



ORAU TEAM Dose Reconstruction Project for NIOSH

Oak Ridge Associated Universities | Dade Moeller | MJW Technical Services

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DOE Review Release 04/03/2014

Feed Materials Production Center – Site Description	ORAUT-TKBS-0017-2	Rev 01
	Effective Date:	03/31/2014
	Supersedes:	Revision 00
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New
 Total Rewrite
 Revision
 Page Change

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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
05/20/2004	00	New technical basis document for the Fernald Environmental Management Project (FEMP) – Site Description. Incorporates comments from OCAS and Task 5 reviewers. Incorporates additional comments from reviewers. First approved issue. Initiated by Samuel L. T. Chu.
03/31/2014	01	Revision initiated to incorporate updated site information and add Special Exposure Cohort information. Changed title to use Feed Materials Production Center rather than Fernald Environmental Management Project. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by Billy P. Smith and Karen S. Kent.

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ACRONYMS AND ABBREVIATIONS

AEC	U.S. Atomic Energy Commission
Bq	becquerel
CFR	Code of Federal Regulations
Ci	curie
d	day
DOE	U.S. Department of Energy
DOL	U.S. Department of Labor
dpm	disintegrations per minute
DU	depleted uranium
D&D	decontamination and decommissioning
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
EU	enriched uranium
FMPC	Feed Material Production Center
FR	Federal Register
ft	foot
g	gram
gal	gallon
hr	hours
in.	inch
kW	kilowatt
L	liter
m	meter
MAC	maximum allowable concentration
MeV	megaelectron-volt, 1 million electron-volts
mrad	millirad
mrem	millirem
MT	metric ton
MTU	metric tons of uranium
nCi	nanocurie
NIOSH	National Institute for Occupational Safety and Health
NTS	Nevada Test Site
NU	natural uranium
ORAU	Oak Ridge Associated Universities
P	page
PCB	polychlorinated biphenyl
POC	probability of causation
POOS	plutonium out of specification

psig pounds per square inch gauge

RMI Reactive Metals, Inc.
RTS Radon Treatment System
RU recycled uranium

SRDB Ref ID Site Research Database Reference Identification (number)

t ton
TBD technical basis document
TRU transuranic

U.S.C. United States Code

wk week

yd yard
yr year

°F degrees Fahrenheit

§ section or sections

2.1 INTRODUCTION

Technical basis documents and site profile documents are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historical background information and guidance to assist in 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 NIOSH staff 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 [DOE] facility” as defined in the Energy Employees Occupational Illness Compensation Program Act [EEOICPA; 42 U.S.C. § 7384l(5) and (12)]. EEOICPA defines a DOE facility as “any building, structure, or premise, including the grounds upon which such building, structure, or premise is located ... in which operations are, or have been, conducted by, or on behalf of, the Department of Energy (except for buildings, structures, premises, grounds, or operations ... pertaining to the Naval Nuclear Propulsion Program)” [42 U.S.C. § 7384l(12)]. Accordingly, except for the exclusion for the Naval Nuclear Propulsion Program noted above, any facility that performs or performed DOE operations of any nature whatsoever is a DOE facility encompassed by EEOICPA.

For employees of DOE or its contractors with cancer, the DOE facility definition only determines eligibility for a dose reconstruction, which is a prerequisite to a compensation decision (except for members of the Special Exposure Cohort). The compensation decision for cancer claimants is based on a section of the statute entitled “Exposure in the Performance of Duty.” That provision [42 U.S.C. § 7384n(b)] says that an individual with cancer “shall be determined to have sustained that cancer in the performance of duty for purposes of the compensation program if, and only if, the cancer ... was at least as likely as not related to employment at the facility [where the employee worked], as determined in accordance with the POC [probability of causation¹] guidelines established under subsection (c) ...” [42 U.S.C. § 7384n(b)]. Neither the statute nor the probability of causation guidelines (nor the dose reconstruction regulation, 42 C.F.R. Pt. 82) restrict the “performance of duty” referred to in 42 U.S.C. § 7384n(b) to nuclear weapons work (NIOSH 2010).

The statute also includes a definition of a DOE facility that excludes “buildings, structures, premises, grounds, or operations covered by Executive Order No. 12344, dated February 1, 1982 (42 U.S.C. 7158 note), pertaining to the Naval Nuclear Propulsion Program” [42 U.S.C. § 7384l(12)]. While this definition excludes Naval Nuclear Propulsion Facilities from being covered under the Act, the section of EEOICPA that deals with the compensation decision for covered employees with cancer [i.e., 42 U.S.C. § 7384n(b), entitled “Exposure in the Performance of Duty”] does not contain such an exclusion. Therefore, the statute requires NIOSH to include all occupationally-derived radiation exposures at covered facilities in its dose reconstructions for employees at DOE facilities, including radiation exposures related to the Naval Nuclear Propulsion Program. As a result, all internal and external occupational radiation exposures are considered valid for inclusion in a dose reconstruction. No efforts are made to determine the eligibility of any fraction of total measured exposure for inclusion in dose reconstruction. NIOSH, however, does not consider the following exposures to be occupationally derived (NIOSH 2010):

- Background radiation, including radiation from naturally occurring radon present in conventional structures
- Radiation from X-rays received in the diagnosis of injuries or illnesses or for therapeutic reasons

¹ The U.S. Department of Labor (DOL) is ultimately responsible under the EEOICPA for determining the POC.

2.1.1 Purpose

This technical basis document (TBD) of the Feed Materials Production Center (FMPC) site profile describes the facilities and processes at FMPC over the life of operations and the radioactive sources that were associated with those facilities and processes. This TBD provides technical basis information about the FMPC for the purpose of supporting estimates of occupational worker radiological dose based on exposure to the conditions and materials in the facilities.

2.1.2 Scope

The FMPC was a large-scale, integrated facility that produced uranium metal products (e.g., derbies, ingots, billets, and fuel cores) that were used as feed materials in the nation's defense programs. Since operations ended in 1988, the Fernald site has been variously named the Fernald Environmental Management Project, the Fernald Closure Project, and is now the Fernald Preserve. Site remediation began in 1989 and is complete. The DOE Office of Legacy Management currently controls the site. This TBD refers to the Fernald site as FMPC throughout. The descriptions in this TBD provide technical bases that dose reconstructors may use to support dose reconstruction analyses including situations for which monitoring data are unavailable and/or other methods might not be appropriate for claimant dose reconstruction.

Section 2.1.3 describes the Special Exposure Cohort (SEC) classes for the FMPC. Section 2.2 is an overview of the site background and history. Section 2.3 details production facility activities and processes, and Section 2.4 discusses waste management facilities and activities. Section 2.5 describes remediation and environmental restoration from 1989 to the present, and Section 2.6 summarizes the radioactive materials on the site and their characteristics.

2.1.3 Special Exposure Cohort

The Secretary of the U.S. Department of Health and Human Services has designated three classes of employees at Fernald as additions to the Special Exposure Cohort:

All employees of DOE, its predecessor agencies, and their contractors, or subcontractors who worked at the Feed Materials Production Center in Fernald, Ohio, from January 1, 1968 through December 31, 1978, for a number of work days aggregating at least 250 work days, occurring either solely under this employment, or in combination with work days within the parameters established for one or more other classes of employees included in the SEC (77 FR 150; August 3, 2012).

It was determined that NIOSH lacked the sufficient information to allow it to estimate with sufficient accuracy the potential internal doses from exposure to thorium, which employees at this facility may have been subjected (Sebelius 2012).

All employees of the DOE, its predecessor agencies, and their contractors and subcontractors who worked at the Feed Materials Production Center in Fernald, Ohio, from January 1, 1954, through December 31, 1967, for a number of work days aggregating at least 250 work days, occurring either solely under this employment, or in combination with work days within the parameters established for one or more other classes of employees included in the Special Exposure Cohort (78 FR 229; November 27, 2013).

It was determined that NIOSH lacked the sufficient information to allow it to estimate with sufficient accuracy the potential internal doses from exposure to thorium, which employees working at this facility may have been subjected (Sebelius 2013a).

All employees of the Feed Materials Production Center in Fernald, Ohio, who were not employed by National Lead of Ohio, NLO, or the Department of Energy or its predecessor agencies, who worked at FMPC from January 1, 1951, through December 31, 1983, for a number of work days aggregating at least 250 work days, occurring either solely under this employment, or in combination with work days within the parameters established for one or more other classes of employees included in the Special Exposure Cohort (78 FR 229; November 27, 2013).

It was determined that NIOSH lacked the sufficient information to allow an estimate with sufficient accuracy the potential internal doses from exposure to uranium, which employees of subcontractors at FMPC working at this facility may have been subjected.

This dose reconstruction infeasibility for the period 1951 through 1983 applies only to subcontractors. NIOSH has access to an electronic data set that contains the results of the uranium urinalysis bioassay program for all the years of FMPC operations, and the overwhelming majority of employees of the prime contractor (National Lead of Ohio, later named NLO Inc.) have results in the bioassay data set. However, the data set does not contain bioassay results for employees of companies other than the prime contractor (i.e., non-prime contractor employees). NIOSH has obtained a limited number of bioassay samples from non-prime contractor employees through data captures, but cannot be certain that all non-prime contractor employees' bioassay data were retained by the site or captured by data capture efforts. Additionally, there are some reasons to conclude that the prime contractor did not consistently evaluate whether non-prime contractor employees should be monitored for radiation exposure because of the transitory nature of their work (Sebelius, 2013 b).

Dose reconstruction guidance in this document for the period before January 1, 1984, is presented to provide a technical basis for partial dose reconstructions for claims not compensated under the SEC (i. e., nonpresumptive cancers and SEC employment <250 days). Although it is not possible to completely reconstruct internal radiation doses for all workers for the period January 1, 1951, through December 31, 1983, NIOSH has determined, and HHS has concurred, that it is feasible to reconstruct external radiation doses for all FMPC workers for the period from January 1, 1951, through December 31, 1983 (Sebelius 2013b).

2.2 SITE BACKGROUND AND HISTORY

The FMPC began operations at the Pilot Plant in 1951 and was fully operational by the end of 1954. Its primary function was to convert uranium ore concentrates and recycled materials to either uranium oxides or highly purified uranium ingots and billets for machining or extrusion into tubular forms of assorted uranium enrichment. These products were prepared for use as production reactor fuel cores and target fuel elements. In addition, small amounts of thorium were processed (ASI ca. 1986, pg. 2).

Uranium metal production peaked in 1960 at approximately 10,000 metric tons of uranium (MTU), and in 1964 began to decline to a low in 1975 of approximately 1,230 MTU. A MTU is equal to 1,000 kilograms uranium (kg U) or 1,000,000 grams uranium (g U). During the 1970s, consideration was given to closing the FMPC. From 1972 through 1979, the staffing level, which peaked at 2,891 in 1956, slowly declined from 662 to 538 (ASI ca. 1986; p. 4). In FY 1981, FMPC received direction to plan the restoration of the site to accommodate projected product requirements approaching the original production capacity. Significantly increased production levels, rapid staff buildup in many areas, and implementation of a major facilities restoration program followed. Accomplishments since that time included production output of three times the 1979 level and a staff increase from 538 to more than 1,000.

The production of uranium metal at the FMPC ended in July 1989 to concentrate on site cleanup efforts. Operations after production were completely dedicated to site remediation and restoration.

2.2.1 Site Location and Facilities

The FMPC is near the unincorporated village of Fernald in the Great Miami River Valley, about 20 miles northwest of Cincinnati in southwestern Ohio. The FMPC site covers an area of 1,050 acres. The production area encompassed approximately 136 acres in the center of the site.

Historically, production area facilities included nine separate plants, the pilot plant, ancillary buildings, and administrative buildings that were connected with a network of roadways. These facilities, along with concrete storage pads, gravel ground cover, railroad access, sanitary landfill, and metal scrap piles, were surrounded by security fencing. Outside the 136-acre fenced production area, the Waste Storage Area included six low-level radioactive waste storage pits, two earthen-bermed concrete silos containing K-65 residues (high specific activity radium-bearing residues), one concrete silo containing metal oxides, and all affected adjoining areas. This area also included two fly ash piles approximately 3,000 ft south-southwest of the waste storage area, as well as the burn pit between Pits 3 and 4. Production operations were handled in Plants 1 through 9 and the Pilot Plant (ASI ca. 1986; Mead, Savage, and Fugate ca. 1985). As of 2013, remedial actions on the site were complete, and the DOE Office of Legacy Management routinely provides monitoring and surveillance of the site. The following sections provide a historical overview of the facilities and processes at the FMPC in relation to information and data to support the dose reconstruction efforts.

2.2.2 Site Operations

The FMPC used a wide variety of chemical and metallurgical process steps to support the primary mission of supplying metallic fuel cores for production reactors at the Hanford Site in Washington and the Savannah River Site in South Carolina. In addition, some metal was shipped directly to DOE facilities at Oak Ridge, Tennessee, and Rocky Flats, Colorado (Mead, Savage, and Fugate ca. 1985).

The first step in the FMPC production process was the purification of uranium. In the early years, the site processed uranium ore, including pitchblende ore from the Belgian Congo, through a series of chemical processes. Later, FMPC extracted uranium from scrap metal or recycled material (e.g., floor sweepings, dust collectors, and production residues) from onsite operations and other DOE sites. FMPC uranium production began with ore concentrates, recycled uranium (RU) from spent reactor fuel, or various uranium compounds as feed materials. Impure starting material was dissolved in nitric acid to produce a crude uranyl nitrate solution (UNH) for solvent extraction purification. Purified UNH was concentrated by evaporation and thermally denitrated to uranium trioxide (UO₃, orange oxide). Orange oxide was converted to uranium tetrafluoride (UF₄, green salt) for reduction to metal. In addition, green salt was produced from uranium hexafluoride (UF₆) from other DOE sites (Mead, Savage, and Fugate ca. 1985).

Uranium metal was produced by reacting UF₄ and magnesium metal in a refractory-lined reduction vessel. The uranium metal was shaped in forms called derbies, each weighing 136 to 168 kg. This primary uranium metal was remelted with scrap uranium metal to yield a purified uranium ingot that was extruded to form rods or tubes. Sections were cut and machined to final dimensions. These machined cores were shipped to other DOE sites for canning and final assembly into reactor fuel elements. Since the late 1960s, all cylindrical ingots were center drilled at FMPC and sent off the site for extrusion. Most of the extruded tubes were returned to FMPC for heat treatment and final machining before they were shipped for use at other DOE sites (Mead, Savage, and Fugate ca. 1985).

Periodically, a few metric tons of thorium were processed, but in amounts that were small fractions of the uranium mass that was processed. Thorium production steps, in general, were similar to those for uranium production. Final products were purified thorium nitrate solution, solid thorium compounds, or metal. Since 1972, the FMPC served as the thorium materials repository for DOE. Approximately

two-thirds of the material in the repository was processed at the FMPC. The remainder originated at other DOE facilities (Mead, Savage, and Fugate ca. 1985, p. 148-151).

FMPC supported the Hanford N-Reactor by processing enriched uranium (EU) scrap residues from the metal production steps along with recycled UO_3 from the plutonium-uranium extraction process. Enriched UF_6 was required to replenish the ^{235}U that was consumed in N-Reactor operations. All three material types were converted to UF_4 , which was the starting point for metal production operations. Production of depleted uranium (DU) metal for the Savannah River Site Mark 31 stream, the Y-12 Plant, and the Rocky Flats Plant began with UF_4 from inventories (Mead, Savage, and Fugate ca. 1985).

The uranium processed was depleted, natural, or slightly enriched. The average content was close to natural uranium (NU) isotopic ratios. Uranium-235 enrichments in raw materials ranged up to approximately 20%. However, the maximum product enrichment was 1.25%, and the average product was slightly depleted. In general, 2% EU was the highest enrichment that FMPC processed in significant quantities (Tomes 1997, p. 24 and Mead, Savage, and Fugate ca. 1985, p. 82, 157, 179).

RU, discussed in Section 2.5.2, introduced additional isotopes in trace quantities.

2.2.3 Radiological Access Controls

All FMPC workers had to enter the controlled area through a security station and present a valid authorization badge for entry. Access to the FMPC site was limited to authorized personnel with a valid security credential. During both the operational and remediation/decommissioning periods, the access controls gradually evolved. Once inside the controlled area, workers were allowed to enter into the various plants, buildings, and radiological areas if they met the craft or labor requirements for the plant in which they were to work (Mead, Savage, and Fugate ca. 1985, p. 192). Later, as DOE requirements evolved, workers had to meet the personal protection equipment and training requirements authorized by the radiological work permit for the area of entry.

2.2.4 Major Radiological Incidents

There were many minor radiological incidents over the lifetime of the operation and decommissioning of the FMPC that involved spills, airborne contamination releases, personnel contamination events, chip fires, and other events. These potentially serious exposure events resulted in significant exposure to several involved workers. There were three documented major accidents that resulted in the potential for exceptionally high or significant internal or external exposures to workers at the FMPC. Two of the incidents resulted in fatalities. The first incident was a thorium blender incident in Plant 9 in 1954 that resulted in the deaths of two operators from the explosion and fire (Quigley et al. 1954, p. 3). The second was a significant accidental release in 1966 of UF_6 that engulfed and exposed a worker who was treated and returned to work 7 days after the accident (Warner et al. 1966, p. 6-7). The third accident occurred in 1985 in Plant 8 when a worker was accidentally exposed to black oxide and the worker died 12 days after the exposure. An expert physician in epidemiology and nuclear medicine felt that radiochemical pneumonitis and radiochemical myocarditis were the most likely cause of death (Hackworth 1988, p. 4-8).

General criteria for incident reporting are provided in DOE Orders and in the Manufacturing Standard Practices Manual. Lines of communication for reporting incidents to the Health, Safety, and Environmental Division were established (Gilbert 1985). Employees notified supervisors, who completed an incident report, a copy of which went to the Health, Safety and Environmental Division. In addition, the Health, Safety and Environmental Division received the bioassay results and

dosimetry measurements on the involved individual(s) to ensure that adequate dosimetry follow-up was accomplished.

2.3 PRODUCTION FACILITY ACTIVITIES AND PROCESSES

Table 2-1 summarizes activities in each production area and identifies radionuclides of concern for those facilities. Figure 2-1 shows the volume of uranium shipments beginning in 1952. The following sections present descriptions of each FMPC facility or operation and the associated processes in a manner that aids the historic dose reconstruction analyses, making use of available and obtainable site data and information. Each facility description contains (1) the physical description of the facility and its associated processes and activities and (2) the description of the radiation sources that include the technical basis for internal dose and external dose reconstruction analyses specifically for the described facility. Section 2.5 provides the discussions, radiological data, and technical basis germane to all of the FMPC facilities (Mead, Savage, and Fugate ca. 1985).

The FMPC was designed as a large-scale, integrated facility capable of converting uranium ore and recycled material into uranium metal through a series of chemical and metallurgical conversions. Production operations were conducted in Plants 1 through 9 and the Pilot Plant (Mead, Savage, and Fugate ca. 1985).

There were 10 buildings, or plants, at the FMPC, each of which had specific internal dosimetry concerns. Internal and external dose potential existed in the Pilot Plant throughout the history of the

Table 2-1. Area information and parameters.

Area/Plant	Description	Period	Radionuclides of concern	
			Radionuclides processed	Periods and volumes
Pilot Plant UF ₆ to UF ₄ Reduction Plant	Reduction of UF ₆ to UF ₄ . Conversion of thorium nitrate solution to various thorium compounds. Shot blasting uranium derby metal. Plasma spray coating graphite crucibles.	1951–1989	DU, U, EU, Th, Ra	1953–1989; see Figure 2-1 1966–1973; 790 MT Th nitrate 1969–1971; 51 MT Th derbies 1964–1970; 686 MT thoria gel 1971–1976; 153 MT Th oxalate
			U, RU, EU, Rn	
			Th	
Plant 1 Sampling Plant	Shipping, receiving, sampling, and storing large amounts of depleted, normal, and EU materials in open and covered storage areas. Drying, crushing, milling, grinding and classifying feed materials for processing. Digesting enriched residues assaying 5% to 20% U-235 in geometrically safe equipment. Opening unirradiated fuel pins containing EU dioxide pellets. Reconditioning steel drums for reuse and baling deteriorated drums for salvage.	1953–1989	DU, U, EU, Ra, Th	1953–1989; see Figure 2-1 1966–1972; 207 MT
			U, RU, EU	
			Th	
Plant 2/3 Refinery	Convert uranium ore concentrates to UO ₃ . Digesting EU recycled materials in nitric acid and storing blended feed solutions in stainless-steel tanks. Performing solvent extraction operations in stainless-steel, perforated-plate pulse columns to purify the uranium solution. Concentrating pure uranium solution by evaporation, and converting the uranium to UO ₃ . Recovering nitric acid from NO _x discharges from the digestion and denitration operations. Recovering uranium from internal process waste solutions. Very limited thorium operations including production of thorium nitrate and thorium oxide.	1953-1989	DU, U, EU, Ra, Th	1953–1989; see Figure 2-1 1964; 20 MT
			U, RU, EU	
			Th	

Area/Plant	Description	Period	Radionuclides of concern	
			Radionuclides processed	Periods and volumes
Plant 4 Green Salt Plant	Processing UO ₃ to uranium tetrafluoride, UF ₄ , or green salt, in continuous-flow reactor banks designed and staged for gas-solid reactions. Blending and packaging depleted UF ₄ for the Metal Production Plant (Plant 5). Operating the tank farm to supply production plants with bulk quantities of required liquid chemical agents. Produce dry ThF ₄ from the ThO ₂ (limited to a short campaign in 1954).	1953–1980 (not continuous)	NU, DU, U, EU, Ra, Th	
			U, RU, EU	1953–1980; see Figure 2-1
			Th	1954–1956; 460 MT
Plant 5 Metals Production Plant	Reducing uranium tetrafluoride to high-purity depleted, normal, and EU derby metal with magnesium in electric resistance furnaces. Casting DU derbies and recycled metal scrap into ingots using vacuum melt induction furnaces. Sawing ingots to size. Sampling metal products for quality. Machining graphite into almost any shape using lathes, saws, milling machines, routers, and grinders. Milling MgF ₂ slag byproduct for reuse in lining reduction pots.	1953–1989	DU, U, EU, Ra, Th	
			U, RU, EU	1953–1989; see Figure 2-1
			Th	
Plant 6 Metals Fabrication Plant	Heat treating machined ingots for extrusion using neutral salt (NuSal) furnace and salt-oil baths. Heat-treating and final machining of target elements or fuel cores. Sawing ingots to size. Cropping, surface milling, and inspecting products for shipment. Metal pickling and chip briquetting. Inspecting finished target element cores and final products before shipment.	1953-1980	DU, U, EU, Ra, Th	
			U, RU, EU	1953–1980; see Figure 2-1
			Th	1959–1963; 218 MT
Plant 7 Hexafluoride Reduction Plant	Convert uranium hexafluoride to green salt (1954–1956). Store drums of green salt and empty containers (1969 forward).	1954–1956, 1956-1969 idle, 1969-1989 storage	DU, U, EU	
			U, RU, EU	1954–1956; see Figure 2-1
			Th	1968–1989; storage

Area/Plant	Description	Period	Radionuclides of concern	
			Radionuclides processed	Periods and volumes
Plant 8 Scrap Recovery Plant	Residues and scrap from uranium processing were upgraded before being sent to the refinery. Furnacing various enriched residues from onsite generation and offsite receipt to prepare refinery feed by removing moisture, oil, graphite and metallic impurities. Filtering large volumes of low-level radioactive waste slurries using rotary vacuum precoat filters. Drying and heating in a furnace waste materials for offsite disposal, including contaminated filter cakes from neutralized process waste streams and Refinery slag leach operations. Drum washing operations.	1953–1989	DU, U, EU, Ra, Th	
			U, RU, EU	1953–1989; see Figure 2-1
			Th	1966; 59 MT 1967–1969; 148 MT 1970–1971; 162 MT
Plant 9 Special Products Plant	Thorium metal production. Casting larger ingots than those produced in Plant 5. Machining as-cast ingots and billets for extrusion. Cleaning DU derbies for offsite shipment. Decladding unirradiated copper-zirconium fuel cores.	1954–1989	DU, U, EU, Ra, Th	
			U, RU, EU	1954–1989; see Figure 2-1
			Th	1954–1956; 380 MT

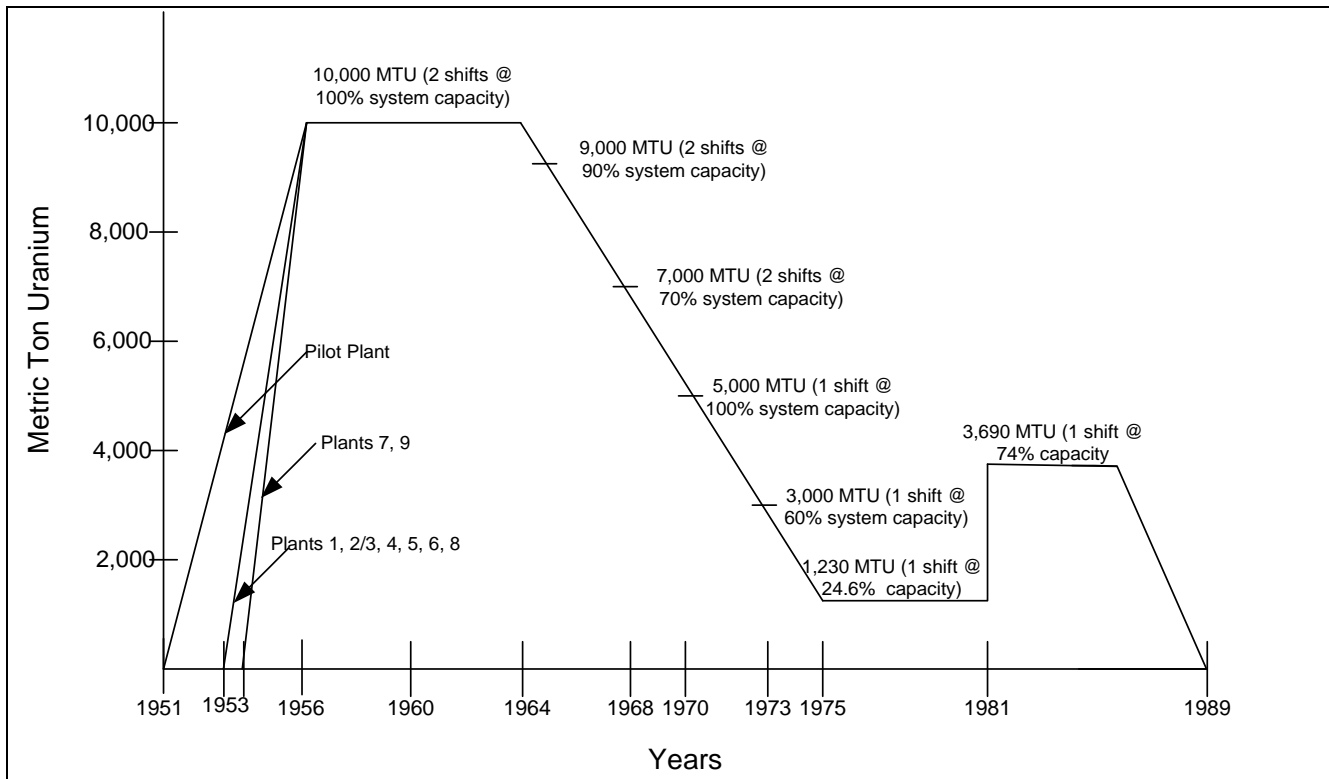


Figure 2-1. Uranium shipments (Mead, Savage, and Fugate ca. 1985, p. 124).

site as a result of continuing processes with a variety of uranium compounds. Each of the other plant operations also had internal and external exposure potential. In addition, 70% of the thorium production at the site was performed in the Pilot Plant. Plant 1 was designated as the official U.S. Atomic Energy Commission (AEC) sampling station for determining uranium and isotopic assays of uranium ores and concentrates; internal exposure potential resulted from releases from equipment and during handling. Plants 2 and 3 conducted the chemical processing of ores and residues, which involved large quantities of uranium and its progeny in liquid and solid forms that resulted in the release of significant quantities of uranium compounds to the work environment. Plant 4 conducted a chemical conversion process that resulted in measurable levels of activity of in-process uranium compounds in the air of the work environment. Plant 5 metal handling processes were inherently dusty and produced air contamination. Plant 6 fabrication activities produced internal exposure potentials of significance through relatively frequent uranium fires and handling operations. Plant 7 handled UF_6 for 3 years, which is volatile and inherently difficult to contain and produced significant releases. Plant 8 processed large quantities of uranium and thorium with resultant releases. Plant 9 provided fabrication of uranium and thorium metal parts, and exposure potential was consistent with the other FMPC plants with similar operations (Boback 1981 and Mead, Savage, and Fugate ca. 1985).

Each plant also had waste or scrap products that it stored or processed for reuse or disposal in areas called Production Area Waste Sites. Each of these waste and scrap operations had relatively high internal exposure potential in relation to other FMPC operations (Mead, Savage, and Fugate ca. 1985).

Other waste sites include the K-65 storage silos and the disposal pits that were constructed for radioactive waste products from plant processes. Internal exposure potential existed for disposal operations personnel and resulted from materials in the silos and wind-borne waste materials from the pits (Mead, Savage, and Fugate ca. 1985).

2.3.1 Pilot Plant – UF₆ to UF₄ Reduction Plant

The Pilot Plant was located in the southwest corner of the fenced production area and was completed during 1951; it had a ground floor area of 23,500 ft². Its primary function was to convert UF₆ to UF₄ for use in the metal production process. In addition, the Pilot Plant had the capability of coating, by plasma spray, the crucibles for casting uranium metal. The principal functions of the Pilot Plant were (ASI ca. 1986, p. 26):

- Reduction of UF₆ to UF₄ assaying up to 2.5% ²³⁵U;
- Purification and conversion of thorium nitrate solution to various thorium compounds; and
- Miscellaneous operations for shot-blasting uranium derby metal and plasma spray coating graphite crucibles.

This unit of the FMPC production complex had a wide range of chemical and metallurgical process equipment for the production of small quantities of uranium and thorium products. A variety of operations and assorted tasks occurred in this plant (ASI ca. 1986, p. 26).

A considerable part of the metal FMPC produced was DU. The principal source for DU was the UF₆ tails, the byproduct from uranium enrichment at the gaseous diffusion plants.

2.3.1.1 Processes and Activities

The Pilot Plant converted gaseous UF₆ to solid UF₄ green salt. The UF₆ arrived in solid form in large cylinders. To produce UF₄, the UF₆ was first heated to form a gaseous compound and subsequently reduced to UF₄. Three autoclaves and twin tube reactors were operated using a distributed control system. The UF₆ flow rate from the autoclave to the reactor tubes was approximately 2,200 lb/hr (50 psig and 230°F). Both reactor tubes operated in the ranges of 900°F to 1200°F and 5 to 20 psig. Under these conditions, the facility was designed to produce 16 MTU per day at 100% on-stream factor. Enriched UF₆ assaying as much as 2.5% ²³⁵U could be processed (ASI ca. 1986, p. 26).

Other equipment was available for such operations as metallic shot preparation; plasma-spray coating of casting crucibles for controlling carbon pickup; shot-blasting uranium derbies for removal of slag material; and salt-bath heat treating. Single uranium melts as large as 3 t could be cast in the special 6-ft-diameter vacuum casting furnace (ASI ca. 1986, p. 27).

Thorium ores, crushed thoria (powdery form of thorium dioxide) pellets, thorium oxalate, and other thorium materials were processed through the Pilot Plant thorium digestion and/or extraction system from about 1964 through 1980. These systems were used to produce a purified thorium nitrate solution that could be used as feed for the production of high-quality thorium compounds (thorium hydroxide) or metal. In addition, purified thorium nitrate solution was shipped as product. The digestion and extraction systems were not used continuously during the period they were in service. During some years the systems achieved throughput rates as high as 1 t/d of purified thorium nitrate solution; in other years they operated periodically or not at all (Hill 1989, p. 27).

When thorium was processed in the Pilot Plant, the waste liquors were neutralized with barium carbonate and aluminum sulfate to reduce the ²²⁸Ra activity. Because of its higher ²²⁸Ra content, raffinate from the thorium extraction process was segregated from other thorium liquid wastes and subjected to a double BaCO₃A1₂(SO₄)₃ treatment and filtration before the resultant filtrate was pumped to the general sump (ASI ca. 1986, p. 48).

Available production records indicate that 790.4 MT of thorium in the form of purified thorium nitrate solution was produced from 1966 to 1973. No production records have been found for other years. No production data are available for the digestion system (Hill 1989, p. 27).

The solvent extraction refining was followed by a multi-tank system for precipitation, several filters, and an oven-drying system to produce thorium oxalate, thoria gel (hydrated gel oxide), or thorium tetrafluoride. Metal was produced by further processing ThF_4 through atmospheric furnaces for dehydration and metal reduction, vacuum furnaces for dezincing, and all auxiliary systems. A portion of the integrated extraction-precipitation system converted impure thorium nitrate solution to a storable dried thoria gel product for future DOE requirements. Production records indicate that 809 thorium derbies weighing a total of approximately 51 MT of thorium metal were produced by this process between 1969 and 1971 (Hill 1989, p. 31).

Production records also indicate that 492 MT of thorium as thoria gel was produced from 1966 to 1970. Production for 1964 and 1965 was estimated based on a linear extrapolation of the quantity produced in 1966 through 1970. The estimated total production from this process is 686 MT assuming linear production from 1964 to 1970. From 1971 through 1976, 153 MT of thorium, as thorium oxalate, was produced by the precipitation process at the Pilot Plant. From 1977 through 1979, production records indicate that 350 MT of thorium as thoria gel was produced by similar processes for storage (Hill 1989, p. 33). In 1966, thorium nitrate tetrahydrate crystals were produced during a short-term test. Purified thorium nitrate tetrahydrate solution was boiled in a tank to a defined concentration. The molten salt was fed onto a water-cooled conveyor where it crystallized, and the product was drummed at the end of the conveyor. A total of 425 kg of thorium as thorium nitrate tetrahydrate crystals were produced during this test (Hill 1989, p. 29-33).

2.3.1.2 Radiation Sources

Radioactive sources in the Pilot Plant were primarily uranium and RU that consisted of UF_6 and UF_4 powder with mixed enrichment from depleted to 2.5% ^{235}U by mass. Other radioactive sources included thorium metal and compounds.

2.3.2 Plant 1 – Sampling Plant

The Sampling Plant was completed in 1953 with a ground floor area of 22,040 ft². This plant supported operations throughout the site. Its principal capabilities were (ASI ca. 1986, p. 20):

- Shipping, receiving, sampling, and storing large amounts of DU, NU, and EU materials in open and covered storage areas.
- Drying, crushing, milling, grinding, and classifying feed materials for processing.
- Digesting enriched residues assaying 5% to 20% ^{235}U in geometrically safe equipment.
- Opening unirradiated fuel pins containing EU dioxide pellets.
- Reconditioning steel drums for reuse and baling deteriorated drums for salvage.

The Sampling Plant weighed and sampled FMPC-generated and offsite recycled materials using various equipment to establish nuclear materials control data for accountability and control of fissionable materials that were processed at the FMPC. All incoming receipts were verified using nondestructive testing in the isotopic verification facility. The isotopic verification of incoming EU materials began in April 1972. At one time, the principal function of the Sampling Plant was to obtain representative samples of large quantities of incoming ore concentrates. In 1988, however, the

primary function was to store recycled materials until they were required by other production plants. The available storage area was 43,100 ft² of open pads in a fenced area (ASI ca. 1986, p. 21).

2.3.2.1 Processes and Activities

The sampling operation included a number of supporting operations. Several large-scale systems existed for crushing, grinding, and blending solid materials. These systems had a combined capacity of more than 10 t/hr. Major equipment included hammer mills, ring-roll mills, and falling-stream samplers. Some of this equipment was shielded for handling radioactive materials. Special dust collecting and ventilating equipment permitted the processing of toxic and radioactive materials. EU slag and selected recycled materials were processed through a ring-roller mill for reuse in the production of uranium derby metal or for chemical processing to UO₃ in the refinery. This equipment could reduce particulate size to 95% minus 325-mesh at a rate of up to 9 t/d (ASI ca. 1986, p. 21).

A safe geometry digestion system provided a capability of safely processing EU materials assaying from 5% to 20% ²³⁵U at a rate of about 100 kg per shift (ASI ca. 1986, p. 21).

Other facilities were available for opening fuel rods containing enriched UO₂ pellets and powder, reconditioning steel drums, and scrap metal baling (ASI ca. 1986, p. 21).

2.3.2.2 Radiation Sources

The principal types of radioactive materials that were received and sampled at the outset of Sampling Plant operations were (ASI ca. 1986, p. 21):

- Q-11 material (code name for pitchblende), most of which was mined in the Belgian Congo. Because no processing was performed on this material before its receipt at the FMPC, it contained the equilibrium quantity of radium and its progeny, including ²²²Rn, which required shielding against radiation during processing of the radium-bearing streams.
- Uranium in magnesium precipitate (MgX) from a leaching process.
- Q-11 containing less than 25% uranium. This low-grade Q-11 was processed in the Belgian Congo, and production was discontinued about the time the refinery was ready for operation. Only small quantities were received.
- Black oxide from concentration of low-grade uranium ores of U.S. and Canadian origin.
- Uranium in sodium salt (NaX) from precipitation of leach liquors (from low-grade U.S. or Canadian source uranium ores) with sodium hydroxide.
- Canadian ores that contained thorium. These ores started arriving in 1956 and reached large-quantity levels by June 1957.
- Uranium compounds of up to 5% enrichment. In 1965, the FMPC became the official receiving station for uranium compounds of up to 5% ²³⁵U from licensees. With the startup of EU operations in the refinery in 1966, more than 1,500 safe mass batches of up to 10% ²³⁵U feed materials were prepared for drum digestion. This was RU including contaminants as discussed in Section 2.5.2.
- Higher enrichment uranium compounds. In 1967, the isotopic level for the digestion operation was reduced to a maximum assay of 5% ²³⁵U as a further nuclear safety measure. Feed materials in the 5% to 10% assay range were set aside for the Safe Geometry Digestion

System that started up in 1970 to provide the capability of safely processing EU materials up to 10% ^{235}U . In subsequent years the range was increased to accept up to (but less than) 20% enriched material.

- Concentrate and residue drums. After the Mallinckrodt Chemical Works Refinery was shut down in 1966, more than 20,000 drums of concentrates and residues were shipped to the FMPC and stored on the Plant 1 pad.
- Shipments of purified uranium concentrates from Grand Junction, Colorado, began arriving in mid-1972. Shipments were resumed in 1974, and use of this material in the refinery was given priority to avoid storage.

Air samples were collected and reported in terms of the maximum allowable concentration (MAC). Early in the program the MAC was set at 70 dpm alpha/m³ (Quigley 1963, p. 3).

2.3.3 Plant 2/3 – Refinery

The Refinery was built in 1953 and had a ground floor area of 36,604 ft². The refinery converted the Government stockpile of NU ore concentrates to UO₃. In 1988, the refinery operated intermittently on a sequential campaign mode to convert enriched recycled materials to oxide. The principal capabilities of the refinery were (ASI ca. 1986, p. 22):

- Digesting EU recycled materials in nitric acid and storing blended feed solutions in stainless-steel tanks.
- Performing solvent extraction operations in stainless-steel, perforated-plate pulse columns to purify the uranium solution.
- Concentrating pure uranium solution by evaporation, and converting the uranium to UO₃.
- Recovering nitric acid from NO_x discharges from the digestion and denitration operations.
- Recovering uranium from internal process waste solutions.

The three steps in the process of producing UO₃ from scrap residue materials were digestion, extraction, and denitration. Auxiliary operations included the recovery of nitric acid from nitrogen oxides and uranium from internal process liquors (ASI ca. 1986, pg. 23).

2.3.3.1 Processes and Activities

Recycle materials from various sources were conveyed into agitated tanks for digestion using nitric acid. The resulting slurry consisted of acid insolubles and a digest liquor of impure uranyl nitrate and excess nitric acid. Adjustments were made to ^{235}U and nitric acid concentrations. After a check for proper solution concentrations, the blended feed was pumped to the extraction system. Low-grade uranium slurries, primarily from the leaching of EU slag materials, required filtration and evaporation (ASI ca. 1986, p. 23).

In the extraction columns, two immiscible liquids entered from opposite ends and were pumped counter-current to each other in a pulsating manner through a large number of perforated plates. The combined actions of the pulsations, the counter-current flow, and the turbulence created by perforated plates caused the two liquids to become intimately mixed. In the primary extraction columns, the two liquids brought into contact were the aqueous feed slurry and an organic solvent – a mixture of tributyl phosphate and kerosene. The uranyl nitrate in the feed slurry was preferentially attracted to the

organic solvent in the presence of nitric acid. Most of the nitric acid and impurities were left behind in the aqueous raffinate, which is excluded in uranium (ASI ca. 1986, p. 23).

A raffinate mixer-settler was used in series with the primary extraction columns to further reduce the uranium content of the aqueous waste stream leaving the columns. Extraction raffinate was sent to the general sump for neutralization with slaked lime. Neutralized raffinate was sent to interim waste processing facilities for conversion to a dry solid for offsite burial (ASI ca. 1986, p. 23).

Additional purification of the uranium in the extract stream was achieved by scrubbing with a small counterflow of water. The aqueous stream from the scrubbing operation was recycled to the digestion operation for use in preparing feed slurries (ASI ca. 1986, p. 23).

Purified uranyl nitrate was recovered from the organic solvent stream by re-extraction with deionized water in perforated-plate pulse columns. In the absence of nitric acid, uranyl nitrate in the solvent was preferentially attracted to the water phase. After treatment with a sodium carbonate solution for removal of degradation products, the stripped solvent stream was reacidified and recycled to the primary extraction columns. The aqueous uranium nitrate product was sampled and analyzed to ensure conformance with strict chemical purity specifications before introduction to the denitration system (ASI ca. 1986, p. 23). This aqueous uranyl nitrate product, at a concentration of approximately 100 g/L U, was sent to the denitration process.

In the denitration process, pure aqueous uranyl nitrate solution was concentrated by forced convective evaporation and high-pressure steam boildown to approximately 1,300 g/L U. It was calcined in batches in nominal 1,900-L agitated denitration pots to yield UO_3 , the end product of refinery operations. After milling, the uranium trioxide was packaged in hoppers, with each hopper containing approximately 4.5 MTU, or into 55-gal drums (ASI ca. 1986, p. 24).

Nitric acid and uranium were recovered in auxiliary operations. The nitric acid recovery system consisted of two bubble cap absorption towers operating in series at atmospheric pressure. This system operated in conjunction with the refinery to recover nitric acid from the NO_x fumes generated from the digestion and denitration areas and from other minor sources. The acid was returned to the digestion area for reuse in preparing feed slurries. The acid recovery operation reduced operating costs by saving acid, and it reduced discharges to the environment (ASI ca. 1986, p. 24).

Uranium in aqueous waste streams from the solvent treatment and cleanout operations was precipitated with magnesia and recycled to the digestion area (ASI ca. 1986, p. 24).

In 1968, Plant 2/3 was used to process thorium as a thorium production test for a short duration. Few details are available about this process. Thorium nitrate crystals were produced in a denitration pot in Plant 2/3. Interviews with long-time employees indicated that this was a short-term operation; probably one pot of crystals was produced. Other records discuss the production of thorium oxide in Plant 2/3 by a process of denitration, redigestion, and drying (ASI ca. 1986, p. 26).

2.3.3.2 Radiation Sources

The radioactive materials that were handled and processed in Plant 2/3 included (ASI ca. 1986):

- Enriched RU as discussed in Section 2.5.2.
- Uranyl nitrate solution with variable concentrations. The solvent extraction product was at a concentration of 100 g/L U, and the evaporative concentrate was at 1,350 g/L U.
- Solid powder of UO_3 .

- Extraction raffinate (K-65 material).

2.3.4 Plant 4 – Green Salt Plant

In October 1953, the Green Salt Plant began to produce green salt (UF_4) from UO_3 . The ground floor area was 26,500 ft². The UO_3 was either produced in the refinery or recycled from other DOE sites. The primary functions of the Green Salt Plant are (ASI ca. 1986, p. 24):

- Processing UO_3 to uranium tetrafluoride, UF_4 , or green salt, in continuous-flow reactor banks that were designed and staged for gas-solid reactions
- Blending and packaging depleted UF_4 for the Metal Production Plant (Plant 5)
- Operating the tank farm to supply production plants with bulk quantities of required liquid chemical agents

In the Green Salt Plant, UO_3 was converted to uranium dioxide, UO_2 , or brown oxide, by reducing it with hydrogen. The UO_2 was converted to UF_4 in a reaction with anhydrous hydrogen fluoride. The UO_3 recycled from the reactor sites underwent double pass reduction-oxidation-reduction processing to achieve high yields of product UF_4 (ASI ca. 1986, p. 24).

2.3.4.1 Processes and Activities

Mobile hoppers delivered the orange oxide to stainless-steel fluid bed reactors, which were heated to approximately 1,100°F. Dissociated ammonia entered the bottom of the reactors through a gas diffuser. The hydrogen and nitrogen held the UO_3 powder in suspension. Partially converted UO_3 overflowed from the first fluid bed reactor into the second, where the reaction with hydrogen was completed (ASI ca. 1986, p. 24).

Hydrofluorination took place in groups of three heated horizontal ribbon-screw reactors arranged in vertical stacks. Uranium dioxide entered at one end of the top reactor, and was conveyed slowly to the other end and stirred by a power-driven ribbon screw. The operating temperature was progressively higher for each reactor, starting at approximately 300°F at the first and ranging up to 1,200°F at the third. Anhydrous hydrogen fluoride gas entered at the discharge end of the first and third reactors and flowed countercurrent to the powder flow. The UF_4 product was weighed, blended, sampled for chemical analysis, and packaged in 38-L cans for transportation to Plant 5 (ASI ca. 1986, p. 25).

Initial production throughput from Plant 4 did not progress as rapidly as expected. It was not until 1956, when 5,029 MTU was achieved, that the design rate of 5,193 MTU/yr was approached (ASI ca. 1986, p. 25).

Normal and enriched UF_4 production decreased during 1967 and 1970 because of declining demand. Plant 4 operated only 4 months in 1971 and 2 months in 1972 on enriched UF_4 production. The plant was idle during 1973 (ASI ca. 1986, p. 25).

In April 1974, production began on enriched UF_4 for the New Production Reactor Stream and continued through June. Another enriched campaign occurred from January through April 1975 (ASI ca. 1986, p. 25).

The Plant 4 process was idle from the 1975 enriched campaign through 1977. A small campaign occurred in 1978, and the plant was again shut down in 1979. In 1980, the process was restarted and

operated packaging depleted UF₄ from T-hoppers into cans for the Mark 31 stream, processing UO₃ and UF₄ T-hoppers, and operating the Tank Farm (ASI ca. 1986, p. 26).

In 1954, Plant 4 was used for a short campaign to produce dry ThF₄ from the ThO₂ that was dried and calcined in Plant 9 in hydrofluorination Bank 7. The ThF₄ was returned to Plant 9 and used to produce thorium metal. This was a short-duration process due to mechanical difficulties in Bank 7 and it is believed that this process was only operated for a short period and the potential for emissions was very slight. Production quantities are not available for ThF₄ production in Plant 4 (Hill 1989, p. 27).

2.3.4.2 Radiation Sources

NU oxide concentrated from offsite ore refineries, and the same uranium and thorium produced in Plant 2/3, were used in Plant 4.

2.3.5 Plant 5 – Metals Production Plant

Construction of this facility was complete in 1953. The ground floor area was 58,620 ft². At the Metal Production Plant, UF₄, the product of Plant 4 and the Pilot Plant, underwent a thermite-type reaction with magnesium to produce uranium metal. The principal functions of the Metals Production Plant were (ASI ca. 1986, p. 28):

- Reducing uranium tetrafluoride to high-purity DU, NU, and EU derby metal with magnesium in electric resistance furnaces.
- Casting DU derbies and recycled metal scrap into ingots using vacuum melt induction furnaces.
- Sawing ingots to size.
- Sampling metal products for quality.
- Machining graphite into almost any shape using lathes, saws, milling machines, routers, and grinders.
- Milling MgF₂ slag byproduct for reuse in lining reduction pots.

2.3.5.1 Processes and Activities

To begin the reduction process that produced uranium metal, UF₄, and magnesium granules, totaling about 500 lb, were blended and charged into a steel pot lined with magnesium fluoride slag. The pot was capped with slag to protect it from the intense heat of the reaction. Materials handling systems were included in the Productivity Retention Program to reduce worker contact with uranium materials in this area. The pot was fitted with a steel cover and heated in a resistance furnace to a temperature range of 1200°F to 1500°F for 3 to 4 hours, until the contents reacted spontaneously. At this point, the internal temperature of the pot might have reached 3,000°F. Approximately 5 minutes after the reaction occurred, the pot was removed from the furnace and stored in an air-cooling tank for at least 1 hour, and then transferred to a water-cooling tank for several hours. After cooling, the contents were removed and the uranium mass, called a derby, was separated and cleaned by slag chipping hammers (ASI ca. 1986, p. 29).

Standard depleted production derbies weighed approximately 167 kg U. Enriched derbies weighed approximately 152 kg U. Most of the derbies were transferred to the Metals Production Plant casting area, some were sent to the Special Products Plant casting area, and others were sent to other DOE

sites. The MgF_2 slag from the thermite reaction was milled for reuse as liner material (ASI ca. 1986, p. 29).

In the casting process, cleaned DU or normal derbies together with recycled metal scrap were charged into a graphite crucible. The loaded crucible was placed in a vacuum induction furnace and heated for about 95 minutes at 130 kW input to approximately 2,700°F, at which temperature it was ready to pour. A shear plug in the bottom of the crucible was broken to permit the molten metal to flow into a heated graphite mold directly under the crucible. After cooling, the mold was separated from the ingot, cleaned, and prepared for reuse. Crucibles were flame-treated to oxidize residual uranium. On occasion, metal spills occurred from mold breakage. All product ingots cast in the Metals Production Plant were for supplying target element core requirements for reactors at the Savannah River Site. Slab billets were cast from derby metal for the Rocky Flats Plant (ASI ca. 1986, p. 29).

As-cast ingots were cropped by sawing approximately 2 in. from the top section to remove shrinkage cavities and impurities that rose to the top of the melt after pouring and during solidification. Ingot dimensions ranged from 23 to 40 in. in length. Longer ingots were sawed in half, producing two billets for the extrusion step. After sampling, cropped ingots were transferred to the Special Products Plant for center drilling and surface machining. Before machining, as-cast ingots weighed up to 653 kg U. Machined billets weighed as much as 520 kg and were heat-treated in Plant 6, the Metals Fabrication Plant, before being moved to another site (ASI ca. 1986, p. 30).

2.3.5.2 Radiation Sources

Radioactive sources in Plant 5 consisted of uranium and RU as UF_4 granules, uranium metal derbies, billets, and ingots, and uranium oxide in MgF_2 .

2.3.6 Plant 6 – Metals Fabrication Plant

The ground floor area of the Metals Fabrication Plant was 206,270 ft². At this plant, uranium metal products were heat-treated to improve their strength and grain structure. Some of these products were shipped off the site for extrusion. The extruded tubes were returned to the Metals Fabrication Plant to be machined into final products. After being inspected to ensure the highest quality, the products were shipped to other DOE sites. The principal capabilities of the Metals Fabrication Plant were (ASI ca. 1986, p. 31):

- Heat treating machined ingots for extrusion using neutral salt (NuSal) furnace and salt-oil baths.
- Heat treating and final machining of target elements or fuel cores.
- Cropping, surface milling, and inspecting products for shipment.
- Metal pickling and chip briquetting.
- Providing standby capabilities for rolling as-cast ingots into rods that had close dimensional tolerances.
- Inspecting finished target element cores and final products before shipment.

2.3.6.1 Processes and Activities

All center-drilled and machined ingots and billets from the Special Products Plant were heat-treated in a molten salt bath (50% NaCl, 50% KCl) at 1,350°F and water-quenched to achieve the beta phase grain structure for improving extrusion and final machining yields. Heat-treated ingots and billets were extruded into tubular forms having various inside and outside diameter dimensions. Extruded billets for the N-Reactor were fabricated at Hanford, while extruded tubes for the Savannah River Site were returned to the FMPC for target element core fabrication (ASI ca. 1986, p. 31).

Extruded tubes were cut into 8-in. lengths using a cut-off lathe. After salt heating in the beta range and oil quenching, final machining was performed automatically on the Cross Transmatic machine. The machined elements were individually stamped for identification and processed through a degreasing step. Machining chips were recrushed, pickled, rinsed, dried, briquetted, and recycled to casting operations. NO_x destruction equipment was installed on the pickling system exhaust. Cleaned finished pieces were conveyed to the Final Inspection Area for testing by instrumental nondestructive techniques (ASI ca. 1986, p. 31).

DU nonbriquettable turnings were oxidized in a Recovery Plant furnace; nonremeltable metal spills and secondary top crops were stored on an outdoor concrete pad for potential sale to the commercial nuclear industry. EU nonbriquettable turnings were sent to the Recovery Plant for oxidation; the nonremeltable metal spills and top crops were recovered by dissolution in a refinery metal dissolver tank using nitric acid (ASI ca. 1986, p. 32).

The standby rolling mill facility consisted of an ingot preheating furnace, blooming mill, crop shear, equalizing furnace, flying shear and related conveying, and cooling and rod straightening equipment. The rolling capacity for oval billets and round rod was approximately 36 MT/d based on one-shift operation (ASI ca. 1986, p. 32).

2.3.6.2 Radiation Sources

Radioactive sources associated with Plant 6 included uranium and RU metal.

2.3.7 Plant 7 – Hexafluoride Reduction Plant

Plant 7 operations began in June 1954. The plant converted uranium hexafluoride to green salt using the same process as the Pilot Plant. The green salt was used in Plant 5 to produce uranium metal. After only 2 years of operation, AEC directed the shutdown of Plant 7 because a similar processing plant was operating in Paducah, Kentucky. For the next 13 years, site management considered several proposals for the idle facility, but none were accepted. In 1969, all equipment was excessed and sold, and the building was used to store drums of green salt and empty containers (ASI ca. 1986, p. 27).

2.3.7.1 Processes and Activities

Plant 7 was designed for the conversion of UF₆ to UF₄ in a gas-gas reaction. UF₆ gas vaporized from storage cylinders was mixed with hydrogen gas produced by ammonia dissociation in a specially designed nozzle inside a tapered vertical reaction tower that was maintained at approximately 1000°F with 100-kW heaters and forced-air cooling (ASI ca. 1986, p. 28).

Most of the solid UF₄ that was formed in the reaction settled downward in the tower as a fine powder and was collected in a surge hopper. Some of the product was carried out of the reactor with byproduct HF and excess hydrogen and collected. The product UF₄ was conveyed through a micropulverizer, batch-blended, packaged into 10-gal cans, and weighed (ASI ca. 1986, p. 28).

The filtered gases, HF, H₂, and N₂, from the solid collection system were passed through a Monel wool filter, cooled to 150°F, passed through a CaF₂ chemical trap, and refrigerated to -90°F. The condensed anhydrous liquid HF was sent to the Tank Farm for in-plant storage before its use or sale. The uncondensed HF was absorbed and neutralized in a lime slurry system. Hydrogen leaving the scrubbers was burned, and the combustion gases vented to the atmosphere (ASI ca. 1986, p. 28).

The design capacity of this plant was 12 t/d of uranium as uranium tetrafluoride, split evenly between DU and normal uranium from two sets of four reactors each. One on-stream spare reactor per set was included (ASI ca. 1986, p. 28).

At the completion of plant construction, the capacity was determined to be a UF₆ feed rate of 300 lb/hr. Based on a 75% on-stream factor for the eight-reactor capacity, the UF₄ production rate was calculated to be 14.6 t/d. By December 1955, the UF₆ feed rate was at 550 lb/hr, and the UF₄ rate was at 26.76 t/d (ASI ca. 1986, p. 28).

2.3.7.2 Radiation Sources

The sources of radioactivity during the limited years of operation for Plant 7 were UF₆ and UF₄.

2.3.8 Plant 8 – Scrap Recovery Plant

Plant 8 construction was complete in 1953, and production began in November of that year. The ground floor area was 25,500 ft². In the Scrap Recovery Plant, recycled residues and scrap from uranium processing were upgraded before being sent to the refinery for uranium extraction. In addition to recycling functions, the plant equipment was used to treat EU residues. The primary functions in the Scrap Recovery Plant included (ASI ca. 1986, p. 27):

- Furnacing various enriched residues from onsite generation and offsite receipt to prepare refinery feed by removing moisture, oil, graphite, and metallic impurities.
- Filtering large volumes of low-level radioactive waste slurries using rotary vacuum pre-coat filters.
- Drying and heating in a furnace, waste materials for offsite disposal, including contaminated filter cakes from neutralized process waste streams and Refinery slag leach operations.
- Drum washing operations.

2.3.8.1 Processes and Activities

The Scrap Recovery Plant process primarily involved upgrading EU recycled materials from FMPC and offsite operations to produce feed materials for head-end processing in the refinery. Recycled materials that contained metallic uranium or magnesium, oil, graphite, or other troublesome agents were roasted to oxidize the components. Oversize pieces were screened and milled. Wet materials were dried; several furnaces were used for these purposes: a rotary kiln, multiple-hearth vertical furnaces, and small single-hearth furnaces (ASI ca. 1986, p. 27).

All roasted materials were used as feed in the refinery. Recycled materials of significantly different isotopic assays were segregated throughout processing and in storage. The size of production equipment limited processing of enriched materials to 1.25% ²³⁵U. Filtration equipment was used for reclaiming low-level solid waste for drying, packaging, and shipment off the site for burial (ASI ca. 1986, p. 27).

Various thorium residues were processed through the Plant 8 oxalate system to thorium hydroxide to return them to the production stream. Residues were digested in hydrochloric acid and the solution was filtered on a rotary vacuum filter. The filtrate was pumped to a precipitation tank and mixed with oxalic acid. Thorium oxalate precipitated out of the solution. The thorium oxalate precipitate was filtered, slurried, and reverted with sodium hydroxide solution to thorium hydroxide. The thorium hydroxide was filtered on a rotary vacuum filter and the solution was recycled back to the precipitation tank. The filter cake was calcined in a multiple hearth furnace called the uranium ammonium phosphate furnace. The dried thorium hydroxide was digested in the Pilot Plant digestion system (Hill 1989, p. 36).

Approximately 310 MT of thorium as thorium hydroxide were produced through the Plant 8 oxalate system (Hill 1989, p. 36).

Thorium hydroxide was produced in Plant 8 for 6 months in 1966 in the reversion system. Thorium tetrafluoride was reverted to thorium hydroxide by heating it in a reverter tube with hydrofluoric acid. The offgas from the reverter was neutralized in a caustic scrubber. Approximately 59 MT of thorium, in the form of thorium hydroxide was produced by this system (Hill 1989, p. 33).

2.3.8.2 Radiation Sources

Radioactive sources in Plant 8 included uranium, RU metal, and thorium compounds.

2.3.9 Plant 9 – Special Products Plant

Construction of the Special Products Plant was complete in 1954; the facility had a ground floor area of 48,500 ft². This facility was originally designed and constructed as a thorium metal production plant. The two basic processes, hydrofluoric acid precipitation of thorium fluoride and induction dezincing and melting, which were used to start the plant, were not able to produce a pure metal. However, improvement in production techniques permitted the eventual development of an oxalate precipitation process capable of producing pure thorium metal (ORAUT 2007a, b). The process began with the dissolution of solid thorium nitrate tetrahydrate in nitric acid. Hydrofluoric acid was added to the solution to precipitate a wet thorium tetrafluoride (ThF₄). The ThF₄ was dried in a pre-dryer and a retort dryer and then was pulverized. The pulverized ThF₄ was blended with calcium metal and zinc chloride and placed in a refractory lined furnace pot. Thorium tetrafluoride was co-reduced by the calcium to form a zinc-thorium derby, from which the zinc was removed and remelted in a vacuum furnace. The resulting 500 kg thorium metal ingot was machined to produce the final thorium metal product. An estimated 380 MT of thorium metal were produced in Plant 9 from 1954 through 1955 (Hill 1989, p. 25).

2.3.9.1 Processes and Activities

Because thorium processing was infrequent and in small amounts, the primary function of the Special Products Plant became casting larger ingots than those produced in Plant 5 and machining uranium metal pieces for extrusion. The principal capabilities of the Special Products Plant were (ASI ca. 1986, p. 30):

- Casting EU derbies and recycled metal scrap into large-diameter ingots for the N-Reactor.
- Machining as-cast ingots and billets for extrusion.
- Cleaning DU derbies for offsite shipment.
- Decladding unirradiated copper-zirconium fuel cores.

Operations in the Special Products Plant primarily involved machining uranium metal pieces and casting EU ingots up to 13 in. in diameter and 25 in. in length and weighing up to 900 kg uranium.

Shrinkage cavities and impurities were removed by cropping the top section, as with smaller ingots. Cropped ingots from both plants were center-drilled on a unique LeBlond-Carlstadt Rapid Boring machine. Surface machining was performed on standard lathes. All ingots cast in the Special Products Plant are for supplying the enriched N-Reactor fuel core requirement for the Richland reactor site. Machined ingots weigh as much as 520 kg U and undergo heat treating in the Metals Fabrication Plant (ASI ca. 1986, p. 30).

A chemical decladding process, called Zirnlo, was performed in the Special Products Plant. Reject co-extrusion sections from the cladding operation at Hanford were immersed in dilute nitric acid to remove the outer copper layer that served as a lubricant during co-extrusion of Zircaloy-2 and uranium. The decoppered coextrusion sections were treated with dilute HF to remove the Zircaloy-2 jacket that encased the uranium metal core. The totally declad bare uranium metal cores were recycled to the casting operation for remelting to ingot form (ASI ca. 1986, p. 31 and Dolan and Hill, p. 62).

2.3.9.2 Radiation Sources

Radioactive sources in the Special Products Plant were RU and uranium metal, and thorium metal and compounds.

2.3.10 Radiation Generating Equipment

There was a Cockcroft-Walton neutron generator located inside a shielding cave in the courtyard of the Analytical Laboratory facility (Building 15) that was protected by a locked and controlled 8-ft chain link fence (Marshall 1965, p. 13). The neutron generator was used to activate uranium residue samples, with 14-MeV or thermal neutrons, to determine the percent of ^{235}U from counting spectral analysis of the activated products.

The radiation sources that were associated with the operation and maintenance of the generator were neutrons produced during its operation and tritium exposure from the generator's targets during maintenance and target change-outs.

2.4 WASTE MANAGEMENT FACILITIES ACTIVITIES AND PROCESSES

Locations of waste treatment and storage facilities were inside and outside the fenced production area of the FMPC.

The Waste Storage Area outside the production area included six low-level radioactive waste storage pits, two earthen-bermed concrete silos that contained K-65 residues (high specific activity, low-level radium-bearing residues), one concrete silo that contained metal oxides, and affected adjoining areas. It also included two fly ash piles approximately 3,000 ft south-southwest of the waste storage area as well as the burn pit between Pits 3 and 4.

2.4.1 Production Wastes

A wide variety of chemical and metallurgical processes were used at FMPC to produce high-purity uranium metal. As a result, various waste forms were generated. Both solid and liquid wastes were produced. Radioactive and mixed wastes from FMPC production processes included wet filter cake, sludge, neutralized raffinate, dry slag, ash, metallic uranium fines, oxides, and miscellaneous trash.

Dry filter cakes from the Recovery Plant, from the filtration of raffinate and sludge that accumulated in the general sump, were stored in drums for disposal at the Nevada Test Site (NTS). Wet filter cakes

were drummed and stored on the FMPC and later (after 1986), the wet filter cakes were further dried in a rotary hearth furnace and drummed for disposal at NTS.

Combustible residues, sewage sludge, graphite, and oils that contained low-level radioactive wastes were treated as process residues and incinerated in various facilities. Uranium was recovered from the generated ash in the Recovery Plant of the refinery.

Noncombustible solid wastes, including clothing and gloves, were boxed or drummed for offsite shipment and disposal at NTS. The uranium content of these wastes was low, and uranium recovery was not feasible.

The chemical composition of the production wastes was quite varied, but major components were metal oxides and nitrates of copper, aluminum, and iron; calcium oxide; free uranium and uranium in various oxidation states; magnesium fluoride; and traces of free magnesium.

Several radionuclides, including uranium and thorium and RU contaminants (Section 2.5.2), were present in the radioactive and mixed wastes.

The uranium content of the various waste streams varies from about 0.0005 g U/g of solids in the neutralized refinery raffinate and slag leach filter cake to 80% to 100% uranium in discarded metal and oxides. The percent enrichment in ^{235}U was 0.2% to 1.1% in the waste materials (ASI ca. 1986, p. 32).

Beginning in 1972, the FMPC served as the thorium materials repository for DOE. Approximately two-thirds of the material in the repository was processed at the FMPC. The remainder originated at other DOE facilities (Robinson 2002, p. 7). An inventory of thorium was stored in the production areas and in Plant 8 silo.

2.4.2 Production Area Waste Treatment and Storage Facilities

The waste treatment, storage, and management facilities directly associated with FMPC production operations included the Thorium Overpacking Operation, Ferrous Metal Scrap Pile, Copper Scrap Pile, Waste Oil Storage Pad, Oil Burner, Plant 1 Storage Pad, Solid Waste Incinerator, Pilot Plant Tank Farm, Pilot Plant Warehouse, KC-2 Warehouse, and Refinery Storage Pad (ASI ca. 1986).

2.4.2.1 Thorium Buildings and Overpacking Operations

The thorium buildings (Buildings 64, 65, 67, and 68) were constructed with pre-engineered storage buildings. During the 1990s, drums of thorium in various plant locations, including those in Buildings 65 and 67, were overpacked and transferred to Buildings 64 and 78 for interim storage and eventual offsite shipment. Structurally unsound drums were placed inside larger containers by overpacking. The overpacked and structurally sound drums were transferred to Buildings 64 and 78 and subsequently placed in strong tight containers suitable for offsite shipment.

The stored thorium compounds (thorium hydroxide, oxide, and oxalates) came from two separate periods. In the 1950s, thorium metal was produced for the nuclear propulsion program that was cancelled in 1961. In the mid-1960s, thorium oxides were produced for the Light Water Breeder Reactor Program. The stored materials were out-of-specification production runs, process byproducts, or excess materials returned from downstream production facilities when the materials were no longer required.

2.4.2.2 Ferrous Metal Scrap Pile

The FMPC had approximately 5,000 MT of metallic scrap that contained above-background levels of uranium. This material was stored on a controlled curbed pad on the northeast corner of the site. The scrap pile consisted primarily of ferrous material; the remainder was a mixture of aluminum, stainless steel, copper, brass, and nickel. The scrap included, but was not limited to, vessels, wiring, cable, duct, pipe, tubing, valves, grating, sheets, plates, and miscellaneous abandoned equipment. Some materials at the facility were classified as low-level radioactive waste (ASI ca. 1986, p. 33).

2.4.2.3 Pilot Plant Tank Farm

The Pilot Plant Tank Farm was the location of the FMPC hazardous waste tank container facility. The facility consisted of two 10,000-gal stainless-steel storage tanks (T-5 and T-6) on a concrete pad that was surrounded by a concrete containment dike (ASI ca. 1986, p. 35).

The FMPC inventory of these tanks was 13,000 gal or 136,874 lb of spent degreasing solvents. Annual generation averaged approximately 110 gal (1300 lb) of RMI degreasing solvents (45% methylene chloride, 55% perchloroethylene) and 110 gal (1,110 lb.) of 1,1,1-trichloroethylene (ASI ca. 1986, p. 60).

2.4.2.4 Pilot Plant Warehouse

The Pilot Plant Warehouse was a totally enclosed and roofed warehouse facility with a poured concrete floor and side walls, so no rain would fall directly on the storage area. The storage area for hazardous waste at the Pilot Plant Warehouse was 7 ft wide by 62 ft long and equipped with curbed storage areas to contain leaks or accidental spills of liquid wastes (ASI ca. 1986, p. 36).

The Pilot Plant Warehouse container storage facility was used as the storage area for waste barium chloride salts that were shipped to the FMPC from RMI in drum containers with U.S. Department of Transportation specifications numbers 17H (ASI ca. 1986, p. 37).

2.4.2.5 KC-2 Warehouse

The KC-2 Warehouse container facility was a curbed storage facility 42 ft long by 7 ft wide in Bay No. 5 of the warehouse. The warehouse was roofed with a poured concrete floor, concrete block divided (side) walls, and chain-link front and back walls (ASI ca. 1986, p. 37).

In 1986, the KC-2 Warehouse container storage facility stored still bottoms and sludges from the spent solvent from the CIP/CUP program. This material was shipped to the FMPC from National Electric Coil, Louisville, Kentucky in the period of 1979 through 1981. The solvent used in the CIP/CUP program was 1,1,1 trichloroethane, which was used as a degreaser (ASI ca. 1986, p. 37).

Spent solvents that were generated on the site (1,1,1-trichloroethane), as well as spent solvents from off the site (45% methylene chloride/55% perchloroethylene) at the RMI facility, were generated as a result of degreasing operations. These solvents might temporarily have been stored at the KC-2 Warehouse container storage facility until the liquid waste could be transferred to the bulk storage tanks at the Pilot Plant Tank Farm (ASI ca. 1986, p. 37).

The KC-2 Warehouse (Bay 5) was used to store polychlorinated biphenyls (PCBs). Although PCBs are regulated by the Toxic Substances Control Act, polychlorinated biphenyl (PCB) wastes at the FMPC also contained uranium and were classified as mixed wastes. Solvent still bottoms and sludges, and PCB-containing capacitors were the two types of PCB-contaminated wastes stored at the KC-2 Warehouse (ASI ca. 1986, p. 37).

The inventory of PCB still bottoms and sludges was approximately 20,000 lb (37 55-gal drums) and two 55-gal drums of absorbent from cleanup operations. In addition, 19 55-gal drums of capacitors, one drum of rags from capacitor cleanup, one drum of PCB-containing water (30 gal) and one drum of laboratory samples were stored at this warehouse; this totals 51 drums of PCB-contaminated materials.

2.4.2.6 Refinery Storage Pad

In addition to the other production storage areas, a controlled pad at the Refinery (Plants 2/3) was used for storage of waste oil and oil sludges. The FMPC inventory at the Refinery Storage Pad was 900 55-gal drums of waste cutting and cooling oils. Approximately one 55-gal drum of waste oil was generated per day at the FMPC. In addition to the waste oil, 48 drums of oil sludges were stored at the Refinery Storage Pad (ASI ca. 1986, p. 38).

2.4.3 Waste Facilities Outside Production Area

Waste management facilities outside the FMPC Production Area include the Storage Silos, Low-Level Radioactive Waste Pits, Underground Storage Tanks, and Sanitary Landfill.

2.4.3.1 Storage Silos

Four above ground silos (Silos 1 to 4) used for storage of radium-bearing residues from the uranium ore processing were on the west side of the FMPC.

Silos 1 and 2 (K-65 Silos)

The two above-ground K-65 silos were constructed in 1955. They were used for storage of radium-bearing residues, a byproduct of uranium ore processing (ASI ca. 1986). The silos were of cylindrical concrete construction, 88 ft in diameter and approximately 27 ft high.

The silos were designed to be loaded with metal oxides in slurry form at a maximum rate of 8,000 gal/d. The radioactive residues were allowed to settle and the water was decanted, leaving sludge with a density of 100 lb/ft³ (ASI ca. 1986). The maximum allowable height of solid material was 23 ft, and the water level was limited to a maximum height of 25 ft.

In 1963, berms were constructed around each silo to provide lateral support to the silo walls and, as a secondary benefit, to provide shielding. In 1990, a protective coating was applied to the silos to minimize concrete deterioration and reduce radon emissions (Byrne, J. M. et al 1991, p. 230). Radon-222 (3.8 day half-life) is generated at a rate in secular equilibrium with its ²²⁶Ra parent (Dugan, et al 1990, p. 63). The nature of radon, being an inert radioactive gas, resulted in the continual release of the radionuclide from K-65 residues into the headspace of the silos. The actual quantity of radon present in the silo headspace was determined by the production rate (secular equilibrium) and the loss rate. There were essentially two loss mechanisms: the natural decay of radon gas and the escape of the gas from cracks and openings in the silo structure. After a period of time, there was a steady-state quantity of radon in the headspace. A Radon Treatment System (RTS) was added to reduce the level of radon gas in the headspace above the residues. This system was operated only when access to the silo domes for sampling or maintenance was required (FDF 1998a and FERMCO 1996).

Radon treatment involving a carbon collection system similar to the existing RTS results in a highly concentrated radon inventory with the carbon and a significant external radiation hazard. A person in proximity to the collection system without adequate controls would receive radiation exposures above allowable limits in a short period. Maintenance activities involving system entry must consider worker

exposure to gamma radiation and radon and its immediate progeny, and ^{210}Pb , which built up with time (FDF 1998a).

The K-65 silo area represented one of the most prevalent sources of gamma exposure at the FMPC (Fluor Fernald 2000, p. 131). Past projects involving significant stay times in the proximity of K-65 have produced some of the larger personnel whole-body exposures at the FMPC since 1990.

From 1953 through 1955, the FMPC refinery processed pitchblende ore from the Belgian Congo. No chemical separation or purification had been performed before the receipt of the ore at the FMPC. The generated residues were not mixed with other site wastes but were placed in two dedicated silos. Pitchblende residues were first added to the concrete storage silos in 1953. The residues were batch-pumped from the FMPC refinery to the silos as aqueous slurry. The supernatant liquid was withdrawn and pumped back to the refinery to be used in the slurring step. Additions to the silo ended in 1955 when the last pitchblende was processed at the FMPC. Also in 1955, pitchblende residues from another site were added to the silos. Core sampling of silo contents in 1972 showed a dry free-flowing powder at the surface and 40% moisture in the samples from the bottom.

A radiochemical analysis of the material in each silo material was performed in the past. Core sampling was performed on both silos and isotopic analyses were reported for uranium, thorium, radium, and other radionuclides.

External dose characteristics of the silos depended on the radon and radon progeny activity in the silo headspaces that emit gamma radiation. The actual quantity of radon present in the silo headspace was determined by the production rate (secular equilibrium) and the loss rate. After a period of time, there was a steady-state quantity of radon and radon progeny in the silo headspace. The Preliminary Hazard Analysis Report for OU4 Silos used 10 Ci (each silo) for the release calculation and projected a releasable radon inventory per silo headspace after clay covering dried and cracked could exceed 30 Ci per silo. The general area exposure rate at either silo dome was about 25 mrem/hr (FDF 1998b, p. 14).

Silo 3

Silo 3 contained approximately 138,000 ft³ of waste residues, known as cold metal oxides, which were generated during extraction operations in the 1950s involving uranium concentrates. The concentrates were received from a variety of uranium mills in the United States and abroad. The residues in Silo 3 were substantially different from those in Silos 1 and 2. First, Silo 3 residues were dry (~10% moisture) while K-65 material was wet (~30% moisture). The material was calcined before placement in Silo 3 and became a fully oxidized fine powder. Second, while the radiological constituents were similar to those in Silos 1 and 2, some radionuclides such as radium were present in much lower concentrations. The major fraction of metal impurities, including radium, was removed by the uranium mills before transfer to the FMPC site. Without the radium contribution, Silo 3 exhibited a much lower direct radiation field and radon emanation rate than Silos 1 and 2. The immediate concern about Silo 3 was the risk of inhalation dose from suspended material after a release. The radionuclide having both the largest specific activity (60 nCi/g) and the greatest fraction of relative dose (83%) in Silo 3 was ^{230}Th , which was produced from the natural decay of ^{238}U (FDF 1998b, p. 9).

The external dose characteristics for Silo 3 were based on the radium content. While the material stored in Silo 3 was similar to that in Silos 1 and 2, much of the radium had been removed by uranium mills before transfer to the FMPC site and was present in much lower concentrations than in Silos 1 and 2. Without the radium contribution, Silo 3 exhibited a much lower direct radiation field and radon emanation rate than Silos 1 and 2. The primary hazard for workers was the inhalation of the fine powder in the silo (FDF 1998b, p. 9).

Silo 4

As with Silo 3, Silo 4 was designed to receive cold metal oxides from uranium processing. Due to a process change in 1957, storage of the waste cold metal oxide was no longer necessary; Silo 4 was never used (FDF 1998b, p. 9).

2.4.3.2 Low-Level Radioactive Waste Pit Area

The Waste Pit Area was located west of the former production area and covered approximately 37.7 acres. It consisted of Waste Pits 1, 2, 3, 4, 5, and 6 and the Burn Pit (also used for the disposal and burning of waste).

Waste Pit 1

Waste Pit 1 was constructed in 1952. Its surface area was oval-shaped with dimensions at the bottom of approximately 165 ft wide by 347 ft long. Its depth averages 29.5 ft, including approximately 18 ft of waste, 11 ft of lining, and a 6-in. cover. Waste Pit 1 was a dry pit because waste slurries were filtered or calcined to remove water before they were placed in the pit. This pit primarily received neutralized waste filter cakes, vacuum-filtered sludge (from production activities), magnesium fluoride slag, scrap graphite, and contaminated brick. Waste Pit 1 was closed and covered with clean fill in 1959 (ASI ca. 1986, p. 42). Waste inventory records indicate that Waste Pit 1 contained 1,075 MT of uranium.

Airborne radioactive material concentration due to air particulate emissions at Waste Pit 1 for dose reconstruction purposes can be estimated using the fugitive uranium and thorium emissions from wind erosion.

Direct radiation for Waste Pit 1 is within the beta/gamma dose rate contour of 1.0 mrad/hr. Radiological analyses for soil samples taken in these areas indicate that uranium was the principal constituent for the elevated dose rates.

Waste Pit 2

Waste Pit 2 was constructed northeast of Waste Pit 1 in 1957 and operated from 1957 to 1964. In 1964, it was closed and covered with clean fill (ASI ca. 1986, p.43). The surface area boundary of Waste Pit 2 resembles a six-sided polygon with dimensions at the top of approximately 19 ft wide by 270 ft long. It is approximately 23.5 ft deep including 15 ft of lining and 1 to 4 ft of cover. Waste Pit 2 was a dry pit that received primarily waste filter cakes, vacuum-filtered production sludge, magnesium fluoride slag, scrap graphite, contaminated brick, and concentrated raffinate residues. Waste inventory records indicate that Waste Pit 2 contained 175 MTU.

Waste Pit 3

Waste Pit 3 was placed in service in December 1958. The surface area boundary of the pit is oval-shaped and has dimensions of approximately 450 ft wide by 720 ft long. This pit is approximately 42 ft deep, which includes a maximum of 14 ft of cover material, 27 ft of wastes, and an estimated 1 ft of native clay. Waste Pit 3 was the first waste pit built specifically for settling solids from liquid waste streams. Primarily lime-neutralized raffinate slurries and contaminated surface-water runoff were pumped to this pit. After Waste Pit 2 was filled, Waste Pit 3 received vacuum-filtered production sludge, neutralized liquid from process systems, neutralized refinery sludges, and cooling water from heat treatment operations. During the late 1960s, large quantities of neutralized residues from acid leaching of uranium-bearing magnesium fluoride slag were pumped to Waste Pit 3. In 1973, fill material (including filter cake, slag leach residue, lime sludge, and fly ash) was placed in Waste Pit 3, and construction activities were initiated to cover this waste with soil. Covering activities were complete in 1977 (ASI ca. 1986, p. 43). Waste inventory records indicate that Waste Pit 3 contained 846 MTU.

Waste Pit 4

Waste Pit 4 was constructed in 1960. The surface area boundary of the waste pit was trapezoidal in shape and has maximum dimensions of approximately 380 ft wide by 310 ft long. The pit was approximately 32 ft deep, including 25 ft of waste, 1 to 2 ft of liner, and 6 ft of cover. It received solid wastes that included process residues, scrap uranium metal, off-specification intermediate uranium products and residues, thorium metal and residues, and contaminated ceramics. Process residues included filter sludges, raffinates, graphite, magnesium fluoride slag, and pyrophoric uranium-bearing materials. Thorium metal and residues were placed in Waste Pit 4 when additional metal recovery was not economically feasible. Waste Pit 4 disposal activities were terminated in 1985. The pit was closed in 1986, and cover activities were started (ASI ca. 1986, p. 43). Waste inventory records indicate that Waste Pit 4 contained 2,203 MT of uranium and 74 MT of thorium.

Waste Pit 5

Waste Pit 5 was placed into service in 1968. The pit surface area boundary was rectangular in shape and is approximately 820 ft long by 240 ft wide. The waste pit is approximately 29 ft deep, including 28 to 29 ft of wastes, with a membrane liner. Waste Pit 5 was a settling basin for slurries including neutralized raffinates, slurries from the acid leaching of uranium-bearing slags, and sump slurries that were generally filtered to remove solids. Supernatant and sludges, produced by the coprecipitation of thorium wastes with barium carbonate and aluminum sulfate and the precipitation uranium with calcium oxide, were disposed of in Waste Pit 5. The discharge of slurried waste materials into the pit ended in 1983, and use of this pit as a settling basin ended in 1987 (ASI ca. 1986, p. 43). Waste inventory records indicate that Waste Pit 5 contained 527 MT of uranium and 72 MT of thorium.

Waste Pit 6

Waste Pit 6 was completed in 1979. It is square in shape with sides measuring approximately 210 ft. It is approximately 24 ft deep, measured from the top of the berm to the liner, but the depth of the wastes in the pit is only 20 ft. Waste Pit 6 received only non-coarse non-pyrophoric materials (this excludes uranium and thorium in metallic form) including magnesium fluoride slag, process residues, and filter cakes from vacuum filtering operations to protect the membrane liner. In addition, extrusion residue and heat treatment quench water were deposited in Waste Pit 6. Use of the pit ended in 1985. Waste Pit 6 was covered by water (ASI ca. 1986, p. 44). Waste inventory records indicate that Waste Pit 6 contained 1,432 MT of uranium.

Clearwell

The Clearwell was constructed in 1959 during Waste Pit 3 construction activities. It was approximately 200 ft long by 180 ft wide, with a maximum depth of 27 ft. It was a final settling basin for surface-water runoff from the waste pits and supernatant from Waste Pits 3 and 5. The Clearwell was dredged in the late 1960s or early 1970s, but was never emptied or dredged again (ASI ca. 1986, p. 44). Measurements indicate the presence of approximately 11 ft of sludge in the bottom of the Clearwell.

The Clearwell was within the beta/gamma direct radiation dose rate contour of 1 mrad/hr.

Burn Pit

The Burn Pit is roughly between Waste Pits 2 and 4; it was initially excavated in 1957 to provide clay for lining Pits 1 and 2. Subsequently, combustible materials including pyrophoric and reactive chemicals, oils, and other low-level contaminated combustible materials were burned in this pit. In addition, laboratory chemicals were disposed at this site. Backfilling of the Burn Pit occurred before 1984. In 1984, all of the contents of the burn pit were transferred to Waste Pit 4 (ASI ca. 1986, p. 58).

Underground Storage Tanks

There were 11 underground storage tanks on the FMPC. As of 1986, Tank 8 was the only tank in use that contained a hazardous substance (soluble oil machine coolant). Tank 6 contained waste oil, but was no longer in use (ASI ca. 1986, p. 63)

Sanitary Landfill

The FMPC sanitary landfill was on a 3-acre tract in the northwest corner of the production area. The facility has 17 individual cells, five of which are full and out of service. The 12 remaining cells were issued an Ohio Environmental Protection Agency permit to install. Each cell was estimated to provide approximately 2,000 yd³ of gross disposal volume. Materials accepted at the facility included nonburnable, nonradioactive sanitary wastes that are generated on the site (20 yd³/wk), nonradioactive construction-related rubble (variable quantity), and water treatment lime sludge (7 yd³/wk) (ASI ca. 1986, p. 35).

2.5 REMEDATION AND ENVIRONMENTAL RESTORATION ACTIVITIES SINCE 1989

The site production mission has been terminated and the site underwent remediation and cleanup from 1989 to 2006. The production level during the first half of 1989 was greatly reduced as compared to earlier years, and operations consisted mostly of processing waste residues. When production was suspended on July 10, most government production programs that used FMPC products were advised to find private-sector suppliers. The FMPC remained in standby mode for some segments of production until the government was confident commercial suppliers could meet future demand for uranium metal. Operations during the second half of 1989 were limited to containing and treating site effluents and packaging and shipping radioactive wastes for offsite disposal. Table 2-2 provides an abbreviated history and further presents a summary of the remediation activities at FMPC since 1989.

Table 2-2. Abbreviated timeline and remediation and environmental restoration activities since 1989 (Fernald Preserve 2010, p. 20).

Year	Activities
Abbreviated Timeline	
1951	Construction of the Feed Materials Production Center began.
1952	Uranium production began (through 1989).
1986	EPA and DOE signed the Federal Facilities Compliance Agreement that initiated the remedial investigation/feasibility study process.
1989	Uranium production was suspended. The Fernald site was placed on the National Priorities List, which is the list of Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) sites most in need of cleanup.
1991	Uranium production formally ended. The site mission changed from uranium production to environmental remediation and site restoration. As part of the Amended Consent Agreement, the site was divided into operable units for characterization and remedy determination.
1993	Environmental remediation activities were initiated at the FMPC.
1994	Environmental remediation activities under each of the operable unit's records of decision were initiated.
1996	All five operable units had signed records of decision, signifying the end of the 10-year remedial investigation/feasibility study process.
1997	Environmental remediation activities continued at the FMPC, including construction of Cell 1 of the onsite disposal facility with the first waste placement beginning in December. Remedy for Silos 1 and 2 was separated from the remedy for Silo 3.
1998	Decontamination of nuclear buildings and facilities (safe shutdown) neared completion, full-scale aquifer restoration was implemented, excavated soil volumes exceeded expectations, and cell construction at the onsite disposal facility continued.
1999	Excavation of the waste pits was initiated and 89,627 t of waste was transported to Envirocare

Year	Activities
	of Utah, Inc. Safe shutdown was completed ahead of schedule and 20 site structures were dismantled. Over 2 billion gal of water were processed and 280,000 yd ³ of contaminated soil were excavated. The remedy for Silo 3 was selected.
2000	The Record of Decision Amendment for Operable Unit 4 Silos 1 and 2 Remedial Actions was signed by EPA in July. Onsite disposal facility Cell 1 was filled to capacity. Southern waste units' excavation was completed to design grade.
2001	Onsite disposal facility Cell 1 was capped. Remediation of the southern waste units was completed.
2002	The Silos 1 and 2 Radon Control System began operations and successfully reduced radon levels within the silos. The offsite transfer of nuclear product material was completed. The onsite disposal facility conducted waste placement into Cells 2, 3, 4, and 5.
2003	The site was renamed the Fernald Closure Project.
2004	Removal of Silo 3 waste initiated, and the first shipment of waste arrived at Envirocare of Utah, Inc. Removal of Silo 1 and 2 wastes from the silos to the holding tank facility was initiated.
2005	First shipment of Silo 1 and 2 waste arrived at Waste Control Specialist, Inc., in Texas.
2006	Comprehensive Legacy Management and Institutional Control Plan established closure and postclosure activities for the site.
Remediation and Environmental Restoration Activities since 1990	
1990–1993	<p>Handling and storing radioactive and hazardous materials</p> <p><u>Radioactive materials</u></p> <ul style="list-style-type: none"> • Pitchblende ore residues containing radium stored in the K-65 silos, • Thorium and thorium compounds stored in several location within the production area, • Radioactive materials in the waste pits, • Uranium metal, • Uranium compounds, • Magnesium fluoride (MgF₂) contaminated with uranium, and • Scrap metal contaminated with uranium compounds. <p><u>Hazardous materials</u></p> <ul style="list-style-type: none"> • Nitric acid, • Laboratory chemicals, • Hydrochloric acid, • Sulfuric acid, • Methanol, and • Process waste. <p>FMPC was refurbishing and adding buildings to store hazardous waste, repackaging some materials into new drums, and removing materials no longer needed since production had ended. For example, two new warehouses originally built to store uranium products had been converted to meet the requirements for hazardous waste storage. Further, thorium previously stored in a deteriorating above-ground silo, in bins, and in drums on an outdoor pad were repackaged in new drums and stored in a warehouse.</p>
1995	<p>UNH Neutralization Project; approximately 200,000 gal of uranyl nitrate hexahydrate were neutralized and prepared for disposal.</p> <p>Vitrification Pilot Plant; construction continued.</p> <p>Thorium Nitrate Stabilization; almost 6,000 gal of thorium nitrate were treated and solidified.</p> <p>Plant 4 decontamination and decommissioning (D&D).</p>
1996	Thorium Overpacking Project to overpack 5,600 deteriorated drums of thorium for safe transportation and permanent, offsite disposal.

Year	Activities
	<p>Vitrification Pilot Plant; construction complete, full-scale remediation would use vitrification to convert residues from Silos 1 and 2 into a glass form. Approximately 36 t of glass were produced during Phase I vitrification.</p> <p>Plant 4 D&D; the building was emptied, cleaned, and stripped down to its structural-steel framework.</p> <p>Plant 1 D&D; continued decontamination and dismantling activities.</p> <p>Above-grade dismantlement of temporary High and Low Nitrate Tanks.</p> <p>Advance Wastewater Treatment Slurry Dewatering Facility online.</p> <p>Legacy mixed waste shipped off the site; shipment of 28,000 lb of legacy mixed waste to Envirocare of Utah.</p> <p>FMPC continued shipments of uranium metal inventory; approximately half of the FMPC's 32 million net lb inventory of uranium metal products had been removed.</p> <p>Liquid Waste Project completed shipping legacy liquid mixed waste to the Toxic Substance Control Act incinerator in Oak Ridge.</p>
1997–2002	<p>Waste Pits Remedial Action Project; this project was responsible for the completion of remediation activities for the excavation, drying, loading, and rail transport of content of Waste Pits 1 to 6, the Burn Pit, and the Clearwell to an offsite disposal facility.</p> <p>Soil Characterization and Excavation Project; this project was responsible for the completion of remediation activities to address contaminated soil at the FMPC and miscellaneous waste units.</p> <p>On-Site Disposal Facility Project; this project was responsible for the construction of an eight-cell engineered disposal facility and operation and maintenance of a leachate collection system.</p> <p>Facilities Closure and Demolition Project; this project was responsible for the completion of decontamination and dismantling of the above-grade portion of the former uranium processing facilities and all remedial action facilities.</p> <p>Silos Project; this project was responsible for the completion of remediation activities for the contents of K-65 Silos 1 and 2 and Silo 3, including the removal, stabilization, and transport of the inventoried residues for offsite disposal.</p> <p>Aquifer Restoration and Wastewater Project; this project was responsible for the completion of remediation activities necessary to restore the water quality in the affected portions of the Great Miami Aquifer.</p>
2006	<p>Waste management and cleanup operations were completed and the site renamed as the Fernald Preserve.</p>

2.6 RADIOACTIVE MATERIALS AND CHARACTERISTICS

The primary radiological materials at the FMPC are uranium and uranium compounds, RU, thorium and thorium compounds, and radon and thoron.

2.6.1 Uranium and Uranium Compounds

From 1951 to 1989, uranium metal production was the primary activity at the FMPC. Because of this, uranium was widely distributed throughout the site and comprised the most likely source of external

beta exposure and internal exposure at the site. Uranium received at the FMPC usually went through one or more chemical separations at other sites. The separations removed most of the progeny. Significant ingrowth of progeny from purified uranium was limited to beta-gamma emitters ^{234}Th and $^{234\text{m}}\text{Pa}$, both of which are progeny of ^{238}U . Those isotopes reached equilibrium within a few months after refining and were insignificant for radiological dose considerations when compared to the uranium isotopes present (ASI ca. 1986).

High quality uranium compounds were introduced into the FMPC processes at several points. Impure starting materials were dissolved in nitric acid, and the uranium was extracted into an organic liquid. The uranium was then back-extracted into dilute nitric acid to yield a solution of uranyl nitrate (ASI ca. 1986, p. 4).

Evaporation and heating were used to convert the nitrate solution to uranium trioxide (UO_3) powder. This compound was reduced to uranium dioxide (UO_2) with hydrogen and then converted to uranium tetrafluoride (UF_4) by reaction with anhydrous hydrogen fluoride. Uranium metal was produced by reacting UF_4 and magnesium metal in a refractory-lined reduction vessel. The primary uranium metal was remelted with scrap uranium metal to yield a purified uranium ingot that was shipped off the site for extrusion (ASI ca. 1986, p. 5).

Based on the discussion of past FMPC operations, there were a variety of compounds of uranium that were used at the FMPC. For example, UO_3 was the major refinery product at Plants 2/3, while the Plant 4 process started with UO_3 and ended with a UF_4 product. The production conducted in Plant 5 generated dusts of UF_4 and uranium oxides (in MgF_2). The principal uranium dust produced in the Plant 5 remelt area, Plant 9, and Plant 8 were uranium oxides that are generally considered to be U_3O_8 . Various compounds were handled in Plant 1, Plant 8, and the Pilot Plant, whereas Plant 2/3 processed uranyl nitrate, UO_3 , and other uranium oxides; Plant 4 handled UO_3 and UF_4 ; Plant 5 handled UF_4 , uranium oxides and metals; Plants 6 and 9 handled uranium metals and oxides (ASI ca. 1986).

During production, the FMPC processed uranium with enrichment levels that ranged from depleted to as high as 20%. In general, 2% EU was the highest enrichment that was processed in significant quantities. A history (1961 to 1984) of the average uranium enrichment in dust collector stack discharges indicated ^{235}U enrichment levels ranging from 0.2% to 1.68% with an average of 0.7% (Tomes 1997, p. 24).

Much of the onsite uranium was stored in drums. These drums contained what are called "uranium residues." These residues were assayed by the analytical laboratory. The analyses provided detailed information on the percent uranium in the drums (as well as the percentage of enrichment of the material in the drums) that closely matches that reported for dust collector stack discharges. Several of the drums contained recycled uranium with enrichment levels of approximately 3% ^{235}U (ASI ca. 1986).

In 1980, 89,000 lb of material identified as "Feed Plant Ash or Other Paducah Scrap" was shipped from the Paducah Gaseous Diffusion Plant to the FMPC. This material contained 24 MT of uranium and transuranic (TRU) contamination that was 200 times higher than what was typical for RU. The material introduced plutonium, neptunium, and technetium to the process stream (Gessiness 1980, p. 2).

2.6.2 Recycled Uranium

In 1985, a DOE Task Force evaluated the processing of RU at several DOE facilities. RU was defined as uranium that had been recovered from irradiated production reactor fuel. RU is known to contain traces of TRU and fission product impurities. TRU impurities were usually limited to ^{237}Np ,

and ^{239}Pu , and the radioactivity of the TRU impurities was generally less than 0.1% of the total radioactivity of the RU. RU also contains trace quantities of ^{241}Am , ^{228}Th , ^{232}Th , and fission products ^{99}Tc , $^{103/106}\text{Ru}$, $^{95}\text{Zr/Nb}$, and others of even lower quantity, assumed to be represented by ^{90}Sr (DOE 2000 and Tomes 1997, p. 61).

From an internal dosimetry perspective, the most significant RU on the site was that which has been dubbed "POOS" for "plutonium out of specification." POOS uranium is that in which the total alpha activity from TRU elements exceeds 0.1% of the alpha activity from the uranium. This equates approximately to 11 parts of plutonium per billion parts of uranium on a mass basis (DOE 2000 and Tomes 1997, p. 61).

ORAUT-RPRT-0052, *Feed Materials Production Center Internal Dose Topics* (ORAUT 2011) documents the resolution of several internal dosimetry issues including the basis for RU default values. Table 2-3 presents the assumed default values for dose reconstruction. No recycled uranium is assumed to exist before 1961 at FMPC.

Table 2-3. RU contaminant radionuclide default values (Bq/g U) (ORAUT 2011, p. 44-45).

Period	Pu-239	Np-237	Tc-99	Th-232	Th-228	Ru-103/106	Zr/Nb-95	Sr-90
1961-1972	2.33E+02	9.25E+01	5.70E+03	4.00E-02	2.80E-02	4.08E+03	1.22E+03	1.63E+02
After 1972	9.31E+02	2.91E+02	2.00E+04	4.00E-02	2.80E-02	4.08E+03	1.22E+03	1.63E+02

2.6.3 Thorium and Thorium Compounds

Since 1972, the FMPC served as the thorium materials repository for DOE. Approximately two-thirds of the material in the repository was processed at FMPC. The remainder originated at other DOE facilities. Thorium was stored on the site in approximately 15,000 containers of various sizes. Many of the containers were removed from the site during the remediation process. The remaining thorium (approximately 500,000 lbs) was stored in approximately 200 metal boxes. The thorium was primarily a mixture of thorium metal, thorium oxides, and process residues. The thorium metals, oxides, and residues were segregated and stored separately from uranium products. These storage areas had the highest gamma dose rates at the FMPC during the operational period. Projects involving thorium material handling routinely yielded the highest worker whole-body doses since 1990. Several operations involved the processing or handling of thorium. A major potential source of exposure to thorium material was the repacking and shipping of the remaining containers of thorium (Tomes 1997, p. 64).

In addition to the stored thorium, a number of locations on the site contained significant quantities of ^{230}Th . These sites included the K-65 silos and the waste pits, and, to a lesser degree, various parts of Plant 2/3 and Plant 8. The ^{230}Th at these locations resulted from the processing of uranium ores. Once the uranium had been extracted from the ore, the remaining material, known as raffinate, contained elevated levels of uranium decay products (Tomes 1997, p. 64).

The thorium metal that was stored on the site was primarily ^{232}Th . Because most of the material was stored for some time, it can be assumed that it had a significant amount of progeny ingrowth but might not have been in secular equilibrium.

The other thorium isotope of concern was ^{230}Th . As previously discussed, ^{230}Th was present as a residue from the processing of ore. Much of the ^{230}Th on the site was the result of processing pitchblende ore from the Belgian Congo.

2.6.4 Radon and Thoron

Past operations at the FMPC resulted in enhanced radon and thoron levels. The site stored materials that are parent materials to both radon and thoron. It stored approximately 8,800 metric tons of

uranium residues produced during plant operations since the 1950s (Dugan et al. 1990, p. 173). During the period of production, uranium was chemically separated from pitchblende ore, and the waste residue, which contained high concentrations of ^{226}Ra , the parent to radon, was stored in the K-65 silos. As ^{226}Ra decays, it produces ^{222}Rn , an inert gas, which could diffuse into the atmosphere through the silo cover. A 12-in sealant barrier of bentonite clay was applied to the contents of the silo in November 1991 to reduce radon emissions (FERMCO 1993, p. 40 and WEMCO 1992, p. 86). As a result of past operations, certain areas of the site were contaminated with ^{226}Ra -bearing materials. This resulted in elevated radon gas concentrations at several locations in the former process area (Tomes 1997, p. 102).

Radon-220, commonly referred to as thoron, is a radioactive gas resulting from the decay of ^{224}Ra , in the thorium decay chain. The thorium metal and residues stored on the site were primarily ^{232}Th . Because most of the material and residues were stored for some time, there was a significant amount of ^{224}Ra present, which resulted in the generation of thoron gas.

Radon and thoron data were collected in specific radium and thorium-bearing areas on the FMPC site to determine areas that had elevated concentrations. Available data were provided above in the descriptions of production plants (Daniels 1995 and Weaver 1987).

Radon-222 has a half-life of 3.82 days. The decay of radon gas results in the production of four short-lived solid decay products: ^{218}Po , ^{214}Pb , ^{214}Bi , and ^{214}Po . The decay products build up rapidly with time and can approach secular equilibrium with the radon gas. The extremely short half-life of ^{214}Po dictates that it is in equilibrium with ^{214}Bi . The effective half-life of the radon progeny is approximately 40 minutes. Therefore, it takes approximately 3 hours for the radon progeny to come into equilibrium with the radon gas in a closed system.

In an open system, the progeny exist in atomic form for a period dependent on the availability of aerosol surfaces for attachment. The percent of radon progeny associated with airborne particulates is referred to as the attached fraction. The higher the concentration of ambient aerosols, the larger the attached fraction. The radioactive aerosol usually contains both attached and unattached progeny. Attached and unattached progeny continually plated out onto floors, walls, etc., or were removed by filtration. As a result, radon progeny would not be in secular equilibrium (Tomes 1997, p. 103).

Thoron (^{220}Rn) has a half-life of 55.6 seconds. The decay of thoron gas produces four progeny: ^{216}Po , ^{212}Pb , ^{212}Bi , and ^{212}Po . For thoron and its progeny, there is a greater degree of disequilibrium in comparison with radon and its progeny. The longer half-life of ^{212}Pb results in a greater opportunity for it to be lost from an air mass by deposition on nearby surfaces. With the exception of the short-lived ^{216}Po , thoron progeny, like radon progeny, were primarily in the attached state. This resulted in a significant increase in equilibrium when there was an increase in aerosol concentrations (Tomes 1997, p. 103).

2.7 ATTRIBUTIONS AND ANNOTATIONS

All information requiring identification was addressed via references integrated into the reference section of this document.

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GLOSSARY

curie

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

depleted uranium (DU)

Uranium nuclide that has undergone a process to remove the ^{235}U isotope, resulting in a relative increase in the percentage of the ^{238}U isotope.

enriched uranium (EU)

Uranium that has been processed to contain a higher abundance of the isotope ^{235}U .

exposure

As used for external dosimetry, exposure refers to a measure expressed in roentgens (R) of the ionization produced by photon radiation (i.e., gamma rays) in air.

isotope

Nuclides having the same number of protons in the nuclei (same atomic number), but having a differing number of neutrons (different mass number).

millirem

A unit of radiation dose equal to one-thousandth of a rem (see rem).

natural uranium (NU)

Uranium occurring in the natural state that has not been through a ^{235}U enrichment process.

rad

A unit of absorbed dose equal to 100 ergs/gm of any material.

radiation

Energy transferred through air or some other media in the form of particles or waves (see ionizing radiation).

radionuclide

A radioactive species of an atom characterized by the constitution of its nucleus specified by the number of protons, neutrons, atomic number, and mass number.

rem

A unit of dose equivalent, equal to the product of the rad absorbed dose and the quality factor.

transuranic materials

Radioisotopes of nuclides having an atomic number greater than 92.