through holes in the reactor's front face, pushing irradiated slugs out the back. Fans pulled cooling air over the fuel slugs. Oak Ridge scientists used X-10 for research and isotope production until it was decommissioned in 1963. *Oak Ridge Graphite Reactor Historic Landmark, Oak Ridge National Laboratory, Tennessee. June 11, 1982.*

The 305 reactor began operation at 50 Watts in March 1944 to test graphite, aluminum, uranium and other materials. These tests allowed Hanford engineers to verify that the materials met the strict specifications for use in the three full-scale reactors. The 305 test pile also provided radiation for instrument development. After the war, the 305 Pile tested reactor materials for six more Hanford reactors. The reactor operated through 1972, when the building was converted to fuel fabrication. The 474,000 ton graphite reactor core was dismantled and buried in 1976 and 1977.

Hanford B, D, and F Reactors – MED built three full-scale reactors during World War II to mass produce plutonium for atomic weapons: the B, D and F Reactors. Although originally planned for Oak Ridge, engineers quickly realized that a larger, more isolated site was necessary to protect the public safety. Hanford, Washington was chosen because of its isolation, abundant supply of pure, cold Columbia River water for reactor coolant, and easy access to abundant and reliable hydroelectric power from the Grand Coulee and Bonneville dams.

The core of the Hanford reactors was a block of graphite, 36 by 36 by 28 feet, surrounded by a 10-inch thick layer of cast iron blocks (the "thermal shield") and a laminated masonite and steel biological shield four feet thick to prevent the escape of gamma radiation. The entire block was encased in a welded steel box with expansion joints. The graphite block, built up from over 100,000 graphite bars, contained 2,004 horizontal aluminum "process tubes" to hold fuel slugs and cooling water. The name, "single pass reactors," comes from the fact that cooling water flowed through the reactor and eventually back into the Columbia River. (See Figure B-11).

Figure B-11. Hanford Single-Pass Production Reactor



Unlike the Clinton pile, the Hanford reactors were gas-tight. A circulating helium atmosphere displaced neutron-absorbing air from the reactor core, and removed gases generated by the reactor. The helium also assisted in the detection of cooling water leaks inside the reactor and helped to dry out the graphite after a leak had been repaired. A separate water cooling system was installed to cool the thermal shield. As in the Clinton pile, DuPont engineers included nine horizontal control rods and 29 vertical safety rods in each Hanford reactor. A backup system would dump a reaction-absorbing boron solution into the safety rod channels. Instrumentation allowed the operators to monitor the reactor power, temperature and other parameters constantly.

Fuel charging and discharging machines inserted slugs into the reactor's front face and removed them from the reactor's rear face. The slugs fell into a pool of water where they were gathered into buckets by remote control to be taken to the separations plants. Dummy slugs made of steel, aluminum or aluminum-canned lead shielded the ends of the process tubes and filled the empty tubes. Engineers devised special machines to replace radioactive process tubes that had become damaged or excessively corroded, and to remove stuck fuel slugs.

Besides the reactor itself, MED built a number of support facilities for each reactor. Key facilities include: the reactor ventilation building; the helium cooling, purification and drying systems; the process water system; and the "lag storage" buildings for spent fuel.

Helium Cooling, Purification and Drying Systems – A blower circulated the helium reactor atmosphere through a filter. Three silica gel dryers removed moisture from the helium as it circulated. Purification of the helium used two activated alumina dryers and four activated charcoal beds. Excess helium vented through an automatic valve. Operators periodically regenerated the charcoal and exhausted the impurities to the plant stack. Despite recycling, the B Reactor consumed 660,000 cubic feet of helium in 1945.

Process Water System – Each of the three wartime Hanford reactors required 30,000 gallons of cooling water per minute at its design power level of 250 megawatts, and each had its own process water system. The reactor areas also "exported" water to the 200 areas and used it locally in boilers and for other miscellaneous uses. River pump houses drew raw water into a 25 million gallon storage reservoir. Filtered, treated raw water was stored in a 10 million gallon "clearwell." Water from the clearwell flowed into two 1.75 million gallon tanks in the reactor pump house. Deaeration, demineralization and chilling plants were also built, but never used because they proved unnecessary. Chlorine, ferric sulfate, sodium silicate, lime, and sodium dichromate additives controlled the chemistry of the intake water, removed impurities, killed bacteria and algae, and reduced corrosion.

Twelve sets of steam and electric pumps pumped the water through the reactor core. After its passage through the reactor, effluent water flowed into a 12 million gallon retention basin, where radioactivity decayed for a few hours before the water was released back to the Columbia River.

"Lag Storage" Buildings for Spent Fuel Storage – Early Hanford workers called irradiated fuel slugs "lags." The slugs were removed from the reactor discharge basins after about a day and moved the Lag Storage Buildings. Irradiated fuel was initially stored for a few weeks to fifty days to allow fission products (especially iodine 131) to decay before reprocessing to separate the plutonium.

Construction began on B Reactor in June 1943, and start-up occurred in September 1944. D and F reactors were complete and operational by early 1945. The original three Hanford reactors, together with possibly a few grams of plutonium from Oak Ridge, supplied the plutonium for the Trinity test at Alamogordo, New Mexico, on July 16, 1945, and the Fat Man bomb used at Nagasaki, Japan on August 9, 1945.

Post-War Production Reactor Operations

The three Hanford reactors continued to operate through 1945. In 1946, B Reactor was shut down to limit the accumulation of radiation-induced swelling and distortion of its graphite core. After engineers discovered a method of reversing this process, AEC authorized the restart of B Reactor in 1947. Brief shutdowns after this period allowed workers to make many repairs and upgrades to the process water and effluent systems, instrumentation and control systems. The addition of enriched uranium fuel and the "flattening" of the reactor's power distribution using poison slugs and "splines" eventually allowed the World War II reactors' power output to reach over three times their original design levels. However, the increased reactor power caused fuel slug ruptures to begin and increase in frequency, causing increased radionuclide releases to the Columbia River.

Savannah River Site – To increase its plutonium production capacity and provide the large quantities of tritium then believed to be necessary for thermonuclear weapons, AEC selected a new production reactor site on the northern side of the Savannah River separating South Carolina and Georgia. This new site also agreed with AEC's philosophy of maintaining redundant facilities for each weapons production mission. Savannah River Site has five production reactors, code-named R, P, L, K and C. A small sixth reactor in the site's A Area tested materials for constructing the production reactors.

Reactors for the Savannah River Site were designed by DuPont. Unlike Hanford's reactors, the SRS reactors were cooled and moderated with heavy water flowing in a closed loop system at low temperatures and pressures. This arrangement allowed greater efficiency and more flexibility than the graphite reactors at Hanford. Each SRS reactor consisted of a large, shielded stainless steel tank holding 600 fuel and target assemblies. Charging and discharging machines allowed fuel to be loaded and removed from

the reactor by remote control. The reactor's "head" housed 491 movable safety and control rods. A helium gas atmosphere was maintained over the heavy water in each reactor.

Six pumps and circulated the heavy water through 12 heat exchangers at each reactor. Cooling water drawn from the Savannah River removed the heat before being returned to the river via surface streams. Two large artificial lakes at the site, PAR Pond (created in 1958) and L Lake, acted as coolant reservoirs. Backup cooling systems allowed the reactors to be cooled after shutdown in the event of a failure in the main cooling system.

Besides the reactor itself, each SRS production reactor building houses an assembly area, where fresh reactor fuel is stored and assembled; a disassembly area, consisting of a large pool of water where irradiated fuel is stored, disassembled for transport to the chemical separations plants, and loaded into transfer containers; and a purification area, for heavy water treatment and purification. The reactor buildings were equipped with filtered ventilation systems to confine airborne radioactivity.

Hot water discharged from the K Reactor at the Savannah River Site flowed through wetlands surrounding Pen Branch stream on its way back to the Savannah River. A cooling tower built in the 1980s eliminated the need to discharge hot water from the K Reactor. However, after the tower was connected to it in 1992, the reactor was never again started up. *K Area, Savannah River Site. January 7, 1994.*

R, P, L, K, and C Reactors began operating between December 1953 and March 1955. By that time, the tritium requirements for thermonuclear weapons had been greatly reduced, and the reactors began producing plutonium using natural uranium fuel, clad in aluminum. Tritium was produced in the lithium-6 reactor control rods and blankets. Besides plutonium and tritium, the SRS reactors produced cobalt-60, uranium-233, neptunium, plutonium-238 and-242, americium, and curium for nuclear weapons and nonweapons programs.

Between 1961 and 1964, engineers used a small seventh reactor at SRS, the Heavy Water Components Test Reactor, to make these various fuel and target assemblies. The Heavy Water Components Test Reactor shut down in 1965.

In 1968, the SRS reactors were converted to use HEU fuel which increased their output and flexibility, was supplied from four major sources: (1) spent research reactor fuel recovered at SRS H Canyon and ICPP, (2) spent Navy reactor fuel reprocessed at ICPP, (3) SRS production fuel recycled at H Canyon, and (4) weapons-grade HEU (often called Oralloy, Oak Ridge Alloy) from the Y-12 Plant reserves.

SRS conducted a dedicated tritium campaign in 1972, and a second in 1981, in which tritium was produced in specially designed fuel and target elements. After 1981, C Reactor was dedicated to tritium production.

R Reactor shut down permanently in 1964. L Reactor was placed on standby in February 1968, but restarted in October 1985. C reactor stopped operating in 1986, and went on cold standby in 1987, after engineers determined that cracks in the reactor vessel, discovered in 1984, could not be fixed. K, L and P Reactors shut down in 1988 for safety upgrades, and were placed on cold standby. K Reactor restarted briefly in 1989 and 1992.

Hanford H, DR, C, KW, and KE Reactors – AEC further expanded its plutonium production capacity by building five new reactors at Hanford. Beginning in March 1948, AEC built the H, DR, C, KW, and KE production reactors. Their designs were largely identical to the original three Hanford reactors, except that the newer reactors were designed for greater power output. C reactor was built adjacent to B Reactor, and DR (for, "D Replacement,") was adjacent to D reactor. The two K Reactors, also co-located, were known as the "Jumbo" reactors because of their size.

The new reactors were upgraded several times during their operating lives. Zirconium alloy process tubes, less susceptible to corrosion, replaced the original aluminum. As early as 1950, LEU fuel was added to increase power levels, thereby increasing plutonium output. Power increases and safety concerns necessitated improvements to the reactors' coolant systems, fuel slugs, control and safety systems, and instrumentation as well. Carbon dioxide was added to the reactor atmospheres to reduce radiation-induced swelling of their graphite cores. Water treatment changed as well.

Irradiated fuel handling at Hanford changed significantly in 1951. The Lag Storage Buildings did not have enough capacity to accommodate the fuel from the five new reactors being built. The storage buildings were phased out, and fuel began to be stored in the reactor discharge basins. Storage requirements also increased because decay times had been extended to ninety days or more. By the early 1960s, irradiated fuel storage times had increased to between 200 and 250 days.

The Hanford B and H Reactors produced tritium between 1949 and 1952 as part of the P-10 project. Lithium-aluminum slugs were irradiated, with highly-enriched "driver" fuel to sustain the chain reaction. The 108-B Chemical Pump House building became the tritium recovery plant. Tritium was recovered by heating the lithium targets in a vacuum furnace with an inert atmosphere. A palladium valve separated the tritium from other gases. Special pumps transferred tritium gas using mercury to vary pressure levels. The P-10 project ended when AEC transferred the tritium production mission from Hanford to the Savannah River Site in 1952.

All of the original eight Hanford reactors were shut down beginning in 1964 and ending in 1971.[4] Irreversible radiation damage had caused the graphite cores to swell and distort, and the decreasing demand for weapons-grade plutonium was being met adequately by the new Savannah River reactors.

Hanford N Reactor – A ninth Hanford reactor, N Reactor (for "New Production Reactor"), began operating on December 12, 1963. Unlike the original 8 Hanford reactors, N Reactor produced steam used to generate electric power as well as plutonium. N Reactor was LEU fueled, graphite moderated, and water cooled. It used a closed-loop cooling system rather than the single-pass system used in the older reactors.

[4] *B Reactor shut down in February 1968; D Reactor, June 1967; F Reactor, June 1965; H Reactor, April 1965; DR Reactor, December 1964; C Reactor, April 1969; K West Reactor, February 1970; K East Reactor, January 1971.*

N Reactor initially produced weapons-grade plutonium from 1964 to 1965. From 1966 to 1973 it produced nine percent fuel-grade plutonium-240 for AEC's breeder reactor program, and from 1974 until 1984, it produced 12 percent fuel-grade plutonium-240. Since the chemical separations plants at Hanford were not operating during most of this period, the irradiated fuel was stored in the K-East and K-West reactor basins. After fuel corrosion became a problem at the K-East basin, water treatment facilities were added to the still-empty K West basin. Then in 1984, N Reactor was converted to produce weapons-grade plutonium (six percent plutonium-240). N Reactor continued to produce weapons-grade plutonium until it was shut down in 1986. The reactor also produced uranium-233 (from thorium-232 targets), small amounts of tritium, and other isotopes.

Beginning in 1981 during a shortage of weapons-grade plutonium and an excess of fuel-grade plutonium, DOE began to blend fuel-grade plutonium from N Reactor with super-grade plutonium (~3% Pu-240) from SRS to make weapons-grade plutonium. All N-Reactor-produced fuel-grade plutonium, except for the amount supplied to and used by the Fast Flux Test Facility (an experimental reactor at Hanford) was considered excess and available for blending. The blending of fuel-grade and super-grade plutonium was performed in F Canyon at SRS. By 1990, all available fuel-grade plutonium had been blended.

Based on the quantity of fuel-grade plutonium used in the blending program, and considering the difference in fuel throughput requirements for weapons and fuel grade plutonium, it is estimated that most of the legacy generated by N Reactor is related to weapons production.

Waste Management for Reactor Operations

Most of the radioactivity in DOE's environmental legacy was created by reactor operations; however, the waste legacy attributed directly to this activity is mostly low-level waste from reactor support operations because the highly radioactive spent fuel and target materials are passed on to chemical separations. Conversely, the volume of legacy of contaminated environmental media and facilities from operation, support and decontamination of the production reactors is very large.

Spent Nuclear Fuel – Spent production reactor fuel and targets are stored at the Hanford and the Savannah River Site. The Hanford fuel was accumulated in the 1970s and early 1980s when the N Reactor was operating but the PUREX plant was shut down. Over 100,000 N reactor fuel assemblies and a much smaller number of single-pass reactor fuel slugs are stored in the K-East and K-West basins. DOE plans to move these materials into dry storage in a new facility away from the banks of the Columbia River.

Savannah River Site has stored thousands of irradiated targets in the K, L and P Reactor disassembly basins for several years after the shutdown of its production reactors. To stabilize the corroding materials, SRS dissolved and processed these targets in 1996. Spent fuel from SRS, containing highly-enriched uranium, continues to be stored in the reactor disassembly basins. These materials will also be dissolved and reprocessed, beginning in late 1996.

Spent nuclear fuel from Naval propulsion reactors, research and test reactors and some commercial nuclear power plants is stored at the Idaho National Engineering Laboratory, the Y-12 Plant, Argonne National Laboratory-East, Argonne National Laboratory-West, Brookhaven National Laboratory, Sandia National Laboratory, Los Alamos National Laboratory, the Fort St. Vrian Reactor in Colorado, and the West Valley Demonstration Project in New York. U.S. origin irradiated fuel is also being returned to the United States by the operators of research reactors in other countries. DOE plans to consolidate these materials based on their cladding type at the INEL and Savannah River.

Reactor Coolant Discharges – The eight single-pass reactors at Hanford discharged coolant to the Columbia River after a few hours' delay in a retention basin. This reactor effluent was radioactive because of activation of dissolved minerals and water treatment chemicals, and entrainment of corrosion products from the surfaces of the reactor fuel and process tubes. Fuel slug ruptures also released radioactivity into the coolant. Periodic "purges" using diatomaceous earth slurry to remove deposits on the surfaces of the process tubes also contributed to the releases. Radioactivity from these discharges was detected in

sediments and fish at the mouth of the river, several hundred miles away. Engineers considered building an inland lake system to increase the delay in releasing radioactive effluent to the river, but the idea was rejected because of concerns with environmental contamination. Conversion to closed-loop cooling systems was determined to be too expensive. Effluent decontamination was successfully demonstrated but proved to be impractical. Water treatment changes were more successful in reducing radionuclide releases to the river.

Besides radioactive contaminants, the Hanford reactor effluents contained hexavalent chromium, a toxic heavy metal used to reduce corrosion of the reactor's aluminum process tubes. Reactor discharges also raised the temperature of the river water, although Hanford workers installed structures to encourage mixing.

Leaks in the effluent retention basins at Hanford allowed contaminants to reach the groundwater beneath the reactor areas. Reactor operators diverted unusually radioactive effluents from slug ruptures or reactor purges to cribs, where it was believed that the radioactive water would be held in the pores of the soil.

At the Savannah River Site, releases of radioactive coolant were not routine because of the reactors' closed-loop cooling systems. However, heat exchanger leaks, reactor purges and other discharges allowed radioactive water to escape the reactors many times. In addition to the activation of native elements, water treatment additives, corrosion products, and fission products released by failed fuel elements, the heavy water in the Savannah River Site reactors contained significant amounts of tritium, which built up as the reactors operated.

During its first years of operation, the Savannah River Site released reactor cooling water and disassembly basin effluents directly to Steel Creek, Lower Three Mile Runs Creek, and the Pen Branch stream. To allow the reactor effluent to cool before leaving the site, engineers created PAR Pond in 1958, and L Lake in 1961, by damming Steel Creek and Lower Three Mile Runs Creek. K Reactor continued to discharge its cooling water directly to Pens Branch. Heat from reactor effluents affected plant and animal life on the site. SRS built a cooling tower in the late 1980s to replace the surface water discharge, and mitigate the effects of the hot water discharge. However, the reactor was not operated after it was connected to the new facility.

Sediments in PAR Pond at the site are contaminated with cesium-137 and transuranics as a result of reactor discharges in the late 1950s and early 1960s. Elevated levels of mercury have also accumulated in the sediments. The mercury came from water pumped from the Savannah River to keep the reservoir full.

Other Liquid Wastes from Reactor Operations – Reactor operations generated many liquid wastes in addition to large amounts of reactor coolant. These wastes included contaminated discharge and disassembly basin water, lubricating oils, solvents and acid solutions used to clean and decontaminate reactor equipment, and laboratory wastes. Operators disposed of contaminated water from water-fog systems used to decontaminate reactor gases at Hanford in soil cribs. Leaks and spills involving paint, gasoline, diesel fuel, water treatment chemicals and other substances also contributed to contamination in the reactor areas at both reactor sites. A total of 21 cribs and 19 ponds and ditches received waste from the Hanford reactor areas. Mercury from the pumps used to handle tritium in the B Area was regularly disposed to the soil.

Water from the fuel storage and disassembly basins at SRS contains tritium and other radionuclides that adhered to the fuel elements when they were removed from the reactor. In 1957, seepage basins began to receive low-level radioactive water from the fuel disassembly basins. These basins were intended to delay the migration of tritium into the surface streams and to allow other radionuclides to remain in the soil. Six seepage basins received effluent from R Reactor. Engineers closed the first basin in 1958 after it received an unusually radioactive discharge. The other basins were closed and backfilled between 1960

and 1964. A single basin at K Reactor closed in 1960. The site replaced its seepage basins with containment basins.

Atmospheric Releases of Radioactivity from Reactor Operations – Reactor operations generate radioactive gases through activation of gases in the reactor, radiolysis (radiation-induced breakdown) of graphite, water and other reactor materials, and fission products escaping from failed fuel and target elements.

Gases generated in the Hanford reactors exhausted directly to the atmosphere. The reactor exhaust included noble gases generated in the fission process (radioactive krypton-85, xenon-133 and argon-39, -41 and -42), halogen gases (iodine-131 and bromine-82), and particulates and aerosols containing cesium -137, tellurium-129, selenium-79, ruthenium-103/-106 and other radioactive elements. Water-fog installed at the Hanford reactors in the late 1950s and late 1960s removed most of the radionuclides, the exception being the noble gases.

Solid Wastes Generated by Reactor Operations – Reactor operations generated considerable solid wastes. Worn out, excessively contaminated, or obsolete reactor and support system components were replaced as needed and buried. These included air filters, instruments, fuel transport casks and handling equipment, "dummy" slugs, poison splines, silica gel for gas purification, process tubes, coolant headers and piping, in-reactor instruments, gaskets, and seals. Contaminated clothing, shoe covers, wipes, etc., used by maintenance workers and operators were also regularly buried. Hanford reactor operators buried most of their wastes in the reactor areas, while SRS buried its solid wastes at a central burial ground.

Nonradioactive solid wastes from reactor operations included activated charcoal and other filter media, water softening resins, and fly ash from steam plant boilers.

CHEMICAL SEPARATIONS

The T Plant was the world's first reprocessing canyon. In 1944, it disolved spent fuel from the Hanford B Reactor and chemically extracted the plutonium, which was then used to form the core of the Trinity and Nagasaki bombs. It continued reprocessing until 1956. Today the plant is used to decontaminate equipment. *Hanford Site, Washington. July 11, 1994.*

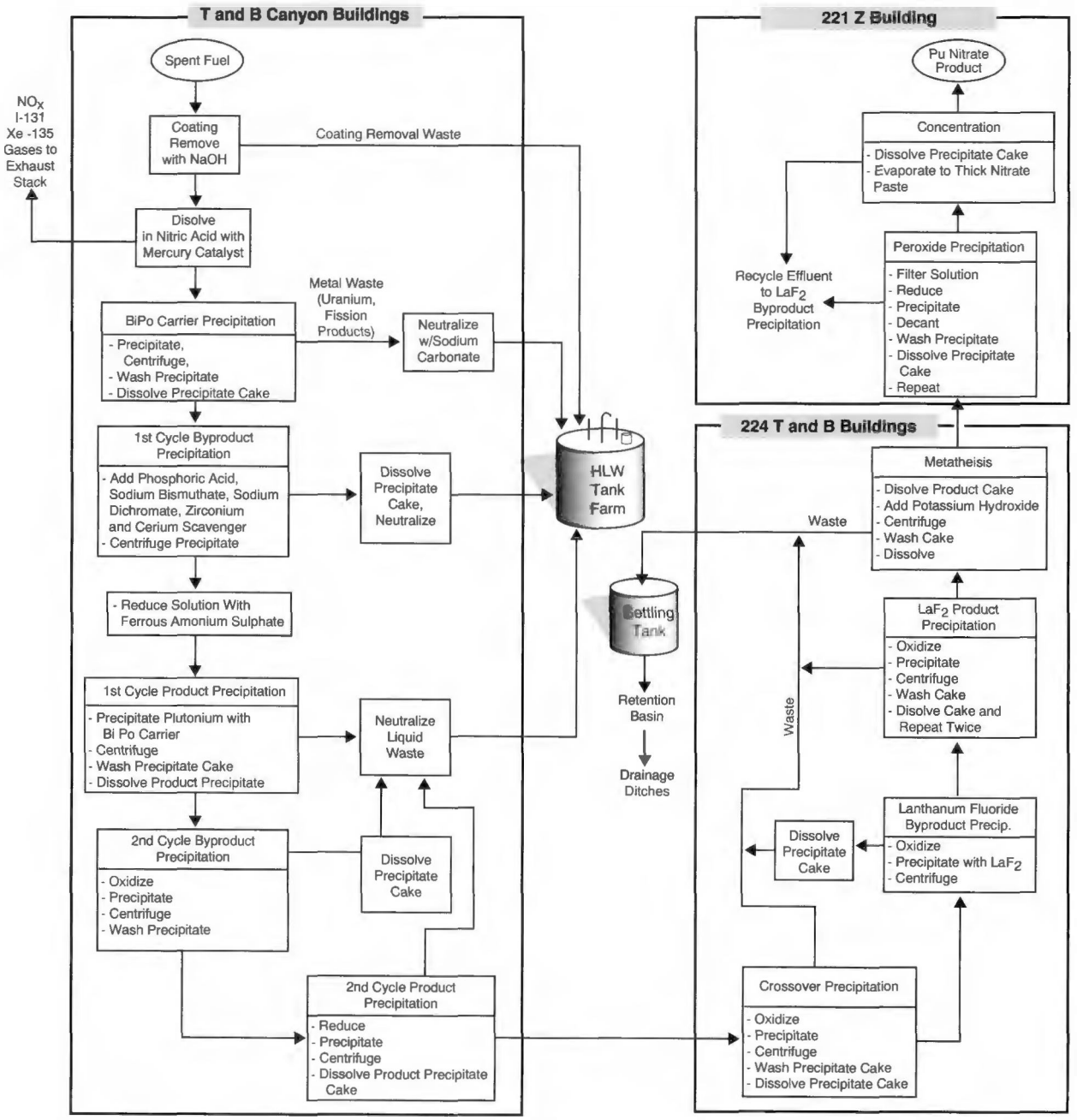
Chemical separation is the process of chemically separating and purifying plutonium, uranium and other nuclear materials from irradiated reactor fuel and targets, and converting the materials to usable forms. The process includes: physical disassembly and chemical dissolution of irradiated items; separation of uranium, plutonium and fission products; decontamination or purification; volume reduction or concentration; and isolation. Operations considered as first stage finishing processes are also included, e.g. the precipitation of heavy metal nitrate solution mixtures, hydro-fluorination, and metal reduction.

Chemical separation of spent fuel and target elements produces large volumes of highly-radioactive, high-level waste (HLW), low-level waste (LLW) and mixed low-level waste (MLLW). Chemical separation of plutonium and other transuranic isotopes also results in transuranic waste (TRUW). Contaminated environmental media and facilities from chemical separations of irradiated reactor materials pose unusual and severe restoration problems.

Manhattan Project Chemical Separation

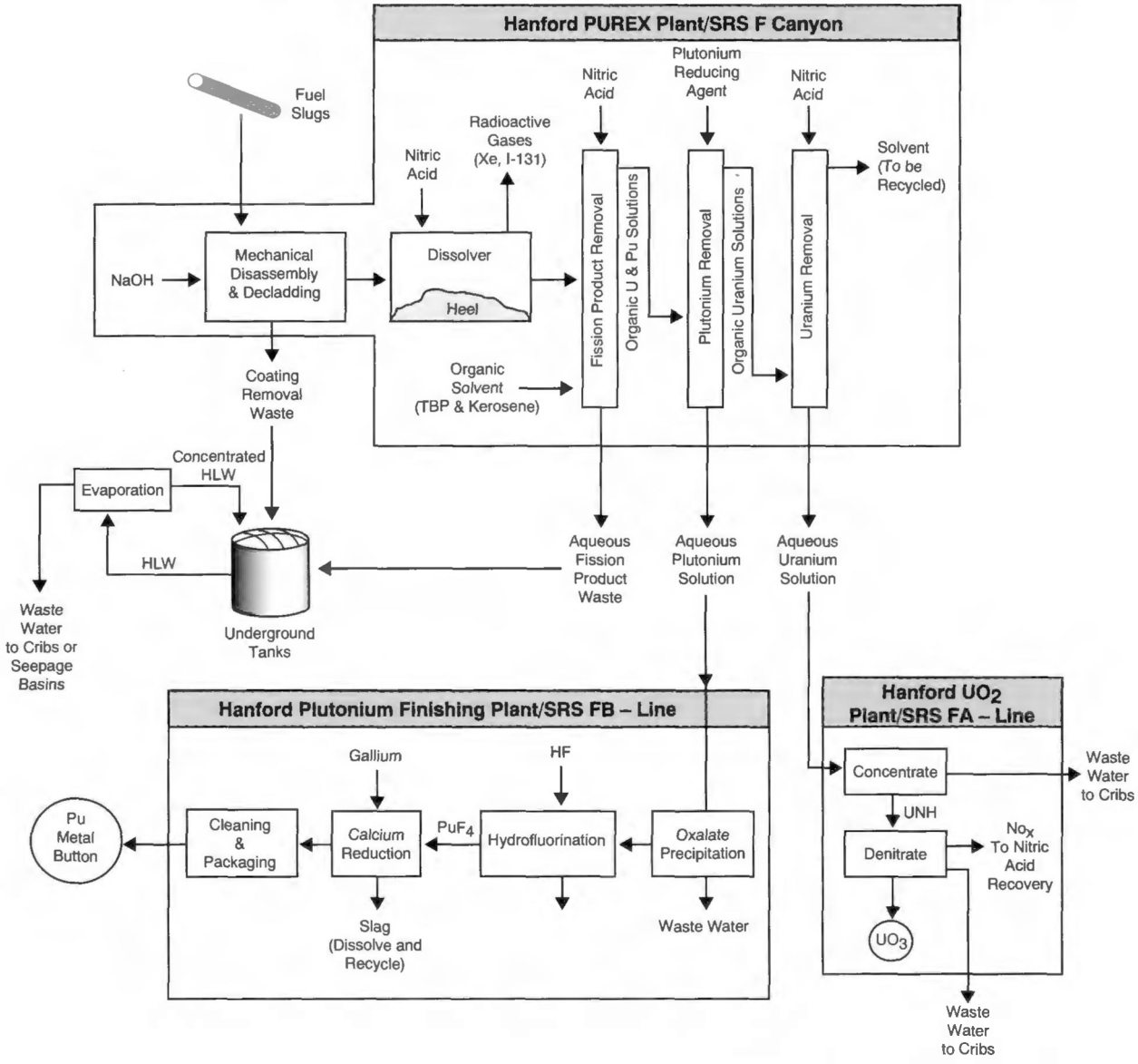
A chemical process was required to separate plutonium to be used in the first atomic bombs from irradiated uranium reactor fuel. The lack of actual irradiated uranium for experimentation, ignorance of the chemical properties of plutonium, and engineering inexperience with high radiation levels, complicated the development effort tremendously. The Metallurgical Laboratory at the University of Chicago was responsible for developing the separations processes and did develop a number of candidate processes. DuPont was chosen to build the plant and on June 8, DuPont engineers in Wilmington, Delaware chose

Figure B-12. Bismuth Phosphate Chemical Separation at Hanford



Note: The bismuth phosphate process separated and purified plutonium through successive cycles of precipitation and dissolution using bismuth phosphate as a carrier. Bismuth phosphate was dissolved along with the irradiated uranium. Changing the chemistry of the solution caused bismuth phosphate to solidify into a fine, powdery precipitate. In each byproduct precipitation, wastes and impurities were solidified with the bismuth phosphate while the plutonium remained dissolved. The waste precipitate was removed from the solution in a centrifuge. The cake of solid waste left in the centrifuge was dissolved and transferred to the waste tanks, while the liquid went on to the next step. Following each byproduct precipitation was a product precipitation. Changing the chemistry of the solution allowed plutonium to be carried out of the solution with the bismuth phosphate precipitate, so that it could be separated from impurities that were not removed with the bismuth phosphate. After centrifuging out the waste liquid, the cake of bismuth phosphate and plutonium was redissolved and sent on for further purification and concentration. Lanthanum flouride replaced bismuth phosphate in the final concentration and purification, using a similar process.

Figure B-13. PUREX Reprocessing



the bismuth phosphate process for the full-scale plants. To save time, construction of the separation plants began even before the process had been selected.

The X-10 Pilot Plant – The bismuth phosphate process was demonstrated on an engineering scale in a pilot plant alongside the X-10 Reactor located in Oak Ridge, Tennessee. The first irradiated uranium from the X-10 reactor was dissolved on December 19, 1943. Beginning in February 1944, X-10 produced several grams of plutonium per month. These first samples of plutonium allowed scientists at Los Alamos to determine the new metal's chemical, metallurgical and nuclear properties. Their unexpectedly high spontaneous fission rate greatly influenced the design of the plutonium fueled atomic bombs.

Hanford T, B and U Plants – Drawing on the experience with the pilot plant in Oak Ridge, MED built the T, B, and U Plants at Hanford which used the bismuth phosphate process. The T and B Plant "canyons" produced a plutonium nitrate solution. This product was sent to the 224-T and 224-B Bulk Reduction

Plants to be further decontaminated and concentrated from 330 gallons down to eight gallons using a lanthanum fluoride carrier process. The concentrated solution from these plants was in turn taken to the 231-Z Building to be made into the Hanford Site's final product, a wet plutonium nitrate paste. See the text box, "Chemical Separations Processes" and Figure B-12 for an explanation of the separation process used in T and B plants. U Plant and its associated facilities were used only for training and as a backup because the T and B Plants had sufficient processing capacity.

The T and B Plants each consisted of a main building over 800 foot long. T Plant was 65 feet longer than B and U Plants to allow extra space for experiments. Workers at the site called these buildings "canyons," or "Queen Marys," because of their shape: they were 102 feet high and 85 feet wide. Thick concrete walls provided shielding from the intense radioactivity. The plants were divided into 20 cells (22 in T Plant) with removable covers. Overhead cranes and remote manipulators allowed equipment to be replaced remotely. The equipment itself was designed for remote handling and replacement. Galleries for electrical and control equipment, pipes, and operators ran the length of the buildings. Closed-circuit television allowed workers to see inside the canyons. A ventilation system drew air into the occupied areas, then through the contaminated areas before it exhausted through filters and a tall stack. The 224 T, B and U buildings and the 231 Z Isolation Plant were also made of reinforced concrete with special ventilation systems.

The T Plant, the first full-scale Manhattan Project era separations plant, began operating in December 1944, while the B Plant started operating in April 1945. The plants sent approximately 10,000 gallons of waste to the tank farms for every metric ton of uranium fuel they processed. T and B Plants also discharged approximately 1.5 million gallons of wastewater into the ground each day.

B Plant shut down in October 1952, and T Plant shut down in March 1956. Over 7,000 metric tons of irradiated production fuel were processed using bismuth phosphate in these facilities. T Plant began to be used as a decontamination facility after its chemical separation mission ended, becoming Hanford's central decontamination plant in 1958. Workers at T Plant used steam, sandblasters, chemical solvents, and detergents to decontaminate equipment. B Plant was later used to recover and encapsulate cesium 137 and strontium-90 from the HLW tanks to make radiation sources.

231-Z Plant (Hanford) – The 231-Z Plant (also known as the Isolation Plant) received concentrated plutonium nitrate from the 224-T and 224-U Buildings. In 231-Z, hydrogen peroxide, sulfates, and ammonium nitrate were added and the plutonium was precipitated out of the solution as plutonium peroxide. The peroxide was filtered, dried, dissolved in nitric acid, and boiled down to a thick, wet paste. The plutonium nitrate paste was shipped to Los Alamos. Z Plant started processing plutonium in 1945.

Post-War Expansion of Chemical Separation at Hanford

Plutonium Finishing Plant (Hanford) – The Plutonium Finishing Plant (234 Building, PFP) was built in 1948 and began processing plutonium in July 1949. When the Plutonium Finishing Plant began converting plutonium nitrate to metallic plutonium in 1949, Z Plant stopped shipping its product to Los Alamos. The plutonium metal "buttons" were made into nuclear weapon "pits" at PFP (1949-1965) or the Rocky Flats Plant (1952-1989). Besides weapons plutonium, PFP also processed fuel grade plutonium beginning in 1964. Processing of nondefense, fuel grade plutonium occupied approximately 30 percent of the plant's capacity in the late 1960s, and defense plutonium production ceased in 1973. PFP was restarted in 1984 and processed defense plutonium again until June 1989.

PFP received plutonium nitrate paste from 231-Z and converted it into metal in a three step process. First, the nitrate was diluted and oxalic acid was added to precipitate plutonium oxalate. The oxalate was then filtered and dried. Next, hot hydrogen fluoride gas was mixed with the oxalate to form plutonium tetrafluoride (PuF_4, also called "pink cake"). Finally, the tetrafluoride and a small amount of gallium were mixed with calcium metal and heated until the reactants ignited. The products of this reduction process are plutonium metal "buttons" and calcium fluoride.

REDOX Plant – The Bismuth Phosphate process, while effective, was inefficient, processing only 1 to 1.5 tons of fuel per day. A new process, called REDOX, was developed beginning in 1947 in the 3706 Building and tested in the 321 Building in Hanford's 300 Area. REDOX was the first continuous-flow solvent extraction process designed for nuclear fuel reprocessing, and it was the first process to recover uranium as well as plutonium. See the text box "Chemical Separations Processes" for an explanation of the REDOX process.

Construction of the REDOX Plant, also known as S Plant, at Hanford began in 1949 enhanced in late 1951. REDOX plant, although large and heavily shielded, was not a "canyon" shaped building like the bismuth phosphate plants. Designed to process up to 3 tons of fuel per day, the plant's capacity increased to 8 tons per day by 1954 and reached 12 tons per day in 1958. Part of this capacity increase was due to the construction of the 233-S Plutonium Concentration Building, where criticality-safe equipment accomplished the third and final plutonium concentration step. Plutonium solutions from REDOX were sent to the 231-Z Plant for reduction to metallic plutonium. The uranyl nitrate hexahydrate product solution from REDOX was solidified in the UO_3 Plant and shipped to Oak Ridge to be recycled as feed for the uranium enrichment plants. Besides plutonium and uranium, REDOX recovered neptunium-237.

The REDOX plant shut down in December 1967. During its operation, the REDOX Plant processed over 19,000 metric tons of spent fuel.

Development of the PUREX Process

REDOX, while an improvement over the bismuth phosphate process, was less than ideal. To increase efficiency and reduce operating costs, a new separations process, called PUREX, was developed. PUREX was developed by Knolls Atomic Power Laboratory in the early 1950s, and demonstrated at the Knolls Laboratory's Separations Process Research Unit in Schenectady, New York. The process was first used at the Savannah River Site and later adopted at Hanford and the Idaho Chemical Processing Plant.

F and H Canyons (Savannah River Site) – To recover plutonium from the Savannah River Site's five reactors, AEC built two chemical separation plants: one in the F Area, and one in the H Area. Savannah River Site's chemical processing plants were the first to use the PUREX process on a large scale. Large-scale chemical separation operations at F Canyon began at SRS in November 1954 and H Canyon started processing irradiated reactor fuel in July 1955. The F and H area separations plants initially

Chemical Separations Processes

Three basic chemical separations processes have been used on a production scale in the United States and have produced the bulk of the DOE HLW: the bismuth phosphate process, the REDuction OXidation (REDOX) process, and the Plutonium URanium EXtraction (PUREX) process.

Bismuth Phosphate Process – This batch process is based on the fact that plutonium will co-precipitate with bismuth phosphate in the +4 valence state, but not in the +6 valence state. Aluminum cladding was dissolved away from the fuel elements using boiling sodium hydroxide solution. The bare uranium was then dissolved in concentrated aqueous nitric acid and plutonium was separated and concentrated by many cycles of precipitation and dissolution using bismuth phosphate. The bismuth phosphate process could only extract plutonium; the uranium remained in the high-level waste stream. See Figure B-12 for a schematic of the process.

REDOX Process – The REDOX process was the first countercurrent, continuous-flow process for recovery of both plutonium and uranium. The heavy radionuclides (plutonium and uranium) and fission products were separated in two liquid streams—an organic solution and an aqueous solution—which are not soluble in one another. REDOX began by decladding and dissolution of spent fuel and targets in nitric acid. An organic solvent is mixed with the resulting aqueous solution and the uranium and plutonium nitrates are transferred into the organic solvent; the fission products remain and are removed in the aqueous phase. Uranium and plutonium nitrate were then each separately reduced chemically and removed in the aqueous phase.

PUREX Process – The PUREX process is capable of recovering plutonium, uranium, and other materials in separate cycles by countercurrent flow with organic solvents. The process begins with dissolution of the irradiated material in nitric acid. An organic solvent is introduced and the uranium and plutonium nitrates transfer into the organic solvent while the fission products remain and are removed in the aqueous phase. The desired materials—plutonium, uranium, and sometimes others, notably neptunium—are extracted and concentrated together in an organic solvent and then purified by chemical scrubbing with dilute nitric acid. Two further cycles of solvent extraction and scrubbing each result in separate, concentrated, and purified aqueous solutions of plutonium nitrate and uranium nitrate. When other materials are extracted, additional cycles of the nitrate solution are required. See Figure B-13 for a schematic of the process.

F Canyon Control Room. From this room, operators controlled the processing of irradiated reactor targets. The targets were dissolved in acid so that plutonium could be separated from the uranium and highly radioactive fission product wastes. *F Area, Savannah River Site, South Carolina. January 6, 1994.*

processed the irradiated NU fuel from the five SRS reactors. The F Canyon area included the FA Line facility to solidify recovered uranium. Recovered uranyl nitrate solution from the H Canyon was brought to the F Area by truck.

After SRS reactors converted to HEU fuel and separate DU targets in 1968, F Canyon, and FB Line on the 6th and 7th levels of F Canyon were the primary facilities for recovering and finishing weapons-grade plutonium from the targets. F Canyon received irradiated DU target elements from the reactors and separated and purified the plutonium nitrate. FB Line solidified the plutonium nitrate solutions to a plutonium oxide powder or metal to be machined into weapon components at the Rocky Flats Plant (RFP). A byproduct of the process was DU in the form of UO_3, some of which was solidified in the FA Line and sent to FMPC to be recycled into more targets. However, more than 35,000 55-gallon drums of excess UO_3 accumulated at SRS.

After 1968, the H Canyon and HB Line facilities recovered HEU nitrate from spent SRS production reactor fuel and some research reactor fuels. H Canyon, HB Line, and the other 200H Area facilities were also used for separation and purification of tritium, neptunium, plutonium-238, americium, curium, and other elements and isotopes. The recovered HEU was shipped to the Y-12 Plant in Oak Ridge for reduction to metal to supplement the HEU stockpile or to be reused as SRS production reactor fuel.

H Canyon and F Canyon also recovered neptunium 237 to be used as targets for the production of plutonium-238. H Canyon recovered plutonium-238 from irradiated neptunium for use in power sources for deep space probes, and sometimes other exotic isotopes for nuclear weapons, civilian research, and medical uses.

These stainless steel canisters, weighing 1,100 pounds each, are engineered to contain vitrified high-level waste for long-term storage and disposal. When full, the canisters weigh 3,700 pounds each and they are extremely radioactive. Although a long- term storage site is not yet available, solidifying the waste greatly reduces the risk of storing it. Eighty-seven canisters have been filled with vitrifed high-level waste as of December, 1996. A total of over 5,500 are planned to be filled during the next 25 years. *Defense Waste Processing Facility, S Area, Savannah River Site, South Carolina. June 15, 1993.*

AEC originally developed the Savannah River Site to produce tritium. Although advances in weapons design greatly reduced the need for tritium by the time the site began to produce it, SRS has been the Unites States' primary tritium production facility since the mid-1950s.

The original SRS tritium processing facility, located in Building 232 -F, began extracting tritium from lithium-6 aluminum target elements irradiated in the five SRS production reactors in 1955. However, in 1958, it was replaced by a new facility located in the 230-H series of buildings in H Area. The original 1955 facility sat idle until it was decommissioned between 1994 and 1996. Although SRS has not produced new tritium since the last production reactor was shut down, a new facility called the Replacement Tritium Facility (RTF) began operating in 1993. RFT currently reloads tritium reservoirs for the nuclear weapons stockpile. DOE's current plans call for this facility to be expanded to process new tritium produced in either a linear accelerator at SRS or commercial nuclear power plants.

Idaho Chemical Processing Plant – The Idaho Chemical Processing Plant (ICPP) at the Idaho National Engineering Laboratory (INEL, called the National Reactor Testing Station at that time) began to process spent Navy, research, and experimental reactor fuel in 1953 to recover and recycle HEU. ICPP used a variant of the PUREX process that was not designed to recover plutonium. The recovered highly-enriched UO_3 was shipped as a solid powder to the Y-12 Plant where it was reduced to metal and became a supplemental source of fuel for the SRS production reactors after they converted to HEU fuel in 1968. Later modifications allowed ICPP to recover radioactive xenon and krypton gases for industrial uses.

Because of the wide variety of fuels processed at ICPP, the plant operated on a custom campaign basis, using a variety of "head end" processes to declad and dissolve different types of reactor fuels. For example, the ROVER facility was built from 1983 through 1985 and used to recover HEU from carbon-

coated uranium carbide particles in a graphite matrix used as fuel for the experimental ROVER nuclear rocket program of the 1960s. Another new "head end" dissolving facility, the Fluorinel Dissolution Process, was built in the mid-1980s.

Construction of a new fuel processing facility at ICPP began in 1987, but was never completed. ICPP shut down in 1992. Spent fuel from many research, test and Naval reactors, along with fuel from several commercial reactors and debris from the Three Mile Island accident, is stored in pools and dry casks at the ICPP.

PUREX Plant (Hanford) – The PUREX Plant, also known as A Plant, at Hanford became operational in January 1956. It received irradiated LEU fuel from the Hanford reactors. The plant was modified in 1963 to process the zirconium-clad fuel from the N Reactor. The products of the Hanford PUREX Plant were pure plutonium nitrate, LEU nitrate, and sometimes other materials, including neptunium-237. The PUREX plant also processed irradiated thorium oxide fuel to recover uranium-233 in 1965, 1966, and 1970.

PUREX shut down in June 1972 for cleanout and upgrades and to allow the accumulation of irradiated fuel. Upgrades for waste management, seismic safety and other reasons delayed the restart of the PUREX plant until November 1983. After the restart, PUREX shipped plutonium to the Plutonium Finishing Plant as an oxide (PuO_2, also known as "green cake") rather than a liquid nitrate solution. For a few months in 1984, the restarted PUREX plant sent PuO_2 to TA-55 at Los Alamos instead, because of an accident at PFP. The PUREX plant closed for six weeks in 1988, and then for the entire year of 1989. PUREX operated for the last time for a short cleanout run in 1990, and the Department decided to close it permanently in 1992.

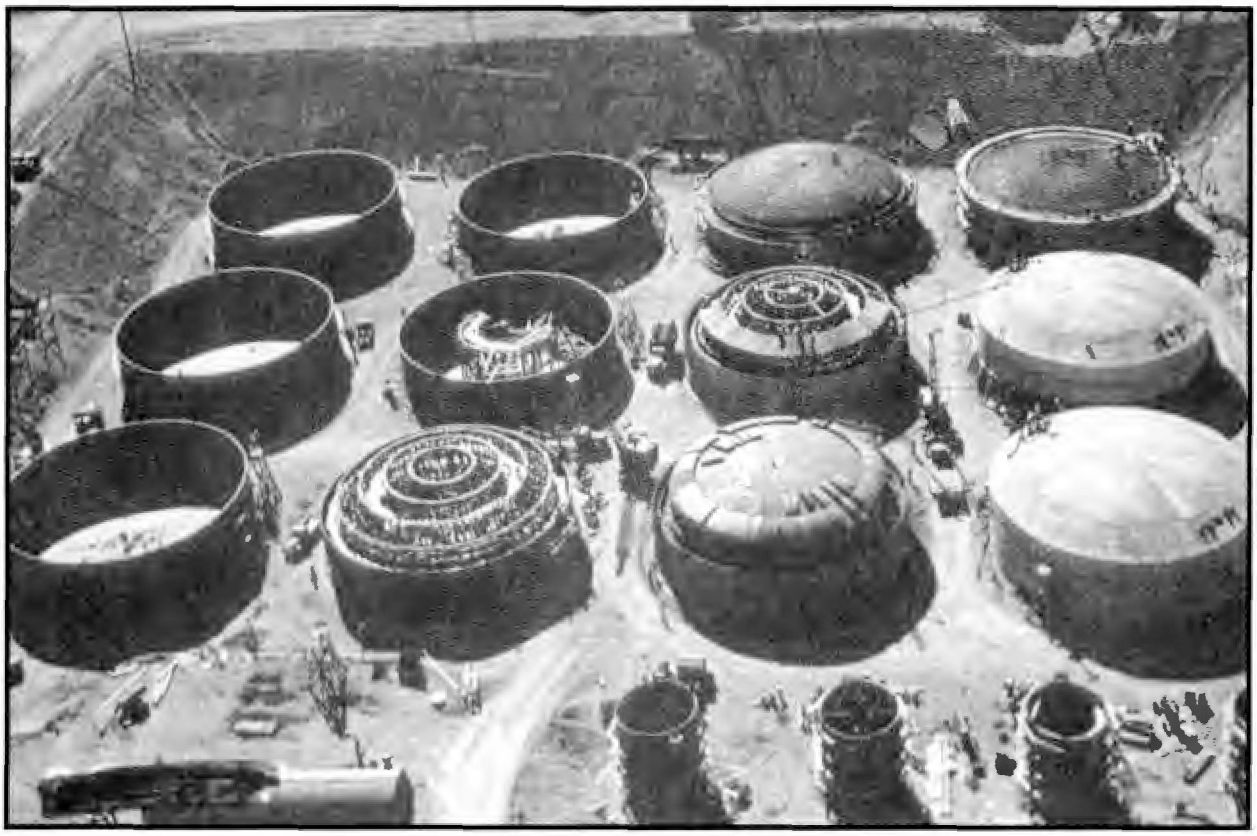
U Plant (Hanford) – Uranium was scarce in the 1940s and early 1950s. The bismouth phosphate process did not recover uranium from the irradiated fuel processed at Hanford. As a result, a significant portion of the uranium resources in the world was stored in the Hanford tanks. Some of this uranium was enriched, making it even more valuable. The U Plant at Hanford, which was built as a chemical separation plant in 1945 but never operated, was retrofitted to use a variant of the PUREX process to recover and recycle uranium from the HLW storage tanks at Hanford. Also known as the TBP Plant and the Metal Recovery Plant, the U Plant began this mission in 1952 and continued it until 1958.

UO_3 Plant (Hanford) – The UO_3 Plant was a major modification of the original, unused 224-U Bulk Reduction Building that began its operations in 1953. This plant solidified uranyl nitrate hexahydrate from the REDOX and PUREX separations plants and the U Plant, which recovered uranium from the high-level waste tanks. The UO_3 plant was shut down during the summer of 1955 for a major expansion, the 224-UA building, and the building resumed service in 1956. The UO_3 plant was again shut down in 1972, at the same time as the PUREX plant, and was restarted in 1984, shortly after the PUREX plant. Because its capacity to solidify UNH from processing of N Reactor fuel exceeded that of the PUREX plant to generate it, UO_3 plant operated as needed, with 17 startups and shutdowns, until April 1993. UO_3 Plant's product was shipped by rail to Oak Ridge to be converted into UF_6 to feed the gaseous diffusion plants.

Chemical Separation Waste Management

Chemical separation process wastes include the "cladding wastes" produced by the removal of the coating from irradiated fuel elements, and the high-level wastes containing the fission products separated from the uranium and plutonium. Miscellaneous low-level and transuranic waste streams came from plutonium concentration and finishing processes, uranium solidification, floor drains, laboratory analysis, and other activities.

T and B Plant Wastes – Hanford categorized bismuth phosphate process wastes as coating removal waste, first- and second-cycle decontamination wastes, and cell drainage waste. The first three waste types were neutralized with sodium hydroxide and stored in 16 underground tanks. Each tank was made of reinforced concrete lined with a quarter inch of steel plate. Twelve of the tanks were 75 feet in diameter, and



These single-shell tanks stored high-level radioactive wastes from Hanford's chemical separations plants. The tank farm shown here was built for the Manhattan project during World War II to hold wastes from the T Plant, which separated plutonium from irradiated reactor fuel. *200 Area, Hanford Site, Washington. Mid-1944.*

four were 20 feet across. The fourth waste stream was discharged to the ground. Wastes from the 224 buildings were stored in a 20 foot diameter settling tank, then combined with used cooling water and discharged to retention basins (two for each plant) and then into drainage ditches.

Hanford constructed additional single-shelled tanks in the late 1940s and early 1950s. To preserve HLW tank space, evaporators in the T and B Plant areas removed water (containing low levels of radioactivity) from the first cycle decontamination wastes and discharged it to the ground. At the same time, wastes from the 224 buildings, second-cycle decontamination, and coating removal (including those already stored in tanks) began to be sent to holding tanks. The supernate from these wastes was discharged to the ground. Several experiments in the 1950s tested the discharge of high-level waste to retention trenches and cribs. Many spills and leaks, some quite large, also released high-level wastes to the environment.

Radioactive air emissions from chemical separation were a continuing problem as well. Xenon and iodine gases emitted as the irradiated fuel slugs dissolved were released through the plants' ventilation stacks. Beginning in the fall of 1947, emissions of radioactive particulates and mists from the stacks appeared. Workers installed scrubbers and sand and fiberglass filters to reduce these emissions. Iodine emissions continued to be a problem, although they were lessened by an increase in fuel cooling times to between 90 and 125 days. (In 1945, fuel storage times were as short as 30 days.) Silver iodide filters installed in 1950 removed most of the iodine from the stack gases. Mercury, silver, potassium and sodium added to the dissolver also reduced the generation of iodine gas by keeping the material dissolved in the waste.

Hanford – The REDOX and PUREX plant wastes differed from those generated by the bismuth phosphate process. High-level wastes continued to be stored in single shelled tanks. Tanks containing REDOX plant wastes generated enough radioactive decay heat to boil. In 1952 and 1953, cooling coils inside these self-boiling tanks ruptured, allowing the high-level wastes to escape through the cooling system. Newer tanks were equipped with mixers to prevent these ruptures. Vapor generated by the hot tank wastes was exhausted to the atmosphere through filters.

During its uranium recovery process, the U Plant added ferrocyanides to its wastes to remove cesium -137. While these additions allowed greater amounts of waste to be discharged to the ground, conserving tank space, the ferrocyanides in the waste returned to the tanks have greatly complicated HLW management at Hanford.

A modified B Plant began to remove cesium and strontium from the HLW tanks at Hanford in 1968. Hanford continued this waste partitioning mission until 1983. B Plant initially stored the cesium and strontium capsules, but they were transferred to the Waste Examination and Storage Facility (WESF), an addition to B Plant, in 1971. DOE and its predecessors leased many of the capsules as intense radiation sources for industrial uses. However, the capsules deteriorated over time, and the WESF accepted the last returned capsule in 1996.

Corrosion eventually caused leaks in single-shelled tanks. Sixty-six leaks, totalling one million gallons, are known to have occurred at Hanford. The last of these tanks was built in 1964, after which double-shelled tanks, which are more resistant to leaks, became the standard. Hanford has a total of 177 HLW tanks, including 149 with single steel shells.

Ground disposal of low-level and transuranic liquid wastes continued after the war. A total of 100 cribs, 45 specific retention trenches, 55 ponds and ditches, 9 injection wells and 29 french drains received wastes from the chemical separations plants at Hanford. Liquid transuranic waste was discharged until 1973, and low-level waste discharges continued until 1994. Although the organic solvents used in the separations processes were recycled, they eventually degraded and were disposed into soil cribs. Other crib wastes included laboratory wastes, floor drain wastes, acid fractionator wastes, process and steam condensate, and condenser cooling water.

Two hundred and five spills and leaks have occurred at the Hanford chemical separations areas since 1944. Most of these releases were small, but some were quite large.

Hanford's 100 Area discharged an estimated 350 billion gallons of wastewater into the ground between 1945 and 1991. The PUREX plant alone discharged up to 10 million gallons of water each day. While waste generation per unit of dissolved heavy metal fell by a factor of 100 between 1945 and 1960, the output of irradiated fuel increased considerably. Groundwater mounds formed beneath the Hanford chemical separation areas as a result of the large amounts of liquid waste discharged to the ground. These mounds caused the flow of contaminated groundwater toward the Columbia River to accelerate and change direction. Engineers relocated ground discharges in an attempt to control the flow of contaminated groundwater. Solid wastes from Hanford chemical separations are also buried at the 200 Area.

The Savannah River Site – Fifty-one underground carbon steel tanks, encased in concrete vaults, store high-level radioactive wastes at the Savannah River Site. There are four different types of HLW tanks at the site. Twenty-four of these tanks are single-walled, with a catch pan to contain leaks. The remaining twenty-seven tanks are double-walled.

To preserve tank space, engineers at Savannah River reduced the 83 million gallons of high-level waste produced at the site to 34 million gallons by evaporation of liquids. Evaporation began at F Area in 1960, and H Area in 1963. The high level waste was initially stored in a settling tank, where solids settle to the bottom. The resultant clear liquid (supernate) was concentrated by evaporation. Evaporator water, containing low levels of radioactivity, was discharged to the F and H Area seepage basins. Since 1990, the

evaporator water has been rerouted to the Z Area Saltstone facility, where it is mixed with concrete and stored in aboveground vaults.

The Defense Waste Processing Facility (DWPF), which DOE began to build in 1983, started processing HLW at SRS into glass logs in 1996. DOE has constructed an In-Tank Precipitation facility to pretreat the tank wastes before they are vitrified in the DWPF.

Hazardous and low-level radioactive liquid wastes from chemical separation at the Savannah River Site were also discharged to the F and H Area seepage basins between 1954 and 1988. After evaporation, some wastes were released to local streams. After 1988, the F and H Area Effluent Treatment Facility received these wastes, including process wastewater, contaminated canyon cooling water, and tank farm runoff. The Effluent Treatment Facility discharges the treated water to Upper Three Runs Creek.

Waste from the semi-works facility and laboratory in the TNX area was also disposed in seepage basins. The Old TNX Seepage Basin received wastes between 1958 and 1980, and the new TNX Basin operated from 1980 until 1988 when it was replaced by the Effluent Treatment Facility. Four more seepage basins were used at the Savannah River Technology Center from 1954 until 1982.

E Area Radioactive Waste Burial Grounds at SRS segregated and buried solid hazardous, low-level and transuranic waste in shallow unlined trenches between 1952 and 1972. Wastes disposed at the facility include irradiated lithium-aluminum targets, oil, and mercury from pumps used in the tritium facility. After 1965, transuranic wastes at the Radioactive Waste Burial Grounds were buried in retrievable concrete containers rather than plastic bags or cardboard boxes. Beginning in 1974, TRU wastes were stored in plastic-lined steel drums. These drums were covered with soil until 1985.

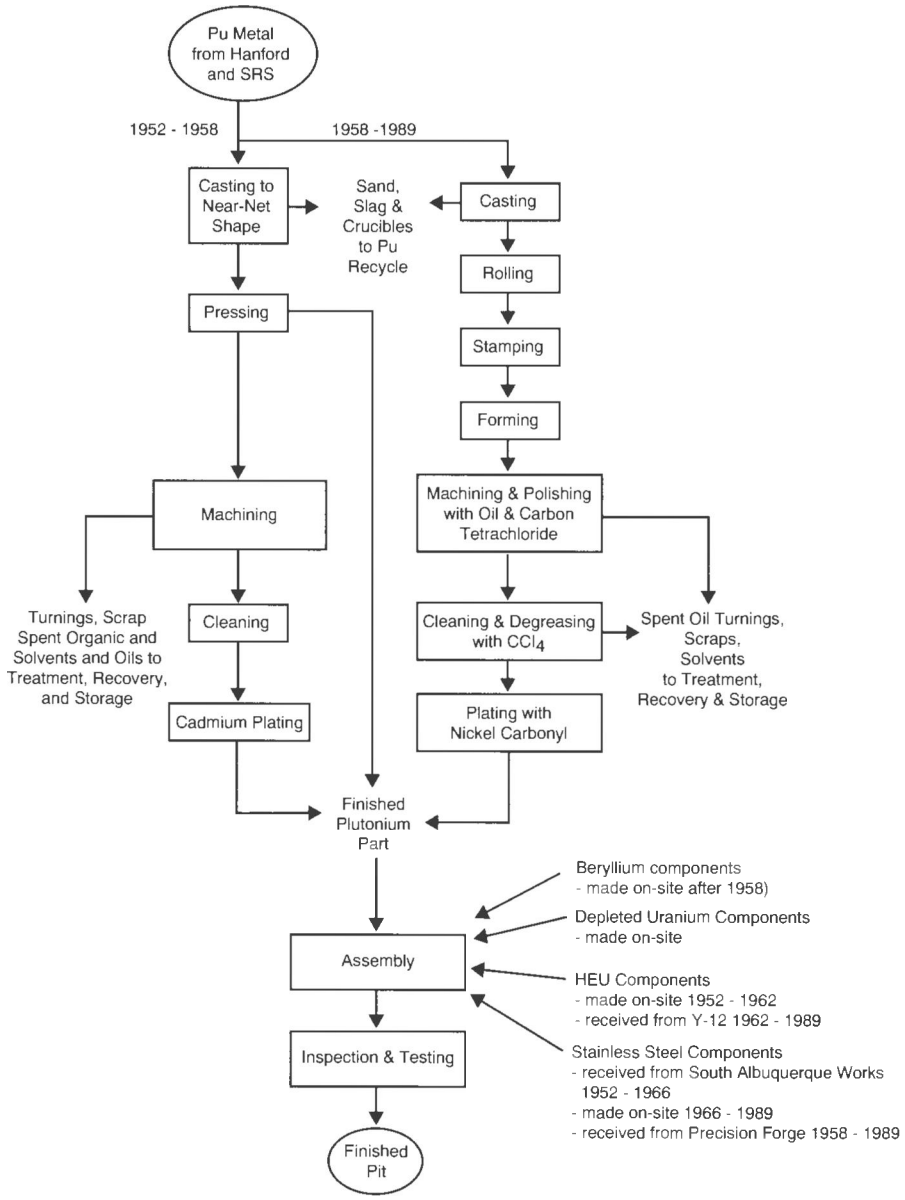
A burial ground also operated in the TNX Area in 1953. Workers excavated most of this waste in 1980 and 1984 and transferred it to the main burial grounds. A new SRS burial ground, the Mixed Waste Management Facility, received mixed wastes from 1969 until November 1988.

Idaho Chemical Processing Plant (ICPP) – To conserve storage space, the Idaho Chemical Processing Plant solidified its high-level wastes into a dry, granular powder. This "calcining" process began in 1963, after 8 years of development. A new waste calcining facility began operating at ICPP in 1982. Calcined high-level waste is stored in stainless steel bins inside concrete silos. Low-level liquid wastes, including those produced by the calcining plants, were discharged to the ground. Sodium-bearing wastes, which could not be calcined, and some other liquid HLW, are stored as acidic liquids in stainless steel underground tanks. Idaho Chemical Processing Plant disposed liquid radioactive wastes using percolation ponds and injection wells.

Solid low-level wastes from Idaho Chemical Processing Plant are buried at the Idaho National Engineering Laboratory Radioactive Waste Management Complex (RWMC). Transuranic wastes were also buried at the RWMC until 1972, when they began to be stored aboveground. While most of these wastes are from component fabrication at the Rocky Flats Plant, a small amount is from the Idaho Chemical Processing Plant. Idaho National EngineeringLaboratory's Waste Experimental Reduction Facility (WERF) reduces the volume of solid wastes by incineration or compaction.

Fabrication of Nuclear and Nonnuclear Weapons Components

Figure B-14. Rocky Flats Plutonium Component Manufacturing



Weapons *component fabrication* includes the manufacturing, assembly, inspection, local testing, and verification of specialized parts and major weapon components. Chemical processing to recover, purify, and recycle plutonium, tritium, and lithium from retired warheads, and from component production scrap and residues, are included in this category, as are maintenance, recharging, and dismantlement of individual components.

Nuclear weapons components can generally be categorized as either nuclear or nonnuclear. They range from small parts to separately functioning subsystems of weapons. Nuclear components are located in the primary stage of the weapon, the secondary stage, and in other systems designed to boost nuclear

Rocky Flats glovebox. The Rocky Flats Plant was closed permanently with the end of the Cold War and renamed "Rocky Flats Environmental Technology Site" to reflect its new mission of nuclear materials stabilization, waste management, and environmental restoration. *Rocky Flats Site, Colorado. July 17, 1983.*

performance. Nuclear components in the primary stage are located in the "pit." The nuclear components contain plutonium, highly enriched and/or depleted uranium, lithium-6, deuterium, tritium, and various other, structural parts. Nuclear components have always been manufactured in specialized facilities. Figure B-14 provides a generalized description of the process of manufacturing a nuclear weapon "pit."

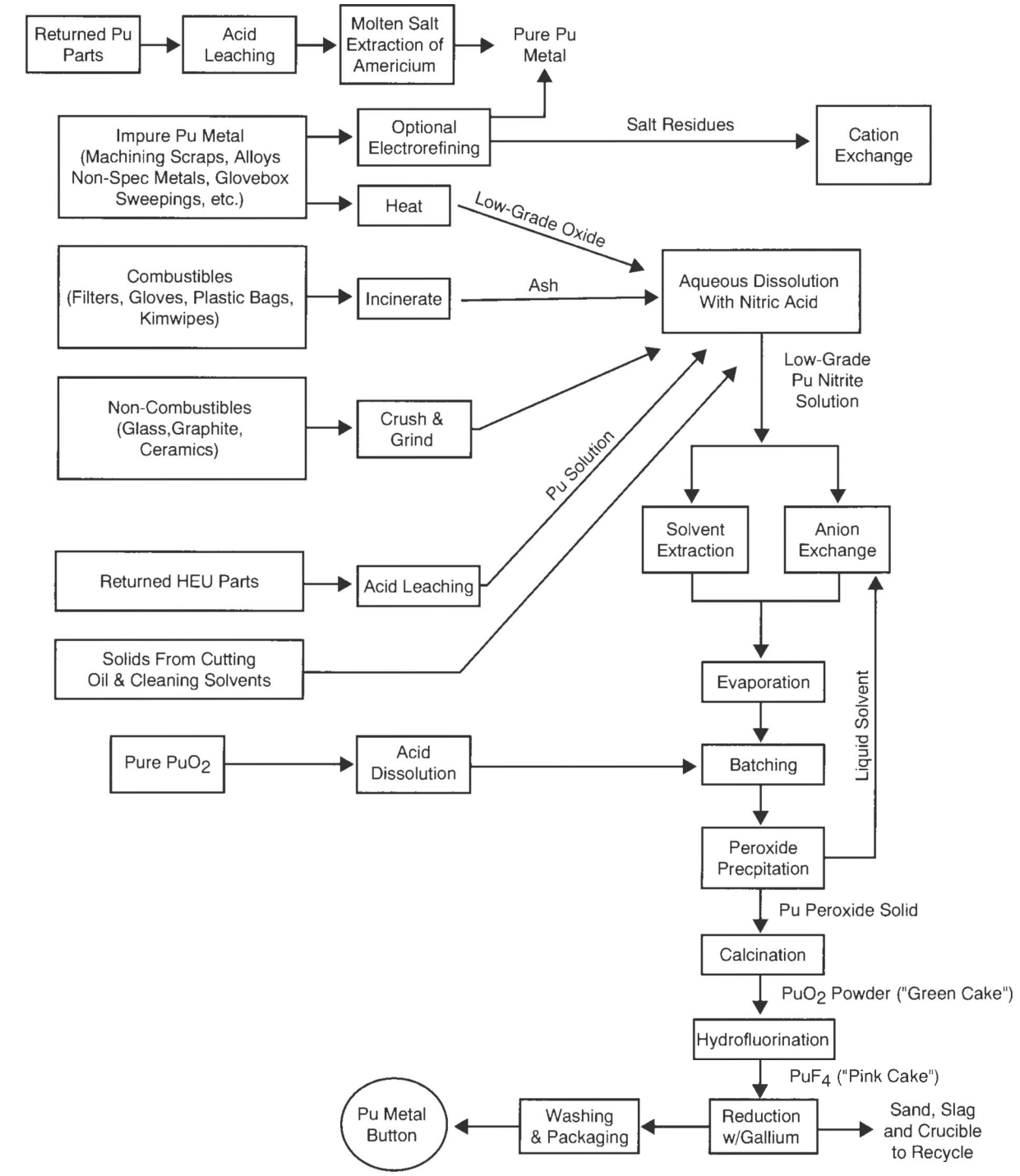
Nonnuclear components include arming, fuzing and firing sets, radars, aerodynamic (outer) casings, high-explosive charges, detonators, boost gas transfer systems, batteries, and neutron generators. Although describing all of the processes used to make this wide variety of parts is beyond the scope of this report, Figure B-16 illustrates the general processes for producing electronic components. High explosive component manufacturing is shown in Figure B-17.

Weapons component fabrication also includes the processing of scrap materials to recover and recycle plutonium, uranium, and other materials. Figures B-15 and B-18 illustrate the scrap recovery processes.

Nuclear Component Fabrication

Manhattan Project through the late 1940s – The nuclear components of the three Manhattan Project devices (Fat Man, Little Boy and the Trinity device), the Operation Crossroads test series devices, and the early weapons stockpile were manufactured at the Los Alamos laboratory. Initially, the main chemistry and metallurgy research laboratory in "D Building" was used for this purpose, but the work soon shifted to the new "DP Site" (also known as TA-21), completed in November 1945. Los Alamos received plutonium nitrate paste from the Hanford site, with a small amount coming from the X-10 pilot plant at Oak Ridge, and highly enriched uranium tetrafluoride from the Oak Ridge Y-12 Plant. Nuclear components continued to be manufactured at Los Alamos' DP Site until the start-up of the Plutonium Finishing Plant (PFP) at Hanford in July 1949, and the beginning of HEU casting and machining at Y-12 in 1948.

Figure B-15. Rocky Flats Plutonium Recovery and Purification



Los Alamos – DP-Site at Los Alamos (also known as TA-21), and its successor, TA-55, fashioned plutonium weapon parts. DP Site was built in 1945 as a production plant for plutonium bomb cores and polonium-beryllium initiators. However, within three years, AEC decided to shift production off site, keeping Los Alamos as a research, development, and design laboratory. DP Site also handled tritium. TA-55 began operations in 1978. After this time, DP-Site nuclear operations were gradually phased out. TA-55 can perform a wide variety of small-scale component fabrication operations, including all of the operations which were conducted at Rocky Flats on a larger scale. For many years, TA-55 had the mission of backup facility to Rocky Flat. However, at Los Alamos, these operations currently are considered part of the RD&T process to support testing. DOE recently announced plans to re-establish Los Alamos as its pit fabrication site.

Oak Ridge Y-12 Plant – Component manufacturing at Y-12 began in 1948 with the casting and machining of HEU weapon parts. Y-12 also processes uranium-bearing scrap and residues, functioning as a central scrap management office for uranium. (See Figure B-18 for a diagram of the scrap management process at Y-12.) Lithium deuteride (Li^6D) weapon components have been made at Y-12 since the fall of 1953. The Plant's capability was greatly expanded in the 1950s to encompass the fabrication and assembly of weapons components of depleted natural and highly enriched uranium, beryllium, lithium deuteride, and other materials. From 1968 to 1990, Y-12 received recovered highly-enriched UO_3 powder from ICPP and HEU nitrate from Savannah River H Area which was reduced to metal and either stockpiled or used as fuel for its production reactors.

Y-12 also has the mission of dismantling Li^6D and HEU components from retired warheads and recycling Li^6D. The plant continues to receive and process the secondary components of the nuclear weapons now being dismantled at the Pantex Plant.

Plutonium Finishing Plant (PFP) – The Plutonium Finishing Plant at Hanford (the 234-5 Z Building) began manufacturing plutonium weapons components in July 1949. PFP was equipped with a series of enclosed gloveboxes rather than the open "hoods" previously used at DP Site at Los Alamos. The initial metal reduction and pit fabrication line at the plant (called the "RG line, for "rubber glove") was supplemented with a remotely-operated line (RMA) in March of 1952, which was itself expanded in early 1953. A second remote line, RMC, that was installed beginning in April 1957 and started production in early 1960. RMA and RMC lines were shut down in December 1965, when Rocky Flats became the sole source of plutonium nuclear weapons parts. RMA was reconfigured to support civilian plutonium fuel development, while RMC continued to supply plutonium metal to the Rocky Flats plant. The pit fabrication equipment at The Plutonium Finishing Plant was removed and buried in between 1975 and 1976.

Rocky Flats Plant – Rocky Flats, near Boulder, Colorado, was established as a second plutonium and HEU component manufacturing center. Rocky Flats' chief mission was to produce "pits," which are the core components in the first stages of nuclear weapons, known as "primaries." Plutonium used in the pit manufacturing process came from Hanford and the Savannah River Site. HEU came from AEC's gaseous diffusion plants through Y-12. Scrap and residue recovery and returned pits were also a major source of plutonium and uranium feed.

Rocky Flats was initially divided into four areas: the A Plant, today's Building 444, which made depleted uranium parts; the B Plant, now Building 881, which made enriched uranium parts and recovered enriched uranium from scraps and residues; the C Plant, now Building 771, where plutonium parts were made and plutonium scrap was processed; and the D Plant, now Building 991, where the parts were assembled with others manufactured off site to produce the finished weapon component. Rocky Flats' plutonium processing lines were built as a duplicate of the pit production facilities at Hanford.

In 1962, Rocky Flats ceased producing enriched uranium parts in Building 881. RFP continued to receive HEU pit components from Y-12 for assembly and shipment to Pantex and Burlington. When stainless steel component manufacture (known as the J Line) transferred from the South Albuquerque Works to Rocky Flats in 1966, it was set up in Building 881. When Hanford ceased producing plutonium parts in 1965, Rocky Flats became the sole producer. Buildings 776 and 777 were built to handle the increased

workload, and the mission of Building 771 shifted to plutonium recovery. A major fire in 1969 caused plutonium foundry and machining to be moved from Building 776 to Building 707. Stainless steel component manufacturing and some nonnuclear metalworking tasks were moved to from Buildings 881 and 444 to Building 460 in 1984.

Initially, plutonium and enriched uranium components from the Hanford PFP and Oak Ridge Y-12 Plants were assembled with locally-made parts in Rocky Flats Building 991. At the time, depleted uranium parts were shipped directly to Pantex to be assembled with the completed "pit." In 1957, a significant change nuclear weapon design greatly reduced the need for depleted uranium parts. Beryllium component manufacturing replaced the depleted uranium component manufacturing in Building 444. These beryllium components were assembled with the fissile components at Rocky Flats rather than at Pantex. The assembly work shifted to the new Building 777. Building 707 was built in 1969, and took over the assembly mission from the fire-damaged portions of 777.

Drums of plutonium-bearing residues at the Rocky Flats Plant contain too much plutonium to be disposed of as transuranic wastes. The residues must be stabilized so that they can be stored safely until final disposition plans have been formulated and carried out. *Building 776/777, Rocky Flats Plant, Colorado. December 20, 1993.*

The Rocky Flats Plant was shut down in December 1989 in order to bring it into compliance with environmental regulations. However, the plant's defense mission was cancelled in 1992 due to a change in the needs of the nuclear weapon stockpile, and the plant became an environmental management site. Stabilizing and repackaging the plutonium and plutonium-contaminated scrap and residues that remain at the site is the major mission of the Rocky Flats Plant today.

Waste management at Rocky Flats has remained fairly constant over the years. Rocky Flats built building 774 in 1952 to treat aqueous liquid wastes from the Building 771 plutonium processing facility. Precipitation removes some radionuclides as a slurry, which is filtered and solidified as transuranic waste. Until 1973, workers discharged the remaining liquids to either the solar ponds or the "B" series of holding ponds (which drain into the Great Western Reservoir), depending on the radioactivity level in the water. An evaporator began treating liquids that had accumulated in the solar ponds around 1965. The evaporator released its vapor to the atmosphere. Rocky Flats stored organic liquid wastes, such as plutonium

contaminated machining oils and carbon tetrachloride degreasing solvents, in drums until a satisfactory treatment could be developed. The Plant first buried drums of organic liquids, then stored them outdoors on a pad. Corrosion caused many of these drums to leak, contaminating the pad and the hillside below it. The contents of some drums were burned. The plant began treating organic wastes by filtering and solidifying the liquids for disposal as TRU waste in 1967.

In 1980, Building 374 opened as the new waste treatment facility at Rocky Flats to supplement Building 774 and eliminate the need to use the Solar Ponds altogether. The same process was used in Building 374 as in Building 774, but the equipment was newer and more efficient.

Rocky Flats shipped transuranic wastes, including contaminated debris from the 1957 and 1969 fires, to the Idaho National Engineering Laboratory until 1988. There have been many instances of radioactive solid waste disposal on site at Rocky Flats in trenches, mounds and burning areas. Nonradioactive solid wastes, such as office waste and cafeteria garbage, have been disposed in two landfills on site. The first landfill operated from 1952 until August 1968, and the second from August 1968 until the present. Sewage sludge burial in on site trenches ended in 1969, when Rocky Flats reclassified the sludges as low-level radioactive wastes.

Nonnuclear Components

Manhattan Project – The Naval Gun Factory in Washington, DC made experimental guns used to develop and manufacture the "Little Boy" device. Other mechanical parts for Little Boy were supplied by the Naval Ordnance Plant in Centerline, Michigan, and the Expert Tool & Die Company in Detroit. Detonators were loaded at the South Mesa site in Los Alamos, using parts from Centerline. After the war, detonator production moved to the larger Two-Mile Mesa site at Los Alamos. Detonating switches and firing assemblies, including radar altimeter fuses, were built by Raytheon in Massachusetts. High explosives from the Yorktown, Virginia, Naval Mine Depot, were molded and machined at Los Alamos' S-Site (also known as TA-16). Initiators had been made at the Los Alamos DP Site using polonium purified by the Monsanto Chemical Company in Dayton, Ohio. The Manhattan Project research at Los Alamos was also supported by many contract shops in the Detroit and Los Angeles areas.

The Salt Wells Pilot Plant at the Naval Ordnance Testing Station, in China Lake, California, assumed the manufacture of high explosive main charges from S Site at Los Alamos in 1946. China Lake, known as "Site I", had been the field location of the MED's "Camel Project," managed by the California Institute of Technology during the war. The MED's Salt Wells Pilot Plant was part of the larger U.S. Navy weapons and testing installation at China Lake. Salt Wells produced high-explosive lenses for MED and AEC until 1954.

Nonnuclear components of nuclear weapons were made at a number of military and private sites in the 1940s. The Rock Island Arsenal in Illinois manufactured armored bomb casings from 1947 until 1951. Private companies manufacturing similar items included the Northrup Aircraft Corporation in Hawthorne, California, the Douglas Aircraft company in Santa Monica, California, the A.O. Smith corporation in Milwaukee, Wisconsin, and the American Car & Foundry corporation in Buffalo, New York, Berwick and Milton, Pennsylvania, and Madison, Illinois. The Picatinny Arsenal, in Dover, New Jersey, has assisted in the development and small-scale manufacturing of components since 1948. Picatinny has worked on fuzes, detonators, firing sets, and generators for U.S. Army nuclear weapons, including nuclear artillery shells, demolition charges, and missile warheads. The Picatinny Arsenal disbanded its nuclear munitions group in the early 1950s, but is still involved in some nuclear-weapons-related tasks.

Iowa Army Ordnance Plant – The Iowa Army Ordnance Plant in Burlington, Iowa, was primarily a weapons assembly facility, but Burlington also manufactured high-explosive components for nuclear weapons from 1947 to 1975.

Mound – The Manhattan Engineer District's Dayton Project to investigate the chemistry and metallurgy of polonium began in 1943. The Monsanto Research Corporation initially analyzed polonium at its Scioto

Workers at a plutonium glovebox. At gloveboxes such as these inside Hanford's Plutonium Finishing Plant, workers once chemically separated and purified plutonium to convert it to metal for nuclear weapon pits. Today, the mission has changed from processing plutonium to storing it. Plutonium is considered a "material in inventory" by the Department of Energy. The workers wear protective suits as an added precaution against any leaks that might occur in the ageing glovebox system. *Plutonium Finishing Plant, Hanford Site, Washington. December 16, 1993.*

research laboratory in Dayton, Ohio. The Dayton Project moved to nearby Miamisburg, Ohio, in 1946, although the Scioto facility remained on standby until the mid 1950s. The Dayton Project became the Mound laboratory in 1947.

The Mound Laboratory's first mission was to manufacture polonium-beryllium initiators for atomic weapons. Mound's initiator manufacturing process included the extraction of polonium-210 from irradiated bismuth slugs and the machining of beryllium parts. Besides producing initiators, Mound focused on polonium research and the search for longer-lived substitute isotopes. The plant picked up several new weapon component production missions over its years of operation. Development, production, and surveillance of detonators began in 1956, and explosive timers developed at the laboratory began to be manufactured on site in 1963. Ferroelectric transducers and firing sets—the electronic components that trigger detonation—began to be built at Mound in 1961. Mound gradually stopped producing initiators after the Pinellas Plant began producing accelerator-type neutron generators in 1957.

Mound began tritium work in 1954, developing and producing nuclear weapon components containing the radioactive isotope of hydrogen. Beginning in 1969, Mound retrieved tritium from retired weapon parts to be recycled.

Nonweapons work at Mound included the development and manufacture of radioisotope thermal generators containing polonium beginning in 1954 and plutonium-238 after 1959. Research at Mound included radioactive waste decontamination studies, investigations of the properties of uranium, protactinium-231 and plutonium-239, and separation of stable isotopes of noble gases. Mound built a plant to process thorium ore and sludge to support breeder reactor programs in 1954 but it never operated. The thorium sludge was stored on site in drums until 1965, and then in a silo until it was sold in 1974.

Mound stopped producing weapons components in 1995, although the plant still produces radioisotope thermal generators for remote power applications, including space probes. Nonweapons polonium work at Mound ended in 1972.

Radioactive waste has never been buried on site at Mound. Oak Ridge accepted Mound's low-level radioactive wastes for burial until 1964, after which they began to be shipped to the Maxey Flats, Kentucky commercial burial site. In 1976, these shipments were rerouted to Barnwell, South Carolina, with high-tritium wastes being shipped to the Nevada Test Site. The Nevada Test Site began accepting all Mound Plant wastes in 1980, however, it stopped accepting Mound wastes in April 1990, causing these wastes to accumulate on site as well. After 1970, transuranic wastes were shipped to Nuclear Fuel Services in West Valley, New York. In 1974, Mound began shipping these wastes to the National Reactor Testing Station (now INEL) in Idaho. After the State of Idaho barred further shipments of transuranic waste in 1988, Mound began storing TRU on site.

Workers at Mound burned and buried hazardous and explosive wastes on site, including beryllium, mercury, trichloroethylene, carbon tetrachloride, benzene, alcohol, nickel carbonyl and plating and photographic processing solutions. These activities were primarily carried out at the Area B Landfill between 1948 and 1969. After 1969, Ohio state law required Mound to dispose of these wastes off site. The Area B Landfill was permanently closed and the waste moved to a new, clay-lined landfill in 1977.

Nonradioactive, combustible solvents and solid wastes were burned at an experimental incinerator at Mound between 1971 and February 1974. Mound also developed and occasionally used a cyclone incinerator for nonhazardous, low-level wastes and a glass melter furnace for treatment of mixed wastes.

A waste treatment plant for liquid low-level wastes from polonium production operated in the WD Building beginning in February 1949. A similar facility in the SM Building treated plutonium 238 wastes beginning in 1961. A second plutonium waste treatment plant in the WDA building started up in 1966. Tritiated wastewater has also been a concern at Mound, beginning with the commencement of tritium processing at the plant in 1954. The SW Building, the plant's principal tritium handling facility since the 1960s, was built in 1953 with a dirt floor with drains to allow spills to seep into the soil. In 1965, an effluent removal system began filtering gaseous releases from the SW Building. By the late 1980s, an integrated tritium recovery and purification facility was removing tritium from Mound Plant waste streams.

Kansas City Plant – Kansas City Plant (KCP) was established in 1949 at the Bannister Federal Complex in south Kansas City, Missouri to make nonnuclear weapon parts: electronics, rubber, plastic foams, adhesives, and others. The plant was initially built to assemble Navy aircraft engines during World War II. In 1995, the Kansas City Plant assumed additional production responsibilities that had been the function of the Pinellas Plant.

Pantex Plant – Pantex Plant was established in the Texas panhandle near Amarillo in 1951 to serve primarily as a weapons assembly plant. However, Pantex also manufactures high explosive (HE) weapons components. Figure B-17 illustrates the HE component manufacturing process. Before becoming part of the nuclear weapons complex, Pantex was a conventional munitions plant operated by the U.S. Army Ordnance Corps.

Workers at Pantex have used firing sites for HE quality control and research since 1952. Some of the test firings at Pantex have involved depleted uranium.

Wastes from the production of high explosive components, including HE-contaminated solid wastes, liquids and solvents, have been treated and disposed of on site at Pantex since 1951. Unlined drainage ditches conveyed runoff and effluents to the playas (shallow artificial lakes) around the plant, where the liquids evaporated. Before it reached the playas, HE-contaminated wastewater was routed through settling and filtering equipment, where most of the HE was extracted in a sludge which was burned on

Rocky Flats was established in 1951 to manufacture plutonium, enriched and depleted uranium, and steel nuclear weapons components. After a similar facility at Hanford shut down in 1965, Rocky Flats became the only source of plutonium "pits" for the U.S. nuclear weapons arsenal. *Rocky Flats Plant, Colorado. July 17, 1983.*

The Mound Plant takes its name from a nearby Native American burial mound. Sited on a hill in the center of Miamisburg, Ohio, Mound was built in 1946 to produce the polonium-beryllium initiators used in early atomic weapons. In the 1950s, the facility began to manufacture a variety of nuclear weapon parts, including cable assemblies, explosive detonators, and the electronic firing sets that activated them. Since 1969, Mound has recovered tritium from retired nuclear warheads. *Mound Laboratory, Miamisburg, Ohio. May 22, 1984.*

The Kansas City Plant manufactured nonnuclear componenets for nuclear weapons. Since 1949, its products included arming, fuzing, and firing systems, radars, power supplies, rubber, plastic and foam parts, and outer casings. This plant is now DOE's only facility for manufacturing nonnuclear components for nuclear weapons. *Kansas City Plant, Bannister Federal Complex, Kansas City, Missouri. July 17, 1982.*

The Pinellas Plant made precisely-timed neutron generators used to initiate fission chain reactions in nuclear weapons. Neutron generators superceded polonium-beryllium initiators which had to be replaced frequently because of polonium's short half-life. Pinellas also made specialized batteries, capacitors, and switches for nuclear weapons between 1957 and 1995. *Pinellas Plant, Largo, Florida. October 19, 1986.*

site. In the 1980s, Pantex replaced the ditches, ponds, and sumps with a system of hazardous waste tanks.

Combustible solid wastes and HE scrap were burned on trays or clay pads in two areas at Pantex. The present burning ground has been in use since 1952, and another was used from 1951 to 1954 and 1959 to 1960. Pantex workers built burn trays on the pads in 1988 to reduce soil contamination. Burn cages disposed of HE -contaminated trash between 1959 and 1967. Pantex no longer uses a chemical burn pit, where waste oils and other chemicals were burned from 1954 until 1980. Between 1980 and 1989, these materials were evaporated before the residues were burned. Since 1989, waste chemicals have been commercially disposed off site. Ash from the burning grounds is buried in landfills on site.

Rocky Flats Plant – Besides manufacturing pits, the Rocky Flats Plant also manufactured tritium gas reservoirs from 1966 until 1989.

Savannah River Site Tritium Facility – In addition to tritium production, SRS purifies and loads tritium into weapons components. SRS also began purifying tritium recovered by Mound from retired warheads beginning in 1969. The tritium loading function (a component fabrication activity) is a continuing process because tritium decays with a 12.3-year half-life — approximately 5.5 percent decays per year. The original SRS tritium facility, 232-F building began operations in 1955. The 232-F tritium facility was replaced by a facility located in H Area in 1958. A replacement tritium facility at the Savannah River Site H Area began operating in 1994, at which time the 1958 facility was shut down.

Pinellas Plant – The Pinellas Plant was built in Largo, Florida, in 1957 to produce precisely-timed neutron generators to initiate nuclear explosions. The Pinellas Plant's accelerator-type neutron generators gradually replaced the polonium-beryllium initiators manufactured at Mound as the older weapons were removed from the stockpile. Pinellas also manufactured special-purpose capacitors and switches, batteries, power supplies, and other components. DOE shut down Pinellas and transferred all of its functions to The Kansas City Plant at Sandia National Laboratory in 1995.

South Albuquerque Works – South Albuquerque Works was established in Albuquerque, New Mexico to manufacture steel weapons parts in 1952. The plant continued to manufacture stainless steel components, including tritium reservoirs, until 1966, when its mission was transferred to the Rocky Flats Plant and the site was transferred to the U.S. Air Force to be used as a jet engine manufacturing plant.

Precision Forge – Precision Forge, established by the Federal Government in Santa Monica, California, in 1958 as a private

Figure B-16. Electronics Fabrication

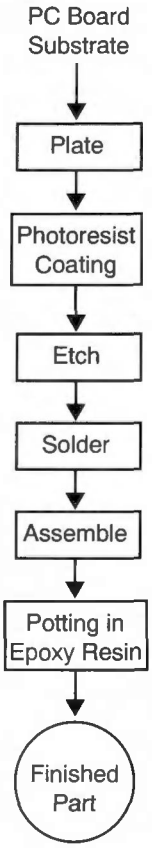
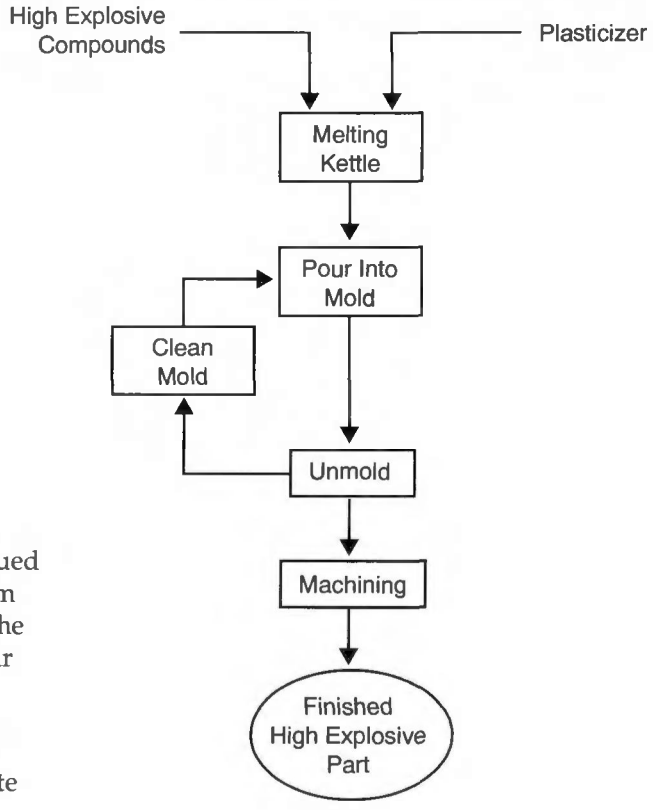


Figure B-17. High Explosive Manufacturing



Burn trays are used to incinerate high explosive charges and debris from high explosive packaging on the grounds of the Pantex plant. Modern plastic-bonded high explosives will burn safely without detonating. Pantex was a conventional Army munitions plant before it began assembling nuclear weapons in 1951. *Pantex Plant, Amarillo, Texas. November 18, 1993.*

Hemispheres of high explosives configured like the models in this display are used in an implosion bomb to rapidly squeeze a subcritical mass of plutonium into a denser, supercritical state. High explosive components for nuclear weapons were first made at Los Alamos, than at a pilot plant in China Lake, California, then finally at full scale in Burlington, Iowa, and Amarillo, Texas. *Bradbury Science Museum, Los Alamos, New Mexico. July 15, 1985.*

company, supplied specialized forging for the weapons complex. The company moved to Oxnard, California in 1983, and was purchased by the Department of Energy in 1984 to be managed as part of the Rocky Flats Plant. Precision Forge was privatized again in 1996.

Nuclear Material Recycling

Because of the high cost of obtaining fissile materials and the need for strict accounting and physical security, plutonium and enriched uranium recycling and recovery have been an integral part of the nuclear weapons complex since its beginnings. Scrap and residues containing lithium-6, low enriched uranium, tritium, and other nuclear materials are also processed. These processes address a wide variety of input materials, such as obsolete weapon parts, off-spec alloys, machine turnings, contaminated equipment, used HEPA filters, plastic bags, cleaning solvents and electrorefining salts, yielding pure uranium or plutonium oxide or metal. Batch processes are the general rule. A wide variety of physical and chemical processes are used, depending on the feed material. Figure B-15 illustrates the plutonium recovery processes used at Rocky Flats. Processes used by the Y-12 Plant to recover enriched uranium from returned weapon parts, scrap and process residues are illustrated in Figure B-18.

Rocky Flats – Recovery and purification of scrap plutonium at Rocky Flats began in the spring of 1953 when Building 771 became operational. Recycling and scrap and residue recovery remained an integral part of the plant's operations until it closed. The initial recovery system was a duplicate of the facilities used at Los Alamos at the time. A second "chem line" was installed in 1955. In a major 1965 expansion, another five dissolution lines were added. A new chemical recovery facility, Building 371, was begun in 1973, but it shut down in 1985 without ever achieving full-scale operation. A number of process changes have taken place at Rocky Flats. For example, molten salt extraction replaced an anion exchange process for removing americium ingrowth from recycled plutonium in 1967.

Rocky Flats also recovered and purified uranium scrap and residues in Building 881 between 1952 and 1962. After 1962, uranium parts were produced at the Y-12 Plant and thus no uranium-bearing scrap was available to be processed at Rocky Flats. The uranium recovery equipment at Rocky Flats was removed from Building 881 and disposed of by 1964.

Over time, the small amount of plutonium-241 present in weapons-grade plutonium decays, resulting in a buildup of americium-241. This process is called americium ingrowth. Americium absorbs neutrons during the fission process, making it undesirable for use in nuclear weapon pits. It also presents a gamma radiation hazard which increases over time. As a result, a backlog of americium-bearing residues accumulated at Rocky Flats. Beginning in 1957, americium ingrowth was removed from plutonium processed in Building 771. Until the early 1970s, americium was sold for various commercial uses. However, in 1980, americium recovery ceased and the material has been discarded as a waste since 1986.

Hanford – The Plutonium Finishing Plant (Building 234-5 Z) processed the plutonium scrap and residues from its own defense and nondefense operations.

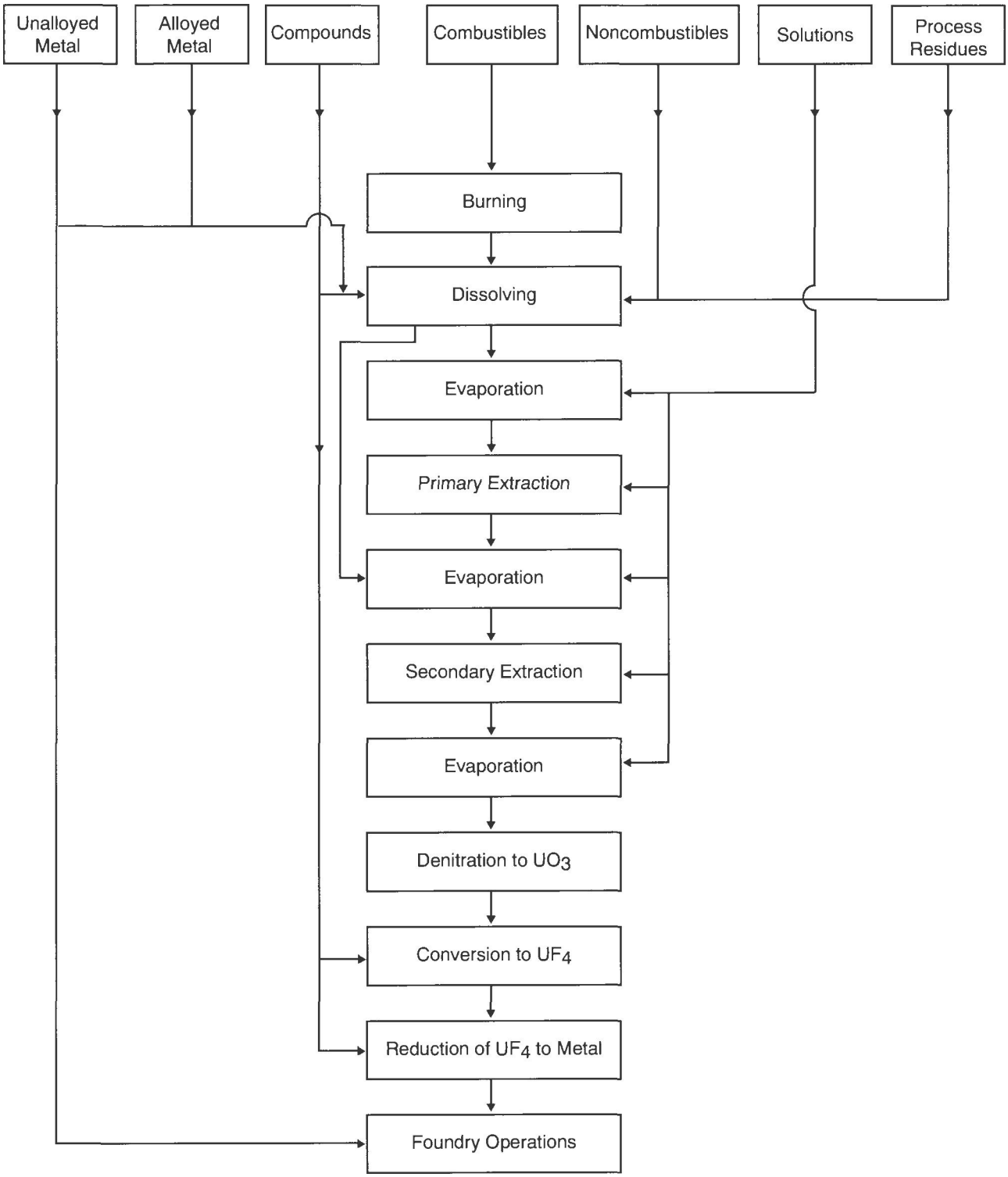
Savannah River Site F Area – The F Canyon and FB Line facilities process scrap and residues containing plutonium and other actinides.

Y-12 Plant – The Y-12 Plant has long functioned as a central scrap management office for all enriched uranium scrap from DOE sites. The Y-12 Plant also recycles lithium-6 from returned weapon secondaries and recovers and purifies lithium-6 from processing scrap and residues.

Los Alamos – Nuclear materials recycling began at the Los Alamos laboratory in the mid 1940s. Because plutonium was scarce during the war, great care was taken to recover it from scrap, wastes and residues. Initially accomplished at DP Site, scrap and residue processing was transferred to TA-55 when that facility became available in 1978.

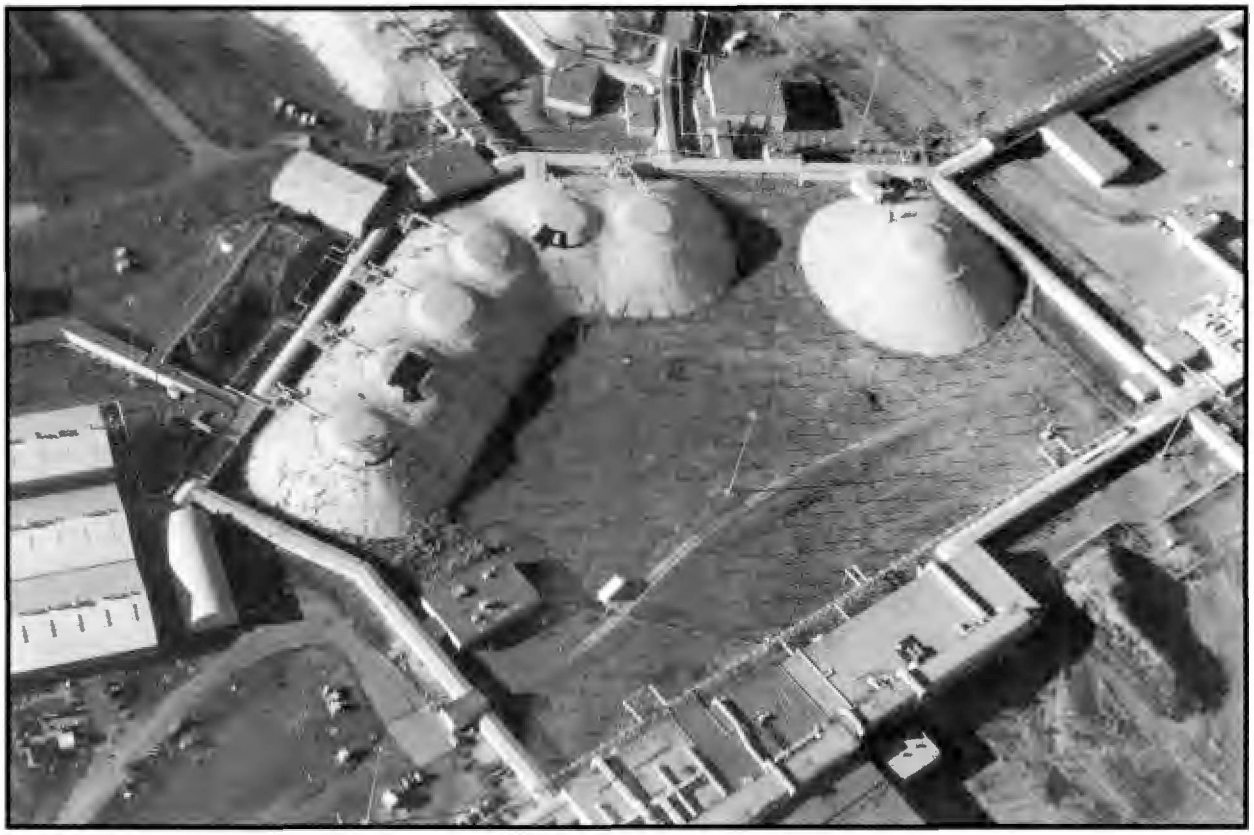
Lawrence Livermore Laboratory – Livermore has a limited plutonium scrap processing capability.

Figure B-18. Enriched Uranium Recovery Process Used at the Y-12 Plant



Note: Uranium scrap and residue processing at Y-12 is similar in many ways to plutonium recycling. Feed materials containing enriched uranium are prepared by incinerating combustibles, crushing and dissolving solid residues and scraps, and concentrating uranium solutions. Solvent extraction purifies the uranium, which is solidified to UO_3 by denitration, converted to UF_4, and reduced to metallic uranium. As with plutonium scrap recovery, Y-12 processes HEU scrap and residues using equipment designed to prevent accidental nuclear criticality.

Weapons Operations



"Gravel Gerties" are circular concrete structures whose roofs consist of cable mesh supporting large amounts of gravel. Beneath them are bays, where workers assemble and disassemble nuclear warheads. Should a warhead's conventional explosives accidentally detonate, the roofs of these structures are engineered to give way, releasing the gravel and trapping the plutonium particles. Up to 2,000 warheads per year are now being dismantled at this site. *Pantex Plant, Amarillo, Texas. November 18, 1993.*

Weapons Operations include assembly, maintenance, modification and dismantlement of nuclear weapons stockpile warheads. Assembly is the final process of joining together separately manufactured components and major parts into complete, functional and certified nuclear weapon warheads for delivery to the Department of Defense (DoD). Dismantlement of retired warheads includes disassembly of weapons and the sanitization, demilitarization and disposition of their component parts. Warhead modifications and maintenance by DOE are also included in this category, although field maintenance by DoD is not.

Only small amounts of radioactive wastes were produced by weapon operations, because most of the radioactive materials in nuclear weapons are handled only as sealed parts. However, weapon operations produced chemical wastes as a result of cleaning, painting, assembly and disassembly activities.

The first test devices and warheads were partially assembled by Manhattan Project scientists on the Pajarito Plateau at the Los Alamos S-Site, or TA-16. The scientists completed the assembly of the Trinity test device at the McDonald ranch house and atop the tower at the Alamogordo, New Mexico test site.

Final assembly of test devices has always been performed at the test site. This activity has been considered in this report as part of the legacy of research, development and testing and at other nuclear testing sites in the Pacific.

To maintain civilian control as required by the Atomic Energy Act, the nuclear cores and initiators of early nuclear weapons were stored separately from the remainder of the weapon. The cores were to be inserted

just before the weapon was used, a procedure known as "in-flight insertion." Pre-assembled bombs—without cores or initiators—were stored in bunkers at military bases. Employees of the Sandia division of Los Alamos Scientific Laboratory and, after it was formed in 1949, Sandia Laboratory, had custody of the nuclear components in adjacent storage bunkers. Maintenance and modification of the U.S. nuclear weapons stockpile was also done at these bases, at the direction of the AEC design laboratories.

Advances in nuclear weapons technology in the 1950s allowed for major changes in these arrangements. Most significantly, weapon designers developed coded locks, called permissive action links, that prevent the arming of a nuclear weapon without the proper code. These devices allowed civilian authorities to maintain control over the nuclear arsenal while completely relinquishing physical custody of the weapon. They also reduced the time necessary to deploy nuclear weapons in case of attack. By 1962, AEC had discontinued its custodial role at military nuclear weapons stockpile bases.

In July 1945, MED acquired part of Oxnard Field (now Kirtland Air Force Base) in Albuquerque and converted it into a weapons assembly site. The site was then known as Sandia Base and was manned by personnel from Los Alamos. The site was reorganized into a separate laboratory in 1949. Weapon assembly functions were performed at Sandia Base beginning in 1945. In 1948, Sandia built a production and assembly line in Technical Area 2 that operated until 1957.

To supplement Sandia's nuclear weapons assembly capacity, AEC built two assembly plants. The Iowa Army Ordnance Plant was built in Burlington, Iowa, in 1947 for final assembly. AEC selected the Pantex Ordnance Plant near Amarillo, Texas in 1950 as its second nuclear weapons assembly facility. Pantex began assembling nuclear weapons in 1951. Between 1942 and 1945, Pantex had been a conventional munitions factory, loading high explosives into bombs and artillery shells. Although the Army initially retained administrative control, Pantex was completely transferred to AEC in 1963. AEC changed the name of the facility to the Pantex Plant.

Staging bunkers, or "igloos," contain nuclear weapons and plutonium pits from dismantled warheads. There are 60 of these earth-mounded bunkers in a high security zone of the Pantex Plant. Sixteen of them store plutonium pits; the remaining 44 house nuclear weapons entering or exiting the plant. *Pantex Plant, Amarillo, Texas. May 23, 1986.*

The Burlington plant operated until 1975 when its functions were transferred to Pantex, which remains the Department of Energy's sole facility for weapon assembly, modification and dismantlement to the present day. DOE built an assembly plant, called the Combined Device Assembly Facility, at the Nevada Test Site in the 1990s, but it has not been used.

Modification of nuclear weapons by the military at its many stockpile storage sites eventually proved too cumbersome to be continued. In the 1950s, AEC began modifying and upgrading nuclear weapons at its assembly plants.

AEC constructed two supporting plants in 1958, the Clarksville Modification Center on the Ft. Campbell Military Reservation in Clarksville, Tennessee, and the Medina Modification Center in Medina, Texas. These sites performed specific tasks that were part of the assembly, dismantlement, and maintenance process, such as weapon repair and modification and component modification and testing. As part of scale-back instituted by President Johnson, the Clarksville and Medina facilities were closed in 1965 and 1966, respectively, and their functions transferred to Burlington and Pantex.

The major mission at Pantex today is dismantlement of nuclear weapons. Once a weapon is dismantled, Pantex sanitizes and demilitarizes many of the nonnuclear components, including electronics, cables, structural parts, parachutes and explosive actuators. *Sanitization* is the removal of classified information from weapon parts; *demilitarization* is the removal of their military function. Pits from dismantled weapons are stored on site, while secondaries, which produce thermonuclear reactions, are returned to the Y-12 Plant in Oak Ridge, Tennessee. Components containing tritium are sent to the Savannah River Site where the tritium is recovered and purified for reuse. The Mound Plant recovered tritium from some components from 1969 until the plant was shut down in 1995.

RESEARCH, DEVELOPMENT, AND TESTING

Los Alamos National Laboratory. Located on top of a mesa in the Sangre de Christo mountains of New Mexico, the Los Alamos National Laboratory was the birthplace of the world's first atomic weapons. It continues to function today as one of America's two main nuclear weapons design laboratories. *Los Alamos, New Mexico. June 15, 1983.*

Weapons *Research and Development* (R&D) is conducted by DOE national weapon laboratories and test sites whose primary mission is to support the nuclear weapons program. This includes basic and applied research with weapon applications and the design and testing of nuclear weapons systems. Weapons-related research has also been conducted by most of the DOE's multi-program laboratories.

Localized R&D to support specific site missions (such as fuel fabrication) is generally considered part of each local site mission, except in specific cases where the legacy generated is clearly distinguishable as resulting from R&D, and the R&D enables the site to better perform its overall mission in support of the national weapons program. Department of Defense laboratories and their activities are not discussed in this report. Research and development activities have produced a broad assortment of wastes, contamination, and large volumes of contaminated soil and debris.

Testing includes the preparation and instrumentation of the test site and device, the placement and detonation of the device, and the post-detonation analysis and cleanup. It also includes nonnuclear tests of weapon ballistics and other aspects of the military utilization of nuclear weapons. Tests which produced only small nuclear yields ("safety experiments") which intentionally did not produce a nuclear explosive yield, are also included in this category. Nuclear testing has resulted in large areas of contaminated soil and other environmental media, some areas being highly contaminated.

Early Research and Development

Much of the early theoretical and experimental work that led to development of the first nuclear weapon was accomplished outside the United States. For example, Rutherford's artificial transmutation of nitrogen into oxygen in 1919 (England); Chadwick's discovery of the neutron in 1932 (England); Fermi's early work with neutron bombardment in 1934 (Italy), and Hahn and Strassmann's discovery of the process of fission in uranium (Germany).

In the United States, nuclear physics research was being done at many institutions, including the University of California at Berkeley, Columbia University, Princeton University, the University of Minnesota, the University of Wisconsin, Stanford University, Purdue University, Iowa State College, Cornell University, the Rice Institute, the University of Chicago, the Massachusetts Institute of Technology, the University of Rochester, Harvard University, the University of Illinois, and the Carnegie Institute of Washington and the National Bureau of Standards. American researchers made a number of fundamental contributions, such as Ernest Lawrence's operation of the world's first particle accelerator, the cyclotron, in 1932 and later development of electromagnetic isotope separation; Bohr and Wheeler's 1939 work on fission theory at Princeton; Zinn, Anderson, Fermi and Szilard's, chain reaction and pile experiments at Columbia University in 1939-40; Dunning and Nier's work on uranium-235 fission at Columbia and Minnesota; and the 1941 discovery of plutonium by Seaborg and his colleagues at Berkeley.

By mid-1942, government support resulted in research being concentrated at Columbia University (gaseous diffusion and gas centrifuge for uranium separations), Berkeley (electromagnetic process for uranium separations), and University of Chicago Metallurgical Laboratory (chain reacting pile to produce plutonium). The thermal diffusion process for uranium separation had been dropped from consideration to produce material for a weapon but retained by the Navy for propulsion research. Many commercial organizations were involved in Manhattan Project research. Some of the larger contributors were E.I. du Pont de Nemours, Monsanto Chemical Company, Westinghouse Electric Company, and the Mallinckrodt Chemical Works.

Construction of a centralized laboratory for atomic bomb research and production began at Los Alamos, New Mexico (called "Site Y"), in November, 1942. In March, 1943, scientists and technicians began arriving at the laboratory. Early organization featured theory, experimental physics, chemistry and metallurgy, ordnance groups and many shops. The laboratory's mission was to develop and apply chain reaction and fissile material assembly theory, measure the physical, chemical, and nuclear parameters of various materials, develop processes for chemically purifying and fashioning uranium and plutonium, and engineer the final bombs. Initially, research concentrated on the "gun assembly" device, which assembled two subcritical masses into a supercritical mass using a gunbarrel. After it was discovered that this method would not work with plutonium because of its high neutron background, development of the plutonium bomb concentrated on implosion. Implosion uses explosives to compress a subcritical mass into a supercritical mass.

Los Alamos was assisted in its task by many other laboratories. The University of Michigan developed radar fuses and ordnance research. Scientists at the Dahlgren Naval Proving Ground, in Virginia, also performed ordnance research and development for the Manhattan Project. Explosives and gun propellant research at the Explosives Research Laboratory in Bruceton, Pennsylvania was crucial to the development of the atomic bomb. The Naval Gun Factory in Washington, D.C. made test guns for the development of the gun assembly device. Monsanto developed purification techniques for the polonium used in the initiators. Ohio State University researched the properties and manufacture of liquid deuterium. Plutonium chemistry and metallurgy were researched at U.C. Berkeley and the University of Chicago. Crucibles for reducing plutonium to metal without introducing light-element impurities were developed and manufactured by MIT, Iowa State College and Brown University. Experimental detonators came from the Hercules Powder Company. The "Camel" project, managed by the California Institute of Technology (CalTech) began in late 1944 to study weapon assembly mechanisms and combat delivery and to research and engineer specialized components including detonators.

The Tower Shielding Reactor. These towers were built to allow prototype aircraft propulsion reactors to be raised several hundred feet in the air for experiments. A small reactor at the base of the towers provided radiation to measure the shielding properties of materials for weapons and nonweapons programs. *Tower Shielding Reactor, Oak Ridge National Laboratory, Tennessee. June 10, 1982.*

The N Tunnel. Nuclear weapons effects tests were conducted in horizontal tunnels dug into the side of Ranier Mesa at the north end of the Nevada Test Site. DOE often cooperated with the Department of Defense to test the effects of nuclear weapons' radiation on military hardware, such as satellites and missile warheads. Workers here prepare for a test code-named "Misty Rain." On April 6, 1985, a nuclear device was detonated in a "zero room" 875 feet from this chamber. Air had been pumped from the pipe and chamber to simulate the vacuum of outer space. Radiation from the explosion traveled down the pipe to the test chamber at the speed of light, while blast doors blocked the explosion's shock wave. *N Tunnel, Area 12, Nevada Test Site. October 29, 1984.*

Signal cables laid out on the desert floor at Yucca Flat. These cables relayed scientific data to recording trailers on the surface as the nuclear device detonated deep underground. The tower above the emplacement hole was used to assemble a package of scientific instruments in a canister attached to the nuclear device. The tower was dismantled before the detonation took place. *Yucca Flat, Nevada Test Site. (No date available.)*

Supercomputers like these at Lawrence Livermore National Laboratory are used to analyze and simulate nuclear explosions. *Lawrence Livermore National Laboratory, California. June 13, 1984.*

Post-World War II Research and Development

After the initial surge of research work at universities and private laboratories in support of the Manhattan Project, nuclear weapons R&D work concentrated in a small number of government facilities. Some research continued outside these laboratories, for example, deuterium research at Ohio State University.

After World War II, the MED installation at Los Alamos, New Mexico became the Los Alamos Scientific Laboratory (LASL). In 1982, DOE directed the national laboratories to incorporate the word "national" in their official names, and LASL became Los Alamos National Laboratory. It is primarily a weapons design laboratory, although its nonweapons work load has grown considerably.

On occasion, Los Alamos has also performed weapons or materials production tasks. For example, in the 1980s, it built selected pits at TA-55 to exercise its mission to provide a back-up for RFP and reduced Hanford PuO_2 to plutonium metal for a short period after an accident at Hanford. However, the primary mission of Los Alamos has always been R&D for the specific purpose of theoretical design of the nuclear components of nuclear weapons and the radioactive legacy, therefore, has been weapons R&D related. A branch of the LANL testing division is also located at the Nevada Test Site.

On November 1, 1949, Sandia Laboratory was formed at Sandia Base on the grounds of Oxnard Field (now Kirtland Air Force Base) near Albuquerque, New Mexico. The new laboratory was formed from the Los Alamos Laboratory's Ordnance Engineering "Z Division," which had operated the site since July 1945 as a nuclear device and weapons assembly point and engineering design organization. The mission of the new laboratory was weapons RD&T, specifically the design of nonnuclear components of nuclear weapons. The location of the original laboratory was chosen to continue direct support to Los Alamos. A branch of SNL is also located at the Nevada Test Site. In 1982, the Sandia Laboratories were renamed the Sandia National Laboratories (SNL) by DOE directive.

In February 1952, Livermore, California was selected as the site for a second, dual capability, nuclear weapons design and R&D laboratory, to focus specifically on the development of thermonuclear weapons. AEC encouraged friendly competition between the two laboratories to stimulate research. The site officially opened in September 1952 as the University of California Radiation Laboratory-Livermore. The laboratory's name changed to Lawrence Livermore Laboratory (LLL) in 1971, and again to Lawrence Livermore National Laboratory (LLNL) in 1982 by DOE directive. It has occasionally performed minor production-related tasks, but its primary mission is weapons RD&T. A branch of Lawrence Livermore is located at the Nevada Test Site. In 1956, a branch of Sandia was formed at Livermore to provide the needed direct support of Lawrence Livermore Laboratory.

Los Alamos, Livermore and Sandia weapons R&D has ranged well beyond theoretical studies and design work. The laboratories have investigated the chemical, physical and metallurgical properties of nuclear materials. Manufacturing techniques to be used at production facilities are developed at the labs. Tests of high explosives have evaluated weapon design features. Simulations of environmental effects on nuclear weapons, including radiation, are also done by the weapons laboratories.

Nuclear Testing Sites

The United States has conducted a total of 1,054 nuclear tests, including 24 joint U.S.-U.K. tests. These tests have been conducted for several purposes. Eight hundred and ninety-one detonations have been weapons related tests to prove that a weapon would function as designed or to advance weapon design. One hundred detonations have been carried out to explore the effects of nuclear weapons on structures, equipment, and other weapons. Eighty-eight safety experiments have been performed to assess the likelihood of an accidental nuclear detonation, along with four storage and transportation related detonations and 24 joint U.S.-U.K. detonations. Seven detonations have been performed to develop means of detecting nuclear explosions from a great distance. Finally, 35 detonations explored non-military uses of nuclear explosives. (Some of the 1,051 tests comprise multiple detonations.)

Alamogordo, New Mexico – The first United States nuclear weapon test, code named "Trinity" by the Manhattan Engineer District, took place on July 16, 1945. The Trinity test site was the Jornada del Muerto region in the northwest corner of the Alamogordo Bombing Range in southern New Mexico. Today, the site is part of the White Sands Missile Range.

Pacific Proving Ground – Bikini Atoll and Enewetak Atoll in the South Pacific were the sites of MED and AEC weapons testing following the end of World War II, beginning with Operation Crossroads at Bikini Atoll in June and July of 1946. After a two-year hiatus, testing in the Pacific resumed in 1948. The primary Pacific test site was the Enewetak Proving Ground, although significant thermonuclear testing was conducted near and on some of the islands of Bikini. The Enewetak Proving Ground was placed on standby after Operation Hardtack I in 1958 and officially abandoned in 1960. Restoration of Enewetak was authorized by Congress in 1978 and performed by the Army Corps of Engineers for the Defense Nuclear Agency between 1978 and 1980. Cleanup was accomplished by entombing contaminated materials, which allowed previous residents to return to the area. The restoration of Bikini Atoll was accomplished by removal of contaminated materials and testing debris in 1969.

Other Offshore Test Sites – The United States conducted nuclear weapons tests in several other offshore locations, including (1) Shot Wigwam, detonated underwater 400 miles southwest of San Diego in 1955; (2) Operation Argus, 3 high altitude test shots in the South Atlantic Ocean in 1958; (3) four shots in the Pacific Ocean, including 2 underwater shots, one submarine-launched missile, and a balloon-suspended device; and (4) at a variety of oceanic locations near Johnston Island and Christmas Island as part of Operation Hardtack I and Operation Dominic, 1958-1962. These locations require no restoration.

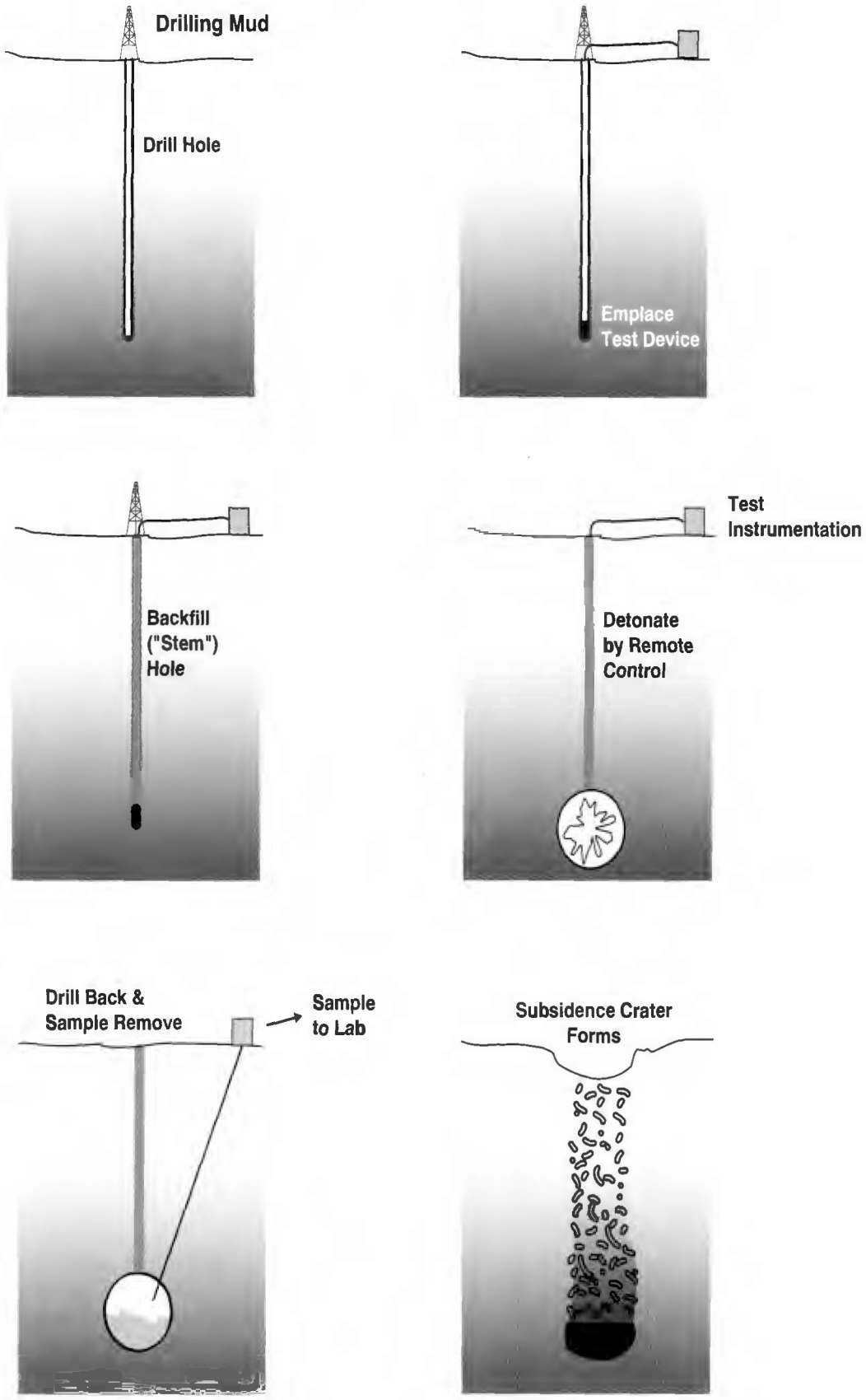
Nevada Test Site (NTS) – NTS was established in 1951 and was originally known as the Nevada Proving Grounds. A test site in the continental United States reduced the costs and logistical delays involved in testing at Bikini and Enewetak. The site also allowed the Army to conduct land-based troop maneuvers to simulate atomic warfare. There have been 925 nuclear tests at NTS since 1951. The first nuclear tests (called "shots") at NTS, the Operation Ranger series in 1951, were air-dropped air bursts which produced relatively small patterns of induced contamination on the ground. However, during subsequent tests through Operation Teapot in 1955, there were many tower-mounted test shots and a few surface and subsurface test shots resulting in significant fallout. Operation Plumbob in 1957 featured the first balloon-suspended shots which significantly reduced but did not entirely eliminate surface contamination. Shots Pascal A & B and Rainier, also in 1957, were the first attempts to gather data for underground containment and prepared the way for confining all tests underground by late 1962 before imposition of the Limited Test Ban Treaty in 1963.

Since 1963, all nuclear tests at The Nevada Test Site have been conducted underground. DOE-sponsored weapons development tests have been fired in deep shafts and weapon effects tests, principally a DoD concern, were fired in tunnels. These explosions have left underground cavities filled with a vitrified mixture of soil and explosion residues. Drilling to create test holes and drillback to retrieve post-test samples has resulted in drilling "mud" contaminated with radioactive and hazardous materials.

The Nevada Test Site currently buries low-level waste on site, and it disposed of mixed low-level waste in the same manner until 1990. Some low-level waste buried there was generated on site, but large quantities were also shipped from other locations. Old test craters U3ax and U3ax-b1 in Area 3 primarily contain contaminated debris from cleanup of atmospheric nuclear test areas at Yucca Flats. Area 5 shallow trenches and boreholes have received significant shipments of waste from Rocky Flats , LLNL, Mound, and Fernald. The Nevada Test Site also currently stores mixed TRU waste from LLNL.

Amchitka Island – Three nuclear tests were conducted on Amchitka Island, Alaska: Test "Long Shot" on October 29, 1965, shot "Milrow" on October 2, 1969, and shot "Cannikin" on November 6, 1971. "Long Shot" was for nonweapons purposes (see "Vela Uniform"), but "Cannikin" and "Milrow" were weapons-related tests. The area is now managed as the Amchitka Island Test Site.

Figure B-19. Underground Testing



Other Continental Sites – Nuclear Test Faultless, a weapons-related seismic calibration test, was detonated in Central Nevada on January 19, 1968.

The United States government investigated the application of nuclear explosives for peaceful purposes during the 1960s and 70s. This effort was called, "Project Plowshare." Project Plowshare conducted 35 nuclear detonations between 1961 and 1973. Most Plowshare detonations were at the Nevada Test Site, but Plowshare experiments were also conducted at Carlsbad and Farmington, New Mexico; and Grand Valley and Rifle, Colorado.

"Vela Uniform" was a Department of Defense program to improve the United States' ability to detect, identify and locate underground nuclear explosions. The program began in 1963 with the "Shoal" detonation in Fallon, Nevada, and it continued though 1971. A total of seven Vela Uniform tests were conducted, including one test at Amchitka, Alaska; two at Hattiesburg, Mississippi; and three at the Nevada Test Site.

Nonnuclear Testing Sites

Manhattan Project Sites – To develop ballistics information for the atomic bombs, drop tests were done at Wendover Field, Utah. Bomb ballistics drop tests were also made at the Camel Project field site, in China Lake, California, and the Sandy Beach area of the Salton Sea, California, Naval Air Station. Arming and fusing systems were field tested at Muroc Air Base (now known as Edwards Air Force base) in California. Radar altimeter fuses were tested at Warren Grove, New Jersey using barrage balloons.

Salton Sea Test Base – Salton Sea Test Base was used in the 1940s and 1950s as a sea-level ballistics range to obtain performance data on inert nuclear weapons prototypes. It was formerly operated by Sandia, and currently is owned and operated by the U.S. Navy. AEC transferred its Salton Sea Test Base activities to the Tonopah Test Range in 1961.

Tonopah Test Range – The Tonopah Test Range (Nye County, Nevada) was established in 1957 for the testing of nonnuclear systems and components of bombs. Typical examples of items tested there are bomb delivery systems, bomb-delivery retardation chutes, and artillery shell trajectories. Tonopah was operated by Sandia National Laboratory in Albuquerque.

Kauai, Hawaii – Sandia National Laboratory has conducted some nonnuclear weapons testing in Hawaii at the Navy facility on Kauai, now managed as the Kauai Test Facility. Among other missions, Kauai has been used to launch missiles carrying experimental, nonnuclear payloads.

Appendix C

Environmental Management Sites Contributing to U.S. Nuclear Weapons Production

This appendix lists the sites contributing to the development and production of nuclear weapons under the Manhattan Engineer District (MED), the Atomic Energy Commission (AEC), or the Department of Energy (DOE) that are now part of the DOE Environmental Management program. This list provides the location, a brief description of the activities conducted in support of weapons production, and identification of the type of legacy remaining at the site.

Sites that are not the responsibility of DOE are not listed. Many other sites provided services to AEC as subcontractors, suppliers, or services providers. No legacy remains at many of these sites, and others are the responsibility of their owners or operators. Also excluded from this list are AEC or DOE sites that were not involved in weapons production. Some listed sites, including most FUSRAP sites, are not owned by DOE. Other listed sites, such as Uranium Mill Tailings Remedial Action Project (UMTRAP) sites, were not owned or operated by AEC while they were in use, but are now being cleaned up by DOE. Many of the sites listed also performed nonweapons functions for AEC or DOE, but the nonweapons activities are generally not identified below.

Table C-1. Environmental Management Sites Contributing to U.S. Nuclear Weapons Production

State	Name	Location	Weapons Production Activities	Weapons Process Categories	Legacy Elements
AK	Amchitka Island	Amchitka	This area served as an underground nuclear weapons testing site for three test shots in 1965, 1969, and 1971.	Mining, Milling, and Refining	Contaminated Environmental Media, Release Sites
AZ	Monument Valley	Monument Valley	Between 1955 and 1967, a uranium mill at this site produced an upgraded uranium product that was further milled at a uranium mill in Shiprock, New Mexico, eventually producing uranium concentrate for sale to AEC.	Mining, Milling, and Refining	Waste, Contaminated Environmental Media, UMTRAP Site
AZ	Tuba City	Tuba City	Between 1955 and 1966, a uranium mill at this facility processed uranium ore, producing uranium concentrate for sale to AEC.	Mining, Milling, and Refining	Waste, Contaminated Environmental Media, UMTRAP Site
CA	Lawrence Livermore National Laboratory – Main Site	Livermore	LLNL is composed of two sites, the Main Site and Site 300. The Main Site, initially used as a flight training base and engine overhaul facility, began to be used for nuclear weapons research in 1950.	Research, Development, and Testing	Waste, Contaminated Environmental Media, Release Sites, Surplus Facilities, Materials in Inventory
CA	Lawrence Livermore National Laboratory – Site 300	Livermore	This site is used as a remote high-explosives testing area. It includes several areas for high-explosive component testing, several instrument firing tables, a particle accelerator, and various support and service facilities.	Research, Development, and Testing	Waste, Contaminated Environmental Media, Release Sites, Surplus Facilities, Materials in Inventory
CA	Oxnard Site	Oxnard	A DOE contractor occupied the site between 1981 and 1984 to produce forgings for weapons parts. DOE purchased the site in 1984 and continued to produce forgings until 1995.	Component Fabrication	Contaminated Environmental Media, Releases Site
CA	Salton Sea Test Base	Imperial County	During the 1940s and 1950s, this site was used by Sandia National Laboratories/New Mexico and the Air Force as a sea level ballistics test range to obtain perofrmance data on inert nuclear weapon prototypes.	Research, Development, and Testing	Waste, Contaminated Environmental Media
CA	Sandia National Laboratories/California	Alameda County	This site was established by AEC in 1956 to conduct research and development in the interest of national security with emphasis on nuclear weapons development and engineering in cooperation with Lawrence Livermore National Laboratory.	Research, Development, and Testing	Waste Contaminated Environmental Media, Release Sites, Surplus Facilities, Materials in Inventory

Table C-1. Environmental Management Sites Contributing to U.S. Nuclear Weapons Production

State	Name	Location	Weapons Production Activities	Weapons Process Categories	Legacy Elements
CA	University of California, Gilman Hall	Berkeley	Gilman Hall was the site of nuclear research involving plutonium and uranium in the 1940s, primarily in the areas of uranium enrichment, reactor experiements, and chemical separation of plutonium.	Research, Development, and Testing	FUSRAP Site; Cleanup Complete
CO	Durango	Durango	Initially the site of a vanodium production plant, this site milled uranium ore for MED and AEC between 1943 and 1963.	Mining, Milling, and Refining	Waste, Contaminated Environmental Media, UMTRAP Site
CO	Grand Junction Mill Tailings Site	Grand Junction	Between 1951 and 1967, a uranium mill at this site processed uranium ore, producing uranium concentrate for sale to AEC. The site also produced vanadium and milled uranium for commercial sale until 1970.	Mining, Milling, and Refining	Waste, Contaminated Environmental Media, UMTRAP Site
CO	Grand Junction Projects Office	Grand Junction	MED established this site in 1943 to refine uranium for the Federal Government. Between 1947 and 1970, the site administered AEC defense-related uranium exploration and purchase programs.	Mining, Milling, and Refining	Waste, Contaminated Environmental Media, Release Sites, Surplus Facilities, Materials in Inventory
CO	Gunnison	Gunnison	Between 1958 and 1962, a uranium mill at this site processed uranium are, producing uranium concentrate for sale to AEC.	Mining, Milling, and Refining	Waste, Contaminated Environmental Media, UMTRAP Site
CO	Maybell	25 miles W of Craig	Between 1955 and 1964, a uranium mill at this site processed uranium ore, producing uranium concentrate for sale to AEC.	Mining, Milling, and Refining	Waste, Contaminated Environmental Media, UMTRAP Site
CO	Naturita	Naturita	Between 1947 and 1958, a uranium mill at this site processed uranium ore, producing uranium concentrate for sale to AEC. Between 1961 and 1963, the site produced a uranium product that was further processed at a uranium mill in Durango, Colorado, eventually producing uranium concentrate for sale to AEC.	Mining, Milling, and Refining	Waste, Contaminated Environmental Media, UMTRAP Site
CO	Old and New Rifle	Rifle	Between 1948 and 1970, two uranium mills at these sites processed uranium ore, producing uranium concentrate for sale to AEC.	Mining, Milling, and Refining	Waste, Contaminated Environmental Media, UMTRAP Site (2 sites)
CO	Rocky Flats Environmental Technology Site	16 miles northwest of Denver	Established in 1952 as the Rocky Flats Plant, this site produced the plutonium pits used as triggers in nuclear weapons as well as other uranium, beryllium, and steel weapons components. Rocky Flats also recovered plutonium from returned weapons parts, production scrap, and residues.	Component Fabrication	Waste, Contaminated Environmental Media, Release Sites, Surplus Facilities, Materials in Inventory
CO	Slick Rock	Slick Rock	Two uranium mills operated at this site. The first, which operated between 1931 and 1943 was a vanadium and radium mill which also produced uronium for MED. Between 1957 and 1961, a second uranium mill nearby processed uranium ore, producing a uranium product which was further milled at one of the uranium mills at Rifle, Colorado, eventually producing uranium concentrate for sale to AEC.	Mining, Milling, and Refining	Waste, Contaminated Environmental Media, UMTRAP Site (2 sites)

Table C-1. Environmental Management Sites Contributing to U.S. Nuclear Weapons Production

State	Name	Location	Weapons Production Activities	Weapons Process Categories	Legacy Elements
FL	Pinellas Plant	St. Petersburg	Between 1957 and 1994, this site produced precisely timed neutron generators to initiate nuclear devices and other nonnuclear weapons parts.	Component Fabrication	Waste, Surplus Facilities, Materials in Inventory
HI	Kauai Test Facility	Kauai	Sandia National Laboratory/New Mexico has conducted some non-nuclear weapons research and development at this site, including launching rockets carrying experimental non-nuclear payloads.	Research, Development, and Testing	Release Site
IA	Ames Laboratory	Ames	Located on the campus of Iowa State University, this site developed and operated the first efficient production-scale process to convert uranium tetrafluoride to metal for use as reactor fuel by MED.	Mining, Milling, and Refining	Release Sites
ID	Idaho National Engioneering Laboratory	Approximately 42 miles northwest of Idaho Falls	AEC established the National Reactor Testing Station in 1949, on the site of a 1940s U.S. Navy bombing and artillery range. Today, the site is known as the Idaho National Engineering Laboratory. Between 1953 and 1992, the Idaho Chemical Processing Plant at INEL reprocessed spent fuel from naval propulsion, test, and research reactors to recover enriched uranium for reuse in nuclear weapons production. Large volumes of transuranic and low-level waste from Rocky Flats Plant component fabrication operations are buried and stored at INEL, including waste resulting from two fires at RFP. Facilities at INEL also conducted various minor nuclear weapons research and development work.	Chemical Separations; Research, Development, and Testing	Waste, Contaminated Environmental Media, Release Sites, Surplus Facilities, Materials in Inventory
ID	Lowman	Lowman	Between 1956 and 1960, a uranium mill at this site processed mineral processing residues, producing uranium for sale to AEC. The source of contamination was residual tailings. The site also produced other specialty minerals for weapons and nonweapons use.	Mining, Milling, and Refining	Waste, UMTRA Project Site
IL	Granite City Steel	Granite City	This site performed quantity control work for AEC. Activities included x-raying uranium ingots and developing film to detect metallurgical flaws.	Mining, Milling, and Refining	FUSRAP Site; Cleanup Complete
IL	National Guard Armory	Chicago	Leased from State of Illinois, this site was used by University of Chicago Metallurgical Laboratory for MED-sponsored activities, including storage and limited metallurgical work with uranium. The site was returned to the State in 1951.	Fuel and Target Fabrication	FUSRAP Site; Cleanup Complete
IL	Site A/Plat M	Palos Forest Preserve	From 1943 until 1956, Site A was the location of two experimental nuclear reactors operated for MED and AEC by the University of Chicago. Radioactive waste generated at Site A was buried at Plot M.	Reactor Operations	Contaminated Environmental Media, Release Sites
IL	University of Chicago	Chicago	The University of Chicago Metallurgical Laboratory performed MED-sponsored research, development, and testing in the areas of fission theory and chemical separations, including operation of the CP-1 nuclear reactor.	Research, Development, and Testing	FUSRAP Site; Cleanup Complete
KY	Paducah Gaseous Diffusion Plant	Paducah	Built in the early 1950s, this plant was initially operated for the sole purpose of enriching uranium for weapons production. Paducah gradually began to supply enriched uranium for Navy and commercial reactor fuel as well. Until the early 1960s, UF6 feed for the diffusion process was also produced at the site. In accordance with the Energy Policy Act of 1992, the diffusion cascade and support facilities at the site have been leased to the government-owned United States Enrichment Corporation since 1993. Paducah is still in operation enriching uranium for commercial customers, primarily nuclear power utilities.	Uranium Enrichment	Waste, Contaminated Environmental Media, Release Sites, Surplus Facilities, Materials in Inventory

Table C-1. Environmental Management Sites Contributing to U.S. Nuclear Weapons Production

State	Name	Location	Weapons Production Activities	Weapons Process Categories	Legacy Elements
MA	Ventron	Beverly	Between 1941 and 1948, the Metal Hydrides Corporation developed and implemented a process at this site to convert uranium oxide (UO2) powder to metal for the National Bureau of Standards, the Office of Scientific Research and Development, MED, and AEC. This site processed uranium used in the CP-1 reactor. The site also included a foundry used to recover uranium from Hanford fuel fabrication scrap and turnings.	Mining, Milling, and Refining	Contaminated Environmental Media, FUSRAP Site
MI	General Motors	Adrian	Operated by Bridgeport Brass Company as an aluminum extrusion plant for Army Air Corps in 1941, this site extruded uranium fuel elements in 1950 for production reactors at SRS and Hanford. It also functioned as an AEC semi-production pilot plant for developmental extrusion work for thorium and depleted, natural, and enriched (up to 2.1% U-235) uranium. In 1951, the large extrusion press at the site was shipped to Ashtabula, Ohio, to perform additional uranium extrusion work for AEC.	Fuel and Target Fabrication	FUSRAP Site; Cleanup Complete
MO	Kansas City Plant	Kansas City	Constructed in 1942 to build Navy aircraft engines, this site was converted to manufacture non-nuclear components for nuclear weapons in 1949. Today it continues to be DOE's main component fabrication plant.	Component Fabrication	Waste, Contaminated Environmental Media, Release Sites, Materials in Inventory
MO	Latty Avenue Properties	Hazelwood	Latty Avenue became contaminated when a private company purchased uranium production residues from AEC and transported them to the site for extraction of valuable nonradioactive metals. The purchaser became insolvent and its lender seized the property. In 1983, Congress directed DOE to perform remedial action at the site.	Mining, Milling, and Refining	Waste, Contaminated Environmental Media, FUSRAP Site
MO	St. Louis Airport Site	St. Louis	Between 1946 and 1953, this site stored residues and contaminated materials from the St. Louis Downtown Site (Mallinckrodt Chemical Works Destrehan Street Plant), including tailings from high-grade uranium ore processing. The property was owned by the government from 1946 until 1973, when it was transferred to the City of St. Louis.	Mining, Milling, and Refining	Contaminated Environmental Media, FUSRAP Site
MO	St. Louis Downtown Site	St. Louis	The Mallinckrodt Chemical Works' Destrehan Street Plant produced NU black oxide (U308) from high-grade African uranium ores for MED and later for AEC. The site also operated industrial scale processes to convert to U03 and U02, and other uranium chemistry and foundry processes. The privately-owned site processed uranium for AEC until 1957.	Mining, Milling, and Refining	Contaminated Environmental Media, FUSRAP Site
MO	St. Louis Airport Site Vicinity Properties	Hazelwood/ Berkeley	Contamination from St. Louis Airport Site. Vicinity properties consist of approximately 78 properties along transportation routes between the St. Louis Airport Site and other uronium processing facilities in the St. Louis area.	Mining, Milling, and Refining	Contaminated Environmental Media, FUSRAP Site
MO	Weldon Spring Site Remedial Action Project	St. Charles County	Located on the site of a former ordnance production facility, this site operated from 1956 until 1966 to sample and refine uranium ore for AEC and manufacture production reactor fuel.	Mining, Milling, and Refining; Fuel and Target Fabrication	Waste, Contaminated Environmental Media, Release Sites, Surplus Facilities
ND	Belfield	Belfield	Between 1965 and 1967, a gas-fired rotary kiln at this site burned uraniferous lignite coal. The ash was shipped to a uranium mill in Rifle, Colorado, eventually producing uranium concentrate for sale to AEC.	Mining, Milling, and Refining	Waste, Contaminated Environmental Media, UMTRAP Site
ND	Bowman	Griffin	Between 1964 and 1967, a gas-fired rotary kiln at this site burned uraniferous lignite coal. The ash was shipped to a uranium mill site in Ambrosia Lake, New Mexico, eventually producing uranium concentrate for sale to AEC.	Mining, Milling, and Refining	Waste, UMTRAP Site

Table C-1. Environmental Management Sites Contributing to U.S. Nuclear Weapons Production

State	Name	Location	Weapons Production Activities	Weapons Process Categories	Legacy Elements
NJ	Dupont (E.I. du Pont de Nemours & Co.)	Deepwater	In the 1940s, this site conducted uranium products research. In mid 1942, the site began to produce UF6 for weapons research. Between 1942 and 1947, the site developed processes to convert UO2 to UF6; produced uranium peroxide, metal, and hexafluoride; and conducted related research. This site produced uranium metal and oxide to fuel the CP-1 reactor at the University of Chicago.	Mining, Milling, and Refining; Fuel and Target Fabrication; Research, Development, and Testing	FUSRAP Site; Cleanup Complete
NJ	Kellex/Pierpoint	Jersey City	From the early 1940s until the early 1950s, the Kellex Corporation used this site to conduct research and development in several areas, including development of the gaseous diffusion barrier material used in uranium enrichment, PUREX fuel repracessing, and refining operations with UF6.	Mining, Milling, and Refining; Uranium Enrichment; Chemical Separations	FUSRAP Site; Cleanup Complete
NJ	Middlesex Municipal Landfill	Middlesex	This closed landfill was used by AEC for disposal of nonradioactive wastes from the Middlesex Sampling Plant. However, the landfill was found to include a 3-acre area containing contaminated wastes from uranium are sampling.	Mining, Milling, and Refining	FUSRAP Site; Cleanup Complete
NJ	Middlesex Sampling Plant	Middlesex	Established by MED in 1943 and now owned by DOE, this site was used by MED and the AEC until 1955 to sample, weigh, store, and ship uranium, thorium, and beryllium ores, including bulk ores from the African Congo. The site also stored uranium processing residues. AEC stored and sampled tharium residues at the site until 1967.	Mining, Milling, and Refining	Waste, Contaminated Environmental Media, FUSRAP Site
NJ	New Brunswick Laboratory	New Brunswick	Between 1948 and 1977, this site was a general radiochemistry laboratory for AEC. Its activities initially supported weapons research ond development, and later focused on nonweapons programs. Its functions were eventually transferred to ANL-E in Illinois. Completion of cleanup is expected in Fall of 1996.	Research, Development, and Testing	Contaminated Environmental Media, FUSRAP Site
NM	Acid and Pueblo Canyons	Los Alamos	Los Alamos refined HEU chemical compounds from Y-12 to metal and converted plutonyl nitrate from Hanford to plutonium metal. Deep canyans were used as discharge areas for untreated liquid radiooctive wastes.	Mining, Milling, and Refining; Chemical Separations	FUSRAP Site; Cleanup Complete
NM	Ambrosia Lake	McKinley County	The facility was a uranium milling site built in 1957. It sold uranium to AEC between 1958 and 1969. Sources of contamination were the residual tailings and discharged process water remaining after the uranium was extracted during the milling process.	Mining, Milling, and Refining	Waste, Contaminated Environmental Media, UMTRAP Site
NM	Bayo Canyon	Los Alamos	Bayo Canyon was a site for high explosive tests for nuclear weapons development. Some of these tests involved radioactive substances. This site includes a waste burial area for debris from decontamination and decommissianing of buildings, sewers, and surface areas at Technical Area 10 at LANL.	Research, Development, and Testing	FUSRAP Site; Cleanup Complete
NM	Chupadera Mesa	White Sands Missile Range	This site covers part of the fallout area from the first atomic bomb test, code-named Trinity, detonated on July 16, 1945.	Research, Development, and Testing	FUSRAP Site; Cleanup Complete
NM	Los Alamos National Laboratory	Los Alamos	Established in 1943 to design, develop, and test nuclear weapons, Los Alamos also produced small quantities of plutanium metal and nuclear weapons components. Its focus now includes academic and industrial research.	Research, Development and Testing; Campanent Fabricatian	Waste, Contaminated Environmental Media, Release Sites, Surplus Facilities, Materials in Inventory

Table C-1. Environmental Management Sites Contributing to U.S. Nuclear Weapons Production

State	Name	Location	Weapons Production Activities	Weapons Process Categories	Legacy Elements
NM	Sandia National Laboratories/ New Mexico	Albuquerque	Established in 1949, this laboratory was formed from the Los Alamos Explosive Ordnance "Z Division" to design nonnuclear components of nucleor weapons. Sandia also housed a weapon assembly line from 1946 until 1957.	Research, Development, And Testing; Weapon Operations	Waste, Contaminated Environmental Media, Release Sites, Surplus Facilities, Materials in Inventory
NM	Shiprock	Shiprock	Between 1954 and 1968, a uranium mill at this site processed uranium are, producing uranium concentrate for sale to AEC.	Mining, Milling, and Refining	Waste, Contaminated Environmental Media, UMTRAP Site
NM	South Valley Site	Albuquerque	Between 1951 and 1967, this site, owned by AEC and known as South Albuquerque Works, fabricated nonnuclear components for nuclear weapons. The site was later transferred to the Air Force for use as a jet engine factory, and eventually sold to General Electric.	Component Fabrication	Release Site
NV	Central Nevada Test Site	60 miles NE of Tonopah	This site was used for one subsurface nuclear test and nonnuclear seismic experiments.	Research, Development, and Testing	Contaminated Environmental Media, Releases Sites
NV	Nevada Test Site	65 miles NW of Las Vegas	Established in 1950, the Nevada Test Site was used for full-scale atmospheric and underground testing of nuclear explosives in connection with weapons research and development. It is also currently used as a disposal site for low-level radioactive waste from DOE sites.	Research, Development, and Testing	Waste, Contaminated Environmental Media, Release Sites, Surplus Facilities, Materials In Inventory
NV	Tanopah Test Range	Nellis Air Force Range	This site assumed the function of the Salton Sea Test Base in 1961. It is used by Sandia National Laboratories/New Mexico to test the mechanical operation and delivery systems for nuclear weapons and other defense-related projects.	Research, Development, and Testing	Release Sites
NY	Ashland Oil 1	Tonawanda	This site is part of an Ashland Oil Company refinery initially leased to MED in 1943. It was the initial storage site for low-grade uranium residues generated by the nearby ore processing and refining operations at Linde Air Products.	Mining, Milling, and Refining	Contaminated Media, FUSRAP Site
NY	Ashland Oil 2	Tonawanda	Beginning in 1974, an unknown amount of uranium residues were moved from the Ashland Oil 1 site to this site.	Mining, Milling, and Refining	Contaminated Media, FUSRAP Site
NY	Baker & Williams Warehouses	New York City	Three adjacent warehouses used between 1943 and 1945 to store uranium concentrates produced in Port Hope, Canada.	Mining, Milling, and Refining	FUSRAP Site; Cleanup Complete
NY	Bliss & Laughlin Steel	Buffalo	Bliss & Laughlin machined and straightened uranium rods in 1951 and 1952.	Fuel and Target Fabrication	FUSRAP Site
NY	Linde Air Products	Tonawanda	Between 1940 and 1948, Linde milled and refined uranium. The site was used to convert uranium ore from the African Congo and concentrates from Colorado plateau concentrates to black oxide (U308). It converted black oxide to brown oxide (UO2) and also included a pilot plant for production of green salt (UF4).	Mining, Milling, and Refining	Contaminated Media, FUSRAP Site
NY	Niagara Falls Storage Site	Lewiston	This site received and currently stores radioactive law-grade residues from the Linde Air Products Site and high-grade residues from the St. Louis Downtown Site.	Mining, Milling, and Refining	Waste, FUSRAP Site
NY	Niagara Falls Storage Site Vicinity Properties	Lewiston	Residues stored at the Niagara Falls Site spread to a number of adjacent properties. Remedial action is complete at all but 3 vicinity properties, which were not remediated due to access restrictions or because they were located on a commercial hazardous waste disposal area.	Mining, Milling, and Refining	FUSRAP Site; Cleanup Complete

Table C-1. Environmental Management Sites Contributing to U.S. Nuclear Weapons Production

State	Name	Location	Weapons Production Activities	Weapons Process Categories	Legacy Elements
NY	Seaway Industrial Park	Tonawanda	In 1974, some low-grade uranium ore tailings and residues deposited on the Ashland Oil 1 site were transported to and disposed of at this site	Mining, Milling, and Refining	Contaminated Media, FUSRAP Site
OH	Alba Craft	Oxford	Operating machine shop near Fernold. This site produced uranium slugs for AEC reactors between 1952 and 1957. Early operations included general machining and developmental work on threaded slugs for SRS, and later operations included production-scale hollow drilling and turning of slugs for reactors at SRS and Hanford.	Fuel and Target Fabrication	FUSRAP Site; Cleanup Complete
OH	Associated Aircraft	Fairfield	This site is on active machine shop near Fernald. For 8 months during 1956, part of the site performed work for AEC consisting of hollow drilling, reaming, and turning of uranium slugs.	Fuel and Target Fabrication	FUSRAP Site; Cleanup Complete
OH	Baker Brothers	Toledo	During 1943 and 1944, this site machined uranium rods for the Oak Ridge X-10 reactor. Later, the site continued to perform specialty uranium machining work for AEC.	Fuel and Target Fabrication	FUSRAP Site; Cleanup Complete
OH	B&T Metals	Columbus	During World War II, B&T Metals extruded uranium bullets into rods in the northeast corner of what is currently an office building.	Fuel and Target Fabrication	Contaminated Environmental Media, FUSRAP Site
OH	Fernald Environmental Management Project	Fernald	FEMP was established as the Feed Materials Production Center in the early 1950s to convert uranium ore into uranium metal, and to fabricate uranium metal into target elements for reactors that produced plutonium and tritium. The site ceased production in 1989.	Mining, Milling, and Refining; Fuel and Target Fabricatian	Waste, Contaminated Environmental Media, Release Sites, Surplus Facilities, Materials in Inventory
OH	HHM (Herring-Hall Marvin) Safe Co.	Hamilton	In 1943, this contractor machined uranium slugs from uranium rods. HHM also perfarmed nonweapons nuclear fuel fabrication work in 1951.	Fuel and Target Fabricatian	FUSRAP Site; Cleanup Complete
OH	Luckey	Luckey	This site aperated as a government-owned beryllium production plant for AEC from 1949 through the 1950s.	Component Fabrication	Contaminated Environmental Media, FUSRAP Site
OH	Mound Plant	Miamisburg	Beginning in 1946, this government-owned site developed and fabricated nuclear and nonnuclear components for the weapons program, including polonium-beryllium initiators. In the 1950s, the plant began to build detonators, cable assemblies, and other non-nuclear products. Mound began to retrieve and recycle tritium from dismantled nuclear weapons in 1969. Nonweapons activities included the production of plutonium-238 thermoelectric generators for spacecraft.	Component Fabrication	Waste, Contaminated Environmental Media, Surplus Facilities, Materials in Inventory
OH	Portsmouth Gaseous Diffusion Plant	Portsmouth	Built in the early 1950s, this site initially produced HEU for weapons. Later, the high-enrichment portion of the diffusion cascade was used to produce HEU for naval propulsion and research and test reactors, and was eventually shut down. In accordance with the Energy Policy Act of 1992, the lower portion of the diffusion cascade and support facilities at the site have been leased to the government-owned United States Enrichment Corporation. These facilities are still in operation enriching uranium for commercial customers, primarily nuclear power utilities.	Uranium Enrichment	Waste, Contaminated Environmental Media, Release Sites
OH	RMI Titanium Company	Ashtabula	Between 1962 and 1988, this privately owned site received uranium billets from Fernald and extruded them into various shapes for reactor fuel and targets.	Fuel and Target Fabrication	Waste, Contaminated Environmentol Media, Release Sites, Surplus Facilities, Materials in Inventory

Table C-1. Environmental Management Sites Contributing to U.S. Nuclear Weapons Production

State	Name	Location	Weapons Production Activities	Weapons Process Categories	Legacy Elements
OR	Lakeview	Lakeview	Between 1958 and 1960, a uranium mill at this site processed uranium ore, producing uranium concentrate for sale to AEC. In 1978, the mill was sold and used as a lumber mill and a stockpile area for sawdust and scrap waste.	Mining, Milling, and Refining	Waste, Contaminated Environmental Media, UMTRAP Site
PA	Aliquippa Forge	Aliquippa	In the late 1940s, this site operated a rolling mill, 2 furnaces, and cutting and extruding equipment for AEC to convert uranium billets into rods. This site also performed developmental extrusion work and considerable nonweapons specialty work.	Fuel and Target Fabrication	FUSRAP Site; Cleanup Complete
PA	Canonsburg	Canonsburg	This site refined uranium for AEC.	Mining, Milling, and Refining	Waste, Contaminated Environmental Media, UMTRAP Site
PA	C.H. Schnoor	Springdale	In 1943 and 1944, this site machined uranium slugs that were used as fuel in the production reactors at Hanford.	Fuel and Target Fabrication	FUSRAP Site; Cleanup Complete
SC	Savannah River Site	Aiken	This site was established in 1950 to produce, purify, and process plutonium, tritium, and other radioisotopes for nuclear weapons programs and other purposes. The site fabricated fuel, operated five reactors and two chemical separation plants, and conducted research and development. SRS also produced heavy water and processed tritium. Nonweapons activities included production of plutonium-238 for use in thermoelectric generators.	Heavy Water Enrichment; Fuel and Target Fabrication; Reactor Operations; Chemical Separations; Research, Development, and Testing	Waste, Contaminated Environmental Media, Release Sites, Surplus Facilities, Materials in Inventory
SD	Edgemont Vicinity Properties	Edgemont	Between 1956 and 1968, a uranium mill at Edgemont milled uranium for AEC. The mill also produced vanadium and milled uranium for other customers until 1974. The mill site was cleaned up by the Tennessee Valley Authority and is not a DOE site, but DOE cleaned up vicinity properties under DOE's UMTRA program.	Mining, Milling, and Refining	Waste, UMTRAP Site
TN	Elza Gate	Oak Ridge	During the early 1940s, this site was used as a staging and temporary storage area for high-grade African uranium ore shipped to Oak Ridge and residues from local processing of ore.	Mining, Milling, and Refining	FUSRAP Site; Cleanup Complete
TN	K-25 Site	Oak Ridge	K-25 was built in 1943 and 1944 to supply enriched uranium for nuclear weapons production. It was later modified to produce commercial grade low-enriched uranium. Shut down since 1987.	Uranium Enrichment	Waste, Contaminated Environmental Media, Release Sites, Surplus Facilities, Materials in Inventory
TN	Oak Ridge National Laboratory	Oak Ridge	In 1942, MED established research facilities in Oak Ridge to produce and separate the first gram quantities of plutonium. Since then, ORNL has primarily supported nonweapons programs, including radiaisotope production and research in a variety of fields. ORNL has also supplied isotopes for the nuclear weapons program.	Reactor Operations; Chemical Separations; Research, Development, and Testing	Waste, Contaminated Environmental Media, Release Sites, Surplus Facilities, Materials in Inventory
TN	Y-12 Plant	Oak Ridge	Originally established by MED to use an electromagnetic process to separate uranium isotopes, Y-12 later enriched lithium and fabricated and stored nuclear weapons components containing lithium and HEU.	Uranium and Lithium Enrichment; Component Fabrication	Waste, Contaminated Environmental Media, Release Sites, Surplus Facilities, Materials in Inventory
TX	Falls City	46 miles SE of San Antonio	Between 1961 and 1968, a uranium mill at the Falls City site milled uranium for AEC.	Mining, Milling, and Refining	Waste, Contaminated Environmental Media, UMTRAP Site

Table C-1. Environmental Management Sites Contributing to U.S. Nuclear Weapons Production

State	Name	Location	Weapons Production Activities	Weapons Process Categories	Legacy Elements
TX	Pantex Plant	Amarillo	Formerly a conventional munitions plant also used by Texas Tech University for nondefense activities, AEC converted this site to a high-explosives component fabrication and weapons assembly plant in 1951. The principal operation of Pantex is currently weapons disassembly and fissile material storage.	Component Fabrication; Weapons Operations	Waste, Contaminated Environmental Media, Release Sites, Surplus Facilities, Materials in Inventory
UT	Green River	Green River	Between 1958 and 1961, a uranium concentrator operating at this site produced an upgraded uronium product for subsequent milling at Rifle, Colorado, and eventual sale to AEC. The site also produced vanadium for nonweapons purposes.	Mining, Milling, and Refining	Waste, Contaminated Environmental Media, UMTRAP Site
UT	Mexican Hat	Mexican Hat	Between 1957 and 1965, a commercially owned uranium mill at this site processed uranium ore, producing uranium concentrate for sale to AEC.	Mining, Milling, and Refining	Waste, Contaminated Environmental Media, UMTRAP Site
UT	Monticello Site	Monticello	Between 1943 and 1960, a uranium mill at this site processed uranium ore, producing uranium concentrate for sale to AEC. The mill was commercially owned until 1948, when AEC purchased the facility.	Mining, Milling, and Refining	Waste, Release Sites
UT	Salt Lake City	Salt Lake City	Between 1951 and 1964, a uranium mill at this site processed uranium ore, producing uranium concentrate for sale to AEC.	Mining, Milling, and Refining	Waste, Contaminated Environmental Media, UMTRAP Site
WA	Hanford	Richland	Established in 1942, this major government-owned nuclear weapons production site fabricated reactor fuel, operated nine reactors and five chemical separation facilities, and fabricated plutonium components for nuclear weapons. Later operations included nonmilitary applications of nuclear energy.	Fuel and Target Fabrication; Reactor Operations; Chemical Separations; Component Fabrication; Research, Development, and Testing	Waste, Contaminated Environmental Media, Release Sites, Surplus Facilties, Materials in Inventory
WY	Riverton	Riverton	Between 1962 and 1965, a uranium concentrator at this facility processed uranium ore, producing an upgraded uranium product which was further processed at Slide Rock, Colorado, eventually producing uranium concentrate for sale to AEC.	Mining, Milling, and Refining	Waste, Contaminated Environmental Media, UMTRAP Site
WY	Spook	Converse County	Between 1958 and 1963, a uranium mill at this facility processed uranium ore, producing uranium concentrate for sale to AEC.	Mining, Milling, and Refining	Waste, Contaminated Environmental Media, UMTRAP Site

Appendix D

Congressional Mandate for this Report

The mandate for the production of this report is found in the National Defense Authorization Act for Fiscal Year 1995, Sec. 3154, reproduced here in its entirety:

> **Sec. 3154. REPORT ON WASTE STREAMS GENERATED BY NUCLEAR WEAPONS PRODUCTION CYCLE.**
>
> *(a) REPORT. -- Not later that March 31, 1996, the Secretary of Energy shall submit to Congress a report that contains a description of all waste streams generated before 1992 during each step of the complete cycle of production and disposition of nuclear weapons components by the Department of Energy. The description for each such step shall be based on a unit of analysis that is appropriate for that step. The report shall include an estimate of the volume of waste generated per unit of analysis and an analysis of the characteristics of each waste stream.*
>
> *(b) DEFINITIONS. -- In this section:*
>
> *(1) The term "waste stream" means waste materials the storage, treatment, or disposition of which is regulated under Federal law, except that such term does not include usable source materials, usable byproduct materials, and usable special nuclear materials.*
>
> *(2) The terms "byproduct material", "source material", and "special nuclear material" have the meaning given such terms in section 11 of the Atomic Energy Act of 1954 (42 U.S.C. 2014).*

Appendix E

Peer Review of the Legacy Report

To evaluate the analytical framework of this report, the Department of Energy's Office of Environmental Management held a peer review meeting in Washington, D.C. on February 5, 1996. Eleven reviewers from a wide variety of backgrounds and organizations provided the Department with feedback on a proposed analytical approach, which was distributed to the reviewers in advance. The reviewers also commented on the document's scope, structure and purpose. The reviewers were:

Dr. William Bibb, Citizens for National Security, Oak Ridge, Tennessee

Dr. Thomas B. Cochran, Natural Resources Defense Council, Washington, D.C.

Mr. Steven Hill, Coleman Research Corporation, Boise, Idaho

Dr. Peter Johnson, National Academy of Sciences, Washington, D.C.

Professor Todd LaPorte, Sr., Department of Political Science, University of California, Berkeley, California

Mr. John Meinhardt, Sandia National Laboratory, Albuquerque, New Mexico

Dr. John M. Pedicini, Los Alamos National Laboratory, Los Alamos, New Mexico

Mr. Stephen Schwartz, Brookings Institution, Washington, D.C.

Mr. Stephen Sholly, Beta Corporation, Albuquerque, New Mexico

Dr. Theodore B. Taylor, Wellsville, New York

Mr. Gordon Thompson, Institute for Resource and Strategic Studies, Cambridge, Massachusetts

The Department greatly appreciates the candid feedback provided by these expert reviewers. However, these individuals' participation in the peer review meeting in no way implies their endorsement of this report or its contents. The views and opinions expressed herein are solely those of the Department of Energy.

Glossary

(Italicized words are defined in glossary.)

11e(2) byproduct material. The tailings or *waste* produced by the extraction or concentration of *uranium* or *thorium* from any ore processed primarily for its *source material* (i.e., uranium or thorium) content. 11e(2) byproduct material is defined in Section 11e(2) of the *Atomic Energy Act*, as amended.

Accelerator produced. Any material made *radioactive* by the normal operation of a particle accelerator.

Activity. Short for *radioactivity*.

Activated. Describes non-*fissile* material that has become *radioactive* as a result of *neutron irradiation*.

Alpha particle. A particle consisting of two protons and two *neutrons*, given off by the decay of many elements, including *uranium*, *plutonium*, and *radon*. Alpha particles cannot penetrate a sheet of paper; however, alpha-emitting *isotopes* in the body can be very damaging.

Atmospheric fallout. *Radioactive* particles resulting from a nuclear explosion that gradually descend to earth.

Atmospheric testing. The aboveground or underwater explosion of a nuclear device in order to test it or its effects.

Atom. The basic component of all matter. The atom is the smallest particle of an element that has all of the chemical properties of that element. Atoms consist of a *nucleus* of protons and *neutrons* surrounded by electrons.

Atomic Energy Act. The federal law that administers and regulates the production and uses of atomic power. The act was passed in 1946 and amended substantially in 1954 and several times since then.

Atomic Energy Commission (AEC). AEC was created by the *Atomic Energy Act* in 1947 as the civilian agency responsible for the production of nuclear weapons. AEC also researched and regulated atomic energy. Its weapons production and research activities were transferred to the *Energy Research and Development Administration* in 1975, while its regulatory authority was transferred to the new *Nuclear Regulatory Commission*.

Beryllium. The forth-lightest element. Some nuclear weapon parts are made of beryllium.

Byproduct Material. Any *radioactive* material (except *special nuclear material*) yielded in or made radioactive by exposure to the *radiation* incident to the process of producing or utilizing special nuclear material, and the tailings or *waste* produced by the extraction or concentration of *uranium* or *thorium* from any ore processed primarily for its *source material* content.

Beta particle. A particle emitted in the *radioactive* decay of many *radionuclides*. A beta particle is identical to an *electron*. It has a short range in air and a low ability to penetrate other materials.

Calcine. A process that uses heat to convert liquid *high-level waste* into a dry, powdery form. Also the powdered *waste* that results from this process.

Canyon. A vernacular term for a *chemical separations* plant, inspired by the plant's long, high, narrow structure. Not all chemical separations plants are canyons.

Cesium. An element chemically similar to sodium and potassium. *Isotope* cesium-137 is one of the most important *fission* products, with a *half-life* of about 30 years.

Chemical separation. A process for extracting *uranium*, *plutonium*, and other *radionuclides* from dissolved *spent nuclear fuel* and *irradiated targets*. The *fission* products that are left behind are *high-level waste*. Chemical separation is also known as *reprocessing*.

Cladding. The outer layer of metal over the *fissile* material of a nuclear fuel element. Cladding on DOE's *spent nuclear fuel* is usually aluminum or zirconium.

Co-extrusion. A process used to *clad* nuclear fuel elements for Hanford *N Reactor* and the Savannah River Site reactors. A press extrudes *uranium* billets welded inside aluminum or zirconium *cladding* material into tubes, bonding the *uranium* to the cladding materials.

Co-product. Hanford site code name for *tritium*.

Cold War. A conflict over ideological differences between the United States and the Soviet Union and their allies lasting from the late 1940s until the early 1990s

and carried on by methods short of sustained military action.

COLEX (Column Exchange). Acronym for the column exchange process that was used at the Y-12 Plant to enrich *lithium*. COLEX was the principal lithium *enrichment* process used at the Y-12 Plant.

Commercial power reactor. Privately-owned *nuclear reactors* used to produce electricity. Commercial power reactors are fueled with *low-enriched uranium*.

Component fabrication. Includes the manufacturing, assembly, inspection, bench testing, and verification of specialized nuclear and non-nuclear parts and major subassemblies. Chemical processing to recover, purify, and recycle *plutonium, uranium, tritium,* and *lithium* from retired warheads and from component fabrication scrap and residues is included in this category.

Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). (42 USC 9601 et seq). A Federal law, enacted in 1980 and amended in 1986, 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 releases of hazardous substances. The 1986 amendments included provisions that require *DOE* and other federal agencies to clean up their facilities under Federal Facility agreements with *EPA*.

Contaminated environmental media. Naturally occurring materials such as soil, sediment, surface water, groundwater, and other in-place materials (e.g., sludge and rubble/debris that have been disposed of and/or intermixed with soil) that are contaminated at levels requiring further assessment to determine whether an environmental restoration action is warranted.

Criticality. A term describing the conditions necessary for a sustained nuclear chain reaction.

Curie. The amount of *radioactivity* in 1 gram of the *isotope* radium-226. One curie is 37 billion *radioactive* disintegrations per second.

Daughter products. *Radionuclides* that are produced from other radionuclides when they decay.

Deactivation. Activities that ensure *surplus facilities* are secure in a safe and stable condition pending their ultimate *disposition*. Includes eliminating immediate safety and environmental hazards as well as removing most contaminants within the facility.

Decommissioning. Retirement of a nuclear facility, including *decontamination* and/or dismantlement.

Decontamination. Removal of unwanted *radioactive* or *hazardous* contamination by a chemical or mechanical process.

Department of Energy (DOE). The cabinet-level U.S. Government agency responsible for nuclear weapons production and energy research and the cleanup of *hazardous* and *radioactive* waste at its sites. It succeeded the *Energy Research and Development Administration* and other federal government entities in 1977.

Depleted uranium. *Uranium* that, through the process of *enrichment*, has been stripped of most of the *uranium-235* it once contained, so that it has more *uranium-238* than *natural uranium*. It is used in some parts of nuclear weapons and as a raw material for *plutonium* production.

Detection level. The level above which a constituent (e.g., metal, organic) can be detected in a medium through sampling and analysis.

Deuterium. A naturally occurring *isotope* of hydrogen. Deuterium is lighter than *tritium*, but twice as heavy as ordinary hydrogen. Deuterium is most often found in the form of *heavy water*.

Disposition. Reuse, recycling, sale, transfer, storage, treatment, or disposal.

Dose. A specific amount of ionizing *radiation* or a toxic substance absorbed by a living being.

Easement. A right or privilege that a person may have in another's land.

Electromagnetic spectrograph. Process used to *enrich uranium* based on the tendency of ions of the *uranium-238* to deflect at a lower rate than *ions* of *uranium-235* as they travel through a magnetic field. This process was used in a device called a "Calutron" and was used at the Y-12 Plant from late 1943 through 1946.

ELEX (Electric Exchange). Acronym for the electric exchange process that was used at the Y-12 Plant to *enrich lithium*.

Energy Policy Act of 1992. (Public Law 102-486). Emphasizes energy efficiency, research and develop-

ment on conventional fuels, alternative fuels, and *uranium enrichment*. Also establishes several guidelines for *radioactive waste* disposal.

Energy Research and Development Administration (ERDA). The agency created in 1975 to take over the weapons production and research responsibilities of the *Atomic Energy Commission*. ERDA was abolished in 1977, and its functions, along with other federal government functions, were transferred into the cabinet-level *DOE* in 1977.

Enrichment. See *isotope separation*.

Entombment. An alternative for dispositioning *surplus facilities* by burial or covering in a vault.

Environmental contamination. The release into the environment of *radioactive, hazardous* and toxic materials.

Environmental Protection Agency (EPA). A Federal agency, established in 1970, responsible for enforcing environmental laws including the *Resource Conservation and Recovery Act* (RCRA); the *Comprehensive Environmental Response, Compensation and Liability Act* (CERCLA); and the *Toxic Substances Control Act* (TSCA).

Experimental breeder reactor. Experimental breeder reactors are located at Hanford, Washington and Idaho National Engineering Laboratory, Idaho. A breeding reactor produces more *fissile* material than it consumes.

Fat Man. The second atomic bomb used in combat by the United States. Fat Man was dropped on Nagasaki, Japan, on August 9, 1945.

Federal Facility Compliance Act (Public Law 102-386). A 1992 amendment to *RCRA*, this law made Federally owned and operated facilities subject to state-imposed fines and penalties for violations of *hazardous waste* requirements and required *DOE* to develop plans for treatment of *RCRA*-regulated *mixed waste*.

Fissile. Capable of being split by a low-energy *neutron*. The most common *fissile isotopes* are *uranium*-235 and *plutonium*-239.

Fission. The splitting or breaking apart of the *nucleus* of a heavy *atom* usually caused by the absorption of a *neutron*. Large amounts of energy and one or more neutrons are released when an atom fissions.

Formerly Utilized Sites Remedial Action Project (FUSRAP). A *DOE*-managed program to clean up privately owned facilities that were contaminated as a result of past nuclear materials research and production. Many of these facilities were part of the *Manhattan Project*.

Fuel, nuclear. Natural or enriched *uranium* that sustains the *fission* chain reaction in a *nuclear reactor*. Also refers to the entire fuel element, including structural materials and *cladding*. Also known as *reactor fuel*.

Fuel and target fabrication. Consists of the foundry and machine shop operations required to convert *uranium* feed material, principally metal, into *nuclear fuel* and *target* elements used in nuclear materials *production reactors*.

Fuel-grade plutonium. *Plutonium* that contains more than 7% plutonium-240 *isotope* by mass.

Fusion. The process whereby the *nuclei* of lighter elements, especially the *isotopes* of hydrogen (*deuterium* and *tritium*) combine to form the *nucleus* of a heavier element with the release of substantial amounts of energy.

Gamma radiation. High-energy, highly penetrating electromagnetic *radiation* emitted in the *radioactive* decay of many *radionuclides*. Gamma rays are similar to X-rays.

Gas centrifuge. A *uranium enrichment* process using a large number of rotating cylinders in a series. The lighter *uranium-235* isotope concentrates at the center of a spinning centrifuge of gaseous *uranium hexafluoride*. This method produced the first gram quantities of enriched uranium in 1944.

Gaseous diffusion. A *uranium enrichment* process based on the difference in rates at which uranium *isotopes* in the form of gaseous *uranium hexafluoride* diffuse through a porous barrier. This process is used to enrich uranium in the United States. The full scale K-25 gaseous diffusion plant was completed and operational at Oak Ridge, Tennessee in August 1945. Two additional, currently operating, gaseous diffusion plants previously used by *AEC* and *DOE* for weapons production are located at Paducah, Kentucky and Piketon, Ohio.

Geologic repository. A place to dispose of *radioactive waste* deep beneath the earth's surface.

Graphite reactor. A *nuclear reactor* using graphite blocks surrounding the nuclear fuel to slow the neutrons to low energy so that a self-sustaining chain reaction is achieved. The first nuclear reactors built near Chicago, Illinois; Oak Ridge, Tennessee; and Hanford, Washington were graphite reactors.

Half-life. The time it takes for one-half of any given number of unstable *atoms* to decay. Each *isotope* has its own characteristic half-life. They range from small fractions of a second to billions of years.

Hazardous waste. Defined under *RCRA* and its implementing regulations in Title 40 of the Code of Federal Regulations, Parts 260 to 279, and corresponding state regulations. A material is a hazardous waste under RCRA if it meets the definition of a solid waste as well as certain criteria for a hazardous characteristic or "listing."

Heavy metals. Metallic elements with high atomic weights (e.g., mercury, chromium, cadmium, arsenic, and lead) that can damage living organisms at low concentrations and tend to accumulate in the food chain. *Uranium, thorium,* and *plutonium* are also heavy metals.

Heavy water. Water that contains *deuterium atoms* in place of hydrogen atoms. Heavy water is used in the Savannah River Site *production reactors.*

High-level waste. Highly *radioactive* material resulting from the *reprocessing* of *spent nuclear fuel,* including liquid *waste* produced directly in reprocessing and any solid material derived from such liquid waste that contains *fission* products in sufficient concentrations.

Highly-enriched uranium. *Uranium* with more than 20 percent of the *uranium-235 isotope,* used for making nuclear weapons and also as *fuel* for some *isotope*-production, research, and power reactors. *Weapons-grade uranium* is a subset of this group.

Hydrofracture. An underground injection disposal technology used in the past to dispose *radioactive* waste.

Initiator. A device that produces a timed burst of *neutrons* to initiate a *fission* chain reaction in a nuclear weapon. Initiators made of polonium-210 and *beryllium* were located at the center of the *fissile* cores of early atomic weapons.

Institutional controls. Long-term actions or restrictions including monitoring, periodic sampling, access controls, and land use restrictions designed to mitigate any risks posed by contamination following remediation. Institutional controls alone may be sufficient to reduce risks posed by low-levels of contamination.

Ion exchange resins. Synthetic material used to selectively remove dissolved contaminants such as *heavy metals* or *radionuclides* from water by replacing or exchanging them with other constituents. Resins are typically used in beads or cartridges of beads or powders through which water is pumped.

Irradiate. To expose to ionizing *radiation,* usually in a *nuclear reactor. Targets* are irradiated to produce *isotopes.*

Isotope separation (enrichment). The process of separating different *isotopes* of the same element. The three elements that have been isotopically *enriched* in large quantities for use in nuclear weapons production are *uranium, lithium,* and hydrogen.

Isotopes. Forms of the same chemical element that differ only by the number of *neutrons* in their *nucleus.* Most elements have more than one naturally occurring isotope. Many more isotopes have been produced in *nuclear reactors* and accelerators.

Lithium. The lightest metal, and the third-lightest element. Lithium has two naturally occurring *isotopes,* lithium-6 and lithium-7. Lithium-6 *targets* are *irradiated* to manufacture *tritium.*

Little Boy. The first atomic bomb used in combat by the United States. Little Boy was dropped on Hiroshima, Japan on August 6, 1945.

Long-lived radionuclide. For *waste* management purposes, a *radioactive isotope* with a *half-life* greater than approximately 30 years.

Low-enriched uranium. *Uranium* that has been enriched until it consists of about three percent *uranium-235* and 97 percent *uranium-238.* Used as nuclear *reactor fuel.*

Low-level waste. Any *radioactive waste* that is not *spent fuel, high-level* or *transuranic waste,* or *11e(2) byproduct material.*

Manhattan Engineer District (MED). Established in August 1942, this district of the U.S. Army Corps of Engineers was the agency authorized to oversee the design, production, and testing of the first nuclear

weapons. On January 1, 1947, the district transferred authority over nuclear weapons stewardship to the civilian authority of the newly established *Atomic Energy Commission*; the district was abolished later that year.

Manhattan Project. The U.S. Government project, named for the *Manhattan Engineer District* that produced the first nuclear weapons during World War II. Started in 1942, the Manhattan Project formally ended in 1946. The Hanford Site, the Oak Ridge Reservation, and the Los Alamos National Laboratory were created for this effort.

Materials in inventory. Materials that are not currently in use (i.e., have not been used during the last year and are not expected to be used within the coming year) and have not been designated as *waste* or set aside by the Nuclear Weapons Council for national defense purposes. For nuclear materials, 'not currently in use' is synonymous with 'inactive' per *DOE* Order 5660.1B.

Mill tailings. The sand-like materials left over from separating *uranium* from its ore. More than 99 percent of the ore becomes tailings. Mill tailings, which are one type of *11e(2) byproduct* material, typically contain about 85 percent of the *radioactivity* present in unprocessed ore.

Mixed waste. *Waste* that contains both chemically *hazardous* waste, as defined under *RCRA*, and source, *special nuclear*, or *byproduct materials* as defined under the *AEA*.

N Reactor. The ninth and last *production reactor* built at the Hanford Site. The N Reactor operated from 1963 through 1987. The code name "N" stands for "New."

National Environmental Policy Act. A Federal law, enacted in 1970, that requires the Federal government to consider the environmental impacts of, and alternatives to, major proposed actions in its decisionmaking processes.

Natural uranium. *Uranium* that has not been through the *enrichment* process. It is made of 99.3 percent *uranium-238* and 0.7 percent *uranium-235*.

Naval Nuclear Propulsion Program. A joint *DOE* and Department of Navy program responsible for activities relating to the use of nuclear power in surface warships and submarines.

Neutron. A massive, uncharged particle that comprises part of an atomic *nucleus*. *Uranium* and *plutonium atoms fission* when they absorb *neutrons*. The chain reactions that make *nuclear reactors* and weapons work thus depend on neutrons. Man-made elements can be manufactured by bombarding other elements with neutrons in *production reactors*.

Neutron Generator. Device resembling a particle accelerator that produces a timed burst of *neutrons* to initiate a *fission* chain reaction in a nuclear weapon. Neutron generators located outside the *fissile pit* supplanted *initiators*.

Nuclear Reactor. A device that sustains a controlled nuclear *fission* chain reaction.

Nuclear Regulatory Commission (NRC). An independent agency of the Federal government created by the Energy Reorganization Act of 1974, which abolished *AEC* and transferred its regulatory function to the NRC. Responsible for ensuring adequate protection of public health and safety, the common defense and security, and the environment in the use of nuclear materials in the United States. Responsible for regulation of commercial nuclear power reactors; nonpower research, test, and training reactors; fuel cycle facilities; medical, academic, and industrial uses of nuclear materials; and the transport, storage, and disposal of nuclear materials as *waste*.

Nuclear Waste Policy Act of 1982 (Public Law 97-425). The federal law that provides for the development of *geologic repositories* for disposal of *high-level waste* and *spent nuclear fuel* and establishes a program of research, development, and demonstration regarding disposal of *high-level waste* and *spent nuclear fuel*.

Nuclear weapons complex. The chain of foundries, *uranium enrichment* plants, *nuclear reactors*, *chemical separation* plants, factories, laboratories, assembly plants, and test sites that produces nuclear weapons.

Nucleus. The cluster of protons and *neutrons* at the center of an *atom* that determines its identity and chemical and nuclear properties.

Office of Environmental Management. An office of the *Department of Energy* that was created in 1989 to oversee the Department's waste management and environmental cleanup efforts. Originally called the *Office of Environmental Restoration and Waste Management*, it was renamed in 1993.

Office of Environmental Restoration. The Environmental Restoration program is a division of the *Office of Environmental Management*. Its overall mission is to protect human health and the environment from risks posed by inactive, *surplus facilities* and contaminated areas.

Office of Nuclear Material and Facility Stabilization. The Nuclear Material and Facility Stabilization program is a division of the *Office of Environmental Management*. Its overall mission consists of three functions: stabilizing and storing nuclear materials prior to final *disposition*, *deactivating surplus facilities*, and managing *spent nuclear fuel* treatment and storage.

Office of Waste Management. The Waste Management program is a division of the *Office of Environmental Management*. Its overall mission is to protect people and the environment from the hazards of DOE *waste* by providing an effective and efficient system that treats, stores, and disposes of stored and newly-generated wastes.

Overpack containers. Containers, such as drums, boxes, or canisters, used to hold one or more internal *waste* containers during storage, transport, or disposal. Overpacks provide structural stability and an additional layer of protection.

Pit. The central core of the *primary* stage of a nuclear weapon consisting of *fissile* materials surrounded by the tamper and sometimes by a sealed metal shell.

Plume. A subsurface zone that contains predominantly dissolved and sorbed contaminants that originate from a contaminant source area. A plume can extend for some distance, depending on groundwater flow and chemistry.

Plutonium (Pu). A man-made *fissile* element. Pure plutonium is a silvery metal heavier than lead. Material rich in the plutonium-239 *isotope* is preferred for manufacturing nuclear weapons. The *half-life* of plutonium-239 is 24,000 years.

Plutonium residues. Materials left over from the processing of *plutonium* that contain enough plutonium to make its recovery economically beneficial.

Polychlorinated biphenyl (PCB). A group of commercially produced organic chemicals used since the 1940s in industrial applications throughout the *nuclear weapons complex*. PCBs are found in many of the gaskets and large electrical transformers and capacitors in the gaseous diffusion plants. They can be toxic to humans and animals.

Primary. Provides the initial source of energy to initiate a nuclear chain reaction for a nuclear weapon. Consists of a central core, called the *pit*, surrounded by a layer of high explosive. The pit is typically composed of *plutonium-239* and/or *highly enriched uranium* surrounded by a tamper.

Process Water. Name for treated Columbia River water used as coolant in the Hanford *production reactors*.

Process Tube. Horizontal aluminum (later zirconium) tube containing *nuclear fuel* and cooling water in Hanford *production reactors*.

Production reactor. A *nuclear reactor* designed to produce man-made *isotopes*. *Tritium* and *plutonium* are made in production reactors. The United States has 14 such reactors, 9 at the Hanford Site and 5 at the Savannah River Site. All have been closed.

PUREX. An acronym for *plutonium-uranium* extraction, the name of a chemical process used to *reprocess spent nuclear fuel* and *irradiated targets*. Also refers to the *chemical separations* plant at the Hanford Site built to use this process. The PUREX Plant operated from 1957 to 1972 and from 1983 to 1988.

Radiation. Energy transferred through space or other media in the form of particles or waves. Certain radiation types are capable of breaking up *atoms* or molecules. The splitting, or decay, of unstable atoms emits ionizing radiation.

Radiation dose commitment. The total theoretical *dose* to be received by an individual or population as a result of a condition or activity, calculated by summing the annual average dose over all time until the material has decayed.

Radioactive. Of, caused by, or exhibiting *radioactivity*.

Radioactivity. The spontaneous emission of *radiation* from the *nucleus* of an *atom*. *Radionuclides* lose particles and energy through the process of radioactive decay.

Radioisotope thermoelectric generators. Devices that use *radionuclides* that produce heat as they decay to generate electricity. Radioisotope thermoelectric generators are used to supply electricity in nuclear weapons, spacecraft, and medical devices.

Radionuclide. A *radioactive* species of an *atom*. For example, *tritium* and *strontium-90* are radionuclides of elements of hydrogen and strontium, respectively.

Radon. A *radioactive* inert gas that is formed by the decay of *radium*. Radium is, in turn, a link in the decay chain of *uranium-238*. Radon, which occurs naturally in many minerals, is a chief hazard of *uranium mill tailings*.

Reactor fuel. Synonymous with nuclear *fuel*.

Reactor operations. Includes *fuel* and *target* loading and removal, reactor maintenance, and operation of the reactor itself.

REDOX (Reduction Oxidation). One of the three *chemical separation* processes used on a large scale in the United States to chemically dissolve *spent nuclear fuel* and *irradiated targets* and isolate and concentrate the *plutonium*, *uranium*, and other nuclear materials that they contain. S Plant at Hanford, also known as the REDOX plant, operated using this process from 1951 until 1967.

Release site. A unique location at which a *hazardous, radioactive,* or *mixed waste* release has or is suspected to have occurred. A release site is usually associated with an area where wastes or substances contaminated with *wastes* have been disposed of, treated, stored, or used.

Reprocessing. Synonymous with *chemical separation*.

Research Conservation and Recovery Act (RCRA) (Public Law 94-580). A Federal law enacted in 1976 to address the treatment, storage, and disposal of *hazardous waste*.

Research, development, and testing (RD&T). Research and development includes the basic and applied science and technology of nuclear weapons and the engineering design of the weapons themselves. Testing includes nuclear explosions and other activities to evaluate the behavior, reliability, safety and effects of nuclear weapons. RD&T was carried out at National Laboratories, the Nevada Test Site, in the South Pacific, and at several other locations.

Research reactor. A class of *nuclear reactors* used to do research into nuclear physics, reactor materials and design, and nuclear medicine. Some research reactors also produce *isotopes* for industrial and medical use.

Residual radioactive material. Defined in Title I of *UMTRCA* as *waste*, including *mill tailings* and other forms of waste, resulting from the processing of ores for the extraction of *uranium* and other valuable constituents of the ores. This includes any residual stock of unprocessed ores or low-grade materials. *11e(2) byproduct material* managed under the *UMTRA Project* is residual *radioactive* material.

Saltcake. A cake of dry crystals of *radionuclides* found in *high-level waste* tanks.

Sanitary waste. *Waste* that does not contain *radioactive* or *hazardous* constituents sufficient to require special management. Sanitary waste includes municipal solid waste, construction / demolition debris, and some waste water.

Sealed source. A small package of *radioactive* materials used as a portable source of *radiation* packaged to minimize the possibility of dispersion of its radioactive contents.

Secondary. Provides additional explosive energy release for detonation of a nuclear weapon. Activated by the explosion from the *primary* assembly. Can be composed of *lithium* deuteride, *uranium* and other materials. Within the secondary, lithium is converted to *tritium* which undergoes *fusion* with *deuterium* to create a thermonuclear explosion.

Short-lived radioisotopes. For *waste* management purposes, *radioisotopes* with a *half-life* less than approximately 30 years.

Single pass reactors. Water-cooled *nuclear reactors* which discharge their cooling water after a single use rather than recirculating it. The first eight *production reactors* at Hanford were single pass reactors.

Source material. *Uranium* or *thorium* in any physical or chemical form, and ores containing at least 0.05 percent uranium or thorium. Source material does not include *special nuclear material* or *byproduct material*.

Special-case waste. *Waste* that is not *high-level* or *transuranic waste*, but requires greater confinement than shallow land burial.

Special nuclear material. Defined under the *Atomic Energy Act* as *plutonium*, *uranium-233*, and uranium *enriched* in the *isotopes uranium-233* or *uranium-235*. Special nuclear material does not include *source material* such as natural *uranium* or *thorium*.

Spent nuclear fuel. *Fuel* that has been withdrawn from a *nuclear reactor* following *irradiation*, the constituent elements of which have not been separated by *reprocessing*. Spent nuclear fuel also includes *uranium*/neptunium target materials, blanket assemblies, pieces of fuel, and debris.

Stabilization. Conversion of chemically active or readily dispersible matter into an inert or less harmful form. Also, activities to reduce the active management required for *surplus facilities* (such as burial ground stabilization and closure).

Strontium. An element chemically similar to calcium. *Isotope* strontium-90 has a half-life of 28 years, and is one of the most common *fission* products.

Surplus facility. A building, structure, or portion of a building or structure that *DOE* no longer needs to fulfill its mission.

Target. Material placed in a *nuclear reactor* to be bombarded with *neutrons* in order to produce *radioactive* materials. *Uranium-238* targets are used to make *plutonium*; *lithium targets* are used to make *tritium*.

Thermal diffusion. A process used to *enrich uranium* based on the faster diffusion rate of *uranium-235* than *uranium-238* in presence of a temperature difference. Employed on a production scale at the S-50 plant in Oak Ridge, Tennessee in 1945.

Thermonuclear weapon. A nuclear weapon that uses *fission* to start a *fusion* reaction. Commonly called hydrogen bomb or "H-bomb".

Thorium. A naturally occurring *radioactive* element.

Toxic Substances Control Act (TSCA). (Public Law 94-469.) A Federal law, enacted in 1976 to protect human health and the environment from unreasonable risk caused by exposure to or the manufacturing, distribution, use, or disposal of substances containing toxic chemicals. *PCBs* are regulated under TSCA.

Transuranic elements. All elements beyond *uranium* on the periodic table, including *neptunium, plutonium, americium,* and *curium.* All transuranic elements are man-made.

Transuranic waste. *Waste* contaminated with *uranium*-233 or *transuranic elements* having *half-lives* of over 20 years in concentrations more than 1 ten-millionth of a *curie* per gram of waste.

Treatability group. A grouping of *waste* on the basis of its radiological, chemical, and physical characteristics, content, and form. Used to group waste for future management activities.

Tritium. The heaviest *isotope* of the element hydrogen. Tritium is produced in *nuclear reactors* and is three times heavier than ordinary hydrogen. Tritium gas is used to boost the explosive power of most modern nuclear weapons. Tritium has a *half-life* of approximately 12 years.

Triple Dip. First process used to *clad reactor fuel* at Hanford. Process involves successive baths of molten bronze, tin, and aluminum-silicon mixture.

TRUPAC. Contact-handled *transuranic waste* will be shipped to the Waste Isolation Pilot Plant via trucks in Transuranic Packaging Transporters (TRUPACTs), containers designed to hold 14 55-gallon drums.

Underground testing. Testing of a nuclear device or its effects by exploding it underground.

Uranium. The basic material for nuclear technology. This element is naturally slightly *radioactive* and can be refined to a *heavy metal* more dense than lead.

Uranium hexafluoride. A gaseous form of *uranium* used in the *gaseous diffusion enrichment* process.

Uranium mill. A plant where *uranium* is separated from ore taken from mines.

Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978. (Public Law 95-604.) The act that directed the *Department of Energy* to provide for *stabilization* and control of the *uranium mill tailings* from inactive sites is a safe and environmentally sound manner to minimize *radiation* health hazards to the public. It authorized the Department to undertake remedial actions at 24 designated inactive *uranium*-processing sites and at an estimated 5,000 *vicinity properties.*

Uranium Mill Tailings Remedial Action (UMTRA) Project. A program to reduce the hazards posed to the public by *uranium mill tailings.* The program was created by *Department of Energy* in response to UMTRCA, which was enacted in 1978. The Department of Energy's *Office of Environmental Management* is responsible for implementing the UMTRA Project.

Uranium mining, milling, and refining. Mining and milling involves extracting *uranium* ore from the earth's crust and chemically milling (processing) it to

prepare uranium concentrate (U_3O_8), sometimes called uranium octaoxide or "*yellowcake*". Uranium concentrate is refined, or chemically converted, to purify it into the form suitable as feed material suitable for further use.

Uranium-233. A man-made *fissile isotope* of *uranium.*

Uranium-235. The lighter of the two isotopes of *uranium;* it is the only naturally occurring *fissile* element. Uranium-235 makes up 0.7 percent of the uranium that is mined from the ground. It has a *half-life* of 704 million years.

Uranium-238. The heavier of the two main *isotopes* of *uranium.* Uranium-238 makes up over 99 percent of uranium that is mined from the ground. It has a *half-life* of 4.5 billion years and is not easily split by *neutrons.*

Vicinity properties. Locations away from inactive mill sites where *uranium mill tailings* were used for construction or were transported by wind or water erosion.

Vitrification. A process that *stabilizes* nuclear *waste* by mixing it with molten glass. The glass mixture is poured into cylindrical metal canisters, where it hardens. Plants for vitrifying *high-level waste* have been built in the United States at West Valley, New York, and the Savannah River Site, South Carolina.

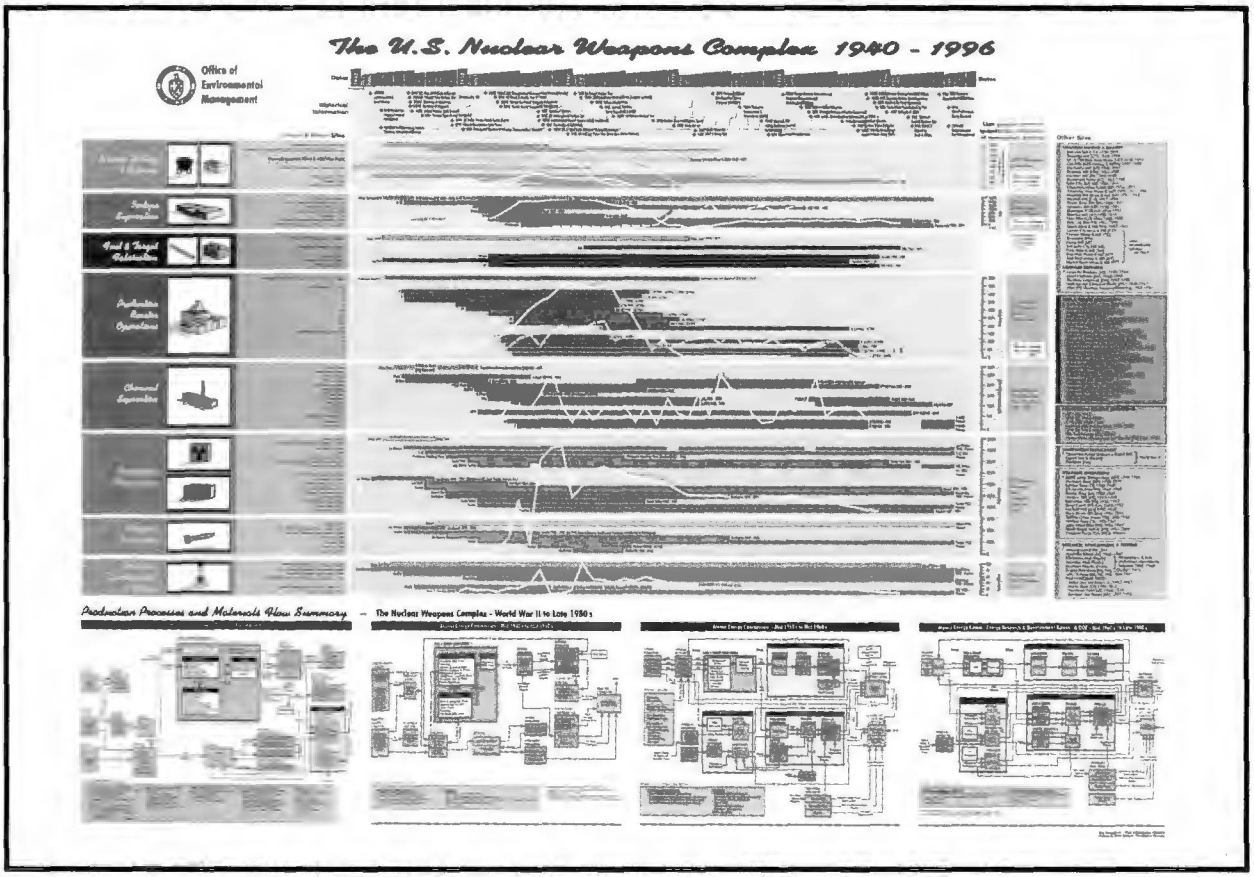
Waste. Includes *high-level, transuranic, low-level, mixed low-level* and *11e(2) byproduct material.*

Weapons-grade plutonium. *Plutonium* that contains at least 93% *plutonium*-239 *isotope* by mass.

Weapons-grade uranium. *Uranium* made up of over 90 percent of the *fissile uranium-235 isotope.*

Weapons operations. Includes the assembly, modification, maintenance, and dismantlement of nuclear weapons. Assembly is the final process of joining together separately manufactured components and major parts into complete, functional, and certified nuclear weapon warheads for delivery to the Department of Defense.

Yellowcake. A common *uranium* compound, U_3O_8, named for its typical color. Uranium is sent from the *uranium mill* to the refinery in this form.



Poster Summarizing the Evolution of the U.S. Nuclear Weapons Complex

The historical information contained in this report is summarized in a 26 1/2 x 37 inch color poster, a copy of which was folded and inserted into this document during initial distribution. The poster chronologically depicts the sites, processes, and performance measures associated with the eight nuclear weapons production steps. World events are also included in the timeline of the poster to anchor the activities portrayed.

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UNITED STATES DEPARTMENT OF ENERGY
WASHINGTON, DC 20585

OFFICIAL BUSINESS

Hanford workers assembling the graphite core of the "C" reactor, 1951.

This book provides an in-depth look at the production of nuclear weapons by the U.S. during the Cold War and the resulting environmental impacts.

LINKING LEGACIES: The U.S. Nuclear Weapons Complex

Office of Environmental Management

The Eight Primary Nuclear Weapons Production Processes

Major & Minor Sites

Historical Information

Dates

Line graphs present quantitative measures of production process

Uranium Mining, Milling & Refining

Middlesex Sampling Plant (NJ)
Australia, Canada, Portugal, South Africa & Belgian Congo
Domestic Uranium Mines & Mills[1] (See note on right)

Other[2] (See note on right)
Grand Junction (CO)
Fernald (OH)
Weldon Spring (MO)

- 12/7/41 Japanese Attack Pearl Harbor
- 8/42 Manhattan Engineer District Established
- 12/42 1st Self-Sustaining Nuclear Reaction, University of Chicago
- 5/8/45 V.E. Day, WWII Ends in Europe
- 7/16/45 "Trinity" First Nuclear Test - Alamogordo, NM
- 8/6/45 Bombing of Hiroshima
- 8/9/45 Bombing of Nagasaki
- 10/45 United Nations (UN) Created
- 8/46 Truman Signs Atomic Energy Act
- 5/49 Chinese Communists Take Power
- 8/49 1st Soviet Atomic Bomb Tested (Joe 1)
- 1/30/50 Presidential Decision to Develop Thermonuclear Weapons
- 10/52 "Mike," U.S. Experimental Thermonuclear Device (10.4 Mt)
- 8/53 1st Soviet H-Bomb, "Joe 4" Tested
- 12/53 "Atoms for Peace" Program Announced
- 2/54 "Castle-Bravo" Largest US Test (15 Mt)
- 8/57 1st Underground Nuclear Test
- 10/4/57 Launch of Sputnik
- 10/57 International Atomic Energy Agency (IAEA) Established
- 1/58 Formation of EURATOM
- 10/58 US & USSR Enter Bilateral Testing Moratorium
- 2/61 1st French Nuclear Test
- 10/61 USSR Explodes 50 Mt H-Bomb (Largest in World)
- 10/62 Cuban Missile Crisis
- 8/63 Limited Test Ban Treaty Signed US & USSR
- 10/64 1st Chinese Nuclear Test
- 7/68 Nuclear Non-Proliferation Treaty
- 1970 Clean Air Act
- 5/72 SALT I Treaty Signed
- 1972 Clean Water Act
- 3/74 Formerly Utilized Site Remedial Action Program (FUSRAP)
- 10/76 Resource Conservation & Recovery Act (RCRA)
- 11/78 Uranium Mill Tailings Radiation Control Act (UMTRCA)
- 3/79 Three Mile Island Accident
- 12/80 Comprehensive Environmental Response Compensation & Liability Act (CERCLA)
- 1982 Nuclear Waste Policy Act
- 2/83 Secretary's Model Decision Subjects DOE to RCRA
- 4/83 Lead v. Model Decision Subjects DOE to RCRA
- 4/86 Chernobyl Nuclear Disaster
- 1987 Nuclear Waste Policy Act
- 12/87 Intermediate-Range Nuclear Forces Treaty (INF)
- 11/88 DOE Estimates Cleanup Cost $100 Billion
- 12/88 DOE Proposes Nuclear Reconfiguration
- 5/89 Hanford Tri-Party Agreement
- 6/89 Rocky Flats Plant Raided By FBI
- 1990 Collapse of USSR
- 9/92 "Divider" Last US Nuclear Test
- 1/93 START II Signed by Presidents Bush & Yeltsin
- 1995 DOE Estimates Cleanup Cost $230 Billion
- 1996 Non-Proliferation Treaty Renewed
- 1996 U.N. Comprehensive Test Ban Approved

AEC Uranium Purchases (Overseas, Canada & Domestic) — Key: OVERSEAS, CANADA, DOMESTIC

Isotope Separation

Other Technologies:
K-25 Gaseous Diffusion Plant (TN)
Savannah River Site Heavy Water (SC)
Dana Heavy Water Plant (IN)
Paducah Gaseous Diffusion Plant (KY)
Y-12 Lithium (TN)
Portsmouth Gaseous Diffusion Plant (OH)

- Y-12 Calutron (TN) 1943 - 1945; S-50 Thermal Diffusion (TN) 7/1944 - 9/1945.
- K-25 1945 - 1964
- Dana 1952 - 1957
- Y-12 1955 - 1963
- SRS 1952 - 1982
- Paducah 1954 - 1992
- Portsmouth 1956 - 1994
- COMMERCIAL ENRICHMENT
- GOVERNMENT ENRICHMENT

Uranium Enrichment Plant Output* (SWU) — Key: GOVERNMENT, COMMERCIAL

* Negative Numbers are Due to Blending Down of Enriched Uranium

Fuel & Target Fabrication

Other Sites[3] (See note at right)
Hanford 300 Area (WA)
Fernald (OH)
Savannah River Site M Area (SC)
Reactive Metals, Inc. (OH)

- Hanford 1943 - 1987
- Fernald 1953 - 1989
- SRS 1953 - 1989
- RMI 1962 - 1991

Production Reactor Operations

Prototype and Test Reactors[4] (See note at right)
HANFORD SITE (WA)
B
D
F
H
DR
C
KE
KW
N
SAVANNAH RIVER SITE (SC)
R
P
L
K
C

- B 9/1944 - 3/1946; 7/1948 - 2/1968
- D 12/1944 - 6/1967
- F 9/1945 - 6/1965
- H 11/1949 - 4/1965
- DR 10/1950 - 12/1964
- C 11/1952 - 4/1969
- KE 4/1955 - 1/1971
- KW 4/1955 - 2/1970
- N 12/1963 - 2/1987
- R 12/1953 - 6/1964
- P 2/1954 - 1/1988
- L 1985 - 1988
- K 10/1954 - 1/1988
- C 3/1955 - 1/1987
- HANFORD SITE
- SAVANNAH RIVER SITE

Production of Weapons Grade Plutonium (Weapons Grade) — Key: HANFORD SITE, SAVANNAH RIVER SITE

Chemical Separation

Other Sites
HANFORD SITE (WA)
T Plant (WA)
B Plant (WA)
PFP/Z Plant (WA)
REDOX (WA)
UO_3 Plant (WA)
U Plant (WA)
PUREX (WA)
IDAHO NATIONAL ENGINEERING LABORATORY (ID)
ICPP (ID)
SAVANNAH RIVER SITE (SC)
H Canyon (SC)
F Canyon (SC)

- X-10 Semi Works, (TN) 1944-1945
- Separations Process Research Unit (NY) 1949 - 1951
- T Plant 12/1944 - 3/1956
- B Plant 1945 - 1952
- B Plant 1968 -1983 Cs and Sr Removal
- PFP/Z Plant 1951 - 1989
- REDOX 1951 - 1967
- UO_3 1953 - 1972
- UO_3 1984-1994
- U Plant 1952 - 1957 (Deactivated in 1994)
- PUREX 1956 - 1972
- PUREX 1983 -1990
- ICPP 1952 - 1992
- H 11/1954 - 1988
- F 10/1955 - 1988
- H 1993 - Pres.
- F 1993 - Pres.
- IDAHO CHEMICAL PROCESSING PLANT

Reprocessing at Idaho Chemical Processing Plant 1953 - 1991 (kg of Total Uranium Recovered)

Component Fabrication

Other Sites[5] (See note at right)
NUCLEAR COMPONENT FABRICATION
Los Alamos (NM)
Y-12 (TN)
Plutonium Finishing Plant (Hanford) (WA)
Rocky Flats Plant (CO)
Savannah River Site Tritium Facility (SC)

NON-NUCLEAR FABRICATION
Los Alamos (NM)
Salt Wells Pilot Plant (CA)
Mound Laboratory (OH)
Kansas City Plant (MO)
Burlington (IA)
South Albuquerque Works (NM)
Pantex Plant (TX)
Pinellas Plant (FL)

- Other Sites[5] 1942 - 1946
- NW-II 1942 - 1946
- Los Alamos 1942 - 1947 (Detonators HE, Lens Timing Devices, Etc.)
- Los Alamos 1945 - Present
- Y-12 1947 - Present
- Plutonium Finishing Plant 1952 - 1965
- Plutonium Finishing Plant (Hanford) 1952 - 1965
- Rocky Flats 1951 - 1989
- SRS Tritium Facility 1952 - Present
- Salt Wells 1947 - 1954
- Mound 1947 - 1995
- Kansas City 1949 - Present
- South Albuquerque 1952 - 1967
- Burlington 1949 - 1975
- Pantex 1952 - Present
- Pinellas 1957 - 1994

U.S. Nuclear Weapons Total Stockpile Explosive Yield (Megatonnage)

Weapons Operations

Other Sites[6] (See note at right)
Los Alamos National Laboratory (NM)
Sandia National Laboratory (NM)
Burlington (IA)
Pantex (TX)
Medina (TX)
Clarksville (TN)

- Other[4] 1945 - 1948
- Sandia 1945 - 1957 (In 1949 Oxnard Became Sandia and Functions Transferred to Burlington)
- Burlington 1949 - 1975
- Pantex 1952 - Present
- Medina 91958 - 7/1966
- Clarksville 1960 - 1965
- Other[4] 1948 - Present
- U.S. NUCLEAR WEAPONS STOCK PILE YIELD

Research, Development, & Testing

Other Test Sites[7] (See note at right)
Research Facilities:
Los Alamos National Laboratory (NM)
Sandia National Laboratory (NM)
Lawrence Livermore National Laboratory (CA)

Pacific Proving Ground (U.S. Territory)
Nevada Test Site (NV)

- Other[7] 1942 - 1993
- Los Alamos 1942 - Present
- Sandia 1945 - Present
- Livermore 1952 - Present
- Pacific 1946 - 1958 (Bikini Atoll 6/30/46 - 7/22/58; Enewetak 4/14/48 - 8/16/58)
- Nevada Test Site (NTS) 1958 - Present
- ANNOUNCED U.S. NUCLEAR TESTS

Announced U.S. Nuclear Tests (Number of Tests)

Other Sites

URANIUM MINING & MILLING
Natrona Mill (CO) 1939 - 1963
Durango Mill (CO) 1942-1946
UC & DI Old Slick Rock Mine (CO) 1945-1957
Old Rifle Mining & Milling (CO) 1947-1958
Monticello Mill (UT) 1948-1960
Shiprock Mill (NM) 1954-1968
Lowman Mill (ID) 1955-1960
Monument Valley (AZ) 1955-1968
Tuba City Mill (AZ) 1956-1966
Edgemont Mine & Mill (SD) 1956-1971
Ambrosia Lake Mine & Mill (NM) 1957-1963
Mexican Hat Mine & Mill (UT) 1957-1963
Maybell Mill (CO) 1957-1964
Green River Mill (UT) 1958-1961
Lakeview Mill (OR) 1958-1961
Gunnison Mill (CO) 1958-1962
Riverton Mill (WY) 1958-1963
New Rifle Mine (CO) 1958-1978
Falls City Mill (TX) 1961-1937
Spook Mine & Mill (WY) 1962-1965
Canon City Mine & Mill (CO)
Uravan Mine & Mill (CO)
Bluewater Mine & Mill (NM)
Moab Mill (UT)
Salt Lake City Mill (UT)
Ford Mine & Mill (WA)
Gas Hills Mine & Mill (WY)
Split Rock Mine & Mill (WY)
Shirley Basin Mine & Mill (WY)
} Used intermittently between 1948-1962

URANIUM REFINING
[2] Linde Air Products (NY) 1940-1948
Metal Hydrides (MA) 1942-1948
Harshaw Chemical (OH) 1942-1948
Mallinckrodt Chemical Works (MO) 1942-1957
Vitro Uranium Recovery/Recycling (PA) 1942-1957

FUEL & TARGET FABRICATION
[3] Brush Beryllium Co. (OH) 1942-1943
Electromet (NY) 1942-1949
Ames Laboratory (IA) 1942-1945
B&T Metals (OH) 1943
Herring-Hall Marvin Safe Co. (OH) 1943-1951
Baker Brothers (OH) 1943-1944
CH Schnoor (OH) 1943-1944
Revere Copper & Brass Inc. (MI) 1943-1946
William E. Pratt Manufacturing (IL) 1943-1946
Wolverine Tube Division (MI) 1943-1946
Quality Hardware & Machine Co. (IL) 1944
Jostyn Manufacturing & Supply Co. (IN) 1944-1949
Aliquippa Forge (PA) 1947-1949
Simonds Saw & Steel Co. (NY) 1948-1956
Allegheny-Ludlum Steel Corp. (?) (NY) 1950-1952
Alba Craft (OH) 1952-1957
Superior Steel Corp. (PA) 1952-1957
Bridgeport Brass (CT) 1952-1962
Buffalo Works (NY) 1954-1958 & 1964-1971
Heppenstall Co. (PA) 1955
American Brass Co. (CT) 1955-1958
Associated Aircraft Co. (OH) 1956
Copperweld Steel Co. (OH) 1943-1946
Horizons Inc. (OH) 1944-1952
ALCOA (PA) 1944-1945

PRODUCTION REACTOR OPERATIONS
[4] CP-1 (IL) 1942
CP-2 (IL) 1943-1956
X-10 (TN) 1943-1963
Hanford 305 Test Pile (WA) 1943-1972
CP-3 (IL) 1944-1956
SRS Test Reactor (SC) 1950's
Heavy Water Component Test Reactor (SC) 1961-1964

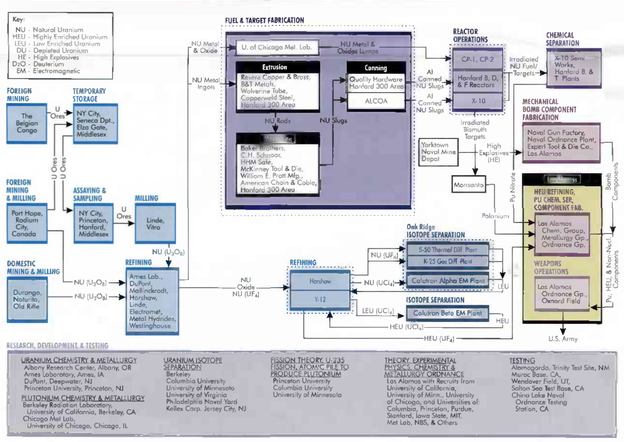
COMPONENT FABRICATION
[5] Centerline Naval Ordinance Depot (MI) } World War II
Expert Tool & Die (MI)
Raytheon (MA)

WEAPONS OPERATIONS
[6] Igloo Storage Area (NM) 1948-1950
Killeen Base (TX) 1948-1969
Manzano Base (NM) 1950-1969
Boosler Base (LA) 1952-1969
Caribou AFS (ME) 1952-1962
Rudmore AFS (SD) 1952-1962
Deep Creek AFS (WA) 1952-1962
Fairfield AFS (CA) 1952-1962
Stony Brook AFS (MA) 1954-1966
Skiffes Creek Annex (VA) 1953-1962
Lake Mead Base (NV) 1954-1969
North Depot Activity (NY) 1957-1962
Precision Forge (CA) 1958- Present

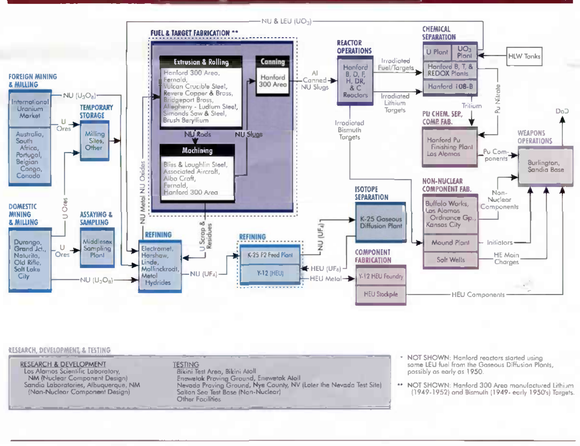
RESEARCH, DEVELOPMENT, & TESTING
[7] Alamogordo (NM) 1945
Christmas Atoll (Pacific)
Johnston Atoll (Pacific)
Southern Atlantic Ocean
} Atmospheric & tests performed intermittently between 1955 - 1962
Project Plowshare (NV, NM, CO) 1961-1973
Velo Uniform (AK, MS, NV) 1963-1971
Amchitka Island (AK) 1965-1969
NON-NUCLEAR TESTS:
Salton Sea Test Base (CA) 1942-1961
Muroc Base (CA) 1944-1945
Wendover Field (UT) 1944-1945
Tonopah Test Range (NV) 1957-1993

PRODUCTION PROCESSES AND MATERIALS FLOW SUMMARY -- The U.S. Nuclear Weapons Complex From World War II to Late 1980's

Manhattan Engineer District - World War II



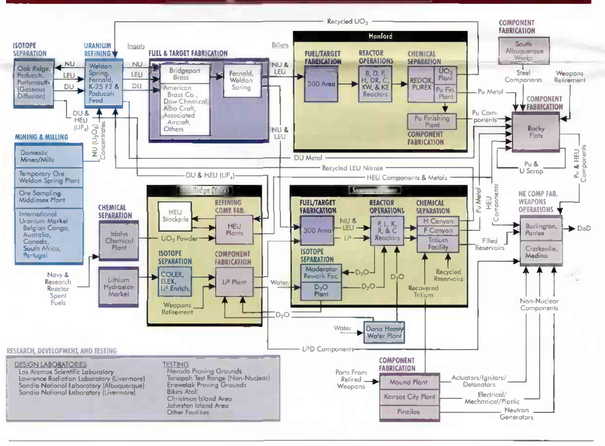
Atomic Energy Commission - Mid 1940's to Mid 1950's



* NOT SHOWN: Hanford reactors started using some LEU fuel from the Gaseous Diffusion Plants, possibly as early as 1950.

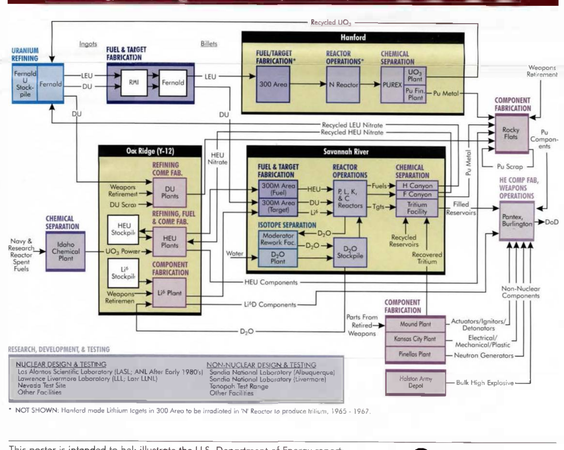
** NOT SHOWN: Hanford 300 Area manufactured Lithium (1949-1952) and Bismuth (1949- early 1950's) Targets.

Atomic Energy Commission - Mid 1950's to Mid 1960's



* NOT SHOWN: Hanford made Lithium Isotopes in 300 Area to be irradiated in 'N' Reactor to produce tritium, 1965 - 1967.

Atomic Energy Comm., Energy Research & Development Admin., & DOE - Mid 1960's to Late 1980's



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This poster is intended to help illustrate the U.S. Department of Energy report: *"Linking Legacies: Connecting The Cold War Nuclear Weapons Production Processes to their Environmental Consequences,"* DOE/EM #97-2392, January 1997.

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