



**ORAU TEAM
Dose Reconstruction
Project for NIOSH**

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ACRONYMS AND ABBREVIATIONS

AEC	U.S. Atomic Energy Commission
BZA	breathing-zone air
Ci	curie
CSS	chemical stabilization and solidification
CEDE	committed effective dose equivalent
CFR	Code of Federal Regulations
cm	centimeter
DOE	U.S. Department of Energy
EDE	effective dose equivalent
EPA	U.S. Environmental Protection Agency
ft	foot
HEPA	high-efficiency particulate air
hr	hour
kg	kilogram
km	kilometer
L	liter
m	meter
MCW	Mallinckrodt Chemical Works
mg	milligram
mR	milliroentgen
mrem	millirem
NIOSH	National Institute for Occupational Safety and Health
NLO	National Lead Company of Ohio
NPL	National Priorities List
ORAU	Oak Ridge Associated Universities
RI/FS	remedial investigation/feasibility study
SWTP	Site Water Treatment Plant
TNT	trinitrotoluene
TSA	Temporary Storage Area
WSCP	Weldon Spring Chemical Plant
WSP	Weldon Spring Plant
WSQ	Weldon Spring Quarry
WSRP	Weldon Spring Raffinate Pits
WSSRAP	Weldon Spring Site Remedial Action Project

U.S.C. United States Code

yd yard
yr year

2.1 INTRODUCTION

This technical basis document describes the Weldon Spring (WSP) site operations and historical health protection practices by Mallinckrodt Chemical Works (MCW), the site's operator. The information in this document is for the evaluation of internal and external exposures to unmonitored and monitored workers, and dose reconstructors can use this information as a supplement to individual monitoring data.

Technical Basis Documents and Site Profile Documents are general working documents that provide guidance concerning the preparation of dose reconstructions at particular sites or categories of sites. They will be revised in the event additional relevant information is obtained about the affected site(s). These documents may be used to assist the National Institute for Occupational Safety and Health (NIOSH) in the completion of the individual work required for each dose reconstruction.

In this document the word "facility" is used as a general term for an area, building, or group of buildings that served a specific purpose at a site. It does not necessarily connote an "atomic weapons employer facility" or a "Department of Energy facility" as defined in the Energy Employees Occupational Illness Compensation Program Act of 2000 [42 U.S.C. Sections 7384l(5) and (12)]. This document supports the evaluation of worker dose from WSP operations and processes. OCAS-IG-001, *External Dose Reconstruction Implementation Guideline* (NIOSH 2002a), and OCAS-IG-002, *Internal Dose Reconstruction Implementation Guideline* (NIOSH 2002b), provide additional guidance on these processes.

WSP operations played an important role in the U.S. development of nuclear power and nuclear weapons. Operations focused on processing of uranium and thorium from feed stocks to metal and other intermediate products for use at other facilities. The purpose of this TBD is to provide information on WSP facilities and operations critical to evaluation of the total occupational dose. This TBD also describes nuclear materials of potential concern.

2.2 SITE ACTIVITIES AND PROCESSES

2.2.1 Site Location and History

The 220-acre Weldon Spring Chemical Plant (WSCP) site is about 2 miles southwest of the community of Weldon Spring and the junction of Missouri State Route 94 and U.S. Highway 40/61 (Figure 2-1). The site contained 44 buildings and support structures as well as remnants of a railroad system, four raffinate pits, and two small ponds. An 8.7-acre limestone quarry, used in part to deposit radioactive wastes from the WSCP, is part of the WSP site, although it is about 4 miles southwest of the plant. Figure 2-2 shows the WSCP and raffinate pits.

In April 1941, the U.S. Department of the Army acquired 17,232 acres surrounding what is now the WSCP as the site for an explosives production facility known as the Weldon Spring Ordnance Works. From November 1941 to January 1944, the Atlas Powder Company operated the Ordnance Works for the Army to produce trinitrotoluene (TNT) and dinitrotoluene explosives. The Ordnance Works began operating again in 1945 but was closed and declared surplus in April 1946. By 1949, all but about 2,000 acres had been transferred to the state of Missouri and the University of Missouri.

In 1956, approximately 220 acres of the former Ordnance Works were transferred to the U.S. Atomic Energy Commission (AEC) for construction and operation of a Feed Materials Plant to process uranium and thorium ore concentrates, which operated from 1957 through 1966 (U.S. Army 1976). Construction was completed in February of 1957; the date of initial operation was June of 1957 (MCW

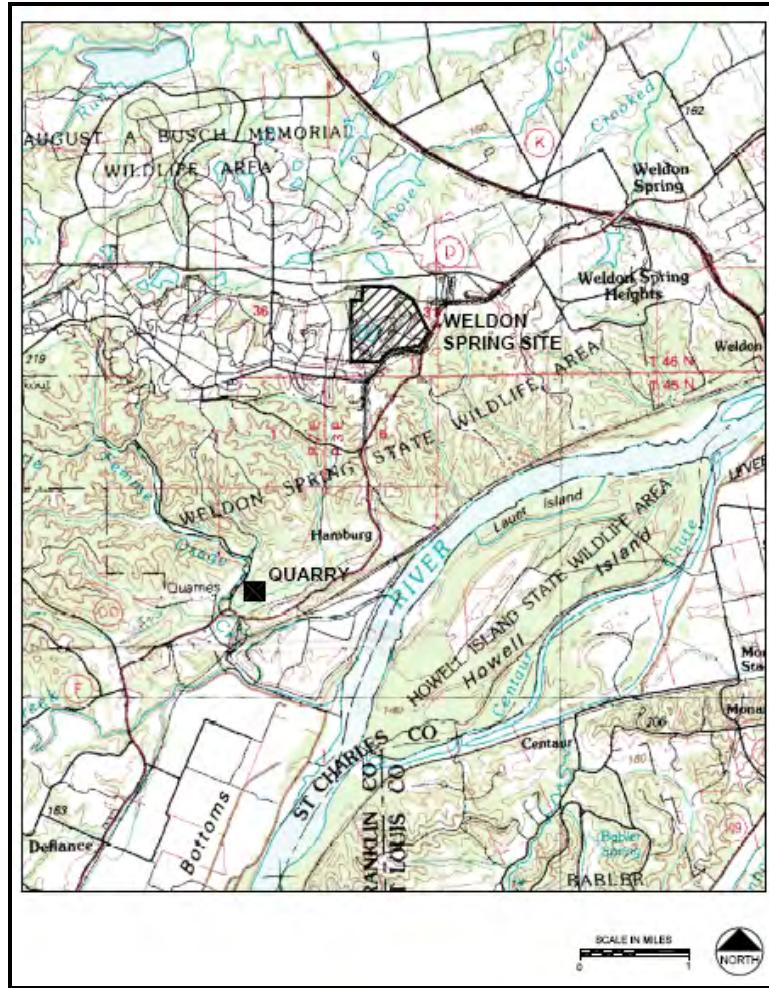


Figure 2-1. Weldon Spring Plant location.

1957). Nuclear materials in the form of natural uranium concentrates were being stored at the site prior to the start of operations, but "since they were not processed, they did not engender operational losses" (DOE 1986a). Thus, it is reasonable to assume exposures prior to operational startup were negligible. This is the WSCP referred to in this document. The raffinate pits were originally part of the WSCP, but are referred to separately in this document as the Weldon Spring Raffinate Pits (WSRP) because they were managed separately from the other area of the WSCP in the post-operational period. In 1958, a 9-acre quarry site was transferred to the AEC, which is referred to as the Weldon Spring Quarry (WSQ) in the following discussion.

In August 1967, the WSCP was returned to U.S. Army control for construction of an herbicide production facility (U.S. Army 1976), but the AEC retained custody of the WSQ and the WSRP. Decontamination of the transferred WSCP facilities was attempted between 1968 and 1970, but abandoned because of cost. The U.S. Department of Energy (DOE) gained responsibility for the WSCP in 1985 and began site characterization and remediation in 1985. The quarry was placed on the U.S. Environmental Protection Agency's (EPA) National Priorities List (NPL) in 1987, and the listing was expanded to include the WSCP and associated waste storage areas in 1989.

2.2.2 Site Development and Operations

Before remediation, four periods of WSP site history can be identified:

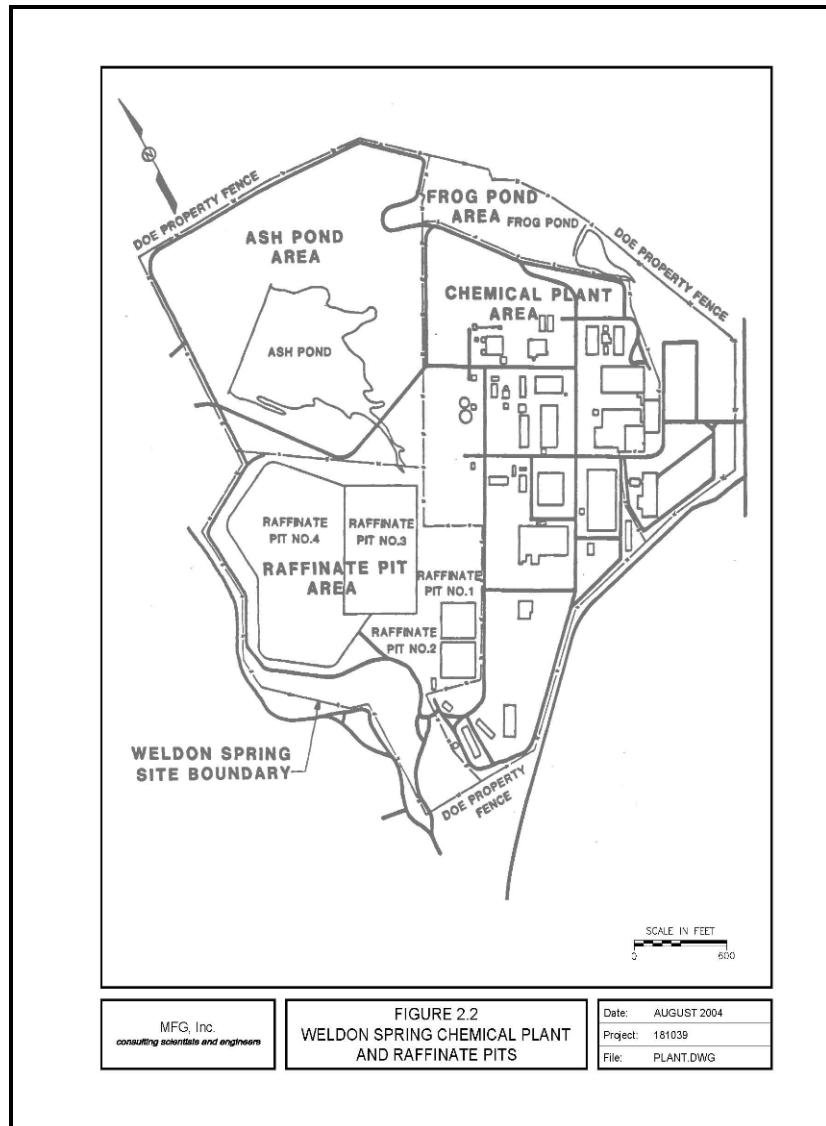


Figure 2-2. Weldon Spring Plant site (adapted from several documents).

- Plant acquisition and development (1954 to 1957)
- Operations (1957 to 1967)
- Department of Defense Control (1967 to 1985)
- Monitoring and Maintenance (1975 to 1985).

The following sections provide more detailed descriptions of these activities. These descriptions are summarized from U.S. Army (1976) and Meshkov et al. (1986) unless otherwise noted.

2.2.2.1 Site Acquisition and Development (1954 to 1957)

In August 1956 Congress officially approved transfer of 205 acres of the former Ordnance Works property from the Army to AEC. An additional 15 acres were later transferred to the AEC for expansion of waste storage capacity. The AEC began designing a feed materials plant in 1954 and constructed the plant now referred to as the WSCP in 1956 and 1957 on this property for processing

uranium and thorium feed stocks into metal and intermediate products. This facility replaced a more limited plant of similar operational capability in St. Louis (on Destrahan Street). The WSP facility was initially designed specifically to process uranium mill concentrates (yellow cake) produced elsewhere in the United States and Canada. These materials were shipped to the WSP site for sampling to determine payment. Fractions of the total mill concentrates were processed through chemical treatment operations. Other fractions, after sampling, were shipped to other DOE facilities for further processing.

2.2.2.2 Plant Operations (1957 to 1967)

The WSCP was operated for AEC by the Uranium Division of MCW from 1957 to 1966. The WSCP processed materials from June 1957 to December 1966. Shutdown procedures were completed in 1967. DOE (2000a) estimated the employment at the site for the Uranium Division at about 600 employees, of whom about 300 would have handled the materials. Four types of nuclear material were processed in the DOE-owned WSCP: natural uranium, depleted uranium, slightly enriched uranium, and natural thorium (DOE 1986a). The following paragraphs describe the use of these materials at the WSCP.

Natural Uranium: Natural uranium was received as continental ore concentrates that were refined to extract the uranium, after which the uranium was converted to various compounds and metal forms and shipped off the site. Processing of natural uranium was a continuous operation during the life of the plant.

Depleted Uranium: Uranium depleted in ^{235}U isotope below its natural isotopic abundance ratio was received and processed on an intermittent basis. This form of uranium was used primarily in product development activities and flow-sheet improvements. Use was confined primarily to pilot plant activities.

Slightly Enriched Uranium: Uranium enriched to 1% or less ^{235}U by weight was also received and processed on an intermittent basis. This type of uranium was typically received in the form of scrap metal or residues. The uranium contents were recovered, processed to various chemical forms, and shipped off the site. The coefficient of variation about the values assigned to all flows of this type of material was slightly greater than that for natural uranium, primarily because of the heterogeneous nature of receipts.

Natural Thorium: Natural thorium was typically received in either a nitrate or an oxide form and processed on an intermittent batch basis in the refinery and oxide production/firing systems. Only a limited area of the WSCP (refinery and pilot plants) was exposed to the material. In addition, Dupree (1979) stated that approximately 3.6×10^5 kg (400 tons) of "impure thorium nitrate and enriched uranium" were processed starting in 1965. MCW (1966) summarized operations with thorium as shown in Table 2-1.

An average of 1.2×10^7 kg (1.4×10^4 tons) of uranium-containing material was processed per year (DOE 1986a). Natural uranium processing accounted for more than 97% of the nuclear materials throughput. Total material balance closures (i.e., percent of material accounted for) for natural uranium, depleted uranium, and slightly enriched uranium for the 10 yr of plant operations were 99.94%, essentially 100%, and 99.27%, respectively. An average of 3.1×10^5 kg (350 tons) of natural thorium was processed per year during 1964 through 1966, with an associated total material balance closure of 98.52%.

Table 2-1. Chronological summary of thorium operations.

Operation title	Building	1963	1964	1965	1966
TNT crystal repackaging	403	Nov-Dec	May-Sep		
	301		Oct-Dec		
Denitration of TNT crystals & sol drying-hand unloading	103	Nov-Dec	May-Aug		
Denitration of TNT crystals & sol drying-vacuum uploading	103		Sep-Dec		
Denitration of TNT liquor & sol drying-vacuum uploading	103			Jan-Jul	
Denitration by fluid bed-product packaged in drums	403			May-Jul	
Denitration by fluid bed-liquor feed & sol product	403			Aug-Dec	Jan; Jun-Sep
Denitration of TNT liquor-scoop & pail transfer to sol tank	103			Oct-Nov	
Sol drying-vacuum uploading	103			Aug-Dec	Jan; Jun-Sep
Th ₂ high firing-recast furnace	301	Nov-Dec	May-Sep		
Th ₂ high firing-billet heaters	301		Oct-Dec	Jan-Dec	Jan; Jun-Sep
Th ₂ product packaging	403	Nov-Dec	May-Jul; Sep-Dec	Jan-Sep	
	103		Aug		
	301			Oct-Dec	Jan; Jun-Sep
Rotary kiln calcining of sump cake	301				Apr-Jul
Digest feed repackaging	101				Apr-Aug
Scrap digestion & raffinate disposal	103				May-Sep
Extraction	105				Jun-Sep

The WSCP's main activity was to convert uranium concentrate to uranium trioxide (UO₃), uranium tetrafluoride (UF₄), and uranium metal. The material received at the plant was yellowcake (uranium concentrate). Figure 2-3 shows a schematic diagram of a wet solvent extraction method used for UF₄ production. Before entering the refinery, the ore concentrate underwent a sampling and preparation process in the sampling plant. Table 2-2 lists the WSCP buildings and the activities that took place in them (MCW 1962, 1964; Meshkov et al. 1986).

Building 101 was the sampling building. Ore concentrate of about 60% to 70% uranium content arrived in drums. Concentrate in opened drums was sampled using one of the two sampling methods—auger or mechanical sampling—and the drums were emptied into hoppers at the top of the building. From the hoppers, material was transferred to portable hoppers for transfer to the refinery (Figure 2-4). Yellowcake dust was collected in three large dust collectors, each with its own stack. Some yellowcake was repackaged in drums and shipped out; the rest was put into hoppers and moved to Building 103 for digestion. The dust collection system was vacuum cleaned from time to time, and the collected dust was reprocessed. Uranium dust was washed off the drums, equipment, and floors, and this dust was also reprocessed.

UO₃ (sometimes known as orange oxide) was produced, or refined, in three steps: Digestion, purification by solvent extraction, and denitration (Figure 2-5). Building 103 was the first building of the refinery plant. Concentrate was brought in hoppers to the top of the building where there was one dust collector with one stack to collect yellowcake dust. The concentrate was heated and digested with nitric acid to produce a solution of uranyl nitrate. The digested material was passed to Building 105 in liquid form where pure uranyl nitrate solution was extracted and remained in liquid form. The highly purified uranyl nitrate solution was evaporated and pumped to gas-fired denitration pots in Building 103 where the remaining water was removed, producing pure UO₃. According to Meshkov (1986), this was the dustiest part of the process. Impurities generated in the purification process were bled off in the raffinate, which was pumped to pits. This raffinate contained a conglomerate of radionuclides including thorium and radium in small concentrations.

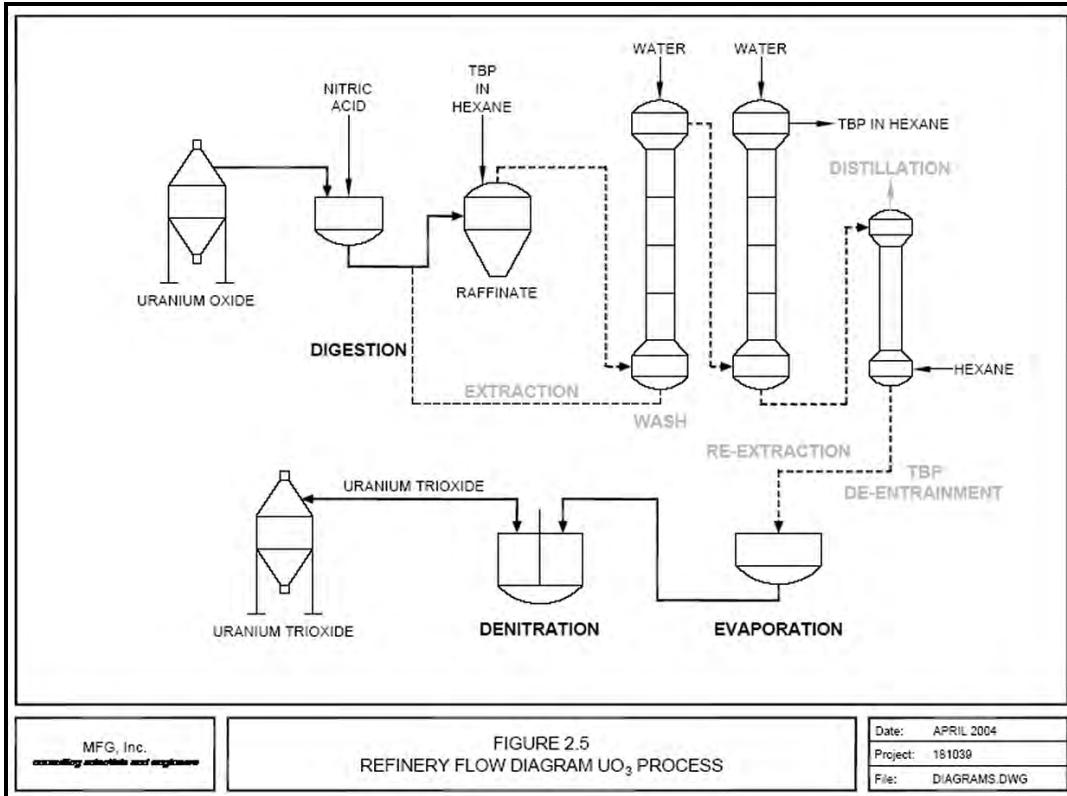


Figure 2-3. Wet solvent extraction of uranium (adapted from US Army 1976).

Table 2-2. Description of WSP buildings.^a

Building	Description	Dates	Operations performed
101	Sampling Plant	Jun 1957–1966	Preparation and sampling building designed to process approximately 75 tons of low-assay uranium ore concentrates per day. Housed equipment and facilities for drying, grinding, screening, blending, and sampling of ore concentrates and process residues. Incoming ore concentrates and residues were stored in drums on concrete pad.
Area 102 A&B	Refinery Tank Farm	Jun 1957–1966	Provided facilities for unloading, storing, and transferring liquid process material required in the refinery operation and were supplied or handled in tank-car and tank-truck quantities.
103	Digestion and Denitration	1957–1966	Originally the nitrating, denitrating, and raffinate processing and storage area. <ul style="list-style-type: none"> The northern digestion section received uranium ore concentrates that were digestion and transferred as a slurry to Building 105 where the solvent was purified by extraction. The middle denitration section received the purified uranium nitrate solution, which was denitrated to yield uranium nitrate solution, which was further denitrated to yield UO₃. During later years, thorium products were also processed in this building.
104	Lime Storage		Facility for storing lime.
105	Extraction	Feb 1957–1966	Purification building. Previously used for producing a highly purified uranyl nitrate hexahydrate (UNH) solution by means of extraction columns, process vessels, evaporators, and tributyl phosphate and hexane reaction tanks.

Table 2-2 (Continued). Description of WSP buildings.^a

Building	Description	Dates	Operations performed
106	Refinery sewer sampling		Used as a sampling station for process waste streams.
108	Nitric acid plant	1957–1966	Used for recovering and reconcentrating nitric acid and oxides of nitrogen.
109, 110	West Drum Storage, East Drum Storage		Used to store drums containing ore concentrates and process residues.
201	Green Salt Building	Feb 1958–1966	Used for converting UO ₃ to UO ₂ and UF ₄ .
202 A&B	Green Salt Tank Farm	1957–1966	Used for tank car unloading and storage of hydrofluoric acid (HF) and ammonia.
301	Metals Building	Apr 1958–1966	Used for converting UF ₄ to uranium metal.
302	Magnesium Building	1957–1966	Powdered magnesium handling building used for storage of magnesium.
Pad 303			Served as a material storage pad.
401	Steam Plant	1956–1966	Steam-generating plant including coal conveyor and coal yard.
403	Chemical Pilot Plant	1957–??	Demonstration of pilot operations.
404	Metallurgical Pilot Plant	1957–??	Provided facilities for metal processing studies, ceramic work, and metal testing; housed metallurgical pilot plant.
405A & B	Pilot Plant Maintenance	1957	Building 405A was a small shop and storage building spare pilot plant equipment storage. The dust collectors and vacuum cleaning system for Buildings 403 and 404 were on Pad 405B.
406	Warehouse	1956	Served as a warehouse and office area.
407	Laboratory	1957	Used as an analytical chemistry laboratory.
408	Maintenance and Stores	1956	Contained numerous maintenance shops, office area, garage, receiving and shipping area, decontamination room, and a large storage area.
409	Administration	1957	Contained offices for administrative staff.
410	Services Building	1957	Contained the main gate, administrative offices, plant security office, health and safety office, kitchen, dining room, laundry facility for contaminated clothing, and clean and contaminated locker rooms with shower facilities.
412	Electrical Substation		Substation for electrical supply.
413	Cooling Tower and Pump House		Water-cooling tower and pump house
414	Salvage Building	1956	Served as a salvage shop and equipment storage space.
415	Process Incinerator		Incinerator for process materials.
417	Paint Shop	??	Served as the paint shop.
426	Water Tower		Used for water storage (elevated water storage tank).
427	Primary Sewage Treatment Plant		Served as the primary sewage treatment plant for the site.
428	Fuel Gas Plant		Storage facility for fuel gas.
429	Water Reserve Facilities		Water storage (pump house and ground storage tank). Also noted to have been a propane gas storage facility.
430	Ambulance Garage		Used as an ambulance garage.
431	Laboratory Sewer Sampler		Used as a sampling station for process waste streams.
432	Main Sewer Sampler		Used as a sampling station for process waste streams.
433	Garage		Large equipment garage area.
434	Storage		Ore concentrate storage building.
435	Storage		Salvageable equipment storage.
436	Storage		Salvageable equipment storage.
437	Records Retention Building		Facility used for storage and retention of records.
438	Storage		Salvageable equipment storage.
439, 443	Fire Training and Storage Building		Facility used for fire training purposes and storage.
441	Cylinder Storage		Facility used for storage of UF ₆ cylinders.

a. Adapted from U.S. Army (1976).

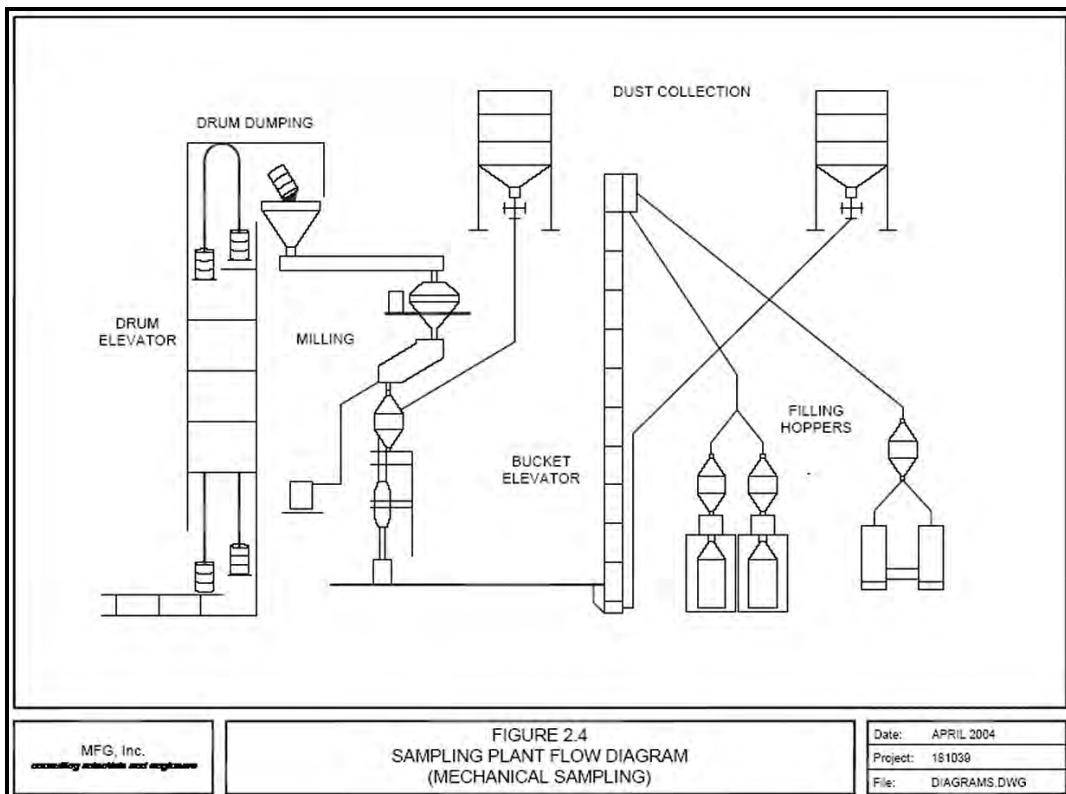


Figure 2-4. Sampling plant flow diagram (adapted from US Army 1976).

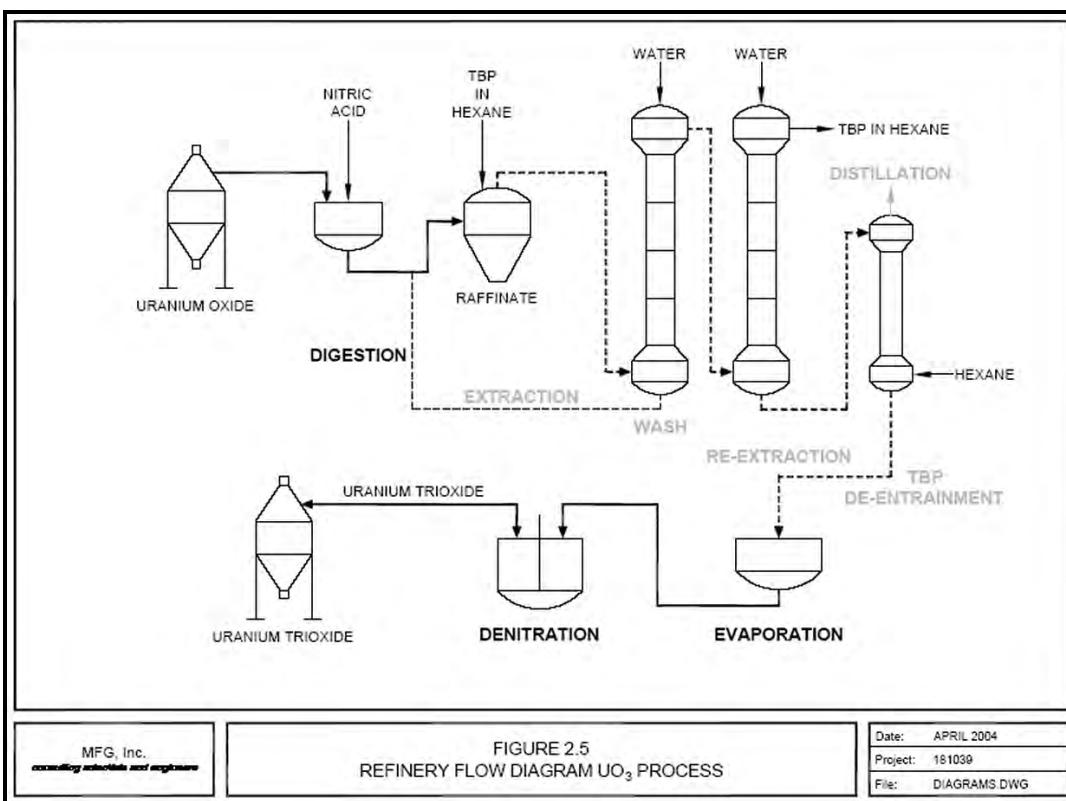


Figure 2-5. Digestion, purification, and denitration (adapted from US Army 1976).

UO_3 was packaged into transfer hoppers and transferred from Building 103 to the top of Building 201, the green salt (UF_4) plant. Figure 2-6 shows the reduction and hydrofluorination process used to produce UF_4 . Hydrogen gas reduced UO_3 to uranium dioxide (UO_2).

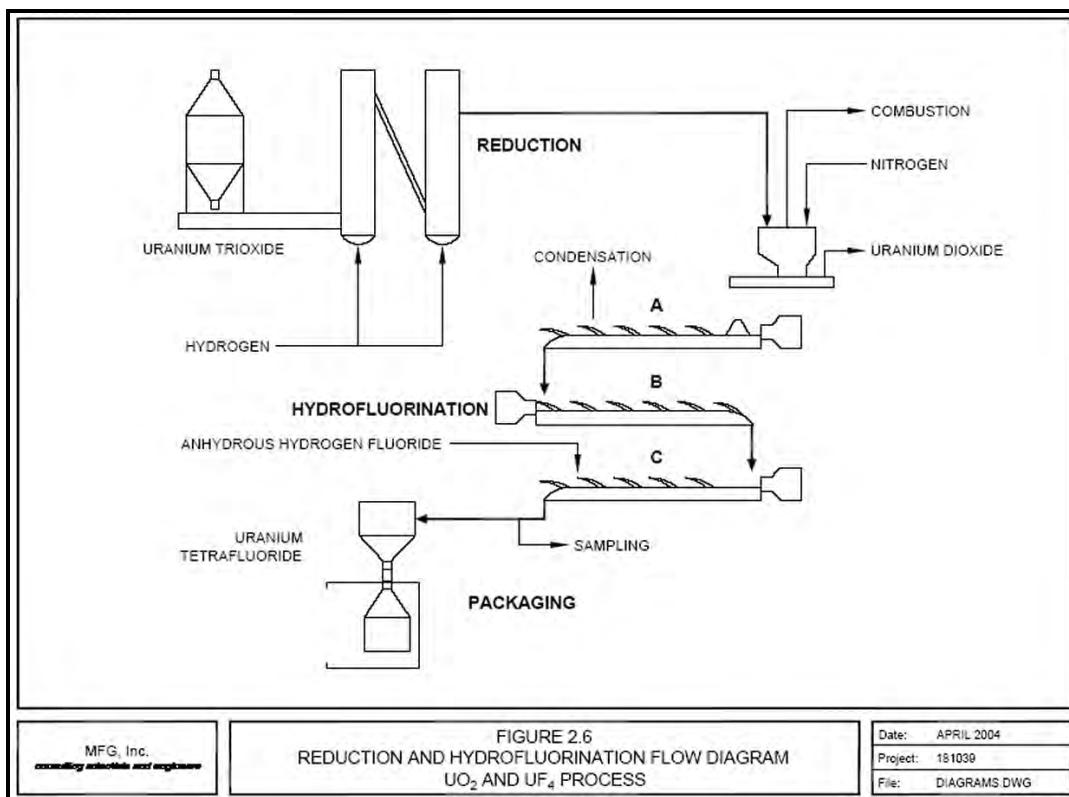


Figure 2-6. Reduction and hydrofluorination process (adapted from US Army 1976).

The next step was hydrofluorination, in which UO_2 was transformed to UF_4 or green salt. Excess hydrogen fluoride (HF) gas from the process was filtered through carbon filters to recover uranium, which was recycled to black oxide (U_3O_8). Discharge from the UF_4 reactor system was mechanically collected, crushed, and blended to obtain desired particle sizes. There were two additional dust collectors on the roof of Building 201 associated with the system to collect UF_4 dust, and there was a reverter in the building to convert UF_4 into U_3O_8 .

Green salt was packaged in transfer hoppers and moved to Building 301, the metals plant. Magnesium was used to convert UF_4 to solid uranium metal in a multistep process. Figure 2-7 depicts this process. The reaction occurred in refractory-lined steel "bomb" shells, which were charged with a mixture of green salt and magnesium chips. Green salt and magnesium were mixed in a blender; the mixture was then placed in individual steel shells at the filling machine and sent to the furnaces for firing. Within the furnace, the shell was heated to about 500°F and the charge was ignited electrically. Once ignited, the reaction proceeded spontaneously. Complete shells were moved to an outdoor cooling pad for about 3 days. The process generated green salt dust. UF_4 and magnesium fluoride (MgF_2), with 1% to 2% of residual uranium in various forms, were discharged from several dust collectors at the ground level on the south side of the building. A rotary kiln in Building 301 calcined uranium metal chips to convert them to U_3O_8 . One standard dust collector was used for the dusty discharge, mostly U_3O_8 , produced in this operation.

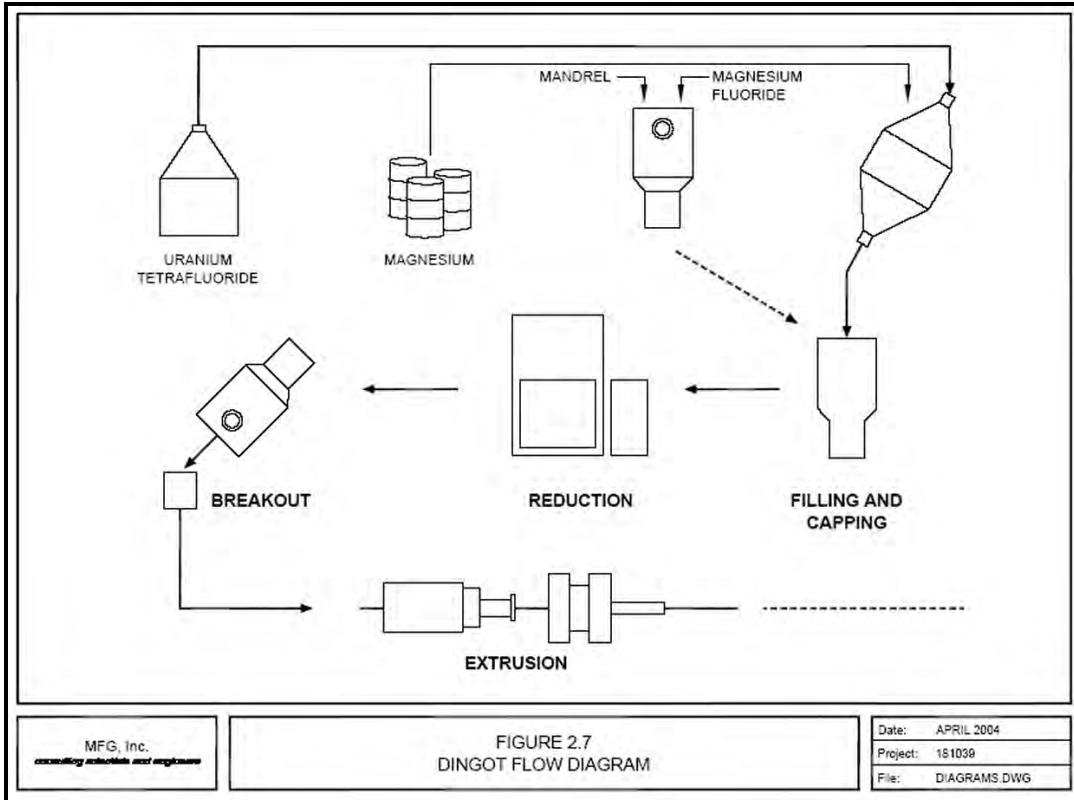


Figure 2-7. UF_6 conversion to uranium metal (adapted from US Army 1976).

Uranium fuel cores were produced in Building 301. Uranium billets were extruded to rods of suitable size to produce cores for use in reactors. The rods were straightened, cut to lengths, heat treated, degassed, machined, inspected and shipped. Rods or tubes approximately 22 ft long were straightened and fed to a six-spindle automatic machine, which turned off a thin layer of material from the outside diameter and sectioned them into about 8.5-inch lengths. The rough cores were then treated at 950°F in a vacuum furnace to remove hydrogen gas from the metal. Degassed cores were heat treated in molten salt at 1,350°F and quenched in water at 130°F to randomize the grain structure. Cores were further machined to remove the warp and oxide layer that resulted from heat treatment and degassing. Holes were drilled in the solid core, and it was reamed to final size. Good cores were inspected in an ultrasonic machine to ensure that the grain structure was neither too small nor too large. A dimensional inspection was performed to ensure that specifications were met. All acceptable cores were packaged in boxes and shipped by rail directly to reactor sites.

The Analytical and Research Laboratories were housed in Building 407. The Analytical Laboratory had four sections. The Production Section had laboratories for process control, uranium accountability, sampling, and specifications testing. The Spectrographic Section measured impurities in raw materials and in finished products. The Method Development Section provided analytical procedures for the laboratory. Equipment included infrared and ultraviolet spectrophotometers, vapor phase chromatograph, X-ray spectrometer, ultra-high-vacuum equipment, an isotope ratio mass spectrometer, and a time-of-flight mass spectrometer. The Special Analysis Section performed analytical work for the research laboratory and pilot plants in addition to running production and uranium inventory samples.

The Research Laboratory consisted of three sections. The Dry Chemistry Section was concerned with problems in fluoride chemistry and with metallurgical studies. The Wet Chemistry Section

worked on such studies as the digestion and extraction of raw material feeds, solvent quality, uranyl nitrate purity, and nitric acid recovery. The Instrumental Techniques Section used a wide variety of optical equipment: X-ray diffraction equipment for qualitative and quantitative analysis, and electron and optical microscopes for particle-size distribution studies, identification of minerals, and studies of physical properties.

Buildings 403 and 404 housed the Chemical and Metallurgical Pilot Plants, respectively. The chemical and metallurgical pilot plants had development facilities on a scale intermediate between the laboratory and the plant. After new processes and equipment were demonstrated on a small scale in the laboratory, they were investigated further in the pilot plants. Research was performed on the design, installation, and operation of an integrated fluid-bed system for producing uranium trioxide, uranium dioxide, and green salt. Also studied in the chemical pilot plant was a process for the simultaneous denitration of uranyl nitrate and reduction of UO₃. The metallurgical pilot plant was equipped for large-scale development of the bomb-reduction step of the process.

Table 2-3 lists job titles and locations for the plant during its operational phase. These were taken from an anonymous list that accompanied a memorandum (Dupree 1979) written to describe a visit by Mont Mason to Oak Ridge. The notes were presumed to have been made by Mason, who was head of Health and Safety for Mallinckrodt for a number of years.

Table 2-3. Partial list of job titles and locations during operational phase.

Job title	Job type	Job location or building*
103 DX men	Porter	Refinery – Digestion and Denitration (103)
105 DX men	Porter	Refinery - Extraction (105)
201 DX men	Porter	Green Salt Plant (201)
201 Production Office porter	Porter	Green Salt Plant (201)
301 DX men	Porter	Metals Building (301)
408 porter	Porter	Maintenance (408)
Accountability Lab	Technical	Analytical Laboratory (407)
Assistant foreman	Supervisory	Stores (408)
Assistant Superintendent	Supervisory	Green Salt Plant (201)
Auxiliary dissolving Operator	Operator	Refinery – Digestion and Denitration (103)
Blending Operator	Operator	Metals Building (301) – Conversion
Bomb Cooling Operator	Operator	Metals Building (301) – Conversion
Bomb Unloading Operator	Operator	Metals Building (301) – Conversion
Capping & Tamping Operator	Operator	Metals Building (301) - Conversion
Carpenter	Carpenter	Maintenance Department (408)
Casting Operator	Operator	Metallurgical Pilot Plant (404)
Ceramics Operator	Operator	Metallurgical Pilot Plant (404)
Clerical and Steno	Clerical	Stores (408)
Clerical and Steno	Clerical	Production Control office
Control	Technical	Analytical Laboratory (407?)
Decontamination room DX	Porter	Various process buildings?
Digester Operator	Operator	Refinery – Digestion and Denitration (103)
Dingot Chipping Operator	Operator	Metals Building (301) – Conversion
Dishwasher	Labor	Analytical Laboratory (407?)
Draftsmen	Draftsmen	Engineering
Electrician	Electrician	Maintenance Department
Employee Benefits officer	Clerical	Industrial Relations
Engineer	Engineer	Maintenance Department (408)
Engineer	Engineer	Engineering
Extrusion Press Operator	Operator	Metals Building (301) – Fabrication and Extrusion
Feed Operator	Operator	Refinery – Digestion and Denitration (103)
Filling Operator	Operator	Metals Building (301) – Conversion
Fluoride Chemistry technician	Technical	Research Laboratory
Foreman	Supervisory	Stores (408)

Table 2-3 (Continued). Partial list of job titles and locations during operational phase.

Job title	Job type	Job location or building*
Foreman	Supervisory	Warehouse (406)
Foreman	Supervisory	Sampling Plant (101)
Foreman	Supervisory	Maintenance Department (408)
Foreman	Supervisory	Metallurgical Pilot Plant (404)
Foreman	Supervisory	Wet (Chemical?) Pilot Plant (403)
Forge Press Operator	Operator	Metallurgical Pilot Plant (404)
Furnace and Saw Operator	Operator	Metallurgical Pilot Plant (404)
Furnace Operator	Operator	Green Salt Plant (201)
Furnace Operator	Operator	Metals Building (301) – Conversion
General foreman	Supervisory	Refinery (103-105)
General Foreman	Supervisory	Green Salt Plant (201)
General Foreman	Supervisory	Metals Building (301)
General Foreman	Supervisory	Maintenance Department (408)
General Labor	Labor	Boiler House (401)
General Labor	Labor	Water Plant (429?)
General Office	Clerical	Health Department (410)
General Office	Clerical	Industrial Engineering
General Office	Clerical	Engineering
General Office	Clerical	Industrial Relations
General Office	Clerical	Safety and Fire
General Office	Clerical	Accounting
General Office	Clerical	Purchasing
General Office	Clerical	Administrative Services (409)
General Office	Clerical	Payroll (409?)
General Office	Clerical	Tabulating Office
General Office	Clerical	Research Laboratory (407?)
General Office	Clerical	Production Technical Department
Guard	Plant protection	Plant Wide
Guard Captain	Plant protection	Plant Wide
Guard Lieutenant	Plant protection	Plant Wide
HF Operator	Operator	Green Salt Plant (201)
Industrial Hygiene	Industrial Hygiene	Health Department (410)
Inspectors	Inspector	Safety and Fire
Jolter Operator	Operator	Metals Building (301) – Conversion
Laborer	Laborer	Maintenance Department (408)
Lathe Operator	Operator	Metals Building (301) – Fabrication and Extrusion
Lead Operator	Operator	Metallurgical Pilot Plant (404)
Lid Chipping Operator	Operator	Metals Building (301) – Conversion
Locker room porters	Porter	Services Building (410?)
Machine maintenance	Laborer	Maintenance Department (408)
Magnesium Building Operator	Operator	Metals Building (301) - Conversion
Maintenance Clerks	Clerical	Maintenance Department (408)
Messenger	Messenger	Administrative Services
Metallurgical technician	Technical	Research Laboratory
Methods Development	Technical	Analytical Laboratory
Misc. digestion Operator	Operator	Refinery – Digestion and Denitration (103)
Motor and equipment Tagger	Labor	Accounting (409?)
Nitric Acid Operator	Operator	Refinery – Digestion and Denitration (103)
NOK Operator	Operator	Refinery – Nitric Acid in Hexane (NAH)
Office and Steno	Clerical	Analytical Laboratory (407)
Oiler	Laborer	Maintenance Department (408)
Operator	Operator	Wet (Chemical?) Pilot Plant (403)
Operators	Operator	Sampling Plant (101)
Packaging Operator	Operator	Refinery – Digestion and Denitration (103)
Packaging Operator	Operator	Green Salt Plant (201)
Painter	Painter	Maintenance Department (408)
Pipe Maintenance	Laborer	Maintenance Department (408)

Table 2-3 (Continued). Partial list of job titles and locations during operational phase.

Job title	Job type	Job location or building*
Plant Porter	Porter	Plant-wide
Pot room Operator	Operator	Refinery – Digestion and Denitration (103)
Production Clerk	Clerical	Sampling Plant (101)
Production Clerk	Clerical	Refinery (103-105)
Production Clerk	Clerical	Green Salt Plant (201)
Production Clerk	Clerical	Metals Building (301)
Production Machinist	Operator	Metallurgical Pilot Plant (404)
Production Operator	Operator	Metallurgical Pilot Plant (404)
Pulse column Operator	Operator	Refinery (105/108)– Nitric Acid in Hexane (NAH)
Pumper decanter Operator	Operator	Refinery (105/108)– Nitric Acid in Hexane (NAH)
Raffinate Operator	Operator	Refinery (103) – Digestion and Denitration
Recovery Operator	Operator	Refinery (103) – Digestion and Denitration
Residue Operator	Operator	Metallurgical Pilot Plant (404)
Rigger	Rigger	Maintenance Department (408)
Sampling plant DX men	Porter	Sample plant
Saw Operator	Operator	Metals Building (301) – Fabrication and Extrusion
Shift assistant foreman	Supervisory	Refinery
Shift foreman	Supervisory	Refinery
Shift Foreman	Supervisory	Green Salt Plant – 201
Shift Foreman	Supervisory	Metals Building (301)
Shift Foreman	Supervisory	Metallurgical Pilot Plant (404)
Shift Foreman	Supervisory	Wet (Chemical?) Pilot Plant (403)
Slag Building Operator	Operator	Metals Building (301) – Conversion
Special analysis	Technical	Analytical Laboratory
Special techniques technician	Technical	Research Laboratory
Specification testing	Technical	Analytical Laboratory
Spectrographic	Technical	Analytical Laboratory
Stenographer	Clerical	Maintenance Department (408)
Storekeeper	Stores	Stores (408)
Stripper Operator	Operator	Refinery (105/108)– Nitric Acid in Hexane (NAH)
Sump Operator	Operator	Metals Building (301) – Fabrication and Extrusion
Superintendent	Supervisory	Refinery (103-105)
Superintendent	Supervisory	Metals Building (301)
Superintendent	Supervisory	Maintenance Department (408)
Superintendent	Supervisory	Production Technical Department
Supervisor	Supervisory	Production Control office
Technical	Technical	Metallurgical Pilot Plant (404)
Technical	Technical	Wet (Chemical?) Pilot Plant (403)
Technical Services Staff	Technical	Production Technical Department - Sampling Plant (101)
Technical Services Staff	Technical	Production Technical Department – Refinery
Technical Services Staff	Technical	Production Technical Department -Green Salt Plant – 201
Technical Services Staff	Technical	Production Technical Department – Metals Building (301)
Tinner	Laborer	Maintenance Department (408)
Utility Operator	Operator	Green Salt Plant (201)
Vacuum techniques technician	Technical	Research Laboratory (407)
Warehouse Yard Operator	Operator	Sampling Plant (101)
Warehouse Yard Operator	Operator	Refinery (103-105)
Warehouse Yard Operator	Operator	Green Salt Plant – 201
Warehouse Yard Operator	Operator	Metals Building (301)
Warehouse Yard Operator	Operator	Various
Welder	Welder	Maintenance Department (408)
Wet chemistry technician	Technical	Research Laboratory (407)

* A question mark denotes disagreement in the various documents that describe jobs or locations.

Table 2-4 provides a partial history of cost center designations from MCW (1966) that could be useful in understanding job types or classifications. However, these designations are not suggested for cross-referencing job titles and locations with time or dosimetry card entries. An October 25, 1983,

memorandum from Dupree to the MCW file of the Oak Ridge Associated Universities (ORAU) worker epidemiology study reported on a trip to MCW (Dupree 1983). Item five of that memorandum states, "Beginning in 1954 the [cost center] codes changed about once every 6 months. Documentation of changes was made only to the extent that was necessary to obtain the money for the UD [Uranium Division] operations from the government." Assuming that the practice continued into the WSP operations of 1956 and beyond, using cost center codes to help assess worker dose may not be reliable.

Table 2-4. Partial cost center history cross-referenced with work groups.

Work group		Cost center name	Cost center code numbers							
Title	Group unit no.		11/59 & 4/60	7/60	7/61	7/62	7/63	7/64	1965	1966
Sampling Plant	0402	Sampling	310	310	310	310	110	110	110	110
		Repackaging								
Digest-Raffinate	0501	Refinery	321	321	321	321				
Extraction	0503		320	320	320	320	120	120	120	120
Pot Room (Denitration)	0502		320	320	320	320	120	120	120	120
Green Salt Plant	0401	Green Salt	320	320	320	320	120	120	120	120
Dingot Production	0701	Dingot Reduction	330	330	330	330	150	150	150	150
Dingot Machining	0702	Extrusion General	360	360	360	340	180	180	180	180
							200			
301-Other than Dingot Production	0702	Extrusion General						200	200	200
Extrusion		Extrusion General					359			
Extrusion, Recast, Kiln	0703	Gamma Extrusion (Dingot Extrusion)	361	361	361	351	210			
	0703	Alpha Extrusion (Dingot Conversion to Rods)				364	352	220		
Core Area	0703	Metal Plant Scrap Activity					358	280		
		Vacuum Outgassing			363	363				
	0704	Core Fabrication	362	362	362	366	250			
					365	367				
					366	368				
						369				
Building 403		Chemical Process Development	420	420						
		Development				450	450			
Building 404	0601	Scrap Plant						290	290	290
		Metallurgical Development	410	410						290
	0602	Special Projects				460	460	460	460	460

Table 2-5 lists work groups and units as taken from MCW (1966). The table is not dated; in conjunction with data in Tables 2-2 and 2-3, it is useful in ascertaining the worker's job type.

Table 2-6 lists the buildings that produced most of the air discharges and summarizes the types of discharge and stack heights.

The processing of uranium and thorium generated several chemical and radioactive waste streams, which were piped to the raffinate pits. The solids settled to the bottom of the pits, and the supernatant liquids were decanted to the plant process sewer that drained off the site to the Missouri River. Of the discards (i.e., material known to have been disposed of via plant stacks, sewers, and raffinate pits rather than shipped off the site), approximately 67% of the uranium and essentially all of the thorium went to the raffinate pits (DOE 1986a).

Between 1958 and 1964, four raffinate pits were constructed in the southwest portion of the site to contain process wastes from the plant (NLO 1977). Pits 1 and 2 were constructed in 1958, and were used for almost 2 yr. The design volume of each of these two pits was 14,000 m³ (500,000 ft³).

Table 2-5. Listing of work groups and units.

Group 01	Unit 01	Clean up
	Unit 02	Laundry Operations
	Unit 03	Custodians
Group 02	Unit 01	Storekeepers
	Unit 02	Yard Operators
Group 03	Unit 01	Tool and Die Makers
	Unit 03	Painters
	Unit 04	Carpenters
	Unit 06	Riggers
	Unit 07	Welders
	Unit 18	Tinners
	Unit 12	Millwrights
	Unit 13	Oilers
	Unit 11	Machinists
	Unit 20	Auto Mechanics
	Unit 14	Pipefitters
	Unit 17	Instrument Mechanics

Group 01	Unit 01	Clean up
Group 04	Unit 01	Green Salt Plant
	Unit 02	Sampling Plant
Group 05	Unit 01	Refinery Digest, Etc.
	Unit 02	Pot Room, Etc.
	Unit 03	Extraction in 105
	Unit 04	Water Plant
Group 06	Unit 01	Building 403
	Unit 02	Building 404
Group 07	Unit 01	Dingot Production and Mag
	Unit 02	Dingot Machining
	Unit 03	Extrusion, Recast & Kiln
	Unit 04	Core Area
Group 08	Unit 02	Electricians
Group 09	Unit 01	Boiler House
Group 10	Unit 01	Guards
Group 11	Unit 01	Dishwasher

Table 2-6. Location and height of stacks at the WSCP (Meshkov et al. 1986 Table 3.2).

Building number	Number of stacks	Discharge	Height of stack (meters)
101	2-3	Yellowcake dust	35
103	1	Yellowcake dust	23
	Several	UO_3	
201	6	UO_2 , UF_4 , and U_3O_8	14-34
301	Several	UF_4 and MgF with 1% uranium	23
	1	U_3O_8	

Because of the high production rate, the first two raffinate pits filled rapidly, requiring the construction of the third and, eventually, fourth pit. Pit 3 was constructed and put into use in 1959 with a design volume of $127,000 \text{ m}^3$ ($4.5 \times 10^6 \text{ ft}^3$). Pit 4 was constructed and put into operation in 1964, and its design volume was $340,000 \text{ m}^3$ ($12 \times 10^6 \text{ ft}^3$).

In 1958, AEC acquired the WSQ, which was previously part of the U.S. Army's WS Ordnance Works (Bechtel 1985a). The WSQ was first used for storing radioactive waste in 1959, when an estimated 150 m^3 ($5,400 \text{ ft}^3$) of drummed 3.8%-thorium residues were placed there. In 1963 and 1964, uranium- and radium-contaminated building rubble, equipment, and soils were deposited in the Quarry following demolition of the MCW's Destrehan Street Feed Plant. In 1966, approximately $13,500 \text{ ft}^3$ of drummed and bulk 3%-thorium residues were deposited in the WSQ.

In 1965 and 1966, first pure and then impure thorium oxide was processed, initially on a pilot scale in Buildings 403 and 404 and later on a large scale in Buildings 103, 105, and 301. Wastes were deposited in Raffinate Pit 4.

In early 1966, the AEC decided to close WSCP at the end of the year because more cost-efficient processes made the plant obsolete. The workforce began to decline as employees sought other employment. Decontamination of the buildings and equipment for unrestricted use were not part of the AEC shutdown directive. Under the shutdown procedures, hoppers and process lines were emptied, and dust collectors and other points of material accumulation were cleaned out. All access

ports were used to remove as much of the pure uranium compounds as possible from the production equipment.

2.2.2.3 Department of Defense Control (1967 to 1985)

As noted, the plant was closed at the end of 1966 and shutdown procedures were initiated in 1967. Only a few pounds of pure compounds were present in any single piece of equipment. The bulk of the radiological materials that remained on the site was outside the primary production lines in building sumps and in secondary pieces of process equipment and piping without routine access ports. For a short time after closure, some of the buildings were used for interim storage of drummed yellowcake from other mills. This yellowcake was later shipped to various plants for refining and processing.

AEC returned the WSP facility to the Army in 1967 (DOE 2003) for the purpose of using portions of the feed materials plant for the production of Herbicide Orange to meet needs in Southeast Asia. AEC maintained control of Building 434 (which had been used for the storage of ore concentrates), a 51-acre tract encompassing the four raffinate pits, Building 438, and the WSQ.

The Army selected Buildings 103 and 105 for herbicide production, with blending and packaging to occur adjacent to Building 101. Construction of the herbicide facility began in December 1968 but was terminated when the project was canceled in early 1969. Cleanup and shutdown work was conducted on the site until June 1969. The Army began decontamination and equipment removal in Buildings 103 and 105 in March 1968. About 6,000 yd³ of highly contaminated and unrecoverable material were hauled to the quarry 4 miles south on Highway 94. About 2,400 tons of contaminated scrap was shipped via rail and truck to a Knoxville, Tennessee contractor. Another AEC contractor, National Lead Company of Ohio (NLO), received 20 railcars and one truckload of stainless-steel piping, valves, vessels, and spare parts. Approximately 135 barrels of uranium oxide were recovered from the buildings. A high-pressure hot-water solution containing an acidic wetting agent was used to partially decontaminate Buildings 103 and 105. Portions of some concrete floors were removed and covered with tar and new concrete to mask radiological contamination. In June of 1969, the Kansas City District of the U.S. Army Corps of Engineers obtained custody of the 169-acre tract containing the WSCP. Because the herbicide production program was cancelled in 1969, no major activities took place between 1969 and 1985.

2.2.2.4 Monitoring and Maintenance (1975 to 1985)

The AEC did not have any contractors performing work on the 52 acres surrounding the WSRP and the 9-acre WSQ until August of 1975, when it contracted with National Lead of Ohio to perform environmental monitoring in the pits and the quarry. In 1981, Bechtel National, Inc. assumed management and maintenance responsibility for the pits and quarry. In 1985, custody of the chemical plant was transferred from the Army to DOE (DOE 2004a).

2.2.3 Summary of Processed Nuclear Materials

In 1986, DOE prepared *Historical Nuclear Materials Balance Report for the Former AEC-Owned Weldon Spring Chemical Plant* (DOE 1986a), which summarized the types and quantities of nuclear materials received and processed through WSP. This DOE report indicated that four types of nuclear materials were processed during the operational period of WSP: 1) natural uranium, 2) depleted uranium, 3) slightly enriched uranium, and 4) natural thorium. The great majority of material processed at WSP was natural uranium (approximately 98% of the total mass of processed materials).

The natural uranium was received as ore concentrates, from which uranium was extracted and converted to various compounds and metal forms and shipped off the site. Depleted uranium was received as metal and various intermediate chemical forms, processed on an intermittent basis, and used primarily in product development activities. Slightly enriched uranium was processed on an intermittent basis only, and was typically received in the form of scrap metal or residues. Natural thorium was received in either a nitrate or an oxide form and processed on an intermittent basis in the refinery (DOE 1986a). Table 2-7 summarizes the total receipts by fiscal year of operation.

Table 2-7. Annual uranium and thorium mass receipts (kg) (DOE 1986a).

Fiscal year ^a	Natural uranium material	Depleted uranium material	Slightly enriched uranium material	Natural thorium material
1958 ^b	8,000,407	128	0.4	44
1959	12,898,013	11,255	0	0
1960	15,032,283	30,203	0	0
1961	15,546,776	94,260	0	0
1962	16,009,091	22,225	0	0
1963	18,873,351	0	94,695	0
1964	16,661,427	47	265,323	13,111
1965	11,445,290	2,769	441,977	313,699
1966	7,077,000	6,936	27,700	614,693
1967	472,339	0	12,890	0
Totals	122,015,977	167,823	842,585	941,347

a. Fiscal year begins on July 1 of the previous calendar year and ends on June 30 of the calendar year corresponding to the designated fiscal year.
 b. Includes startup period in FY 1957.

In 1999, DOE initiated the complex-wide Recycled Uranium Mass Balance Project (DOE 2000a), which identified WSP as a site that likely received recycled uranium in relatively small quantities of materials after 1961. The significance of these receipts of recycled uranium is that this material contains trace amounts of residual transuranic elements (including plutonium and neptunium), fission products (such as technetium), and reactor-produced uranium isotopes (such as ^{236}U) (DOE 2000a). Site records do not include the level of detail needed for accurate estimate of the amount of recycled material received and processed at WSP. It is known that the plant received shipments of uranium materials from other DOE sites that processed and shipped recycled uranium from fiscal years 1962 to 1967 (the period of recycled uranium shipment), but the amounts of recycled uranium versus natural uranium are not known. Due to the lack of information about recycled uranium quantities, the May 15, 2000, DOE report addressing WSP recycled uranium (DOE 2000a) assumes that all uranium receipts after 1961 (71,413,060 kg) were recycled, which is a large overestimate of the actual quantity because the same document reports that the majority of material processed through WSP was natural uranium.

2.2.4 Site Remediation

In 1985, DOE proposed designating control and decontamination of the chemical plant, raffinate pits, and quarry as a major project to be called the Weldon Spring Site Remedial Action Project (WSSRAP). In July 1986 a DOE project office was established on the site, and the project management contractor for the WSSRAP was a partnership of MK-Ferguson Company and Jacobs Engineering Group, Inc. The quarry was placed on the EPA NPL in July 1987. The chemical plant and raffinate pits were added to the NPL in March 1989.

The purpose of the WSSRAP was to eliminate potential hazards to the public and environment and to make surplus real property available for other uses to the extent possible. The scope of work included dismantling the 44 WSCP buildings and structures and disposing of both radiologically and chemically contaminated structural materials and soils. The project also disposed of as much material

as possible (including water, sludge, abandoned waste materials, and structural materials) from the raffinate pits, quarry, and nearby properties (DOE 2000b).

The *Record of Decision for the Management of the Bulk Wastes at the Weldon Spring Quarry* (ANL 1990) was signed in September 1990. The quarry bulk wastes were excavated and placed in the Temporary Storage Area (TSA) at the WSCP site based on an accelerated cleanup strategy involving limited characterization, a focused Remedial Investigations/Feasibility Study (RI/FS), and a limited baseline risk evaluation. Excavation of approximately 120,000 yd³ of WSQ bulk wastes was completed in October 1995 (DOE 2003). Material at the TSA was eventually placed in the onsite engineered disposal facility referred to as the Disposal Cell. Following bulk waste excavation, the selected remedy for residual contamination at the quarry site is long-term monitoring to verify that conditions at WSQ are protective of human health and the environment.

Remedial investigations were conducted at the chemical plant and raffinate pits areas in 1988 and 1989 under the Comprehensive Environmental Response, Compensation, and Liability Act RI/FS process. These investigations included characterization of groundwater, on-site soil contamination, contaminated sediment in off-site surface drainages, lakes, surface water and springs, and radiological contaminants in the raffinate wastes. The *Record of Decision for Remedial Actions at the Chemical Plant Area of the Weldon Spring Site* (DOE 1993) identifies the selection of the final remediation and disposal method for the chemical plant and bulk wastes for the quarry (DOE 2003). Remediation activities included the removal of contaminated soil, demolition and removal of remaining concrete pads and foundations that supported the 44 structures and buildings, removal and treatment of the raffinate pits wastes, and disposal of site wastes in an onsite engineered disposal facility (DOE 2004b). Remediation via removal was completed in 2002, and DOE decided that remediation of the shallow groundwater aquifer under the former WSCP would involve institutional controls and monitoring to achieve remediation objectives (DOE 2004b).

Several temporary staging areas and process structures were constructed or commissioned for the purpose of treating or storing excavated wastes and raffinate pit water during the remediation process. Two water treatment facilities were used: A Quarry Waste Treatment Plant and the Site Water Treatment Plant (SWTP). A TSA for the WSQ bulk wastes was an area designed and designated on the WSCP to store excavated waste before placement in the Disposal Cell. A Chemical Stabilization and Solidification (CSS) facility operated to produce a grout for use in the engineered disposal facility. By mixing the contaminated raffinate pit sludges with fly ash and Portland cement, the plant provided a means for managing the contaminants as well as a material to fill voids and increase the structural stability of the facility. The full-scale CSS plant began operation in mid-1998. On November 13, 1998, the CSS plant completed dredging and processing sludge from Pit 3, treating approximately 122,000 yd³ of sludge since April 1998. More than 75 million gallons of water with an average of 8 to 10% solids was pumped through the dredge. The sludge was screened for oversized materials then thickened with a polymer before it was blended with binder materials and transferred to the Disposal Cell. Approximately 188,000 yd³ of grout were produced in the process. Demolition work on the SWTP was initiated on April 23, 1999, with activities completed in late June 1999. As of 2002, construction of the Disposal Cell was 85% complete and nearly 1.5 million yd³ of contaminated wastes had been placed in it. Final site grading for the raffinate pits, Ash Pond, TSA, SWTP, Frog Pond, and material storage areas was performed in 2000.

2.3 RELEASES TO THE OUTDOOR ENVIRONMENT

Table 2-8 summarizes the activities that released radionuclides to the Weldon Spring environment. The following discussion is restricted to the periods for which the WSP has been listed as a "covered facility" according to the DOE Office of Worker Advocacy list (DOE 2004a), which are from 1955 to

1967 and from 1975 to the present. Operations did not begin until 1957; thus, this discussion is limited to a beginning date of 1957. The site did not have AEC or DOE contractors performing work at WSCP outside of these periods (DOE 2004a).

Table 2-8. History of radioactive effluent-generating activities (1957 to 2002).

Date	Event
1957–1966 ^a	Operation of uranium feed materials plant. Uranium concentrate converted to UO_3 , UF_4 , and uranium metal. Some thorium processing. Raffinate from the processing removed to raffinate pits. 14,500 metric tons of uranium materials received for processing and sampling per year from 1958 to 1964. Some thorium processed from 1965 to 1966. Uranium and thorium residues disposed of in the WSQ.
Dec 1966 ^a	Plant closed; hopper and process lines emptied; dust collectors cleaned out.
1975–1985	Site remained essentially undisturbed.
1986–2002	Remediation involving excavation of contaminated soils and rubble.

a. Expanded from Meshkov et al. (1986).

2.3.1 Airborne Emissions

According to Meshkov et al. (1986), air concentrations of uranium were measured during the WSCP operational period along the plant site perimeter, around buildings on the site, and at the south edge of the quarry. Air concentrations of radon were measured from 1979 through 2000 around the chemical plant, pits, and quarry perimeters (Meshkov et al. 1986; Weidner and Boback 1982; Bechtel 1983a, 1983b, 1984, 1985a, 1986; MK-Ferguson 1987; 1988; 1989; 1990; 1991; 1992; 1993; 1994; 1995; 1996; 1997; 1998; 1999; 2000a; and 2001a). Air concentrations of particulates were measured during some of the postoperational period. This information suggests that air emissions were of potential concern not only during operational activities when radionuclide-laden dust was created, but also from subsequent contamination of the surrounding terrain.

The total amount of uranium emitted to the atmosphere during the operational period (1957 to 1966) has been estimated from monitoring data (Meshkov et al. 1986) and a materials balance study (DOE 1986a). Table 2-9 summarizes the reported atmospheric discharges from the materials balance study, which were engineering estimates derived from airflows and other process factors along with stack-monitoring data. Based on these two methods, the amount of uranium activity emitted from the plant is estimated to range between approximately one and 5 Ci/yr. Release rates for uranium decay products (^{230}Th , ^{226}Ra , and ^{210}Pb) were also estimated by Meshkov et al. as a fixed percent of the (estimated) amount of released ^{238}U . An estimate of radon release based on the amount of uranium processed during the period ranged from 12 to 34 Ci/yr.

Beginning in 1981, annual environmental monitoring reports have provided estimates of air concentrations of particulate radionuclides and of radon at the WSCP and WSQ. These estimates reflect emissions during the later maintenance period and throughout remediation activities. Because the site remained in the monitoring and maintenance phase from 1975 to 1985, data from the period from 1981 to 1985 could be useful for estimating emissions from 1975 to 1980.

2.3.2 Waterborne Emissions

Waterborne emissions from the WSP site have been a result of discharge of solubilized radionuclides to surface water or groundwater. The four raffinate pits at the WSCP and the WSQ presented conditions where contaminated sludge, soil, and rubble were covered or partially covered with standing water. During the operational period (1957–1967), the raffinate pits at the WSCP were a

Table 2-9. Estimated annual discharges to stacks (kg).^a

Fiscal year ^b	Natural uranium	Depleted uranium	Slightly enriched uranium	Natural thorium
1958	— ^c	— ^c	— ^c	— ^c
1959	— ^c	— ^c	— ^c	— ^c
1960	7,200	— ^c	— ^c	— ^c
1961	7,200	0	0	0
1962	7,200	0	0	0
1963	7,200	0	0	0
1964	7,483	0	0	0
1965	4,200	0	300	0
1966	4,158	0	0	0
1967	100	0	0	0
Total	44,741	0	300	0

a. From Table 7 in DOE (1986).

b. Fiscal year begins on July 1 of the previous calendar year and ends on June 30 of the calendar year corresponding to the designated fiscal year.

c. No values given for these years.

source of radionuclides that were discharged to surface water. After the WSP operations ceased in 1967, a small but continuous discharge at the process sewer outfall occurred (Weidner and Boback 1982). During operations and in the years following plant closure, leaching of sediments in the pits and quarry provided a route of discharge to groundwater (Weidner and Boback 1982).

The four raffinate pits received neutralized residues and waste streams from the various processing steps at the WSCP (Ficker 1981). The sludges in all the pits are essentially the same with the exception of those in Pit 4, because the latter was used predominantly during thorium processing. The pits were used as settling lagoons: The solids would settle out as a sludge, and the remaining supernatant would overflow to the plant process sewer. The solids were mostly acid insoluble compounds contained in the original ore material as well as hydroxides and precipitates that formed when the raffinates were neutralized with lime.

About 30% of the residues in Pits 1, 2, and 3 came from the uranium metal production step. Magnesium fluoride was produced as a scrap material during the reduction of UF_4 to uranium metal, and the slag contained about 5% uranium. This uranium was leached from the slag and then washed to remove the remaining soluble uranyl nitrate. The washed slag, almost uranium free, was pumped to the pits. In addition to residues from thorium processing, Pit 4 also contains drums and rubble dumped during plant closure (Ficker 1981).

During the operational period, the total amount of uranium discarded to the raffinate pits was measured, and it is reported in the materials balance study cited earlier (DOE 1986a). Table 2-10 summarizes the recorded discharges to the raffinate pits.

When the raffinate pits were in use, the supernatant solution from Pits 1 through 3 was decanted and fed to the plant storm sewer system via buried pipes (Weidner and Boback 1982). Sewage treatment effluent added to this flow, and the combined wastewater was discharged off the site into a natural streambed. The discharge point, called the process sewer outfall, was within a fenced right-of-way that enclosed the stream all the way to the Missouri River. Table 2-11 lists the estimates of discharges to the sewer from the materials balance study (DOE 1986a). Supernatant from Pit 4 was never decanted, which is why Table 2-11 does not indicate thorium discharges to the sewer.

While the majority of the thorium and uranium in the raffinate pits and quarry is insoluble, their progeny are likely to be more soluble. Therefore, both the WSCP and WSQ pose a potential source

Table 2-10. Estimated annual discharges to raffinate pits (kg).^a

Fiscal year ^b	Natural uranium	Depleted uranium	Slightly enriched uranium	Natural thorium
1958	— ^c	— ^c	— ^c	— ^c
1959	— ^c	— ^c	— ^c	— ^c
1960	46,193	— ^c	— ^c	— ^c
1961	12,502	0	0	0
1962	8,831	46	0	0
1963	18,448	0	0	0
1964	35,243	0	0	2,469
1965	13,069	0	2,828	16,170
1966	18,067	0	(20)	26,809
1967	29	0	0	30,750
Total	152,382	46	2,808	76,198

- a. From Table 7 in DOE (1986).
- b. Fiscal year begins on July 1 of the previous calendar year and ends on June 30 of the calendar year corresponding to the designated fiscal year.
- c. Discharges to raffinate pits in AEC Fiscal Years 1958 and 1959 were held in inventory as "potentially recoverable." Beginning in AEC Fiscal Year 1960, all previous and then current releases to the raffinate pits were treated as discharges and removed from the operating inventory as they occurred.

Table 2-11. Estimated annual discharges to sewer (kg).^a

Fiscal year ^b	Natural uranium	Depleted uranium	Slightly enriched uranium	Natural thorium
1958	— ^c	—	—	—
1959	—	—	--	—
1960	3,472	—	—	—
1961	6,461	0	0	0
1962	4,304	0	0	0
1963	6,374	0	0	0
1964	3,239	0	0	0
1965	1,254	0	979	0
1966	1,411	0	0	0
1967	205	0	0	0
Total	26,720	0	979	0

- a. From Table 7 in DOE (1986).
- b. Fiscal year begins on July 1 of the previous calendar year and ends on June 30 of the calendar year corresponding to the designated fiscal year.
- c. — = no values given for these years.

of groundwater contamination near the WSP site. Ongoing remediation involves active monitoring of the groundwater in this region.

2.4 ACCIDENTS

No information is currently available about accidental releases of radioactive materials to the environment during operation of the WSP. If additional information becomes available, it will be assessed for value and added to this section as appropriate.

Dupree (1979) cites two accidental exposures of workers which occurred during plant operations and were described by Mason during a visit to ORAU in August 1979. In one instance, a worker overfilled a pot with molten uranyl nitrate solution which spilled onto the floor. While attempting to turn off the valve, he fell into the material on the floor. He was hospitalized and ultimately returned to work approximately 11 weeks after the accident. A full report of the incident was made (MCW 1961). In the other case, a worker inhaled soluble uranium while trapped in a dust enclosure. The notes report that

the worker suffered from “CNS effect” (presumably central nervous system effect). Mason further speculated that this reaction was due to the chemical toxicity of the uranium exposure. There are no notes about longer-term effects on either employee.

2.5 HEALTH PROTECTION PRACTICES

2.5.1 Operational Period (1957 to 1967)

The health protection program in place when operations began at the WSP in 1957 is not specifically detailed in any of the technical reports available at this time. However, since MCW transferred many of its activities and personnel from the Destrehan Street site in St. Louis at the startup of the WSP, it is likely that the program in place closely resembled that documented by Mason (1955). If anything, changes to the health protection program were likely more effective due to experience gathered in previous years of involvement in uranium-processing operations. According to a descriptive report of the Mallinckrodt contributions between 1942 and 1967 (Fleishman-Hillard 1967), the design of the WSP “took advantage of the Company’s and the Atomic Energy Commission’s (AEC’s) accumulated wealth of experience concerning the handling of health and contamination problems encountered in uranium processing.” The WSP layout was planned with the goal of minimizing the spread of contamination; advanced dust-control systems were used, and on-site health facilities were provided. This 1967 document states, “...existing health programs were continued... at the new site, and a number of supplemental programs were initiated at the Weldon Spring plant.”

A 1965 revision of the *Summary of Health Protection Practices* for the MCW Uranium Division is documented in MCW (1965). The policies and basic principles underlying the health protection program are described, and information is included about survey meter checks, film-badging procedures, bioassay procedures, and restrictions on work assignments based on previous accumulated exposures. It is likely that this represents a revision of the 1955 program, but it is not clear what or when specific changes were made over the intervening years.

Both the 1955 and 1965 documents rely on AEC standards of radiation exposure to the extent that health protection decisions were made about worker rotation based on a comparison of monitored personnel exposures with these standards for radiation workers (i.e., individuals in controlled areas). Table 2-12 summarizes the 1955 document’s list of tolerated cumulative doses in use at MCW. In addition, the 1955 document states that the goal was to keep each individual cumulative exposure at no greater than one-half of the tolerance when averaged over 3 months. The methods claimed for controlling exposure are shielding, semi-remote operations, and worker rotation.

Table 2-12. Tolerated dose limits in 1955.

Type of radiation	Tolerated dose limit
Beta	500 mrep ^a /wk, whole body or part
Gamma	300 mR/wk, whole body or part
Beta & Gamma	500 mrep ^a /wk, whole body or part
Not specified	1,500 mrep ^a /wk hands and forearms

a. rep = roentgen-equivalent-physical, an obsolete unit of absorbed dose for types of radiation other than X-rays and gamma rays; replaced by the gray.

Table 2-13 lists the WSP guides for prescribing restricted work so that AEC standards would not be exceeded (MCW 1965). Work restriction involved temporary relocation of the affected personnel from usual duties until the cumulative average was at an acceptable level.

Table 2-13. Guides for prescribing restricted work based on radiation exposure in 1965.

Type of radiation or radioactive material	Dose limit
Gamma	3 rem per 3 consecutive calendar months.
	10 rem per 12 consecutive calendar months.
	5 rem per 12 months averaged over employment beginning 1955.
Beta	10 rem beta + gamma to whole body per 3 consecutive months.
	30 rem beta + gamma to whole body per 12 consecutive months.
	25 rem beta + gamma to whole body per 3 consecutive months.
	75 rem beta + gamma to whole body per 12 consecutive months.
Internal radioactive materials (when principal effect of the material is radiation dose to tissues)	50% of the acceptable body burden specified in the recommendations of the National Council on Radiation Protection and Measurements (NBS 69).
	Time-weighted exposure concentration averaged over any 4-week period exceeds more than 5 times the quantity in Table 1 of AEC Appendix 0524.
Uranium	Average urine concentrations for 3 evenly spaced samples over a 72-hr period exceeds 0.15 mg/L and one sample exceeds 0.25 mg/L.
	Time-weighted exposure air concentration averaged over 5 consecutive workdays exceeds 0.25 mg/m ³ .
	Concentration in exposure air averaged over a 1-hr exposure exceeds 2.0 mg/m ³ (a reduction factor of 5 is allowed for a well-fitted mechanical respirator, and a factor of 50 for positive pressure respirator).
	Uptake by other than inhalation suspected or known, average urine concentrations for 3 evenly spaced samples over a 72-hr period exceeds 0.10 mg/L.

2.5.1.1 Badging

According to Mason (1955) health protection program document, “each employee except office females wears (a) combination film badge-security badge.” The stated procedure was to change these badges biweekly “or more often as indicated.” Film monitors were placed at selected points throughout process areas to serve as integrating area monitors, and routine meter surveys were used to detect hot spots and provide information for decisions about protective measures. Data from these area monitors or meter surveys have not been found at this point.

The MCW (1965) health protection program document states that personnel in operating areas of the plant and in some laboratories wore badges continuously while at work and exchanged them monthly for processing. Permanent badges were assigned to persons who frequently went into badged areas. Spare badges were available for persons having a casual need to enter badged areas. Badges other than operations badges were exchanged on a 3-month schedule.

2.5.1.2 Radiological Exposure and Access Control

Workers at the WSP had the potential for exposure to airborne radionuclides from uranium or thorium ore processing and to external radiation from the onsite radioactive materials. Film badges and bioassay were used to evaluate actual exposures throughout the operational history. Measures were taken to control potential exposures to below AEC standards. According to Mason (1955) these measures involved:

1. Instituting a work permit program (aimed primarily at protecting maintenance workers in hazardous areas), which involved establishing time limits and survey meter checks for areas with radioactive materials

2. Conducting investigations and counseling to study causes for exposure trends or unusual individual exposures and to educate employees about protective measures
3. Providing shielding, semi remote operations, and worker rotation to control exposure
4. Providing work clothing from the skin out for personnel working in regulated areas (where radioactive materials were processed and handled), which could not be worn outside of these areas except under cover clothing
5. Use of respirators as specified by the MCW Health Department
6. Instituting a job time-limit program, for personnel who worked routinely in areas wherein the exposure rate was known to be above the AEC-based tolerance limits

MCW (1965) is more general than Mason (1955), but it is reasonable to assume all of the above measures were still in place based on language in the 1965 report.

2.5.2 Postoperational Period (1975 to Present)

During the monitoring and maintenance period (1975 to 1985), contractors to the Energy Research and Development Administration and DOE maintained the integrity of embankments of the pits, controlled vegetation, and conducted environmental sampling for assessment in relation to the maintenance role. Documentation of the health protection program in place for these workers has not been found. However, NLO (1977) states, "no personnel are employed or directly assigned to the Weldon Spring site", and "NLO personnel perform sampling and engineering duties on assignment from the Feed Materials Production Center, Fernald, Cincinnati, Ohio." Therefore, exposures to radionuclides on the WSP site were limited because the site was essentially undisturbed during this period and the external exposure rate and airborne concentrations of radioactivity were minimal in terms of potential short-term exposures to caretakers (NLO 1977).

During the remediation period (1985 to present), the WSSRAP project management contractor implemented health protection practices in compliance with DOE guidelines and regulations on occupational radiation protection (DOE 1981, 1986b, 1989, 10 C.F.R. pt. 835). Because inhalation was recognized as the primary pathway of concern at the WSP site in relation to worker exposure during active remediation (i.e., excavation and dismantling of structures), the focus of the radiation protection program was to control dust emissions and prevent inhalation intakes (MK-Ferguson 2001b). Intake by ingestion was considered possible, but less of a potential dose hazard than inhalation. Administrative controls were implemented to minimize ingestion hazards by limiting eating, drinking, and smoking in contamination areas; by using personal protective equipment such as coveralls, face shields, and gloves; and by meeting monitoring requirements.

Active remediation began in 1993 with the dismantlement of structures at the WSCP and the removal of bulk wastes at the WSQ. Applicable DOE guidelines and regulations were specified in 10 CFR pt. 835 at that time. Monitoring to assess internal exposure hazards to remediation workers included area monitoring for airborne radionuclides other than radon and thorium, area monitoring for radon and thorium, breathing-zone air (BZA) samplers, and bioassay. In work areas where long-lived airborne radioactivity concentrations were likely to exceed 2% of the DOE-established limit, BZA sampling was conducted on 25% of the workers spending more than 1 hr/day in the area. Bioassay requirements included baseline, routine, special, contamination incident, and exit urine samples analyzed for uranium for radiological workers who were likely to receive 100 or more mrem/yr

committed effective dose equivalent (CEDE) and who declared pregnancy and routinely entered controlled areas. The BZA-sampling results were used to determine bioassay participation.

According to the WSSRAP project management contractor (MK-Ferguson 2000b), "external dose rates are very low at the WSP site. General area external beta dose equivalent rates are at background levels (i.e., 0.03-0.05 mrem/hr)", with external gamma dose equivalent rates ranging from background (about 60 mrem/yr) to about 113 mrem/yr for continuous exposure in general areas. These exposure rates were expected to remain constant for the duration of site remediation. The use of nuclear density gauges by remediation workers increased the gamma radiation fields near the equipment (3 mrem/hr at 30 cm from the source), so control measures were instituted in these special areas to limit worker exposure. Raffinate sludge could produce a contact gamma dose rate in the range of 1 to 3 mrem/hr (with shallow dose equivalent rates up to 10 mrem/hr). Therefore, most raffinate sludge treatment and disposal activities were performed remotely to limit exposure.

2.5.2.1 Badging (post-operational)

Information on badging procedures during the monitoring and maintenance period (1975 to 1985) is not available. For the remediation period (1985 to present), the following information has been derived from documentation generated by the project management contractor for the WSSRAP, which was a partnership of MK-Ferguson Company and Jacobs Engineering Group, Inc.

According to the January 2000 *External Dosimetry Technical Basis Manual* (MK-Ferguson 2000b), the "WSSRAP has provided personnel dosimetry to radiological workers since October 1986," just following the establishment of the DOE office on the site. According to this manual, only one worker's monitoring results indicated an external effective dose equivalent (EDE) above 100 mrem/yr (the results for this worker were 170 mrem EDE in 1994). In addition, the highest measured shallow dose equivalent was 1,450 mrem (in 1994), and all measured extremity dose equivalents were less than this value. Therefore, the DOE regulated action level of 5,000 mrem annual shallow and extremity dose equivalent was never exceeded. Therefore, during the fourth quarter of 1995, the number of dosimeters issued to personnel was reduced by approximately 95% due to completion of many of the activities that could have resulted in a significant external dose in relation to DOE regulations and because future WSSRAP activities were judged to be similar to previous activities, which did not lead to significant exposure. The issuance was reduced to include only declared pregnant workers who entered controlled areas and those radiological workers likely to receive 100 mrem EDE in 1 yr from external sources or 5,000 mrem shallow dose equivalent to the skin or any extremity. The issuance decision was made by the Worker Protection Supervisor based on area radiation monitoring results and estimated exposure times.

2.5.2.2 Radiological Exposure and Access Control

Access to the WSP was limited to authorized personnel during the maintenance period by a 7-ft chain-link cyclone fence topped with three strands of barbed wire. The site was completely enclosed by Army-owned areas, and security patrols were provided by the Army to hinder unauthorized access (NLO 1977).

During active remediation, measures were taken to control potential internal and external exposures according to DOE guidelines, many of which are noted above. Access to areas in which exposures could exceed regulatory limits was administratively controlled. The Worker Protection Supervisor (or designee) made decisions about access to areas based on area monitoring that evaluated external exposure rates as well as air concentrations of radionuclides including radon, thorium, and progeny (MK-Ferguson 2000b, 2001b).

Workplace intake controls included:

- Area decontamination
- Air-handling units equipped with high efficiency particulate air (HEPA) filters
- Dust suppression using water sprays
- Dust elimination using surface wipe down and/or HEPA vacuuming
- Plastic dust barriers
- Limiting work area access to essential personnel and equipment
- Prohibiting eating, drinking, smoking, and chewing in the work area
- Training for hazard recognition prior to entry in controlled areas

Respiratory protection was required when workplace control measures were not possible or sufficiently effective, and the need for such was generally assessed when annual intakes of radionuclides other than radon, thorium, and progeny were likely to result in dose equivalents exceeding 100 mrem CEDE, or when intakes of radon, thorium, and progeny were likely to result in dose equivalents above 500 mrem CEDE.

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GLOSSARY

annual dose equivalent

The dose equivalent received in a year, expressed in units of rem or sievert.

alpha particles

Positively charged particles of discrete energies emitted by certain radioactive materials; alpha particles usually expend their energy in short distances and will not usually penetrate the outer layer of skin; they are a significant hazard only when taken into the body where their energy is absorbed by tissues.

U.S. Atomic Energy Commission (AEC)

Original agency established for nuclear weapons and power production; a predecessor to the Energy Research and Development Agency and the U.S. Department of Energy.

beta radiation

Radiation consisting of charged particles of very small mass (i.e., the electron) emitted spontaneously from the nuclei of certain radioactive elements. Most (if not all) of the direct fission products emit beta radiation. The beta particle is physically identical to an electron moving at high velocity.

curie (Ci)

A special unit of activity. One curie equals 3.7×10^{10} nuclear transitions per second.

dose equivalent (*H*)

The product of the absorbed dose *D*, the quality factor *Q*, and any other modifying factors. The special unit is the rem. When *D* is expressed in gray, *H* is in sieverts, where 1 sievert equals 100 rem.

dosimeter

A device used to measure the quantity of radiation received. A holder with radiation-absorbing elements (filters) and an insert with radiation-sensitive elements packaged to provide a record of absorbed dose or dose equivalent received by an individual.

dosimetry

The science of assessing absorbed dose, dose equivalent, effective dose equivalent, etc., from external or internal sources of radiation.

dosimetry system

A system used to assess dose equivalent from external radiation to the whole body, skin, or extremities. This includes the fabrication, assignment, and processing of dosimeters as well as interpretation and documentation of the results.

exposure

As used in the technical sense, exposure refers to a measure expressed in roentgens of the ionization produced by photons (i.e., gamma and X-rays) in air.

extremity

That portion of the arm extending from and including the elbow through the fingertips, and that portion of the leg extending from and including the knee and patella through the tips of the toes.

film

In general, a packet that contains one or more pieces of film in a light-tight wrapping. When developed, the film has an image caused by radiation that can be measured using an optical densitometer.

gamma rays

Electromagnetic radiation (photons) originating in atomic nuclei. Gamma rays are physically identical to X-rays, the only essential difference being that X-rays do not originate in the nucleus.

hydrofluorination

Chemical conversion to a form containing fluorine.

isotope

One of a set of chemically identical species of atom which have the same atomic number but different mass numbers (different isotopes of an element having the same number of protons but different numbers of neutrons and thus different atomic numbers).

neutron

A basic particle that is electrically neutral weighing nearly the same as the hydrogen atom.

operating area

Designation of major onsite operational work areas.

photon

A unit or "particle" of electromagnetic radiation consisting of X- or gamma rays.

quality factor (Q)

A modifying factor used to derive dose equivalent from absorbed dose.

radiation

Alpha, beta, neutron, and photon radiation.

radioactivity

The spontaneous emission of radiation, generally alpha or beta particles, gamma rays, and neutrons from unstable nuclei.

radionuclide

A radioactive isotope of an element, distinguished by atomic number, atomic weight, and energy state.

raffinate

A term loosely applied to waste from the uranium or thorium extraction step. Solids that result from the neutralization of this waste are also called raffinates.

rem

A unit of dose equivalent equal to the product of the number of rad absorbed and the quality factor. The word derives from *roentgen equivalent in man*.

roentgen

A unit of exposure to gamma (or X-ray) radiation. It is defined precisely as the quantity of gamma (or X-) rays that will produce a total charge of 2.58×10^{-4} coulomb in 1 kilogram of dry air. An exposure of 1 roentgen is approximately equivalent to an absorbed dose of 1 rad in soft tissue for higher (more than about 100 kilovolt-electron) energy photons.

shallow absorbed dose

The absorbed dose at a depth of 0.007 centimeter in a material of specified geometry and composition.

shallow dose equivalent (H_s)

Dose equivalent at a depth of 0.007 centimeter in tissue.

shielding

Any material or obstruction that absorbs (or attenuates) radiation and thus tends to protect personnel or materials from radiation.

sievert

The International System unit for dose equivalent, where 1 sievert equals 100 rem.

skin dose

Absorbed dose at a tissue depth of 7 milligrams per square centimeter.

whole-body dose

Commonly defined as the absorbed dose at a tissue depth of 1.0 cm (1000 mg/cm^2); however, also used to refer to the recorded dose.

X-ray

Ionizing electromagnetic radiation of external nuclear origin.