ORAU Team **NIOSH Dose Reconstruction Project** Technical Basis Document: Basis for Development of an Exposure Matrix for the Mallinckrodt Chemical Company St. Louis Downtown Site, St. Louis, Missouri, Period of Operation: 1942–1958	Document Number: ORAUT-TKBS-0005 Effective Date: 10/24/2003 Revision No.: 00 Controlled Copy No.:_____ Page 1 of 124
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TABLE OF CONTENTS

LIST OF TABLES

Table Page

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Draft	08/18/2003	00-A	New document to establish the technical basis for the development of a radiation exposure matrix for the Mallinckrodt Chemical Company St. Louis Downtown Site, St. Louis, Missouri. Initiated by Janet L. Westbrook.
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10/24/2003	10/24/2003	00	First approved issue. Initiated by Janet L. Westbrook.

ACRONYMS AND ABBREVIATIONS

AEC	Atomic Energy Commission
AP	anterior-to-posterior
Ci/L	curies per liter
DWE levels	time-weighted daily average exposure levels
EEOICPA	Energy Employees Occupational Illness Compensation Program Act
FMFL	fluorinated MFL
HASL	Health and Safety Laboratory (of the Atomic Energy Commission)
LOD	limit of detection
MAC	Maximum Allowable Concentration
ME or MEP	Minor Elements Production
MED	Manhattan Engineer District
MFL	MgF_2 liner
MPC	maximum permissible concentration
mR	milliroentgen
mrad	millirad
mrep	millirep
NBS	National Bureau of Standards
NCRP	National Council on Radiation Protection and Measurements
NRC	Nuclear Regulatory Commission
NYOO	New York Operations Office (of the Atomic Energy Commission)
ORGDP	Oak Ridge Gaseous Diffusion Plant
RBE	relative biological effectiveness
RMF	reject MgF_2 material
ROT	rotational
SLAPS or SLAPSS	St. Louis Airport (Storage) Site
SLDS	St. Louis Downtown Site
UNH	uranyl nitrate hexahydrate
VLE	very low enrichment
WL	working level
WLM	working level month

Code terms for the various uranium forms (e.g., TA-7) are given in Table 5 in Attachment A.

PURPOSE AND SCOPE

This technical basis is established for the reconstruction of radiation doses to workers at the Mallinckrodt Chemical Company St. Louis Downtown Site, which refined uranium under contract to the United States government from 1942 to 1958. The two principal purposes of this technical basis document are (1) to provide information sufficient to enable dose reconstructors to estimate claimant-favorable doses for these workers on an individual basis under the provisions of the Energy Employees Occupational Illness Compensation Program Act (EEOICPA) and (2) to allow claimants, federal assessors, and others to understand the information sources and assumptions on which the dose estimations are based.

This document covers workers in Mallinckrodt Plants 1, 2, 4, 6, 6E, and 7 (including 7E) over the time period of the start of contract operations for the Atomic Energy Commission (and its predecessor agency) through the cessation of these operations, which is different for each plant. The whole period of such operations covers April 1942 through July 1958. Additionally, exposure due to residual contamination left in these plants after decontamination and decommissioning is considered for the period 1959-1995. Operations at the St. Louis Airport (Storage) Site (SLAPS or SLAPSS), a waste repository site north of the former St. Louis Municipal Airport, are not included.

1

INTRODUCTION

The Manhattan Engineer District (MED), the predecessor agency of the Atomic Energy Commission (AEC), asked the Mallinckrodt Chemical Works in April 1942 to begin research on uranium refining and processing operations to lead to large-scale uranium production operations (Fleishman-Hillliard 1967; FUSRAP 1996; FUSRAP Undated b). The work began immediately and by July 1942 Mallinckrodt was producing almost a ton of UO_2 per day (Fleishman-Hillliard 1967; Mallinckrodt 1994; FUSRAP 1996; FUSRAP Undated b). Later in 1942, Mallinckrodt started production of UF4 and in July 1953, it started the first uranium metal plant (Fleishman-Hillliard 1967; Mallinckrodt 1994). It is estimated that between 1942 and 1957, Mallinckrodt processed more than 50,000 tons of natural uranium products at the St. Louis facilities (FUSRAP 1996).

The first three Mallinckrodt plants (1, 2, and 4) were not built for the purpose of uranium refining but were converted on an urgent basis from other uses and were intended to operate for only six to eight months. The permanent status of the Mallinckrodt site was not established until 1946 (Mason 1958a); a full-scale health program was not authorized until 1947 and did not get under way until 1948, as a joint AEC-Mallinckrodt effort (Mason 1958a). Film badging started only in late 1945 and urinalysis some time later. Thus there is little data on radioactivity concentrations in air or on internal and external doses prior to the late 1940's.

Although Mallinckrodt had its own industrial hygiene group and did most of its own safety work (Eisenbud 1975; MCW 1955; AEC 1950a), AEC's Health and Safety Laboratory (HASL) also did periodic air sampling and other surveys for the operating plants. While some records of the Mallinckrodt surveys survive, they essentially cover the same work and time periods as AEC's surveys. In this document preferential use is made of the AEC air concentration data because AEC developed and used the standard survey methods. During the early years, film badge servicing, urinalysis, and breath radon analyses were done under the aegis of HASL (AEC-NYOO) (Eisenbud 1975); later, Mallinckrodt took over this work for its own plants and created the corresponding records. Eventually, however, HASL resumed doing the urinalysis and breath radon analysis (MCW 1955). It appears that most of the records of this monitoring are available. Thus the external dose records needed for dose reconstruction are mostly available from 1946 on, but are missing for the period 1942-1945, and the internal dose records (as bioassays) are mostly available from 1948 on, but are missing for the period 1942-1947.

In this document, the context for interpretation of the existing records is established, along with the basis on which to determine missing doses for periods in which records do not exist.

HISTORY OF SITE USE

At their height, uranium-refining operations took place in about 60 buildings on the so-called St. Louis Downtown Site (SLDS), of which about 20 were left after decontamination (Applied Nuclear Safety 1986; FUSRAP 2003a). All of these 20 buildings and most of the other 40 buildings are listed in Table 1 along with their principal uses. (See Attachment A for all tables). A summary chronology of the use of the site is shown in Table 2.

Plants 1 and 2 were already in existence and in use by Mallinckrodt at the time uranium-refining operations stated. Uranium-refining operations began at Plant 2 in April 1942 and by July 1942 it was producing approximately a ton of uranium oxide (UO2) per day (Mallinckrodt 1994). Facilities for batch production were installed in Buildings 50, 51, 51A, and 52 to produce uranium trioxide (UO3) from ore concentrates (Mallinckrodt 1994). The concentrates were digested in nitric acid in Building 51 to produce uranyl nitrate (Mallinckrodt 1994; Fleishman-Hilliard 1967), which was then transferred to Building 52 to be purified by ether extraction to uranyl nitrate hexahydrate (UNH) (MED 1944b; Mallinckrodt 1994). The UNH was converted in Building 51A first to UO3 and then to UO2 (Mallinckrodt 1994). Building 50 was used as a warehouse to store incoming feed materials, outgoing product material, and tanks of process liquids (Mallinckrodt 1994). Building 55 contained the "shotgun" laboratory that tested samples. In the spring of 1945, an annex to Building 52 (presumably 52A) was added to serve as a pilot plant for a continuous countercurrent ether extraction process to replace the existing batch process (Fleishman-Hilliard 1967). Work at Plant 2 continued until 1946, when the plant was closed and the work moved to the newly built Plant 6 (Mason 1958a; Eisenbud 1975; ORNL 1981; Mallinckrodt 1994).

Developmental work at the laboratory level to support Plant 2 and Plant 4 took place in Plant 1, specifically the Building 25 laboratory and the alley between Buildings K1E and 25 (Mallinckrodt 1994). Experimental processing of radium-containing pitchblende ores began in Plant 1 in 1944 (Mallinckrodt 1994), with the laboratory for the work in Building 25-2 and the pilot plant to test radium-extraction methods in Building K-1E (Mallinckrodt 1994) and in the alley (Fleishman-Hilliard 1967). Building 25 also contained the project offices and Buildings "P" and "Z" contained the engineering and other offices (MED 1944b). Buildings 40, 45, 45A, and 47 were used as warehouse buildings for raw, in-process, and finished materials (MED 1944b). Plant 1 was not used after about 1945 (ORNL 1981); the offices and laboratories apparently moved to Plant 6.

Late in 1942, Plant 4, a former lumber sash and door works, was hastily converted for uranium refining (Mason 1958a) and dubbed "the metal plant" (AEC 1949). In April 1943 (Fleishman-Hilliard 1967) or July 1943 (Mallinckrodt 1994), production of uranium tetrafluoride (UF_4) began in Plant 4. The metal production took place in Buildings 400 and 401B and the UF4 production in Building 400 (Mallinckrodt 1994). Production of metal moved from Plant 4 to Plant 6E in 1946 (Mallinckrodt 1994) and the UO_2-to-UF_4 process moved to Plant 7 in 1951 (Fleishman-Hilliard 1967; Mallinckrodt 1994). In about 1950 (ORNL 1981 says 1956), Plant 4 was refitted as an experimental development and a metallurgical pilot plant processing uranium metal and was then referred to as the "Pilot Plant" (ORNL 1981; FUSRAP 1996; Deblois undated). The "dingot" metal production process was developed and conducted at Plant 4 in the mid-1950's (AEC 1956b; Fleishman-Hilliard 1967), along with sporadic ordinary metal "derby" production on a developmental basis. Plant 4 was used until 1956 (ORNL 1981; Mallinckrodt 1994; FUSRAP 1996; FUSRAP 2003c). (Note that Plant 4, in its post-AEC uses, was referred to as "Plant 10".)

Due to the need to increase production and also due to the recognition by MED and Mallinckrodt of significant safety problems with dust and external doses (partly arising from the prospective extensive use of radium-containing pitchblende ore (ORNL 1981; Mallinckrodt 1994)), Plant 6 was built in 1945-

46 on a large site fronting on Destrehan Street (Mason 1958a; Fleishman-Hilliard 1967; Mallinckrodt 1994) and was then referred to as “the refinery” (AEC 1949). Most of the administrative offices, laboratories, and support facilities for the uranium refining operations were located there. The ore-to-UO_2 part of the refining process was moved there in early 1946 from Plant 2 and apparently the laboratory work from Plant 1, while the UO_2-to-metal production remained at Plant 4 (FUSRAP 1996; FUSRAP 2003c; AEC 1949; Mason 1958a). However, some reduction of UO_3 to UO_2 appears to have been done at Plant 4 also, perhaps as part of pilot plant operations, as indicated by Mason (1958) and AEC (1950m). The incoming ore arrived by rail and was stored in Building 110; however, in late 1950 or early 1951 an outdoor ore storage area was added for pitchblende ore (Q-11) (AEC 1950h). Building 104 housed the continuous process equipment, which replaced the batch process equipment that had been used in Plant 2, and processed mostly pitchblende ore (Mallinckrodt 1994); in 1949 a second digest line was added in this building to process uranium ore concentrates (Mallinckrodt 1994). Most of the UO_2 produced at Plant 6 was trucked over to Plant 4, with the rest going by rail to Harshaw and Linde for some years (AEC 1949). When equipment was added to Plant 7 to allow continuous UO_3-to-UF_4 conversion, Plant 6 began to produce only UO_3 (Mallinckrodt 1994). Milling of UO_3 and pre-digestion ore grinding, both conducted at Plant 6, were discontinued in 1950 and 1955 respectively (Mason 1958a). Pitchblende ore continued to be used as feed until early 1955 (AEC 1959). In 1957, a pilot-scale fluid-bed denitration reactor from Argonne was installed for testing and developmental improvements at the Destrehan site, presumably at Plant 6 (Fleishman-Hilliard 1967).

In 1949 it became clear that process improvements to Plants 4 and 6 were not enough to bring about satisfactory control of dust and other hazards (AEC 1949). AEC became concerned and authorized funding for dust control and mechanization improvements, which were installed in 1949-1950 (see Table 3). Plant 6 was shut down for a time in late 1949-1950 for this purpose. It is not clear what the workers did during the time the plant was shut down, although it seems likely that those who had the necessary skills worked on the installation project.

These improvements were regarded as an interim measure, however. Mallinckrodt and AEC agreed to build a new pair of plants that were located at the Destrehan Street site (AEC 1949; Mason 1958a). The first was Plant 6E, the new metal plant, which went into operation in late 1950. Metal production (UF_4-to-U metal) operations at Plant 4 moved to Plant 6E, which was from then on referred to in records as "the metal plant”. Metal production took place in Building 116 (Mallinckrodt 1994). Building 116C was built in 1954 to recycle magnesium fluoride slag (Mallinckrodt 1994).

The second new plant was Plant 7, the green salt plant, which went into operation at some point in the first half of 1951. Note that FUSRAP (1996) and AEC (1949) appear to indicate that Plant 7 operations began in late 1952, while Mason 1958a indicates a 1948 start date. The confusion may be due to the nature of the new direct or continuous UO_3-to-UF_4 process used at Plant 7 and the apparent use of Plant 4 facilities to test out the process, as a pilot plant, and to work out difficulties even after Plant 7 went into production. At Plant 7, a continuous process replaced the batch-type process used at Plant 4; later, equipment was added to allow the continuous production of UF_4 from UO_3 directly (Mallinckrodt 1994). Uranium metal recovery and some storage operations were moved to Plant 7 in 1952 (FUSRAP 1996; Mason 1958a). Some reversion of UF_4 to UO_2 or UO_3 was done in 1954 and perhaps later. A new wet slag (interim residue) recovery operation was added in late 1955 in Building 701 (Mallinckrodt 1994. In 1955, very low enrichment uranium (probably only a small amount) as UF_4 was processed at Plant 7 (AEC 1955b); about 5.5 kg of 20%-enriched uranium was processed in August 1956, presumably in Plant 7 (MCW 1956); and at some time in the late 1950’s machining of (nuclear) reactor core (elements) was done on a temporary basis in a fabrication facility in Building 700 (Mallinckrodt 1994).

Plant 7E, regarded administratively as part of Plant 7, was used from 1955-1957 to process pitchblende raffinate (solids removed during uranium refining by wet filtration) to produce a concentrated thorium solution (FUSRAP Undated b, FUSRAP 2003a) by an acid digestion process similar to the uranium ore digestion (AEC 1955c). The concentrate was sent to the Mound site for further processing.

In 1957, all uranium refining operations ceased at all the plants (FUSRAP 1996; FUSRAP 2003c; Deblois undated; DOE 1981) and the work moved to Fernald and Weldon Spring. Eisenbud (1975) stated that all Plant 6 work was transferred to Weldon Spring in March 1957 (steps through UO_3 production, at that time). However, Mason (1958a) stated that some Plant 7 production operations continued up to July 1958, when they were transferred to Weldon Spring; this was probably to use up the store of orange oxide that had been produced. This is supported by the statement of Mallinckrodt (1994) that the last of the site was put on standby in 1958.

Decontamination and surveys were performed at Plants 1 and 2 in 1948-1950 by Mallinckrodt personnel, applying AEC criteria (ORNL 1981); however, Mallinckrodt (1994) stated that further decontamination took place in 1954 and 1970. In 1951, these plants were released for unrestricted use to Mallinckrodt and no further AEC work was performed there (FUSRAP 1996; Deblois undated, DOE 1981). Some of these buildings were still extant as late as 1990. Plants 4, 6, 6E, and 7 were surveyed and decontaminated or taken down by AEC in 1957-1961 and released to Mallinckrodt without restriction in 1962 (FUSRAP 1996); the buildings removed during that time, included all of the Plant 4 buildings and all wet-process buildings in Plant 6 (ORNL 1981; Mallinckrodt 1994) (see Table 1 for details). These decontaminations were done to the AEC standards then in force, i.e., not to background (ORNL 1981; FUSRAP 1996; Deblois undated; DOE undated). The remaining Plants 6, 6E, and 7 buildings were decontaminated to modern standards in the 1990's and demolished in 1997 (FUSRAP 1996).

Note that the term "Destrehan Street site" seems to have been used in the literature sometimes in reference to all the Mallinckrodt St. Louis facilities and sometimes just to those on the Destrehan Street site proper. In this technical basis, the former interpretation will be used, i.e., Plants 1, 2, 4, 6, 6E, and 7 will be covered. For clarity in using the references, note that Plant 4 fronted on Broadway Street and although Plants 1 and 2 did not, either Plant 4 or all three plants could be referred to as “the Broadway site”. Thus the "Broadway" and "Destrehan" terms appear to be a loose reference to geographical location and not necessarily to a division of function or operations. Also, as will be explained later, due to a rotation practice, Mallinckrodt workers were apt to have worked in multiple plants over the course of their employment.

To summarize, work performed at the Mallinckrodt downtown facilities in St. Louis on a continuing basis included the following.

1. Production of UO_2 and UO_3 from ore, with some being shipped to Harshaw and other sites and with some natural and low-enrichment UO3 coming from Hanford and other sites in the 1950's (FUSRAP 1996; DOE 1997; Mallinckrodt 1994; MED 1946a)

2. Production of UF_4, with some being shipped to Harshaw and K-25 (FUSRAP 1996; DOE 1997; Mallinckrodt 1994; MED 1946a; FUSRAP Undated b)

3. Production of uranium derby metal and vacuum recasting of ingot metal, with the ingots being the final product shipped to other sites (FUSRAP 1996; DOE 1997; Mallinckrodt 1994; MED 1946a; FUSRAP Undated b)

4. Recovery of scrap uranium metal, some from other sites, such as Hanford (FUSRAP Undated b; DOE 2000; Mallinckrodt 1994)

Other work performed for a limited period or on an occasional basis included the following.

1. Production of dingots (Fleishman-Hilliard 1967; AEC 1956b)

2. Machining of metal rods for reactor fuel slugs (Mallinckrodt 1994; FUSRAP Undated b)

3. Reversion of UF_4 to UO_2 or UO_3 (FUSRAP Undated b, which says UO_2 or U_3O_8; Mallinckrodt 1994; AEC 1954g)

4. Production of UO_2F_2 (FUSRAP Undated b)

5. Extraction and concentration of Th-230 from pitchblende raffinate (FUSRAP Undated a; FUSRAP Undated b; Mallinckrodt 1994; AEC 1955c)

6. Experimental processing of very low enrichment UF4 (FUSRAP Undated b; Mallinckrodt 1994; ORNL 1981) and some 20% uranium metal (MCW 1956)

7. Conversion of small research quantities of aqueous uranyl nitrate hexahydrate to UO_3 (DOE 2000)

From 1946-1955, personnel provided by Ledoux and Co. of New York performed uranium ore assays at the Mallinckrodt downtown site in St. Louis (DOE 2001). This work was done in the "Ledoux Laboratory" located in Buildings 110A and 111 of Plant 6 (FUSRAP 2003b) and possibly in other labs at the site as well. The Ledoux Laboratory is also mentioned in Mallinckrodt film badge records, so presumably the Ledoux and Co. personnel were badged under Mallinckrodt's aegis.

MED (1944b) stated that non-MED Mallinckrodt employees and employees of the St. Louis Sash & Door Works (the former operator of Plant 4's Building 400 in its pre-MED days) had occasion to enter respectively Buildings 45, 45A, and 47 in Plant 2 and "Building 1" at Plant 4 (presumably Building 400) respectively. These employees were presumably not monitored in any way other than having their access controlled for security reasons. They are not considered to be atomic workers for the purposes of this dose reconstruction.

Mallinckrodt processing of black oxide (pre-milled ore), sodium salt, UO_3 (orange oxide), and UO_2 (brown oxide) was done under AEC/MED Contract W7401-Eng 1; UO_2 and UF_4 (green salt) under Contract W7405-Eng 29, 1st Phase; and UF_4, biscuit metal (U), slag processing, ingots (billets), croppings, sawdust processing, and other metal production under Contract W7405-Eng 29, 2nd Phase (MED 1945a; MED 1944b).

Starting in 1952, some recycling of uranium was done by the AEC and its contractors nationwide. Thus the question arises whether this was done at the Mallinckrodt facilities in St. Louis. However, Mallinckrodt (as a company) did not begin to receive recycled uranium until 1962, which was after the St. Louis facilities had been shut down and their work had shifted to Fernald and Weldon Spring (the latter run by Mallinckrodt) (FUSRAP 2003b). Also, ORNL (1981) stated that in its pre-survey review of the site, including interviews with Mallinckrodt old-timers, no indications were found that there had ever been any process conducted under AEC contracts involving the purification or working of Th-232, highly enriched uranium, fission products, or byproduct material. Thus it is assumed that no

recycled uranium or any of the materials listed by ORNL (1981) was handled at Mallinckrodt's St. Louis facilities as part of AEC work.

In 1949, AEC requested that Mallinckrodt produce in their AEC-owned facilities 200 pounds of uranium metal for "nonproject and educational uses" (MCW 1949c); however, there is no indication that Mallinckrodt ever did so. Mallinckrodt apparently also carried on some commercial processing of euxenite (an ore) at Plant 5 at some point in the 1950's.

Waste residues produced at Mallinckrodt were taken by truck to the St. Louis Airport (Storage) Site (SLAPS or SLAPSS), a waste repository site north of the former St. Louis Municipal Airport, also known as Lambert Field (FUSRAP 1996). The SLAPS site was operated by MED/AEC from 1946 until July 1953 when the operation was turned over to Mallinckrodt (AEC 1959). Guards were maintained at the site from 1946 to 1951 (AEC 1959). It is not clear whether the truck drivers and guards were Mallinckrodt employees or not, although there are a few mentions of "airport" in urinalysis records that indicated work assignment or area. Because this remains to be clarified, SLAPS operations are not included in the scope of this TBD.

DESCRIPTION OF THE MALLINCKRODT URANIUM REFINING PROCESS AND OTHER PROCESSES

It is important to understand the Mallinckrodt uranium refining process in order to understand the radiological hazards, to follow the changes in source terms and exposure potential, and finally to estimate the doses to individual workers. The basic process will be described here. Then particulars will be discussed for three cases: the early wartime period, the late wartime and early postwar period, and the later postwar period. Details regarding the types and quantities of ore, uranium products, and residues are shown in Table 4; Table 5 is provided as a reference for technical terms and keywords. An additional table is given within the text of Section 4.4 to illustrate the variety of feed forms that was used in later years.

THE BASIC PROCESS

First the ore was prepared for uranium extraction, as follows. Milled ore, as ore concentrate ("black oxide"), was taken from its storage location(s), thawed if necessary in an enclosed "thaw oven" in the thaw house, and dried. It was then "digested" (dissolved) in nitric acid in a digestion vessel or tank (MED 1946a; AEC 1949; AEC 1978; Fleishman-Hilliard 1967). Sulfuric acid was then added to the solution in the vessel to precipitate the radium and lead (MED 1946a; AEC 1949; AEC 1978; Fleishman-Hilliard 1967). The uranium was left in solution as uranyl nitrate and the precipitate was filtered out (MED 1946a; AEC 1949; Fleishman-Hilliard 1967) using a string-discharge rotary vacuum filter (AEC 1978) referred to by the name of its manufacturer, Feinc (or FEinc). The filtered solids formed a radium-bearing residue also called raffinate or "cake" and referred to as the K-65 residue (AEC 1949; AEC 1978) or GLC ("gangue lead cake") (MED 1946a). Next, a slurry of barium carbonate was added to the uranyl nitrate solution to remove the sulfates, when present (MED 1946a; AEC 1949; AEC 1978; Fleishman-Hilliard 1967). To remove the solids, the mixture was run in a continuous solid-bowl centrifuge (also referred to by the name of its manufacturer, Bird) (MED 1946a; AEC 1949; AEC 1978). The uranium remained in solution as uranyl nitrate and the precipitate formed a barium sulfate cake. The uranyl nitrate solution -- the "liquor" -- was then boiled (MED 1946a). Calcium nitrate was added to the solution to assure nitrate saturation (MED 1946a), then the solution was filtered to remove any solids formed. The acidity of the solution was adjusted as needed by adding acid (AEC 1978; Fleishman-Hilliard 1967).

Second, uranium oxide as UO_3 was extracted from the solution, as follows. In the two-step ether extraction process, diethyl ether was added to the solution in extraction columns. The first step was the acid ether extraction, including ether addition, nitric acid addition, and re-extraction into water (also called a "water wash"), while the second step was a neutral ether extraction followed by re-extraction into water (MED 1946a; AEC 1949; AEC 1978; Fleishman-Hilliard 1967). Eisenbud (1975) states that in the ether extraction process, the isotopes of thorium and protactinium were left in "the aqueous phase" while the uranium was stripped off by the solvent (ether), so presumably the thorium and protactinium were separated from the uranium in the first step of the ether extraction process, before or as part of the water wash. After the ether extraction was complete, the uranyl nitrate extract solution was boiled to the molten salt to form uranyl nitrate hexahydrate ("hex liquor" or "OK hex liquor") (MED 1946a; AEC 1949; Fleishman-Hilliard 1967). The molten salt was then directed in batch form to gas-fired denitration "pots" or boildown vessels, which were continuously heated and agitated so as to produce the dissociation of the hexahydrate and the formation of UO_3 (also called orange oxide or QM-2) (MED 1946a; AEC 1949; Fleishman-Hilliard 1967). The UO_3 lumps were often broken up by crude mashing, but there was also a formal double grinding process requiring the material to be moved to the grinding area (MED 1944a).

Third, the UO_3 was placed on thin trays, placed in airtight boxes, and loaded into a batch electric (muffle) furnace to react with dissociated (cracked) ammonia to form UO_2 (also called brown oxide or LF-9), a step that took about 7 hours (MED 1949b; MED 1946a; AEC 1949; Fleishman-Hilliard 1967). Usually the UO_2 was further processed at Mallinckrodt, but some was shipped to non-Mallinckrodt sites such as Harshaw (DOE 1997).

Fourth, the UO_2 was converted to UF_4, as follows. The UO_2 was removed from the fiber containers and placed into large stainless steel drums for temporary storage (AEC 1949). As needed, it was removed onto steel (later monel) trays and weighed (MED 1946a; AEC 1949; Fleishman-Hilliard 1967). The trays were then set into airtight graphite or nickel boxes placed in a hydrofluorination reactor (MED 1946a; AEC 1949; Fleishman-Hilliard 1967). (Note that this was not a nuclear/atomic type of reactor but rather a chemical reaction vessel.) In the reactor, hydrogen fluoride gas was passed over the UO_2, forming UF_4 (also called green salt or TA-7) and water (MED 1946a; Fleishman-Hilliard 1967). The UF_4 was unloaded and put through a pulverizer or mill and then a blender, followed by packing into metal containers (AEC 1949). Most of the UF_4 was further processed at Mallinckrodt, but some was regularly shipped to non-Mallinckrodt sites (DOE 1997; AEC 1949); MED (1946), however, implies that all of the UF_4 produced at Mallinckrodt was also further processed there.

Fourth, the UF_4 was converted to uranium metal, as follows. The UF4 was blended with magnesium powder and mixed in a tumbler (AEC 1949; Fleishman-Hilliard 1967). A special firing container (the "bomb") was lined with a refractory material, variously reported to be lime (1945, per MED 1946a); dolomite (1946 on, per FUSRAP Undated a and FUSRAP 1996, or 1942 on, per Fleishman-Hilliard 1967); or recyclable magnesium fluoride from about 1954 on (FUSRAP Undated a; FUSRAP 1996; Fleishman-Hilliard 1967). The bomb was "jolted" (shaken) on a mechanical jolter until the liner was packed hard enough. The mixture (the "charge") was then placed in the bomb. After the bomb was sealed, it was placed in a gas-fired furnace and heated until it "fired"; the magnesium reduced the UF_4 to uranium metal in this process (MED 1946a; AEC 1949; Fleishman-Hilliard 1967). The molten mass formed a "derby" or "biscuit" of solidified metal as it cooled (MED 1946a; AEC 1949; Fleishman-Hilliard 1967). (The derby form was also called KB-2.) After the bomb cooled, the derby was taken out and the slag on the derby was chipped off pneumatically and sent to uranium salvage (recovery) (MED 1946a; AEC 1949; Fleishman-Hilliard 1967).

Finally, the metal derbies were remelted and cast in an induction-heated, high-vacuum furnace (a process also called vacuum recasting). In this process, the derbies were placed in a crucible, the crucible was placed over a mold, and the crucible-mold assembly was placed in a quartz shield, sealed, evacuated, and placed into the furnace (MED 1946a; Fleishman-Hilliard 1967). There was a stopper rod at the bottom of the crucible that was removed when the critical temperature was reached, allowing the molten metal to flow into the mold and form a cylindrical ingot or billet (MED 1946a; AEC 1949; Fleishman-Hilliard 1967). (The billet form was also called YM-5.) The billet was then removed from the mold by separating its parts. The porous impurity-heavy top section was cropped off and sent for recovery; the other surfaces were cleaned of liner ("C-liner") slag and other impurities (MED 1946a; AEC 1949; Fleishman-Hilliard 1967). A sample was taken from the billet by power hacksaw (AEC 1949). The billets were then packed and shipped to the appropriate non-Mallinckrodt site for further processing (MED 1946a; AEC 1949).

The nitric oxides produced as offgasses in the pots were sent to a recovery system (MED 1946a; AEC 1949; FUSRAP 2003b) where the nitric oxides were converted back to nitric acid. The GLC residue and the barium sulfate cake were usually leached with sodium carbonate to remove the residual uranium (AEC 1978).

The precipitate from the first extraction column was "on occasion" dewatered using a Sperry Filterpress, producing a supernate and a batch of cake called Sperry cake (AEC 1978). The supernate from the press and the aqueous uranium tails from the wash were de-etherized and treated with a hydrated lime slurry (AEC 1978). This was passed through a continuous rotary vacuum leaf filter (referred to by the name of its maker, Niagara); the supernate was discharged to the local river and the limed fraction became the so-called "airport cake" (AEC 1978), from its being stored for several years at the AEC's SLAPS site that had been an airfield; however, it must be noted that several other types of cake were also referred to loosely as "airport cake" due to their being sent there for storage.

THE WARTIME PERIOD (APRIL 1942– APRIL 1945)

Initially, the work consisted primarily of the production of UO_2 and UO_3 from mined ore marginally milled (FUSRAP Undated b); some preliminary milling to "black oxide" (a form of U_3O_8 concentrate) thus had to be done, some of it at Mallinckrodt (DOE 1997). Little information is available as to how or where the early milling operations were performed, but it was likely in Plant 2 (see Table 1). Some “soda salt” (sodium diuranate) was also used (DOE 1997).

Plant 4 began operation in about October 1942 and from that point on, production-level work in converting UO_2 to UF_4 and then to uranium metal took place there. The ore$\rightarrow UO_3 \rightarrow UO_2$ conversion continued to be done in Plant 2.

In the first months of refining by Mallinckrodt, a different extraction process from the ether extraction was used since the latter had not yet been developed. No information could be found as to the details of the first process; however, the ether extraction process seems to have been in the process of development at Mallinckrodt from April 1942 on and in use from July 1942 on (US DOE 1997; AEC 1978; Fleishman-Hilliard 1967), so the first process could have been used for about three months at most (mid-April to mid-July). The magnesium reduction process for metal production was developed by Iowa State by about mid-July 1943 (DOE 1997) and Mallinckrodt established the first metal plant (Plant 4) the same month (Fleishman-Hilliard 1967).

THE EARLY POSTWAR PERIOD (MAY 1945–DECEMBER 1949)

As noted above, processing of significant quantities of pitchblende ores began at Mallinckrodt in about May 1945 and accelerated with the start of Plant 6 in 1946.

During and after the war, African and Canadian ores were milled to black oxides elsewhere and at Mallinckrodt (DOE 1997, Mason 1958a); at Mallinckrodt, this moved from Plant 2 (apparently) to Plant 6 after the latter began operation in 1946. Mason (1958a) gives data showing very high dust levels for ore milling, so the process was apparently not an entirely enclosed one. Ore milling stopped in mid-1949 (Mason 1958a) and after that all ore arrived mill-processed. The ore delivered to Mallinckrodt then had to be pre-processed only minimally before the refining process proper could begin. DOE (1997) states that it was done at Mallinckrodt's "Destrehan Street plant", inferentially at Plant 6 (see Table 1).

The continuous countercurrent ether extraction process was developed in 1945-1946 and put into production with the start of Plant 6 in 1946 (Fleishman-Hilliard 1967). This eliminated the necessity of moving the intermediate materials batchwise from one process location to another as had been necessary at Plant 6; rather, the materials passed from vessel to vessel or filter via piping. Also, the sulfur removal step was added when ores containing high levels of sulfur were used. However, the removal of products such as UO_3 and UO_2 was usually done by manual scooping and the removal of

waste products, such as the filtered-out solid wastes and recovery products, was usually done by manual methods such as scraping.

As noted earlier, Plant 6 was shut down for a time in 1949-1950 for modifications; it seems likely that the end of ore milling coincided with this shutdown. Mechanization improvements during this period decreased the amount of manual and close-in handling of ore and the other uranium forms, but there was still a significant amount, especially with regard to the intermediate solid forms (UO_2, UO_3, and UF_4) produced as particles and chunks of material.

THE LATER POSTWAR PERIOD (1950–1958)

The Middlesex work was transferred to the Fernald plant in 1955 (DOE 1997), which thereafter was the sender of milled ore to Mallinckrodt. An Ore Room was added at some time in the early 1950's to Plant 6; the duties of the operator included opening (deheading) and cleaning ore drums (AEC 1953), hence this was not simply a storage area. During the period 1950-1951, Plant 6E and Plant 7 went into operation as previously described and a number of further process and equipment changes were made to reduce exposures, principally in the area of dust control and mechanization (see Table 3). The main reason for the provision of new plant space was to reduce exposures, but it is notable that in each case, production increased markedly after a new plant was added, sometimes to several times the original anticipated capacity (Mason 1958a). Thus the exposure-reduction changes were sometimes successful and sometimes not.

Some time prior to August 1954, the Ore Room and K-65 sampling operations in Plant 6 appear to have ended, probably due to the end of high-grade ore processing. The Plant 6 pilot plant was constructed in 1949-1951 and began operation at some point during that period (Fleishman-Hilliard 1967); references to it started to appear in AEC air dust study reports by 1953 (AEC 1954c). The purpose of this pilot plant was said to be process and product improvement (Fleishman-Hilliard 1967). An AEC dust exposure report giving time-and-motion information states that a Pilot Plant 6 technician was cleaning old MgF_2 out of a kiln, putting in new MgF_2, and scooping Anaconda feed (sodium diuranate) into a digestion tank (AEC 1956c). Thus it is likely that the pilot plant was working on the development of improved methods for various parts of the refining processes. The research laboratory was constructed and put into operation during the same period as the pilot plant (Fleishman-Hilliard 1967).

An alternative method of producing the metal form was developed at Plant 4 in the mid-1950's. This process (AEC 1956b; Fleishman Hilliard 1967) took the UF_4 to the final cast (ingot/billet) form in one step instead of two, in order to eliminate the need for recasting and the associated contamination with impurities. The result was a massive single ingot, called a dingot, weighing about 3300 pounds. In this process, a bomb was lined at the bottom with MgF_2, a mandrel (mold liner support) was inserted into the bomb, more MgF_2 was poured into the space between the bomb shell (wall) and the mandrel, and the bomb was jolted to pack the liner hard between the mandrel and shell. The UF_4 and Mg were blended and put into a drum, which was then capped and removed to a charging station. The drum was inverted over the station insert collar, the drum cap valve was opened, and the charge was allowed to flow into the bomb. During this step, the operator used a long stainless steel rod to "pole" the charge down into the bomb; the operator also used a mechanical rammer to tamp it down for maximum density. Recycled slag containing MgF_2 and U was added to the top of the charge and tamped. Finally, the exterior of the bomb was vacuumed and a steel lid was applied. The bomb was removed by hoist to a "Hevi-duty" furnace, where the thermite (metal-metal reduction reaction) took place.

Because of the size and purity of the dingot, the postcasting processing differed from that of the derby and billet. The bomb was cooled in air, then transferred to a breakout enclosure where it sat over a downdraft-ventilated floor grill. The bomb was inverted over the grill and the contents jolted out onto the grill. The slag liner was broken with a mechanical sledge hammer and swept onto the grill and down into a hopper. A conveyor took it to a grinder, from which it was discharged into drums and taken for reprocessing (presumably in Plant 6E -- see below). The dingot was cleaned with a pneumatic chipping hammer over the grill and then removed to a machining area, where it was "scalped" (had the outer surface trimmed off) on the top and sides with a vertical turret lathe. If samples were needed, it was then taken to a saw area and sections were cut off with mechanical hacksaws. Finally, the dingot was put into a salt bath and heated for several hours, then put on the bed of a 100-ton forging press that had a mechanical manipulator for positioning. It was pressed into a slab for several minutes, then returned to the salt bath for about an hour for reheating. This process was repeated four more times, with the piece being rotated on the press between passes. The forged slab was then quenched and taken to storage.

Fleishman-Hilliard (1967) implies that Mallinckrodt also produced extruded billets from these dingots, at least on an experimental basis. Once extruded into a much longer and thinner cylinder, the billet was cut into shorter lengths.

Plant 7 was built not only to increase production of UF_4, but also to take advantage of the new continuous process using a “stirred bed” reactor for producing it (Mallinckrodt 1994, Fleishman-Hilliard 1967). At some point not long after this process went into operation, the process was modified to allow production of UF_4 continuously from a UO_3 feed instead of a UO_2 feed, thus eliminating a transfer step (Mallinckrodt 1994, Fleishman-Hilliard 1967). At this point, UO_3-to-UO_2 production at Plant 6 seems to have ceased or at least decreased significantly.

By 1955, Mallinckrodt was using a variety of feed forms from many different sources to produce the various uranium product forms. The table below (AEC 1955a) illustrates this for a typical period in 1955; figures are in tons.

	January	**February**	**March**	**April**	
To be produced:					
QM-2	500	465	535	510	
TA-7	280	355	320	320	
TM-5	205	240	270	260	
Shipments to NLO:					
QM-2	235	155	170	170	
YM-5	All finished metal of the metal plant plus all shippable metal from the pilot plant				
TA-7	0	100	100	45	
Feed type	**January consumption**	**January 31 inventory**	**February receipts**	**March receipts**	**April receipts**
Q-11	76	8	86	---	---
MgX	26	10	40	64	30
South African	---	---	129	80	90
Portuguese	21	---	40	---	20
Colorado soda salt	46	12	50	50	50
Beaver Lodge	23	31	28	28	28
Vitro	9	---	---	---	---
Colorado black	92	12	50	50	50
Canadian black	43	17	25	25	25
NLO Recycle/Scrap Plant	27	15	20	20	20
MCW	18	---	15	15	15

Miscellaneous	---	---	---	---	---
Dissolver	24	77	20	20	20
Sawdust	5	6	5	5	5

OTHER PROCESSES

Uranium recovery operations consisted mostly of processing solid scrap wastes, such as the portions of billets removed as assay samples, to recover the valuable uranium and thus to maximize the uranium obtained per unit quantity of ore. This was probably done in the early years by digestion of the scrap in nitric acid (FUSRAP 2003a). Sawdust was stored under oil until it could be processed in this way and converted to ingots (Fleishman-Hilliard 1967; MED 1944a; MED 1944b). Some processing of residues was also done (e.g., leaching of wastes) to recover uranium, but this seems to have been done as an integral part of the refining process itself rather than a stand-alone operation like the solid scrap salvaging.

In early 1954, a slag separation plant was built at Plant 6E, apparently as a six-level wing (116C) on Building 116, to recover most of the uranium content from the MgF_2 slag produced there in the UF_4-to-derby operation (AEC 1959, AEC 1954f). The slag was fed into a jaw crusher on the first level, then the crushed slag was conveyed on a "vibro conveyor" to a bucket elevator and then to a roll mill hopper on the 6th level. From there the slag was gravity-fed via a roll mill feeder into a series of roll mills and screens on the middle levels. Reject material from the last mill screen flowed by gravity feed into a reject hopper and then to a reject drum on the 1st level. Discharge streams from the roll mill and the roll mill screens were fed into a ball mill. The discharge from the ball mill was conveyed by a bucket elevator to a series of air classifiers; after passing through these, the separate product and reject streams flowed by gravity feed to the respective drums on the first level.

In late 1955 or early 1956, operations to process slag began in Building 701 in Plant 7. This building was then called the Slag Separation Plant or the Slag Processing Plant. According to AEC (1956e), the feed material was uranium concentrate from reject MgF_2 material (RMF). The RMF was charged from drums into a skip hoist that discharged into a hopper serving a rod mill. In the mill, the RMF was crushed and water was added to make a slurry. This was passed through a mechanical screen shaker; the part that did not pass through was recycled through the rod mill and the part that did pass went onto three successively smaller-sized Wolfey gravity feed tables. The tables separated the uranium-bearing slurry from the rest of the slurry, with the former being allowed to run off the last table into a screw conveyor. The slurry was then fed into a drum. This drummed material was referred to as "U-con". The non-uranium-bearing slurry was pumped to settling tanks and then to a rotary filter; the resulting cake (D-701) was discharged into dumpsters (buggies) and taken to the SLAPS waste storage site.

In late 1954 or early 1955, a new subplant, called Plant 7E, was established. This was part of what was referred to as the Minor Elements Production (ME or MEP) facility that did smaller-scale processing and development in Plant 7. The purpose of 7E was to process some of the AM-7 (pitchblende) residues that had been in storage at the SLAPS site (FUSRAP Undated a; AEC 1978; FUSRAP Undated b; FUSRAP 1996). From the beginning of 1955 into 1957, Mallinckrodt produced a concentrated thorium solution for later extraction of Th-230 at the Mound site (AEC 1978; FUSRAP 1996). (Note that the Th-230 was also called "ionium" and was referred to that way in Mallinckrodt records.) The residue was brought back from storage at SLAPS and stored at Plant 6. According to AEC (1955b), the residue was conveyed by dumpster from Plant 6 to Plant 7E, where it was digested in nitric acid in a tank and filtered. The resulting "liquor" was processed in a TBP (a solvent) contactor, forming an aqueous phase and a thorium-bearing TBP phase. The TBP phase was treated with hydrofluoric acid, leaving another aqueous phase, a stripped TBP phase, and thorium fluoride.

The thorium fluoride was treated with aluminum nitrate ($Al(NO_3)_3$) and a pentaether-ether mixture, forming thorium nitrate ($Th(NO_3)_4$) and impurities. The thorium nitrate was stripped from the impurities, yielding the solution that was sent to Mound. The various waste streams were treated in several ways (e.g., the aqueous fractions were treated with lime). This left various cake, slurry, and water filtrate forms; the first two types were sent to storage and the latter to the sewer. The main residual cake, called AM-10, was sent back to SLAPS storage.

Little information could be found about shipping, receiving, and storage operations and about the milling of the UO_3, except that it was apparently done in Plant 2 until the work moved to Plant 6 (Mason 1958a). The ore areas and warehouse areas appeared to be separate, however.

Similarly, regarding the reversion of UF_4 to UO_2 or UO_3 (or U_3O_8) there was little information except for a short reference to the work of a panel board operator's work in an AEC Plant 7 air dust study report (AEC 1954g): the operator was said to vacuum "C-31 material" from a drum into a "reverter". What the C-31 material consisted of was unclear, but usually the "C-" designated scrap material or material captured in a dust collector. Later such AEC reports mention that the reverter was being used by this operator (AEC 1955b, AEC 1956c) but not an earlier one (AEC 1952b), so presumably this work continued from at least 1953 (the date of the AEC 1954g survey) to the end of Plant 7 operation.

There was no information about processing very low enrichment (VLE) uranium beyond what was given in Section 3.0 above, except for a reference in an AEC air dust study report for Plant 7 in which it was stated that the subject AEC survey covered "health and safety problems existing during production and processing green salt, with the added operation of processing enriched uranium"; the panel board operator was said to include among his observed duties "charging enriched UF_4 into hopper" and "replacing enriched material drum and sample bottle" (AEC 1955c). Since there was no further mention of any of these activities in later such reports, it appears that this operation may have been performed for only a short period of time, e.g., to use up excess UF_4 from another site. There is no indication that Mallinckrodt itself produced the VLE UF_4. In any case, the operations described appear to be routine.

There was no information at all about the production of UO_2F_2 or the processing of (supplied) uranyl nitrate hexahydrate, all of which functions were mentioned by only a single reference source (see the summary list of work in Section 3), with no details given. There was information (AEC 1955b) regarding a Plant 7 experimental process begun in Plant 7 in 1956 in which MgF_2 liner (MFL) was treated to reduce the hydrogen content for use in dingot bombs. This created fluorinated MFL (FMFL, perhaps also called D-30). However, this process appeared not to involve any radioactivity except what would likely have been present in the ambient air due to other processes. Also, Fleishman-Hilliard (1967) commented that the reason for adding a little UO_2F_2 to a bomb was to slow down the process themally, resulting in a better separation of slag and metal.

Mallinckrodt (1994) estimated that small-volume batch and experimental uranium-related processes constituted less than .3% of the total uranium produced. Some of the processes considered in this estimate were the conversion of slightly (very low) enrichment feed materials to metal or uranium nitrate liquor, extraction of Th-230 from pitchblende raffinate, production of U_3O_8 and UO_2 using an experimental continuous denitration furnace, experimental extraction of uranium using tributyl phosphate to replace ether, production of uranium metal dingots, and recycling of slag for use as liner material. This supports an assumption that only a negligible part of total processing activities involved such short-term and usually low-volume processes.

1.1 ORES AND OTHER FEED FORMS

In the early years, the ore arrived as a milled concentrate from Canada (Mallinckrodt 1994), consisting mostly of black oxide (U_3O_8) (Mallinckrodt 1994; Fleishman-Hilliard 1967); MED (1945) stated that the Eldorado mine site in Port Huron, Canada, was a source of black oxide to Mallinckrodt. These concentrates were produced at offsite uranium mills and were free of radium and its decay products (Mallinckrodt 1994). That is, in the early years, Mallinckrodt did not process the high-radium-containing ore of later years. Although the uranium was mostly supplied to Mallinckrodt in already milled form (as black oxide), some milling and pre-processing of high-grade uranium ore was performed at Mallinckrodt (FUSRAP 2003c).

The Vitro plant in Canonsburg, Pennsylvania produced sodium diuranate, also called soda salt, some of which was sent to Mallinckrodt for refining to UO_2 and UO_3 (DOE 1997, MED 1945a; MED 1943c); other soda salt may have come from Belgium and Port Hope, Ontario (MED 1943c). This appears to have been digested in the same fashion as the black oxide. Soda salt and other non-ore feeds were referred to as "soluble feed".

Other wartime ore sources were pitchblende ores from Canada (Radium City in the Great Bear Lake Area and Port Hope in Ontario) (DOE 1997; Eisenbud 1975). Later in the war, domestic ores were used also; the principal Colorado source during the war was not the carnotite ore itself, but tailings from vanadium mining and milling, shipped as a concentrated sludge (Eisenbud 1975).

In about 1944, AEC wanted to increase production of uranium, not only by increasing capacity but by using high-grade pitchblende ores. However, such ores had the disadvantage that they contained a high level of radium as a decay product of the uranium. This entailed significant gamma and airborne exposure hazards. It was because of the limitations of Plant 2 with respect to capacity and hazard that Plant 6 was designed and built (Mallinckrodt 1994). Another consideration was that crude concentrates and pitchblende ores tended to have undesirably high levels of sulfur, which necessitated the extra precipitation step for removal (Fleishman-Hilliard 1967). The high-level ore was used as a principal feed material from May 1945 until early in 1955 (AEC 1956a; AEC 1959). However, MED (1943c) remarked in 1943 that there appeared to be more “radiation” in the U_3O_8 being received by Mallinckrodt from Port Hope, suggesting that pitchblende ore concentrates may have been used as feed prior to May 1945. It is known that experimental processing with pitchblende ores was done in 1944 at Plant 1 (Mallinckrodt 1994), so this may explain the 1943 reference.

Most of the high-grade pitchblende ore processed by Mallinckrodt was obtained by AEC as a concentrate from the Belgian Congo in 1944 (AEC 1978), the so-called African ore. From 1943 on, a receiving and storage facility operated at Middlesex, New Jersey (DOE 1997). Middlesex assayed, crushed, riffled, and redrummed the ore as it came into the United States, then sent it to the various refineries, including Mallinckrodt (AEC 1949, Eisenbud 1975), including the African ore. However, SSS states that the African ore came through the Eldorado (Port Huron, Canada) area for processing before being sent on to the US refineries. Whatever the case, it was not likely that significant milling of this ore was done at Mallinckrodt.

After World War II, foreign uranium ore was supplied from the Belgian Congo, Canada, Australia, South Africa, Portugal, and other nations. Besides the foreign ore, domestic carnotite ores began to be mined directly, milled elsewhere, and then sent as ore concentrate (mainly U_3O_8) to Mallinckrodt. Early postwar domestic ore supply areas included Uravan, Durango, Grand Junction, and Naturita, Colorado, and Monticello, Utah (DOE 1997). Once the US began to stimulate domestic mining and milling in 1948, the proportion of domestic ores used appears to have increased; thus the overall concentration of uranium in the ore may have decreased over time.

Soda salt (sodium diuranate) appears to have been sent from several sites; a description of some work indicated that Fernald, Durango, and Anaconda diuranate were being handled by a soluble feed operator (AEC 1956c) and as noted Vitro also supplied soda salt until it was shut down.

1.2 RESIDUES AND EFFLUENTS

The radium-bearing pitchblende residues (wastes) were always stored separately from the non-radium-bearing residues and the barium-bearing and other types of cake (AEC 1978); thus the external exposure implications of handling residue waste depended on what kind of waste it was.

From 1942-1945, MED solid wastes were shipped to the Lake Ontario Ordnance Works in Lewiston, New York (Mallinckrodt 1994). The radium-bearing pitchblende residues were shipped by rail to the Middlesex, New Jersey repository for storage up to about 1946 or 1947 (AEC 1949). From 1946-1948, all residues produced at Mallinckrodt were shipped by truck to the SLAPS waste storage site -- hence the name "airport cake", as noted earlier (AEC 1978; Mallinckrodt 1994). From 1948 to at least 1949, some residues appear to have been shipped to Middlesex (AEC 1949). After about 1949, radium-bearing residues were shipped to the Lake Ontario Ordnance Works in Lewiston, New York (FUSRAP undated a; AEC 1949), although Mallinckrodt (1994) says that these were still sent to SLAPS up to 1956. Some uranium scrap was sent to the Vitro Manufacturing Company for uranium recovery (AEC 1949).

The gangue lead cake wastes (K-65) from pitchblende processing was stored in Building 114 until removed by AEC (Mallinckrodt 1994). The barium sulfate and raffinate cakes were collected in dumpster-type containers, loaded into AEC dump trucks, and transported on a daily basis to SLAPS (Mallinckrodt 1994).

The non-recyclable materials formed a slag waste called "C-liner" or "C-liner slag", which was mainly used dolomite liner with less than 2% uranium content (FUSRAP Undated b; AEC 1949). It resulted from the separation of slag in the reduction (bomb) step in the metal plant (first in Plant 4, later Plant 6E). This waste was created until early 1953 when the dolomite liner was replaced by a recycled magnesium fluoride liner (FUSRAP Undated b). There was another bomb waste called "C-special" (AEC 1949), which may be the same as the C-liner slag since it also originated in the bomb furnace. Yet another bomb waste was the recyclable magnesium fluoride slag that remained after "scalping" the uranium content from the magnesium fluoride slag, beginning in 1955; this was called C-701 (FUSRAP undated a). These wastes were also sent to SLAPS.

The Sperry Cake was found to be a good source of protactinium-231. Some of it was shipped to Mound which processed approximately 20 tons (about eighty 55-gallon drums) of it and obtained approximately two grams of protactinium-231 (AEC 1978). There were also small amounts of raffinates present at the SLAPS waste storage site from the processing of lower-grade uranium ores (AEC 1978). The material obtained from processing carnotite and other low-grade domestic ores was kept separate from the pitchblende residue (AEC 1978).

Most “product” (UO_3, UO_2, and UF_4) was packaged into 75-lb paper sacks and then into a barrel. There was usually a fine film of uranium material clinging to the sacks, so they were burned in an incinerator and the ashes sent to recovery (MED 1944a). Floor sweepings and spillages, swept into sumps; scrapings off the walls and equipment; and dust collected in collectors, usually by vacuum systems, were also sent to a recovery system (MED 1944a).

There were separate sets of sewers running from Plants 1 and 2, Plant 4, and Plants 6, 6E, and 7 out to the streets, under the streets, and out to the Mississippi River (Mallinckrodt 1994). In 1949, about 3

million gallons a day of liquid effluent classed as alkaline filtrate was being sent to the Mississippi River out a drain pipe, presumably a sewer; this was mostly cooling water, but some was process waste containing up to 12 pounds per day of uranium (AEC 1949). A small additional amount of acid waste flowed to the Mississippi via an acid sewer (AEC 1949). Mallinckrodt (1994) stated that a 1956 description of Plant 6/6E/7 operations showed that 12,000 gallons per day of raffinate filtrate from the Plant 6 pitchblende extraction was being discharged to the sewer. These lines were apparently underground for the most part, but it is possible that some of them were aboveground where they ran inside the site (see the Table 1 Notes column).

2.0 RADIOLOGICAL CHARACTERISTICS, CONDITIONS, CONSIDERATIONS, AND AVAILABLE DATA

As AEC (1950a) observed, no radiation measurements or evaluations of dust exposure were made in the Mallinckrodt plants in the first few years of operations because it was expected that the processing of uranium ores and compounds would involve little risk of radiation injury; this was because of the low specific activity of uranium and because of what was thought at the time to be the temporary nature of the work. However, when AEC's New York Operations Office (NYOO), which oversaw the Mallinckrodt work, evaluated the potential hazards (which at this time included those of radium-bearing pitchblende ores), they determined them to be "considerable" (AEC 1950a). NYOO and Mallinckrodt began a program of workplace and personnel monitoring.

AEC and Mallinckrodt had already begun to issue film badges in 1946 (AEC 1950a), with apparently a small-scale effort begun in late 1945. To this was added breath radon determinations in 1946 and a formal dust measurement program in 1948 (AEC 1950a). Urinalysis measurements appear to have begun in 1947 also.

Since little individual monitoring data is available prior to about 1946, some extrapolation of existing data to cover the unmonitored periods is necessary, as AEC itself tried to do (AEC 1950a). Also, data must be analyzed to allow missing dose to be calculated for individual workers where there are gaps in the monitored period. The sections below provide information as to the available data and other information that will allow this to be done.

AEC thought that as a result of improvements planned for 1949 and early 1950, there would be no whole-body radiation exposures greater than 300 mrep/week in Plant 6 and the dust concentrations would be reduced to the AEC's "preferred level" of 50 $\mu g/m^3$, or 70 dpm/m^3 (AEC 1949). AEC was also expected that construction of a new metal plant (Plant 6E), in which UF_4 would be reduced to metal as was currently done at Plant 4, would produce satisfactory (occupational) environmental conditions (AEC 1949). It was also expected that in 1951, the new UO_2-to-UF_4 plant (Plant 7) would further reduce exposures (AEC 1949). However, with the increase in production, these goals were not met in all cases, although there were some successes and although doses and air concentrations did decrease overall. The effects of the various plant changes and improvements were reflected in the airborne and external exposure levels, as shown in the text and tables below.

2.1 UNITS, LIMITS, AND RECOMMENDATIONS

The exposure (dose) units used by MED/AEC during most of the relevant period were milliroentgen (mR) for gamma doses and millirep for beta doses; the abbreviations in the film badge and other records were mr and mrep respectively. The rep is equal to 0.93 rad.

During the war, AEC's recommended ("tolerance") levels of external exposure for the uranium processing plants were 700 mR per week to the whole body and 3500 mrep per week to the hands (AEC 1949; AEC 1950b); AEC (1950b) stated that this was 700 mrep per week "each of beta and gamma", as accepted by the University of Rochester in processing film badges (i.e., Rochester did not flag reported doses as above tolerance if the weekly beta and gamma doses were each below 700 mrep). At some point, when NYOO had assumed the job of reading the film badges, the tolerance level was lowered to 500 mrep per week, which Mallinckrodt continued to interpret as applying to either beta or gamma but not to the total (AEC 1950b). However, Mallinckrodt used a control level of 150 mrep per week, called the "preferred level" in its 1946-1952 film badge records. The number that was compared to this level was the sum of the gamma dose in mR (i.e., mr in the records) and the beta dose in mrep, as registered by the film badge, apparently with no adjustment of the mrep by the

factor of 0.93. MCW gave as the “tolerance cumulative dose” limits in use in 1955 as beta, 500 mrep per week, whole or part body; gamma, 300 mR per week, whole or part body; sum of beta and gamma, 500 mrep per week whole or part body; and 1500 mrep per week, extremity (MCW 1955).

In 1947, the basic dose limit was 0.1 rep/day and the relative biological effectiveness (RBE) for alphas was 10 (Hursh 1975); probably this was true earlier as well.

In anticipation of the lowering of the radiological dose standards (recommended limits) by the national expert committees such as the National Council on Radiation Protection and Measurements (NCRP), AEC began making changes in the plants in about 1948 to meet new "maximum permissible levels" of 300 mR/week for whole body irradiation and 1500 mrep/week for beta radiation to the hands (AEC 1949). In August 1949, AEC established and circulated to its contractor personnel a tolerance level of 300 mrep per week, which was to be taken as the total gamma plus beta dose to the whole body. However, Mallinckrodt misunderstood that the 300 mrep limit was to be applied to the total of beta and gamma and interpreted it as the limit for either beta or gamma (AEC 1950b). Finally, in January 1950 AEC made it clear to Mallinckrodt that the limit applied to the total beta plus gamma (AEC 1950b)

In mid-1950 AEC agreed to allow Mallinckrodt to interpret the 300 mrep total gamma plus beta whole-body limit as being taken as the average weekly dose over a three-month period, thus allowing the 300 mrep to be exceeded in some weeks (AEC 1950d); this was apparently based on the fact that Mallinckrodt was already using a system of personnel rotation to reduce doses (AEC 1950b). However, AEC at the same time suggested that 150 mrep per week be taken as a recommended limit for most purposes and that a weekly dose of 600 mrep be exceeded only in exceptional cases. It should be noted that in 1953, a design contractor was stating that the design criteria for ventilation and dust control equipment his company had put in at Mallinckrodt and Harshaw included a maximum weekly exposure of 300 mR of gamma radiation, with actual design predicated on half that to allow for a safety factor in unusual circumstances (Miller 1953).

During the early days of wartime uranium processing, AEC/MED's acceptable levels of exposure for the uranium processing plants for dust in air were 500 $\mu g/m^3$ for insoluble uranium salts and 150 $\mu g/m^3$ for soluble salts (AEC 1949). In 1944 MED determined that a standard was needed for uranium dusts and adopted the air maximum permissible concentration (MPC) level for lead, 150 $\mu g/m^3$, as the interim standard (Hursh 1975). In 1949, a University of Rochester scientific group suggested an air MPC of 50 $\mu g/m^3$ for soluble uranium forms based on (chemical) injury to the kidney and an air MPC for insoluble forms based on radiation injury to the lung (Hursh 1975). In 1953 the NCRP recommended in National Bureau of Standards Handbook 52 (quoted in Hursh 1975) a limit of 73 $\mu g/m^3$ for both soluble and insoluble forms; it was adopted. These were occupational standards that correspond to a 40-hour week (the number of hours that Hursh (1975) uses in conversions in his discussion of the history of standards).

By 1949, AEC had set a "preferred level" of 50 $\mu g/m^3$ for uranium dust, assuming a routine exposure of 8 hours a day, 6 days a week (AEC 1949). This was taken to be equivalent to 70 dpm/m^3 for alpha and is based on animal studies (Hursh 1975). For dosimetry reference, Appendix A gives the basis for this figure. This was later referred to as the Maximum Allowable Concentration (MAC) and was still in use as of 1953 (Miller 1953). In early 1955, AEC appears to have adopted a MAC of 100 dpm/m^3 for alpha, as AEC (1955c) stated in an air dust study report. In a 1958 report, AEC gave the limit for natural uranium, either soluble or insoluble, in air as 5×10^{-11} µCi/ml for 40 hours/wk (i.e., occupational) and 1.7×10^{-12} µCi/ml for continuous occupancy (AEC 1958, Table I). In 1959 the AEC also recommended against respirator use except in emergency situations (AEC 1949), suggesting that before the relevant period of Mallinckrodt work, extensive use of respirators was still tolerated as a means of minimizing exposure.

However, note that in a 1958 paper by an AEC-NYOO safety official, while the wartime MAC was given as 500 µg/m^3, agreeing with the information above, the "present MAC" (i.e., in 1958) was said to be 110 dpm/m^3 instead of the 70 dpm/m^3 of other references (Breslin 1958). This may be because of the so-called "double curie" or "special curie" uranium radioactive content unit that the NCRP and others used prior to about 1 January 1974. The special curie was defined for the natural uranium mix and was taken to be 2.05 times the nominal number of disintegrations of U-238 because it included allowances for the U-234 and U-235 content (NCRP 1974). If the 110 dpm/m^3 was based on a 48-hour week, this would be equivalent to 65 dpm/m^3, or about 70 dpm/m^3, based on a 40-hour week and multiplying by 2.05 to convert from the special curie to the regular curie. The NCRP MPC value that corresponded to the special curie was given as 6×10^{-11} "special" µCi/cm^3, which agrees with the value of 5×10^{-11} given in the paragraph above if the former was based on a 48-hour week. (The NCRP abandoned use of this unit in 1973 because it caused confusion.) It does not appear that the former use of this unit has caused any disparity or confusion in the interpretation of data used in this document, but this potential problem should be noted.

Prior to 1941, there was no standard for occupational radon exposure. In 1941, the United States Advisory Committee on X-Ray and Radium Protection recommended 10^{-11} Ci/L (curies per liter) as the acceptable occupational radon level, based on a 40-hour work week (Akerblom 1999). (This would be 10 picocuries/liter in the units most used today.) This standard was published as a handbook by the National Bureau of Standards (NBS 1941). According to Raabe (2002), the standard was for ventilated rooms in which work was done with radium (e.g., luminous dial painting) and did not include consideration of radon daughter products. An AEC report (AEC 1949) stated explicitly that the acceptable radon level for "environmental" air (room or outside air breathed by occupational workers) in AEC-sponsored facilities was taken to be 10^{-10} Ci/L, i.e., ten times higher than the NBS standard; the report refers to this level as the " "maximum permissible concentration" " (page 14) and also as the "preferred level" (page 20). However, a value of 1 x 10-12 Ci/L was also mentioned as the tolerance level in 1950 (AEC 1950i). A ventilation design contractor stated in 1953 that the radon design criteria limit for work for Mallinckrodt and Harshaw was 10^{-8} Ci/m^3 of air, or 10^{-11} Ci/L of air (Miller 1953). Thus it is claimant-favorable to assume that the standard that was applied during most of the period in which Mallinckrodt uranium refining took place was 10^{-10} Ci/L (100 pCi/L) and that this applied to radon only and not to the daughters.

Regarding effluents, AEC proceeded on the basis that it was acceptable for liquid and solid effluents to have concentrations up to one order of magnitude greater than natural background (AEC 1949). AEC "recommend[ed] that neighborhood air levels for these radioactive materials [containing uranium and radium] should not exceed 1% of the levels used within the plants" (AEC 1949). No information is available as to Mallinckrodt's approach to effluent control, e.g., whether it followed the AEC recommendation.

2.2 RADIOACTIVITY CONTENT AND HANDLING OF THE ORE, URANIUM PRODUCTS, AND RESIDUES

2.2.1 Ore

The origin of the ores is important in considering source terms at Mallinckrodt facilities because the content of uranium in the ores was greatly variable. Pitchblende ores contained high levels of radium-226 and other radiologically significant daughter products, while other ores and feed materials typically did not. Ra-226 (in equilibrium with its daughter products) constitutes a significant gamma source and thus produced most of the external whole-body dose received by the Mallinckrodt workers, while Th-234 and Pa-234, both beta emitters, produced most of the extremity dose. In addition, radon and radioactive dusts were released in storage and processing, resulting in internal

dose due to inhalation. The concentration of radium and other daughters present in the ore, processed uranium, and processing residue at any given time mostly strongly depended on the concentration of uranium in the ore and its radium content. Thus on a per-ton-of-ore-processed basis (ignoring process differences), the doses received depended on where the ore originated.

Pitchblende ores from the Belgian Congo (the so-called "Congo ore" or African ore), supplied by the Belgium-based African Metals Company, had average concentrations of 25% uranium by weight (Eisenbud 1975), up to a maximum of 65-70% (DOE 1997; Dupree-Ellis et al. 2000). (Note that there is some confusion among the various references with regard to ore specifications, in that some give the percentage as applying to uranium alone and some as applying to U_3O_8. Since the percentage is by weight and the uranium is by far the larger weight constituent of U_3O_8, the differences are not significant.) Other early ore sources were pitchblende ores from Canada (Radium City in the Great Bear Lake Area and Port Hope in Ontario) (DOE 1997), containing uranium concentrations of about 10% (Eisenbud 1975). Later in the war, domestic ores were used also. The wartime domestic supplies were actually tailings from vanadium mining and milling (Eisenbud 1975); although the original ore had uranium concentrations of less than 1%, the tailings were shipped as a 20% sludge concentrate (Eisenbud 1975).

Ores from the Belgian Congo had average concentrations contained up to 100 milligrams of Ra-226 per ton of ore (Dupree-Ellis et al. 2000; Eisenbud 1975), possibly up to 135 milligrams per ton (AEC 1949). Thus there could be a significant dose rate from the ore when it was in drums or when it was being loaded into other containers and hoppers. As previously noted, the ore was dried before use; this was a necessary condition for optimal processing, but the dust levels created during drying and later handling were high. The radon was also significant because it built up over time in containers and enclosed spaces. When drums, enclosed storage areas, the thaw house, etc., were opened, a worker could be enveloped in the escaping radon. Table 4 gives more information about the quantities and radiological characteristics of the ore.

Most of the pitchblende processed by Mallinckrodt was obtained as a concentrate from the Belgian Congo in 1944 and was shipped to St. Louis from there in 55-gallon drums (AEC 1978). After the war, feed materials were usually packed into 30- or 55- gallon steel drums at the mills and shipped by rail in full carload lots (Mason 1958a). It can be inferred from Mason (1958a) that a rough conversion is about 15,000 tons of uranium ore per 100,000 drums, so that each ton represented about 7 drums to be dumped, sampled, and processed.

2.2.2 Uranium Products

Once the Ra-226 was removed following the digestion step and the vessel(s) had been vented, the gamma dose rates were much lower and the radon (which arose from the radium) was no longer an issue. Radium and radon would again build up from the uranium parent, but this took more time than the apparent typical digestion-to-shipout time at Mallinckrodt.

The main hazard after the radium-bearing residue was removed was dust, since a fraction of the uranium salts and oxides tended to aerosolize when dry and when handled. Initially, somewhat crude precautions were taken to control dust during handling and there was extensive manual handling of uranium salts and oxides in the dry form (Eisenbud 1975). For example, in Plant 6 (and presumably in its predecessor plants 1 and 2), the UO_3 dry powder was unloaded from the reaction pots into drums by hand-scooping (Mason 1958a), i.e., manually using handheld scoops. The UO_3 was then moved to the furnace loading area, where it was hand-scooped into trays, which after weighing were placed into the furnaces to be reduced to UO_2 (Mason 1958a). The trays of UO_2 were then unloaded by hand into drums for transport to other areas or sites. The major handling improvement of 1949, the

installation of pneumatic unloading and conveying systems, was supposed to have eliminated all hand-scooping of UO_2 and UO_3. However, AEC inspectors repeatedly noted hand-scooping going on until the end of operations at the plant, often due to the failure of equipment such as the vacuum-type UO3 “gulpers” (AEC 1954d; AEC 1956c).

UO_2 produced at Plant 6 was trucked over to Plant 4 in "small fiber containers" (AEC 1949); no information is given as to how this affected containment of the dust. In Plant 4, there was again extensive hand-scooping and other manual handling of the uranium materials (UO_2, UF_4, and uranium metal) (Mason 1958a). This was reduced by mechanization in 1948 and 1949, but even so dust levels were considered too high (Mason 1958a). AEC agreed to have Mallinckrodt construct Plants 6E and 7 to replace it. These plants were even more mechanized and were said to require little (if any) manual handling (Mason 1958a); however, as various AEC air dust study reports indicate (e.g., AEC 1954g; AEC 1955b), this was not so. AEC (1955c) even reported in 1955 that a Plant 7 operator used a piece of cardboard in lieu of a conventional metal scoop to make up UF_4, with the operator's (presumably gloved) fingers dipping into the material frequently.

2.2.3 Residues (Wastes)

A condition placed on the ores from the Belgian Congo by African Metals was that the Ra-226, the Ra-226 daughters, and the lead and precious metals be extracted, stored, and returned to African Metals (AEC 1978; AEC 1949). Thus the Mallinckrodt process included steps to extract these materials as a separate residue from the bulk of the ore residue; this was the radium- and lead-bearing K-65 residue.

As much as 100 grams of Ra-226 contained in the residues was produced per month at the Mallinckrodt facilities (AEC 1949). This was in fact the quantity produced in December 1948 (AEC 1949). It was reported that 200 grams had been transported at one time to Middlesex (AEC 1949), meaning that up to this quantity had been in storage at the Mallinckrodt site and had had to be loaded for transport at one time. The residues were stored in drums "for health reasons" (FUSRAP 1996). Some of the waste sent to the SLAPS waste storage site was hand-packed by Mallinckrodt workers into barrels (Eisenbud 1975). Radiation levels from the railcars and trucks exceeded those permitted under the regulations of the day, so shipments had to be made under special permits granted by the Interstate Commerce Commission (forerunner of the Department of Transportation) (AEC 1949).

As noted earlier, in 1955-1957 Mallinckrodt processed AM-7 residues (see Table 4) and produced 3600 gallons of a concentrated thorium nitrate solution that was sent to Mound (AEC 1978; FUSRAP 1996; US DOE 2002). AEC (1978) states that Mound purified and concentrated approximately a kilogram of thorium-230 from this material, but DOE (2002) states that although 500 grams was produced and an additional 500 g ordered, the latter was apparently never produced. The claimant-favorable assumption will be made that the entire 1 kg was produced. Thus assuming a high separation percentage, in the original 350 tons of AM-7 during processing there were approximately the one kilogram of Th-230, about 9 kilograms of total thorium, and 0.015 kilogram of uranium. This is consistent with the report by Figgins et al. (1962) that in the solution there were 29 ppm of Th-232 and 3.8 ppm of Th-230, i.e., 11.6% (weight) Th-230 by isotope.

It is not clear how long it had been since the first residue sent in 1946 to the SLAPS waste storage site had been produced in the refining process. That is, this type of residue had been produced since ether extraction started in July 1942, but it is not clear whether the residues produced between 1942 and 1946 were all stored at Mallinckrodt and then shipped to SLAPS, or whether some of the older residues had been shipped elsewhere. The claimant-favorable assumption will be made that the waste was all produced in 1942 and sat in containers for 15 years, until 1957; this will maximize the

radium and radon content. As Table 6 shows, although the Th-230 and Th-232 daughters would have had some time to build up, only the Th-232 daughters would be nearing equilibrium with the parent. The maximum Ra-226 content over the 2.25 possible years of processing (i.e., the 15-year maximum) was 0.158 mCi (ignoring decay of Ra-226) and the maximum Rn-222 content was 0.158 mCi (ignoring decay of Rn-222).

Regarding the protactinium processing of residues, there is no suggestion in any reference that the Sperry press cake was processed in any way at the St. Louis downtown site and the waste appears to have been shipped out to Mound directly from SLAPS. Thus, it will be considered that there are no radiological implications of protactinium processing associated with the Mallinckrodt downtown site.

2.3 INTERNAL DOSE CONSIDERATIONS

The primary route of internal exposure was via inhalation of airborne particulates, although radon was a considerable problem in some areas. The wet operations did not generate as significant a level of airborne particulates as the dry operations (Mason 1958a). Thus the operations that were likely to produce airborne particulates were those in which the uranium-containing material was dry or was heated, although airborne contamination could occur even when the material was not open to the room air because some of the equipment leaked (Caplan and Mason 1952). Material that had settled on the floor and other surfaces could also be resuspended in the course of operations.

Very little internal exposure data (in dose units) is available. In the early days, measurements of airborne concentrations were used per se as indicators of potential exposures and of the need for changes in processes and equipment (as suggested by AEC 1950a). Urinalysis appears to have been performed as a means of retroactively checking for acute exposures or for the onset of damage due to chronic exposure, rather than a dose measurement per se. In addition, as discussed below, the particle size and solubility of the various uranium forms were still being investigated experimentally by researchers in the field, so that the assumptions that were used at that time in calculating internal doses might not be acceptable based on current knowledge. Therefore in this technical basis document, potential internal exposure is presented in terms of airborne concentration data (and the derived inhaled amounts) and surrogate urinalysis results, rather than internal doses, so that dose reconstructors may estimate individual internal doses using modern methods.

2.3.1 Particle Size, Solubility, and Composition Considerations; Sampling Methods

A discussion of the thinking of the time regarding particle size and solubility is included in the discussion below in case questions arise regarding typical operations or regarding notes in the urinalysis and other records.

The uranium refining operations at Mallinckrodt produced nominally insoluble uranium compounds, e.g., UO_2, UF_4, and uranium metal (Lippmann 1958, regarding solubility); no patently soluble forms, such as UF_6, appear to have been produced. However, as some of the literature in the years between 1958 and about 1975 showed, some supposedly insoluble particles produced in these operations seemed to behave like soluble particles (e.g., Lippmann 1958, Heatherton 1975, Archer et al. 1975). More recently, ICRP 71 (ICRP 1995a) states that studies of UF_4 show behavior consistent with Type F in some cases and Type M in other cases, while ICRP 68 (ICRP 1995b) recommends Type M for UF_4. Yet autopsy data from deceased workers showed a far lower concentration of uranium and thorium in lung and other tissues than would have been expected based on the average airborne concentrations inhaled. This led Eisenbud (1975) and others to postulate that the particle behavior formulation at the time was incorrect: they conjectured that due to the high density of the uranium and daughters, particles of respirable diameter behaved like lighter particles of much larger diameters.

Eisenbud (1958) reported that "It has been shown that in these plants [the uranium processing plants] the mass median diameter was about 2 µ [microns]". But he also noted that while the peak for alveolar retention is 1-2 µ for dust of unit density (i.e., 1 g/cm^3), uranium oxide dust has a density of 9 or 10, so that a 1-2 µ particle will behave as though it were a 3-6 µ particle of unit density. An AEC report on uranium mills stated that ore concentrates (the form that arrives at uranium refineries such as Mallinckrodt) had a "mass medium [sic] size" of 2.5 µ (AEC 1958). Some uranium refinery workers were said to have been exposed to UO_3 dust with a mass median diameter of 2 µ; however, with a density for U compounds in the range of 9-10 g/cm^3, the effective aerodynamic diameter is much larger than 2 µ, possibly in the range of 5-6 µ (Eisenbud 1975).

Schwendiman et al. (1975) cited the results of a study by Lippmann and Harris regarding the application of size-selective samplers in the uranium industry. Lippmann and Harris performed a sampling survey of six different uranium processing plants. They used a filter pair such that the second filter was the respirable-particle one, with the first collecting 100% of particles ≥ 10 µm AED, 75% of those ≥ 10 µm, 50% = 3.5 µm, 25% = 2.5 µm, and 0% of those ≤ 2 µm. They found that less than 15% of the airborne material collected on the respirable-particle filter. Schwendiman et al. (1975) noted that this agrees fairly well with the ICRP assumption of a size distribution such that 25% deposits in the lower respiratory passages and, for insoluble compounds, only half of the 25% (or 12.5%) would be retained with biological half-life of 120 days: only 10% of the samples in the study had more than 25% collected on the second filter. Categories studied included U_3O_8, UO_3, UO_2, ore concentrate, and mixed scrap.

Because of the lack of specific information regarding particle sizes at the Mallinckrodt plants, the ICRP 66 default deposition parameters (ICRP 1994) are to be used to estimate internal doses for Mallinckrodt workers. However, where there are particle size issues in specific cases, the information above and in Table 7, which gives measured particle sizes for various uranium forms, should be of general application even when the listing is for depleted or enriched rather than natural uranium. Sanders (1975) also provides a useful general observation that foundry operations (those in which uranium oxides are produced) have the highest percentage of airborne particles in the lower lung-inhalation range, while reduction operations (UF_4 to metal) have the smallest percentage.

Regarding the isotopic and chemical composition of the dusts, no Mallinckrodt-specific information appears to be available. Observations at a large uranium processing mill (probably Anaconda) showed that although the potential for dust creation in the dry processing steps was clear, the wet processing steps, such as grinding, leaching, separation, and precipitation could create aerosols by agitation or by transfer of solutions and slurries. Even so, in the wet processing areas airborne uranium was never a major problem, i.e., local hooding and exhaust ventilation were not required in order to keep the dust concentration below allowable levels. The physical characteristics of the airborne particulates in the dry and the wet areas were thought to be similar; thus it was assumed that nearly all of the mass of the particle was siliceous material, clay, or a mixture of the two. The mass of the particles was found to be less than one percent of the total mass. From specific nuclide analyses done over several years, they concluded that secular equilibrium existed at least through Ra-226 in the ore at the time of mining. Specific nuclide analyses of particles taken in various areas of the mill showed that the U-238:Th-230:Ra-226 ratio was 1:1:0.3 and was fairly constant regardless of the source of the aerosol or dust. But in the yellowcake section of the mill, where the ore had been processed to become mostly U_3O_8, the ratio was 1:0.01:0.001, indicating that these products were removed in the processing (Wilde 1975).

The various AEC air dust study reports state that they are following an established AEC protocol, but the documentation for what the protocol was is lacking. However, some information is known about Mallinckrodt's methods. For the data reported by MCW (1949b), dust samples were collected on 1-

1/8" Whatman #41 filter paper disks, using a modified Fischer pump, at 0.5 ft^3/min, over a period of 45 seconds to 30 minutes depending on conditions and job time. The disks were counted on a parallel plate alpha counter such that statistical variations would be no more than 10% at the 0.9 confidence level. It was stated that a few of the low-level samples might have errors of 20%. AEC (1950a) stated that it was using 1-1/8" Whatman filter paper disks and a handheld air sample with a collection rate of 15-20 lfm.

From reports of sampling at other sites and from unspecific mentions in papers and reports about Mallinckrodt, it appears that typical practice was for the air to be drawn through filter paper (most likely Whatman #41, widely used in the time period) and counted on an alpha scintillation counter (e.g., the laundry samples of Utnage 1958b). In 1958 at the Oak Ridge Gaseous Diffusion Plant, the Whatman #41 was used with fixed counting equipment, for a counting and collection efficiency of 30% (Becher 1958). AEC in-plant air sampling was done by collection on Whatman #41 filter paper and counting of total alphas; a correction for self-absorption in the filter paper was applied (Eisenbud 1975). The results were reported as alpha dpm/m^3 (Eisenbud 1975). The AEC, in sampling stack and environs air at various sites including Mallinckrodt, used Whatman #41 filter discs with "standard sampling equipment and techniques normally employed by HASL" and counted them on scintillation counters (Weinstein 1958). Since the methods of the time seem to have been fairly uniform (with HASL setting the standard), it is assumed that the AEC and Mallinckrodt measurements were taken consistent with these references.

The AEC's HASL staff was committed to the time-weighted average as being most representative of total exposure. As Glauberman and Harris (1958) put it, "HASL has found from experience that the multiple-sample time-weighted average exposure procedure is the most accurate....The GA [general area] sample normally will tend to underestimate an operator's exposure and the BZ [breathing zone] sample to overestimate it, but by time-weighting the average concentrations for both types of samples an operator's exposure may be closely evaluated...[this method] yields reasonably reproducible results". In this technical basis document, time-weighted averages will be preferred to static measurements or short-term maxima as being representative of worker exposures. These time-weighted averages are documented in a series of AEC air dust study reports (e.g., AEC 1954b) and in some Mallinckrodt reports (e.g., MCW 1949b).

2.3.2 Airborne Dust Levels

Eisenbud (1975) stated that "above all other types of exposure, it was the airborne alpha-emitting dust that was the cause of greatest concern." This was particularly true in the sampling and crushing of ore and in the mechanical and manual handling of dry uranium salts and oxides (Eisenbud 1975). Dupree-Ellis et al. (2000) stated that daily average uranium dust concentrations of up to 100-200 times the maximum allowable concentration of 50 µg/m^3 were measured in poorly ventilated processing areas. An industry-wide survey showed the average concentration to be 5000 dpm/m^3, which an AEC-HASL official stated was "a conservative estimate of the levels that existed from 1942 to 1948" (Harris 1958).

Mason (1958a) stated that while no regular dust sampling program was in effect at Mallinckrodt during 1943-1947, enough samples were collected to show that concentrations were high by 1958 standards, that concentrations of 50 to 100 times the MAC level of 70 dpm/m^3 were not uncommon, and that some operations produced concentrations up to 1000 MAC for a few minutes at a time. According to the AEC, many employees were exposed to elevated dust levels for years (AEC 1949). In 1946-1948, respirators were said to be required "for practically all plant operations" (Mason 1958a) but respirators were not used consistently (see Section 5.3.3 below).

Major improvements in dust control and ventilation were made at Mallinckrodt in 1949 under the new AEC health program, such as the installation of pneumatic unloading and conveying equipment in Plant 6 process areas that eliminated most hand-scooping and thus that mode of exposure to dust (Mason 1958a). However, while there was a marked reduction in dust levels, the improvement was not what had been hoped for in some areas, especially with respect to the handling of the UO_3 (Mason 1958a). In 1953, for example, an AEC inspector reported that there were many small openings between the operating area an the drum storage “alleys” in the Ore Room addition; as a result, winds blew into the area and upset the ventilation air balance, causing dust to be blown into the operators’ area (AEC 1953). Even the most modern plant, Plant 7, had dust problems: in 1954 an AEC inspector noted that there was a fine film of UO_3 on supposedly clean drums and as cans of UF4 were transferred from a hooded enclosure to a conveyor, a green dust cloud could be seen to escape from under the lid of nearly every can (AEC 1954f).

Similarly, in 1948 and 1949, much of the manual handling of UO_2, UF_4, and uranium metal in Plant 4 was eliminated, but dust concentrations did not get down to satisfactory levels (Mason 1958a). Even the building of the new Plant 6E and Plant 7 did not completely eliminate the problem: the uranium was never contained well enough that it ceased to create airborne levels of concern in the plant air and in the (multi-building) plants in general (Mason 1958a). A Mallinckrodt official remarked that it had been a constant battle to keep airborne levels at 1 MAC or less (Mason 1958a). An AEC safety official speaking of workers at all the AEC uranium-refining plants (Breslin 1958) reported that even in 1951 approximately half of the workers were exposed to average concentrations above the MAC then in force (which he said was 110 dpm/m^3, although AEC (1954f) indicates that it was 70 dpm/m^3 until at least the end of 1954). He also stated that in 1956 6% still were above the MAC; the percentages for those exposed to average concentrations greater than 1800 dpm/m^3 were 4% and 1% respectively. Finally, he noted that while airborne control in these plants was largely achieved by 1955, there had been a retrogression resulting from a large increase in production volume.

Tables 8 through 11 give a trend overview of airborne uranium concentrations measured over the years at Plants 4, 6, 6E, and 7 (Mason 1958a). The concentrations are given as multiples of the "preferred level" at the time of measurement (1948), i.e., multiples of 70 dpm alpha per m^3. It appears from the reference that they represent typical concentrations rather than maxima. In AEC’s measurements, they did not separate the uranium and radium components of the alpha activity, i.e., they counted gross alpha (AEC 1950a). This was Mallinckrodt’s practice as well (MCW 1950a; MCW 1955-2/21/55); also, beta-gamma activity analysis was not routinely done (MCW 1955). Thus Tables 8-19 must be assumed to be gross alpha measurements, whoever took the measurements. There were no continuous air monitors at the Mallinckrodt site because the results were thought to be of doubtful value (MCW 1955).

Table 12 presents the results of airborne dust surveys made in Plant 4 by, respectively, AEC-NYOO's Medical Division in May 1948 and Mallinckrodt safety officials in September-October 1948. These results are given as time-weighted daily average levels (called DWE levels by AEC) of dust exposure by plant. Table 12 shows that AEC and Mallinckrodt's data were in general agreement, although there were some differences. In this technical basis document, AEC's data are used preferentially because AEC set the standard of measurement for the uranium processing sites and because AEC's figures for the most exposed workers are typically higher than Mallinckrodt's. Thus using AEC's numbers is claimant-favorable, in general. The AEC data is mostly from a series of dust studies that AEC did on a nearly annual basis from about 1948 on. This is presented, with a few additions from Mallinckrodt reports to fill gaps, in Tables 13 through 18.

Some detailed information is available about the particular case of the laundry workers, circa 1958 when the laundry had operated for at least ten years (Utnage 1958b), as shown in Table 18; information was also found in the various AEC dust study reports.

Information from other sites is helpful in deducing what would be typical at Mallinckrodt. In an AEC report in 1958, the breathing zone concentrations in the final ore concentrates packaging areas of over a dozen mills were evaluated; the concentrations ranged from 0.01 to 5.5 pCi/L, with a median of about 0.15 and a mean of 0.91 (AEC 1958, Table V). These figures suggest levels that might be encountered by Mallinckrodt workers unloading the packages (drums) at the beginning of the refining process. See also Section 5.3.4 below regarding resuspension of surface contamination. Resuspension contributions are assumed to be included in all data cited in this technical basis document since dust levels were typically measured while work was taking place.

The reported air concentrations generally pertain to those workers directly and continuously involved in uranium refining work. However, Breslin (1958) defines "auxiliary workers" as workers "not directly connected with production but located in or near production buildings,....[including] chemists, engineers, office workers, garage mechanics, outside maintenance personnel, and the like", noting that some of these had occasion to visit production areas in the course of their work while others did not. Even with the limited access, in 1948 about 13% of the auxiliary workers studied were exposed to average concentrations above the MAC (110 dpm/m^3 at that time) and more than 1% to concentrations greater than 440 dpm/m^3 (Breslin 1958). By 1954 none of these auxiliary workers were exposed to average concentrations above the MAC (Breslin 1958), although some of the process workers still were. These statements are illustrated by the data given in the various AEC dust study reports.

Relatively high potential for dust exposure applied not only to those actually present in the dusty buildings, but to those working elsewhere in the plants and even outside the plants. For example, a Mallinckrodt safety official remarked that one reason to revise the ventilation in about 1952 had been that a study of plant effluents showed that "large bursts of dust found their way outside of the plant immediately after filter cleaning" (Harris and Mason 1953). Mason (1958a) also suggests that co-located (nearby but uninvolved) workers were exposed to elevated airborne levels.

In later years, Mallinckrodt was supposed to sample stacks at least once a year, but it was not being done (MCW 1955). Weinstein (1958) reported on an air sampling study that AEC-HASL did of stack and environs (outside) air at various sites, including Mallinckrodt, in November 1949. They did not take any stack samples at Mallinckrodt, but indicated that previous data implied a probable average rate of emission of uranium from the Mallinckrodt stack(s) of about 0.011 g/sec, with a flow rate of about 20,000 cfm. About 52 tons of uranium as metal was estimated to have been discharged in the stack effluents since the beginning of operation. While nearly every reported (outside) concentration at Mallinckrodt was below maximum permissible levels, it was observed that "1000 feet would circumscribe the MAC" level (out from the plants), i.e., within a few hundred feet of the plant(s) the MAC might be exceeded. The MAC given in the version of 10 CFR 20 in force at the time was 1.7×10^{-12} µCi/ml air for continuous exposure, or 2.5 µg/m^3, which presumably was the "public" MAC and not the occupational MAC. This would help explain the somewhat elevated weighted average concentrations even for workers who did not enter production areas.

Based on the information in the references cited in this and previous sections, Tables 20 and 21 were set up to help dose reconstructors interpret claimant submissions and the Mallinckrodt records. Table 19 lists job titles obtained from AEC and Mallinckrodt reports and from film badge and urinalysis records; in addition, it gives (1) a code(s) corresponding to Table 20 and (2) a geometry factor set appropriate for each job title (for later use as described in Section 7). Table 20 gives a set of codes

that establishes the correspondence between a process and a type of work or functions; this is to assist the dose reconstructor in determining (1) the appropriate job title if claimant information is not clear and (2) the appropriate breathing rate to apply, as discussed in Section 7.

Tables 19 and 20 are to be used with Tables 21 through 24 to help determine the exposure to an individual worker when bioassay data for the worker is missing or is conflicting and when comparable worker bioassay data (see Section 6) is insufficient. Tables 21 through 24 were derived from Tables 13 through 17 and other sources; the data they contain is nearly all average daily weighted air concentrations. All of this data is based on a natural uranium mixture, with one exception, as discussed below.

The process in which AM-7 residue was converted into a concentrated thorium nitrate solution, as explained in Section 4.5, is a special case. No information was found regarding the particle size of this residue, its tendency to be aerosolized, etc. However, the digestion and extraction process appears to be similar to the basic uranium ore digestion and extraction process and so it presents no novel operational or processing features. Besides the AEC-measured data given in Table 17, there is some data from the Mound end of the processing (Mound 1956): the maximum and average air concentrations in the ionium (Th-230) "high-risk" part of the Mound processing area were 48.1 $x10^{-10}$ and 16.3 $\times 10^{-10}$ µCi/cm^3 respectively. In the exhaust line of the hood in which the work was done the maximum and average concentrations were 384.9 $\times 10^{-10}$ and 38.8 $\times 10^{-10}$ µCi/cm^3 respectively. It is not known whether the work at Mallinckrodt was done in a hood and since the nature of the Mound work was further acid digestion and extraction (DOE 2002), the Mallinckrodt exposures were potentially higher.

Also, it must be noted that the concentrations reported by Mound (1956) were of ionium, i.e., Th-230, not of total thorium. Thus the associated source term must include the Th-232 known to have been in the solution as well. From Section 5.2.3, there was 11.6% Th-230 isotopically in the original residue, hence the Th-230/Th-232 ratio will be assumed to be 0.116/0.884, or 0.131. This gives 1.61 $\times 10^{-12}$ µCi/cm^3 of Th-232 to be added to the source term (see Table 6). However, because Th-232 behaves like Th-230 in the body, both are alpha emitters, and both have very long half-lives compared to the human lifespan, the contribution of the Th-232 to the dose from the (total) thorium source will clearly be negligible (the dose per unit intake for Th-232 is higher than for Th-230). Thus only the Th-230 exposure need be considered and the source term in Table 24 for Plant 7E applies to Th-230 only.

2.3.3 Respirator Use

An undated AEC reference that is assumed to be of 1942-1944 vintage (MED undated a) stated that respirator use is mandatory when required and was especially necessary for the grinding and sifting operation. An AEC/MED reference from May 1945 shows layouts indicating the areas of required respirator wear (MED 1945b). Mason (1958a) stated that MED and Mallinckrodt agreed in the early years of the work that production would proceed on a priority basis, with the understanding that in high dust areas extensive use of respirators would need to be made. Thus during 1946-1948, respirators were used for “practically all” plant operations. Thus it is clear that respirators were used from at least the late war years on. Mason (1958a) commented that the exposures received depended partly on the effectiveness of the respirator program (at that time).

Mallinckrodt’s policy in the later years was that routine respirator use was not acceptable practice and that they were a temporary expedient for unusual conditions only (MCW 1955). The requirements for them were spelled out in standard operating procedures (MCW 1955). Even so, AEC inspectors noted instances where visible dust clouds were present or they measured clearly significant dust

levels, yet the operators were not wearing respirators ((AEC 1954b; AEC 1954c; AEC 1954e; AEC 1954f; AEC 1954g; AEC 1955c).

A Mallinckrodt official observed in 1958 that in the plants they tried to keep below the MAC, but that if the concentration were greater than 1 MAC for a specific operation, they would not necessarily require the operator to wear a respirator (Utnage 1958c). He explained that this would depend on the worker's integrated exposure, taking all operations into consideration, and that if some short-term high alpha concentrations in the air were found, they made it a practice to have personnel wear respirators temporarily until the situation was corrected. He concluded that Mallinckrodt did not subscribe to the use of respirators as standard control equipment. Breslin (1958) states that the time-weighted average exposures measured by AEC-NYOO did not include corrections for respirator use and so should be viewed as potential exposure; however, he also asserts that in very few cases would these be substantial overestimates "as the use of respirators was inadequate and spotty". This is borne out by the various AEC dust studies that, as noted above, pointed out cases of significantly elevated dust levels where respirators were not being worn.

In the absence of any firm figures on respirator use and efficacy at Mallinckrodt, it will be assumed that respirators were not reliably used.

2.3.4 Radon

As noted earlier, radon levels could be significantly elevated in enclosed areas where material containing uranium daughter products was stored. Radon concentration in enclosed spaces in refineries produced levels of up to 10^{-8} to 10^{-7} Ci/L, which were eventually significantly lowered by ventilation improvements (Eisenbud 1975). After these improvements were made at Mallinckrodt in about early 1949, all Mallinckrodt operating areas in Plant 6 were found by AEC to be below the preferred level of 10^{-10} Ci/L, with the exception of the K-65 return oven, the ore thaw house, and the "wash Oliver" cell, as shown in Table 25, which covers the years 1947-1957. Most of the information comes from the weekly “M Z” radon reports (MCW 1955; MCW various). Additional data is shown in Table 26, which gives typical radon exposures for different areas at the Middlesex facility over the years 1944-1949 (which cover the early years of pitchblende use); these would be comparable to the railcar unloading and Ore Room operations at Mallinckrodt. Table 25 also gives what little information has been found about the radon levels in the plants other than Plant 6. However, because in the plant with the greatest exposure potential (i.e., Plant 6) the levels were low in all but very enclosed areas and because the thorium and radium were removed in the production of UO_3, it can be assumed that the radon levels were negligible in areas where ore and pre-UO_3 residues were not present.

Regarding the processing of residues to concentrate thorium, it is clear from the data in Table 27 that the average concentration of radon (Rn-220 and Rn-222), under process-applicable and claimant-favorable assumptions, is well below the AEC "preferred level" of 10^{-10} Ci/L. It is also usually less than the 3.0×10^{-12} Ci/L that represented an "undetectable" amount for the AEC during the relevant period of time (as per Eisenbud 1975).

For use in dose reconstruction, the radon concentrations in units of Ci/L may need to be converted to units of working level months (WLM) before they can be used in calculations. One working level (WL) is the total amount of energy given off over a long period of time by the short-lived radon-222 daughters in equilibrium with 100 pCi (10^{-10} Ci) of radon, taken to be in one liter of air. Since the daughters will typically not be in equilibrium with the radon if the ventilation is good, this conversion is not simple, but depends on the ventilation conditions. The claimant-favorable assumption will be made that the daughters are in equilibrium with the given concentration of radon. (Note that Applied Nuclear Safety (1986;1990) assumed a 50% equilibrium for post-operations radon measurements in

the Mallinckrodt buildings.) Thus 10^{-10} Ci/L of radon will be assumed to be equivalent to 1.0 WL. The WLM is 170 WL-hours, i.e., 1.0 WL breathed in for 170 working hours per month. The annual radon exposure can thus be taken to be the radon concentration in units of 10^{-10} Ci/L times 1.0 WL times 12 (months) times the fraction of the annual working hours that exposure occurs. Thus a radon exposure of 6 x10^{-10} Ci/L, occurring 2 hours a day, would be equivalent to 6 × 1 WLM × 12 × .25, or 18 WLM, on an annual basis.

2.3.5 Surface Contamination

Although surface contamination levels per se are not indicative of airborne contamination levels or external dose rate, they can suggest whether or not a potential for exposure exists. MCW (1958) and MCW (1959) give the results of a plant-wide surface contamination and external dose rate study that Mallinckrodt did after some post-operation decontamination of the site. These reports indicate that ground areas adjacent to the production plants were heavily contaminated, with average surface alpha activity of 2500 dpm/100 cm^2 and average beta activity of 2 mrep/hr; high spots of 35,000 dpm/ 100 cm^2 alpha and 15 mrep/hr beta were not unusual. High spots of up to 20 mR/hr gamma were found west of the UF_4 loading dock where ore cars where cleaned prior to 1950. In Plants 6 and 7, the administration building (Building 112) (except for the storeroom and maintenance shop), the Boiler House (115), the Service Building (117) (except for the laundry and the regulated locker room), and the Magnesium Building (708) were not significantly contaminated. The average alpha activity on floors in the excepted areas was 3000 dpm/100 cm^2 and the beta-gamma activity was generally at background levels. In Plant 4, beta activity measured at contact with surfaces in production areas averaged between 10 and 50 mrep/hr with the overall average activity measured at contact with surfaces estimated at a level of 25 mrep/hr; occasional high spots were found up to 80 mrep/hr; activity measured at the three-foot level in the center of production areas ranged from 1 to 5 mrep/hr. Gamma activity measured at contact with surfaces was 0.02-0.9 mrep/hr, with the highest readings being in some yard areas and the slag processing area. The overall plant average measured at the three-foot level in the center of production areas was 0.07-0.1 mR/hr.

Data from this Mallinckrodt study (i.e., MCW 1958 and MCW 1959, quoted by Utnage (1958a)), showed fixed floor surface contamination levels of greater than 10,000 alpha dpm/100 cm^2 at various floor locations in the ore sampling area after vacuuming; it was highest at the hopper loading and weighing stations. In the metal reduction area (Plant 6E), the floors of the crucible disassembly areas and the saw areas measured 2200-3300 dpm/100 cm^2 and the center of the maintenance cage (where there was no uranium processing) measured 1200 dpm/100 cm^2. Other stations in the "pitchblende (ore) area" (Plant 6) showed levels of 1000-60,000 dpm/100 cm^2; in the uranium products warehouse, 4500-21,500 dpm/100 cm^2; and in the metal plant (6E), 1000-9000 dpm/100 cm^2. The UF_4 production plant (Plant 7) had no reading higher than 1200 dpm/100 cm^2. Since these figures represent fixed contamination, loose contamination removed by the vacuuming could have been present at far higher levels (Brobst 1958). Thus these figures, while suggestive of where the worst areas were, cannot be considered to be representative of operational total surface contamination levels.

Although as noted above resuspension is assumed to be included in the measured airborne concentrations, some available information about the relationship between loose surface uranium-bearing contamination and airborne concentrations will be summarized here in case it becomes relevant in individual cases. A study was done at the Oak Ridge Gaseous Diffusion Plant to ascertain the relationship between alpha airborne activity and alpha surface contamination (Becher 1958). The air samples were measured with Whatman #41 filter discs and fixed counting equipment, with an overall counting and collection efficiency of 30%. The surface transferrable activity was measured with a Samson alpha survey meter, with an overall counting and efficiency factor of 20%. The data,

shown in Table 28, indicate that the airborne concentrations ranged from 0.36 to 5.05 dpm/m^3 for every dpm/cm^2 of surface contamination, or an air concentration of 3.6 to 50.5 dpm/m^3 for every 1000 dpm/100 cm^2 of surface contamination. Other fixed surface contamination data is given in Table 29 for various surfaces and pieces of equipment in the laundry (from Table 1 of Utnage 1958b).

With surface contamination there is the potential for two modes of exposure other than inhalation. These are ingestion and skin doses from contamination on skin and clothing. Ingestion would most likely take place during eating or smoking breaks. No information is available as to the likelihood of ingestion during eating or the quantities that might have been taken in. However, some information is available on ingestion as a result of smoking. Tests done in about 1958 at the Oak Ridge Gaseous Diffusion Plant with UNO_4, UF_2, and UF_4 (Bailey 1958) indicated that when loose uranium-bearing material was placed on the palmar surfaces of the hands, the palmar transfer of uranium from the hands to the cigarette amounted to about 1% of the material on the hands and that inhalation of the material during smoking amounted to less than 1%. They also tested absorption by placing material on the backs of the hands. They concluded that a maximum of 2.5×10^5 dpm on the palm of each hand, for a 20-cigarette-a-day smoker, would be allowable for him not to exceed the maximum permissible inhalation of uranium by cigarettes alone; that a maximum of 2.5×10^5 dpm on each hand would correspond to the maximum permissible ingestion; and that a maximum of 2.5×10^5 dpm on the back of each hand would correspond to the maximum permissible absorption dose. Taking the reciprocal of the sum of the reciprocals, they obtained a maximum of 8.6×10^4 dpm per hand for the total considering all three routes of exposure. They assumed a 15% geometry factor for the hands (based on their instruments) and concluded that the total limiting level was 13,000 cpm per hand.

The allowable amounts given in Bailey (1958) corresponded presumably to National Bureau of Standards Handbook 52 allowable intakes, since they cited Handbook 52 although they did not quote the figures. The allowable amount was assumed to be on the hands continuously for 5 days per week, 8 hours per day. This level or greater is likely to have been on workers' hands at times but not to have been on the hands constantly. Thus while a potentially significant contribution to the dose from hand contamination cannot be ruled out, it seems unlikely that most smokers would have had a sustained level of contamination of this magnitude on the hand during breaks, especially since they were likely to have worn gloves during most of the processes (due to heat, acidic content, etc.). Hence it will be assumed that ingestion can be ruled out as a major source of internal dose compared to inhalation.

Also, AEC (1951) observed that in a majority of the jobs evaluated at Mallinckrodt, it was found that the contribution to dust levels from time spent in the smoking (cigarette break) areas was greater than the contribution of dust from the time spent in the operations area; this was because the smoking areas were typically immediately adjacent to the actual work areas. This also suggests that the contribution to the ingestion of radioactivity by a smoker might be significant, although AEC apparently did not do any studies of this at the time.

Regarding clothing, Table 30 shows contamination levels and some associated dose rates from clothing (Utnage 1958b). The contamination measurements in cpm were taken with a Thyac beta-gamma meter with thin-wall tube, while the measurements in mrep/hr were taken with an unspecified air ionization chamber. At the time the measurements were taken in 1957, the laundry had been in operation for ten years and had never been decontaminated; there were nine laundry workers; and the laundry processed 25,000 coveralls and 25,000 "soft" items (handkerchiefs, socks, and underwear) each month. Clothing used in contaminated or potentially contaminated areas ("regulated areas") was kept separate from clothing used in non-regulated areas. However, regulated-area clothing was worn interchangeably by anybody, so that "a uniform contamination level [was] eventually obtained" (Utnage 1958b).

At the Oak Ridge Gaseous Diffusion Plant (ORGDP), test measurements in 1957 on clothing showed that the highest spot reading was typically about 3.5 times the average reading (Becher 1958); this is probably roughly applicable to Mallinckrodt as well, although the uranium compounds at ORGDP were mostly soluble whereas the Mallinckrodt compounds were mostly insoluble. The ORGDP tests also showed 1620 alpha dpm/cm^2 to be equivalent 9700 cpm/100 cm^2 as measured on a Samson alpha meter, giving an "efficiency-geometry" factor of 6%. (Note that for the "surface transferable activity" on filter paper used for air sampling also reported in Becher 1958, an efficiency-geometry factor of 20% was assumed for the Samson alpha meter.) Finally, the ORGDP measurements showed that about half the uranium applied to the clothing at the beginning of the test had dropped off within the first two hours of wearing. This suggests that uranium that gets on clothing can come back off it readily and that surface contamination on clothing can contribute to airborne levels via resuspension.

Railcar interiors were invariably found to be contaminated above 2500 dpm/100 cm^2 after unloading uranium oxide, UF_4, or uranium metal at uranium processing plants, even though the sites made an effort to decontaminate them (AEC 1949). AEC advised that strippable coatings would eventually need to be used (AEC 1949), but there was no evidence that this was ever done. This suggests that even where closed containers of uranium-bearing materials were being unloaded, it must be assumed that surface contamination was typically present.

2.3.6 Information and Available Data Regarding Urinalyses

Mallinckrodt uranium processing workers were given a pre-employment physical that included an initial urinalysis and a blood count and they were given an annual physical that included a routine urinalysis and a blood count (MCW 1955; Mason 1958a). From about the summer of 1948 on, this included a measurement of uranium in the urine. In addition, up to March 1954 some worker classifications had more frequent urinalyses, either every 4 months or every 6 months depending on the worker classification (MCW 1955; Mason 1958a); after this, time the frequency was no more than semiannual (MCW 1955). As urinalysis records indicate, some office workers appear to have been given urinalyses, but it is not clear whether this was done on a regular basis.

The radiological analysis was apparently only for uranium content (referred to as "X in urine" or “uranium-in-urine”). It is not clear how the urinalyses were done, but Ross et al. (1975) states that for all AEC contractors before 1961, estimates of lung dose were made on the basis of urinalysis and that this was usually done on the basis of electrodeposition and subsequent counting.

The urinalyses were performed by AEC-NYOO from about 1948, when Barnes Hospital at Washington University (St. Louis) began to do them. However, an AEC health official stated (AEC 1948) that it was his understanding that the analyses were being done at Barnes Hospital (at Washington University), but it turned out that they were being done in laboratories at the Mallinckrodt St. Louis site. This came to light when it was discovered, apparently in late 1947, that some urinalysis samples were contaminated due to contamination in the laboratory. An undated, untitled urinalysis listing found in dose reconstruction project files indicates that closed, blank samples were found to have significant levels of uranium in them, indicating contamination in the laboratory; it was suggested that this might explain the high levels of some of the non-blank (worker) samples. Thus at least the early urinalysis samples must be considered to be potentially contaminated (i.e., some of the uranium content may have come from the laboratory analyzing them).

Apparently Barnes Hospital resumed doing the urinalyses (MCW 1950b). However, in 1949, AEC compared the Mallinckrodt analyses against those for other sites handling similar material and concluded that the results were consistently high (MCW 1950b). They then sent Mallinckrodt some spiked samples and also had an independent Mallinckrodt party prepare a stock solution of known

concentration. The spiked samples and samples of the stock solution were sent to Barnes as regular samples, while Barnes standards and samples of the stock solution were sent to NYOO for analysis. AEC also compared Barnes methods and equipment. The conclusion was that the samples were indeed reading high at Barnes. Subsequent data analysis showed a gradual precipitation of uranium in the Barnes standards, which meant that the daily standard curves showed a gradual loss of slope over time, up to 30%. Also, Mallinckrodt had been called three times over the previous year to service the Barnes instrument because of sensitivity loss, when the problem was actually the standard. The maximum error in the urinalyses over the preceding 14 months was estimated to be +89%.

AEC technical personnel thought that the affected data was of doubtful value (AEC 1950j). Still, AEC (1950c) asked Mallinckrodt if the urinalysis data could be salvaged, i.e., if there was a consistent factor that could be applied to all of the subject urinalyses; MCW (1950c) thought that there was not. AEC also recommended that a note regarding the problem should be inserted into the medical files of the affected individuals (AEC 1950b), presumably to aid in the interpretation of the results. It is not clear whether this was done or not. AEC-NYOO stated that it was not possible for them to take over the urinalyses again since the number of samples to be analyzed was too high for their capacity (AEC 1950j).

It is not clear who did the urinalyses from 1950 to 1954, although MCW (1950d) suggests that this was no longer being done at Barnes Hospital but at AEC-NYOO. In 1954 AEC gave Mallinckrodt permission to perform their own urinalyses (MCW 1954), presumably in the laboratories at the Mallinckrodt St. Louis site. From the Mallinckrodt Health Office monthly reports, they were analyzing for “X in urine” (i.e., uranium) and it appears that at times there was a significant backlog of overdue analyses, at least in the early 1950's. Eventually AEC-NYOO must have resumed performing the analyses, because a 1955 Mallinckrodt description of its health program stated that NYOO was doing so (MCW 1955). This report states that NYOO was analyzing about 2500 Mallinckrodt urine samples a year and that urine sample that were taken were split, with half going to AEC-NYOO for the radiological analysis and half to Barnes Hospital for the medical analysis.

Because of these questions regarding the validity of the samples and the variations in sample analysis methods, the Mallinckrodt urinalysis data should be used with care. However, it appears that the errors, if any, are in the conservative direction and thus are claimant-favorable.

Urinalysis records appear to be available, but many appear to be handwritten notes on cards. These are found scattered in various dose reconstruction project files. Fortunately, in about the 1970's, the records were entered into a computer data base for research purposes and have been used in that form since then by Oak Ridge Associated Universities and other research groups. The resulting file has more than 40,000 records (i.e., lines, with each line representing one urinalysis). A "stripped" version (ORAU 2003) is also available, with the names and Social Security numbers removed for privacy reasons.

The large stripped urinalysis file (ORAU 2003) was reviewed for comparable or surrogate worker cases that could be used to produce a table of intakes applicable when bioassay data for an individual is missing or spotty. Cases were selected on the basis of their containing a reasonably uninterrupted series of urinalyses and having reasonably clear notations of job title and/or area worked in. The selected cases were then further evaluated and a subset was extracted for each of various categories of identified locations and operations or position titles. These categories are given in Table 31. Where there were more than two applicable cases for a category, the IMBA program was then used with the assumptions of chronic intake and Type M form with the data from these cases to produce a category-specific distribution and standard deviation for the typical daily intake, as shown in Table 31; otherwise, the actual data (i.e., for one or two cases) was given. Since there were changes in

exposure potential at various times due to process improvements, engineering modifications, or the building of new plants, three periods were established for the determination from the cases of the typical daily intake, as given in Table 31.

Table 31 does not include intakes for workers who processed wastes containing thorium (ionium); estimated annual intakes for these workers are given in Table 32. It appears that there were few such workers: (1) AEC (1955c) reports studying only six workers in their Plant 7E dust exposure study whereas, e.g.,119 were studied in Plant 6E, (2) few worker cases were found in the large stripped urinalysis file where it was clear that the worker did this type of work, and (3) the thorium worker in every case that was found had worked in other areas where an intake of uranium material was possible. It is not clear that thorium itself in urine was measured at all, rather than, say, gross radioactivity. Thus there likely was not any differentiation in the urine analyses between uranium (and its daughters) and thorium. Hence in dose reconstruction the urinalysis data from mid-1955 on for workers who processed thorium wastes should be generally be assumed to consist of whichever source set (U-234, U-235, and daughters or Th-230) gives the more conservative result.

2.3.7 Information and Available Data Regarding Other Types of Bioassay

Breath radon measurements began to be made in 1947, but only for workers who worked in areas where there was a potential for radium intake (AEC 1950a). Breath radon samples were sent to AEC-NYOO for analysis; in 1955, AEC-NYOO was analyzing about 500 Mallinckrodt samples a year, taken semiannually at a minimum but about quarterly when permitted by AEC-NYOO sample capacity (MCW 1955). Breath radon records are available in scattered form in reconstruction project files.

Breath radon samples were collected by obtaining one-liter samples of exhaled breath after two days of non-exposure, usually on a Monday morning (AEC 1950a); MCW 1950f). The samples were measured at NYOO by an “automatically recording pulse-counting device” (AEC 1950a). In early 1950 AEC apparently became concerned about the high background that seemed to be present where the samples were being taken (MCW 1950f). Mallinckrodt agreed to take test samples elsewhere than in their usual testing area and also to take a room air sample in their normal testing room; these samples were then sent to AEC-NYOO. The normal testing room sample showed a radon content of 0.8 x 10-12 Ci/L, which AEC judged was a high background for a breath radon testing area (AEC 1950i). It is known that in 1950 the Mallinckrodt medical department was located adjacent to the change rooms, which enabled workers to take their physicals after a shower without getting dressed (AEC 1950k); if the breath radon samples were also taken there, that could explain the relatively high background radon. Mallinckrodt apparently corrected this by moving the breath radon sampling location to a lower-background area.

AEC considered that many of the early breath radon samples likely represented transient as well as fixed burden and that the background level at the point of sampling (which was generally ignored) was likely to have been relatively high; thus the resulting estimates they made of alpha radiation to the bone based on breath radon measurements would typically be higher than was actually the case (AEC 1950a). Up to about 1950, AEC assumed that 1 µCi/L of sample after at least two days of non-exposure represented a total radium burden in bone of approximately 0.2 µg of Ra; however, AEC had then decided to use an RBE of 20 for alpha to bone marrow and a skeletal weight of 7 kg as agreed on at the September 1949 Chalk River Conference, to give 1600 mrem/week to bone for each 0.1 µg Ra deposited (AEC 1950a).

Whole body and lung counts appear to have been performed rarely if at all, since workers had to be sent to sites outside Missouri for this to be done or a mobile counter would have had to be brought to St. Louis. Hence there were evidently so few such counts done as to be of little use in reconstructing

individual doses, except possibly for those individuals actually counted. However, even individual whole body and lung count data appear to be unavailable

2.4 EXTERNAL DOSE CONSIDERATIONS

External doses for Mallinckrodt workers varied widely depending upon the activity they performed. Operations at the refinery (Plant 6) involved primarily gamma radiation, while operations at the metal plants (i.e., Plant 4 and later 6E) entailed primarily beta radiation (AEC 1949).

There is little information about conditions in Plants 1 and 2 during the wartime startup: no dose rate measurements from 1942-1946 appear to have survived and as noted previously, film badging did not start until late 1945, when Plants 1 and 2 were in the process of shutting down. Doses might have been somewhat higher due to greater manual involvement and probably somewhat greater bodily proximity to sources, but on the other hand the quantities involved were much lower. It should be noted, for application to external exposure, the era of pitchblende use (early 1945 on) was mostly covered by film badge monitoring. Thus it is considered to be conservative to assume that the doses at Plants 1 and 2, for the same type of work, were not greatly different from those at Plant 4 and Plant 6 around 1948.

According to MCW (1955), at least late in the life of the site, gamma surveys were done bimonthly in most Plant 6 processing areas and monthly at the vent ducts in the digest area. However, these reports do not appear to be available.

2.4.1 Gamma, Beta (Electron), and Nonspecific Beta-Gamma Exposures

After high-grade pitchblende ores began to be used, refinery workers were exposed to high levels of energetic photons from radionuclides in equilibrium with U-238 and U-235. Ra-226, through its Pb-214 and Bi-214 daughters, contributed energetic gammas to workplaces where ore was stored or processed. Upon removal of the uranium daughters, processed material became radiologically innocuous until the passage of time resulted in the ingrowth of Th-234 and Pa-234m and the consequent domination of the dose profile by electrons. Mallinckrodt worker dose records demonstrate this difference, with significant doses for mixed photons and electrons in the refinery operations and high electron doses with little photon dose in the metal plants. Dose reduction measures in plants and equipment resulted in low doses in Plants 6E and 7 compared with the mixed beta-gamma doses in the refinery operations.

The gamma dose rate could be as high as 50 mR/hr near stacks of drums of Belgian Congo ore at 25% concentration and with a radium content of about 100 mg/ton (Eisenbud 1975). Dose rates at points adjacent to stacks of drums of radium-bearing residues (precipitates) could run as high as 100 mR/hr adjacent to stack of drums (~ 300 mg Ra/ton) (Eisenbud 1975, Table 2). In addition, a 1958 AEC report on uranium mills gave dose rates of 0.8 to 8.0 mR/hr, with an average of 3.0 mR/hr, as the gamma dose rate at three feet from bulk ore concentrates (AEC 1958, Table XI); these dose rates are assumed to be for domestic ores. AEC (1948a) gave the gamma contact dose rate with the (Ra-containing) Feinc filtrate sludge under equilibrium conditions as over 300 mR/hr; however, they stated, they had no way of knowing how close to equilibrium it was.

Some more specific information regarding gamma doses in the ore, refinery, and metal processing areas are shown in Tables 33-35. Dose rates from drums and railcars are shown in Table 33; from ore storage in Table 34, for Middlesex workers (comparable to ore storage areas at Mallinckrodt); and for various Plant 6 locations in Table 35, particularly for GLC (gangue lead cake or K-65, the radium-containing residue). It should be noted that operations that were particularly manual were the various

dumping, scooping, and scraping operations in which feed, UO_2, UO_3, UF_4, and dust were handled or crucibles and furnaces were cleaned; the “plowing” (scraping) of the centrifuges; and the scraping of cake off the Feinc filter cloths (this was the pitchblende cake during the pitchblende years). Thus significant external dose reduction usually followed any mechanization of these processes.

Because the gamma dose arose mainly from the radium and its daughters, the gamma dose was significant only in those areas where the source material had not yet had the radium separated; where radium-bearing residues were present; or where uranium products were stored for long enough periods of time that the daughters built up again. This meant that the gamma doses tended to be highest in Plant 2 and later in Plant 6 (AEC 1949), especially around ore drums and storage areas for the radium-bearing residue, K-65. Shielding had been designed into Plant 6 and more was added in 1948 in some areas (AEC 1949). As noted in Section 5.2 above, there was also up to 2.6 mCi of radium built up in the residue that was processed in 1955-1957 to concentrate thorium, although this was distributed in the 350 tons that was processed into the 3600 gallons of solution sent to Mound (Tables 4 and 6).

Doses registered on film badges worn by people not working directly with the U and equipment, such as guards and office workers, was more likely from gamma exposure than from beta exposure. This is because they were usually at some distance away from the source (the uranium and its daughters). It is true that the dust was found throughout the plant to varying extents, but that would likely not contribute to the external dose rate much in or near buildings where there was a substantial Ra content in any uranium product or residue.

A 1958 AEC report on uranium mills gives 1.5 to 25 mrep/hr, with an average of 15.5 as the beta dose rate at three feet from bulk ore concentrates (AEC 1958, Table XI). AEC (1948a) gave the beta contact dose rate with the (Ra-containing) Feinc filtrate sludge (K-65) under equilibrium conditions as over 500 mrem/hr; however, they stated, they had no way of knowing how close to equilibrium it was. AEC estimated the dose to an operator’s hands from removing lids from ore drums at 200-300 mR/day, even after a proposed body shielding window was erected (AEC 1948b).

Regarding experience at the Paducah site, Baker (1958) reported that the Th-234/Pa-234 combination (from U-238 and U-234) produced about 1500 alpha dpm/mg U and 1500 beta dpm/mg U at equilibrium, producing 240 mrad/hr at the surface of U metal, 208 mrad/hr at the surface of UO_3, and 183 mrem/hr at the surface of UF_4. Further, during UO_3 prep by "our suppliers" (e.g., Mallinckrodt), much of the beta-active material was removed, but built back up to 50-100% by the time it got to the UF_6 production facilities (Baker 1958). This suggests that significant buildup could occur before the UO_3 left the Mallinckrodt facilities since the storage time might be weeks and the transport time was likely less than a few days. Eisenbud (1975) points out that 90% of equilibrium beta activity is restored by 90 days after vacuum casting. Eisenbud (1975) reports high dose rates, up to 1 rad/week to the body and even more to the hands, from loading of UF_4 into UF_6 reaction vessels. This too implies that if enough time elapsed, UF_4 loaded at Mallinckrodt into the bombs could also produce relatively high beta dose rates. Metallic uranium in equilibrium with Th-234/Pa-234 could produce up to 235 mrad/hr to the basal epithelium when the metal was in contact with bare skin; heavy gloves would significantly reduce this (Eisenbud 1975).

In addition to the beta dose rate from the uranium as natural uranium, uranium oxide, etc., there were two waste concentrates that produced high beta dose rates. First, when ether was used with the uranyl nitrate to extract the uranium, Th-234 and Pa-234 (also called UX1 and UX2 respectively) were left in the aqueous phase (also called the aqueous uranium tails) (Eisenbud 1975). This aqueous solution was filtered, resulting in a residue (cake) containing the beta emitters.

Second, in the vacuum recasting of the uranium metal, impurities in the metal volatilized and condensed on the cooler portions of the furnace, creating spot deposits (AEC 1949; Eisenbud 1975). The impurities contained Th-234 and Pa-234, which were concentrated to a significant degree in the deposits (AEC 1949; Eisenbud 1975); this residue could have "up to 1000 times the beta activity of natural uranium" (AEC 1949). Manual contact with these deposits during charging, discharging, cleaning, and repair of the furnaces provided "opportunity for hand irradiation of a greater magnitude than whole body" (AEC 1949), possibly as much as 2-3 rads/week to exposed skin and perhaps to the eyes when the original ore was pitchblende at 25% average enrichment (Eisenbud 1975).

Regarding the processing of residues to concentrate thorium, Table 6 shows that with the interruption in the chain occasioned by the removal of the original radon (by venting) and the radium early in the process, the daughters had to build up again to equilibrium from the time the cake was stored through the maximum 15 years of storage. Consequently the strong beta emitters down the chain, such as Pb-214 and Ac-228 are present only in very small quantities.

Some dose rate information for exposure rates from laundry equipment and clothing appears in Tables 29 and 30 (this data is from the text and Table 1 of Utnage 1958b). This is mainly beta radiation. AEC did some clothing shielding and contamination studies using an 18” x 24” sheet of uranium metal in equilibrium with Th-234 and Pa-234 (AEC 1950h), with the following results. Denim coveralls (9-oz weight) “absorbed” an average of 22% of the beta from the source, with a standard deviation of 7.5%, for distances varying from 5 inches to 3 feet. Neoprene-covered cotton gloves shielding an average of 50%. Measurements on the inside surfaces of three cotton gloves used to handle uranium showed contact beta dose rates of 23-47 mrep/hr from contamination; these gloves had been taken at random from workers. The Mallinckrodt glove program for contact with radioactive material was said to be sketchy and inadequate (MCW 1955), implying that use of gloves was not consistent.

Measurement methods were not specified in most reports and papers. Counters and meters were maintained and calibrated weekly or monthly on a set schedule by Mallinckrodt technicians (MCW (1955-). Utnage (1958b) stated that for surface contamination measurements in the laundry (of clothing, equipment, and floor surfaces), a Victoreen 356 alpha survey meter and a Thyac beta-gamma meter with a thin-wall tube were used. There were no instrument monitors in any area, but film badges placed at selected locations in the process areas served as integrating area monitors (MCW 1955-2/21/55); there is no information as to how often they were collected and read.

2.4.2 Neutrons

No neutron exposure measurements are available but Dupree-Ellis et al. (2000) deemed neutron exposures at Mallinckrodt to be minimal.

2.4.3 Information and Available Data Regarding Film Badges and Extremity Dosimeters

2.4.3.1 Film Badge Monitoring Periods

Workers were not individually monitored for external dose prior to 2 December 1945. From early December 1945 to March 25, 1946, at least some employees participated in a dose monitoring program for which total doses were reported in a memorandum from the University of Rochester School of Medicine and Dentistry (Rochester 1950). Subsequent to this 15-week program, film badges were issued to apparently all workers at Mallinckrodt's St. Louis uranium processing facilities. From 22 April 1946 through the end of MED/AEC work in 1957 or 1958, these were processed on a weekly basis as part of a routine dose monitoring program; however, MCW (1955) states that badges

were changed every two weeks or more often when indicated. Results were summarized quarterly and annually (MCW 1955). From the series of Mallinckrodt health group reports (an example of one is MCW 1951a), some 2000-3600 badges were read per month in the early 1950's.

2.4.3.2 Film Badge Technical and Processing Information

A letter documents the period of time when "Rochester" (i.e., the University of Rochester) processed the film badges (Rochester 1950). The letter states that Mallinckrodt processed the film badges during the period of 1 June 1948 to 1 January 1950. As is indicated by the Mallinckrodt health group monthly reports (e.g., MCW 1951a) and the 1955 Mallinckrodt health program description (MCW 1955), Mallinckrodt continued to process their own badges. As the health group monthly reports and AEC (1950l) indicate, however, Mallinckrodt often had a significant backlog in reading the film badges.

No procedures and little other film badge specification data have been found to date. There is not much information about how the film badges were processed by either Rochester or Mallinckrodt. However, there was a series of meetings and correspondence between Mallinckrodt and AEC regarding whether certain readings were due to beta or soft gammas and whether the AEC and Mallinckrodt methods of correction for shield absorption (in the badge) were consistent (AEC 1950b; MCW 1950g; AEC 1950e; MCW 1950h; AEC 1950f; AEC 1950h). This issue involved the subtraction of the film density value under the beta “shield” from the value under the window. Section 7.3.1 of this technical basis document states the assumption to be made about this subtraction. However, these references may be consulted in case of any suspect beta readings corresponding to the 1949-1950 time frame.

Film badges were issued as a combination security-exposure badge (numbered and with photo ID, per MED (1944b)) to all employees except for “office females” who presumably never entered process areas (MCW 1955). Since there were no potential sources of acute external exposure, the aim was to keep chronic exposures below tolerance levels (MCW 1955). All exposures over 50% tolerance were reported to supervisors (MCW 1955).

2.4.3.3 Film Badge Record Types, Arrangement, and Availability

Mallinckrodt dose records were of three types: complete records of weekly film badge results, listings of total doses by employee over a specified time period such as the "Mallinckrodt_1946" file (MCW Undated), and plant dose summaries. With the exception of records that show total dose by specified time period, records found to date show weekly badge processing cycles. Assignment of individual annual doses was based on deep-dose exposure (Dupree-Ellis et al. 2000).

The complete records are weekly lists of employee names with beta and gamma doses. For the gamma doses some results are shown as "50*" and the asterisk refers to a footnote that reads "indicates less than" (MCW Undated). Values of 60 and 80 are sometimes asterisked in the beta column. Occasional values of "0" are found in the gamma column as well. Some records list employee names with total doses over specified time periods, with a start date and end date.

Listings of total doses by employees over a specified time period other than a week are found in the dose reconstruction project file "Mallinckrodt_1946" (MCW Undated). The earliest results are of this form also and are recorded by total dose and number of weeks worked in the dose reconstruction project file "Mallinckrodt Radiation Summary APR 46 to MAR 48.” This document also supplies other important information for external dose reconstruction.

Dose summaries listed doses by plant, number and percentages of badges in dose ranges from 0-50 mrep/week, 51-100 mrep/week, 101-150 mrep/week, etc. based on the total beta and gamma for an employee. Doses are not listed for employees having less than 150 mrep in a week; for the dose categories above 150 mrep/week, individual names are listed with gamma and beta dose results.

Complete records and/or dose summaries have not been located for all periods of MED/AEC operation as of this writing. This results in gaps for dose monitoring data when no information is available for workers in a given plant, or in some cases, for any Mallinckrodt worker. Dose summaries, when no complete records of weekly film badge results are also available, give no individual data for personnel receiving less than 150 mrep in a week. Many gaps in data are the result of accidents or damage in the workplace or during badge processing. These incidents are usually documented in the record.

2.4.3.4 Extremity Dosimeters

Because of the high extremity doses in cleaning the high-beta deposits out of the recasting furnaces, in 1949, film rings began to be used "by selected groups" in the metal plant (AEC 1949), but the records of these doses do not appear to be available.

2.4.4 Information and Available Data Regarding Occupational X-Ray Examinations

Mallinckrodt uranium processing workers were given a pre-employment physical that included a chest x-ray (MCW 1955); Mason 1958a); they were also given an annual physical that included a chest x-ray (MCW 1955; Mason 1958a). That these x-rays were actually given is indicated in the series of Mallinckrodt Health Office and other reports (e.g., MCW 1951a; MCW 1954; MCW 1955). No information is available as to how much dose was received during these examinations or if all workers received annual x-rays. Therefore, to be claimant favorable, it is assumed that all personnel who worked in the plants covered by this technical basis received an annual diagnostic chest x-ray.

2.4.5 Skin Contaminations and Other Radiological Incidents

No records appear to be available regarding skin contaminations. It seems likely that due to the relatively low radioactivity level of most of the uranium forms and the pervasiveness of the uranium-bearing dust, skin contaminations would have been regarded by safety officials at the time as not significant and thus would not have been recorded. See Section 5.3.5 regarding surface contamination, including clothing and smoker hand data.

No information has been found as to any incidents that may have resulted in significant overexposures to radiation or intakes of radioactivity. However, the following incidents were documented: a 1942 or 1943 explosion in the denitration process area in which agitators began to bind until the motors driving them finally tore loose from the concrete floor (Fleishman-Hilliard 1967); a 1943 ether fire in Buildings 51 and 52 involving a dryer blown apart by an explosion of ether vapors due to burning ether (MED 1943a); a 3 July 1943 fire in a rubbish truck containing “lime” sweepings and other floor sweepings, possibly including metal slag (MED undated b); a 4 May 1946 explosion at Plant 6 involving an explosion due to seepage of ether into the nitric acid tanks due to a malfunction of a check valve; and a 1947 or 1948 explosion causing the rupture of a nitric acid holding tank due to mechanical failure of a check valve (MED 1948; Fleishman-Hilliard 1967). Also, there were indications of frequently occurring incidents, such as the occasional spontaneous catching on fire of uranium metal derbies at the derby cleaning station in Plant 6E, which would have put particulates into the air; this problem was spoken of as being brought under control (AEC 1952a). Another such recurring

incident was the plugging of floor drains, with the consequent formation of puddles of contaminated liquids on the floor at Plant 6 (AEC 1950k).

2.5 OTHER DATA OF DOSIMETRIC INTEREST

2.5.1 Number of Workers

The initial April-July 1942 uranium pilot plant effort included 24 people working as a single project group under a project manager (Fleishman-Hilliard 1967). In 1944, there were 55 guards; 330 workers (including guards) with a clearance for MED work, and 1500 workers on the entire site (presumably including non-MED workers) (MED 1944b). Regarding the total number of workers with potential for exposure, Fleishman-Hilliard (1967) and Mallinckrodt (1994) list the total number of workers as 250, the former stating that this was in 1948; AEC (1948b) lists the total number as 250 at Plant 6, but 400 if Plant 4 was included; AEC (1949) lists the number of workers at Plant 6 as 272 and the number at Plant 4 as 94. Mason (1958a) states that as of the beginning of 1948, more than 100 of the original employees working during the period 1943-1946 were still on the payroll. AEC dust study reports in the 1950's give the number of each classification of workers and the number on each shift (e.g., AEC 1954b); some AEC reports even list the names of process and supervisory workers and their job classifications in an appendix. As noted above in Section 5.4.3.1, over 2000 film badges a month were processed in the 1950's.

2.5.2 Number of Hours Worked per Week

From AEC dust study reports (e.g., AEC 1954b), the following information regarding time spent is provided as follows:

Length of work day, including breaks and locker room time	480-520 minutes (8-8.6 hours)
Lunch break	30 minutes
Smoking breaks	30-40 minutes
Clean locker room	20 minutes
Regulated locker room	15 minutes

The longer work day applied to operators and craftsmen, who presumably had to leave their work areas to smoke. There was a 10-15 minute variation in the work day among plants as well. The total smoking break time was 30 minutes for Plants 6E and 7, but 40 minutes for Plants 4 and 6 through about 1955; after that it was 30 minutes for all plants.

While AEC-NYOO took the weekly number of hours to be 48 (or six 8-hour days) in calculating some of their early time-weighted average airborne concentrations (AEC 1949), Lippmann (1958) used 40 hours in reporting data regarding Harshaw workers. It can be assumed in the case of the Mallinckrodt workers that they typically worked for a full 8 hours a day, 5 days a week, or 40 hours per week, since that will conservatively cover both the actual 5-day and the actual 6-day cases. When using daily weighted average dust sampling data (e.g., in Tables 13-17 and 21-24), it is important to understand that break, lunch, and locker time was factored into the weighted averages reported by AEC and Mallinckrodt in their air dust studies.

Fleishman-Hilliard (1967) states that once the Plant 2 operations started (ether extraction), it was carried out 24 hours per day. It is not clear what other processes ran 24 hours per day. Guardhouses were manned around the clock, with three shifts per day (MED 1944b).

2.5.3 Job Types, Work Areas, and Work and Access Practices

After about 1950, film badge reports included a short note or keyword about the job or work done or the work area occupied by the individual during the week. After about 1948, many urinalysis sheets also list such notes or keywords. Various AEC reports also list job titles and functional work types. Those discovered to date are given in Table 19. Note that in the absence of further information, it is not possible at present to distinguish in these records and documents between ordinary or process decontamination and the decontamination that was part of decommissioning buildings and plants.

As previously stated, to aid in classifying workers whose job titles do not appear in Table 19 and whose work descriptions do not make it clear which job title is appropriate for use, two other tables have been provided. The first is Table 5, the keyword table, which includes information from these notes and from operational information in other references (particularly MED 1946a; AEC 1949; and AEC 1978). The second is Table 20, the process-job association table.

These three tables should be used to help determine the principal occupational activity for an individual with missing or conflicting monitoring data.

Mallinckrodt employed an employee rotation program from about 1950 on (Fleishman-Hilliard 1967; AEC 1950b; MCW 1955), the point of which was to keep the weekly dose below the weekly tolerance level or, after about mid-1950, to keep the average weekly dose over a three-month period below the weekly tolerance level.

Mallinckrodt's 1955 formal description of its health program (MCW 1955) gave the following information; it is not clear back to what year this information applies. Mallinckrodt maintained three levels of controlled areas. These were the regulated areas, which were the areas where radioactive materials were processed and handled; the grey areas, which were areas where any radioactive material and contamination was incidental to the function of the area, e.g., labs and production instruments departments; and clear areas, which were area where radioactive materials were not required and not permitted, e.g., offices and the cafeteria. Although zero contamination was not possible in the latter areas due to their proximity to the other areas, that was the goal of control efforts.

A 1944 MED security survey report (MED 1944b) gives the following information. In 1944 and presumably all other years as well, access into the MED areas was only through guarded entrances. Hourly rounds of the entire site were made during evening and early morning hours and all day Sundays and holidays; it took a guard 40 minutes to make a complete round of Plant 2. Non-Mallinckrodt truck drivers were allowed to come in, but not truck drivers' helpers unless needed to unload; all trucks were escorted while within the site.

MCW (1955) also stated that work clothing "from the skin out" was provided for all persons assigned to regulated areas. Regulated clothing could not be worn outside regulated areas except under cover clothing; cover clothing was provided for brief visits to regulated areas. Because wearing contaminated regulated clothing on public land was undesirable, vehicular transportation was required for workers traveling between regulated areas (even with the cover clothing). Regulated area workers were issued two changes of clothing per day. Workers were required to shower before changing into "clear" (clean) clothing; they typically took two showers a day in 1955, but only one in the 1942-1944 time frame (MED undated a). Both contaminated and clean clothing were laundered on the premises, in separate laundries.

According to MED (1944b), smoking was not permitted in operational areas except in designated smoking areas or smoking rooms; smoking was permitted in offices and labs, except where ether or other flammable substances were handled. In 1944, the penalty for smoking in other than permitted areas was loss of employment. Thus it is likely that nearly all smoking was done in designated spaces.

2.5.4 Miscellaneous Information

Some quantities and dimensions of potential radiological interest (e.g., for special external dose calculations) are as follows. See also Table 4 and Section 4 for other amounts.

Bomb	10" OD × 40" long	(MED 1946a)
Bomb liner (lime, etc.)	Depth: 1"	(MED 1946a)
Uranium billet	4.75" OD × 18" long	(MED 1949b)
Ore barrel	3' high × 18" across	(MED 1945a)
U metal samples		
Glass tube	2" OD × ¾" long	(MED 1945a)
Cardboard packing box	5" sq, 1-2 lbs filled	(MED 1945a)
U eggs (samples from billets)	Packed eight to a box	(MED 1945a)
Billet packing box, wood	5" × 5" × 13"	(MED 1945a)

3.0 DETERMINATION OF RADIOACTIVITY INTAKES AND INTERNAL DOSES

Where urinalysis and other individual-specific bioassay data are available for a given period, it should be used to determine the individual's intake of radioactivity using the IMBA program (ACJ 2002) and the ICRP default parameters.

For analysis of urine samples, only uranium was counted, and in the air sampling, only gross alpha was counted. Thus it is not possible to know, e.g., how much radium was in the urine or air sample.

Also, most workers will have some gaps in monitoring because routine bioassay did not begin until 1948 and because there were undoubtedly some missed bioassays. The intakes over the gap periods will have to be determined either by comparable (surrogate) worker data or failing that, by the use of time-weighted daily average dust exposure data.

There was a great variability in exposure by job, by plant, and by year at the Mallinckrodt St. Louis site. Hence it is not feasible to calculate a matrix of intakes for all occupational types, all locations, and all periods for inclusion in this technical basis document. Rather, Table 31 should be used to determine the annual intake, prorated as necessary for the actual exposure period, for those individuals with missing or spotty bioassay data. Tables 21-24 should also be used, when appropriate, to help determine the time-weighted daily average exposure level to be applied on an individual basis to calculate the internal dose where urinalysis and related information is unavailable or spotty, especially for the period 1942-1947.

Because urinalysis and film badge data is given in the records for the categories "AEC" and "Ledoux" or "Ledoux Laboratory", categories have been created for them as appropriate in Tables 21-24 and Table 31. However, AEC personnel presumably worked for AEC itself and the Ledoux personnel, as previously noted, were employed by the Ledoux Company and rendered services by contract to Mallinckrodt.

For workers employed in years during which no (radiological) urinalysis was done, reference should be made to AEC (1950a), which is a report of an attempt by AEC to estimate the cumulative exposures of Mallinckrodt workers then employed at Plants 4 and 6 who had been employed between July 1942 and October 1949 and who had more than six months of exposure to radioactive materials. Their estimates for the dose to the lung were based on air samples of alpha-emitting dusts (translated to a daily weighted average exposure level) and to the bone, on breath radon analysis (to determine the fixed radium burden and film badge data. Because in dose reconstruction different assumptions are made than AEC made and thus these calculations will have to be redone, their results are not repeated here. However, dose reconstructors should be aware of this report in the case of workers who began MED/AEC work before urinalyses were routinely done and for whom AEC's "back-calculation" estimate may be found listed in dose records as simply an accumulated dose for the pre-monitoring period of operation. It should be noted that workers were not identified by name or work category in this report.

Also with regard to this report, it should be noted that the calculations of lung dose did not include a gamma contribution because AEC deemed it negligible compared to the dose from airborne particle inhalation; that they did not include radon because they could not estimate an average concentration and they assumed that airborne particle inhalation would dominate; that they assumed all the uranium to behave like UO2 in the lung; and that they assumed that biological equilibrium existed since the start of employment. AEC did include the external dose in the bone dose calculation. It should also be noted that AEC thought that the exposures in the unmonitored years were "at least as severe as they were found to be at the time of our initial studies" (in early 1947); conditions probably were not

more favorable and may have been “moderately” more severe. Thus they thought that their extrapolations could possibly be somewhat nonconservative.

Dose incurred during the decontamination and postoperations years (1959-1995) are covered in Section 8.0.

3.1 ASSUMPTIONS

The following assumptions should be made in estimations of radioactivity intakes by inhalation and the resulting internal doses when Tables 21-24 and/or Table 31 is used.

1. The number of work hours per year is 2000, i.e., 40 hours per week, 50 weeks per year. Adjustments can be made in individual cases if more specific information is available.

2. Urinalyses measured uranium only. For inclusion of other isotopes, the following may be assumed and is considered claimant-favorable.

   By activity, natural uranium activity is about 48.9% U-238, 48.9% U-234, and 2.26% U-235. In the absence of other information, it would not be possible to tell what the degree of equilibrium is between the uranium isotopes and their daughters in a urine sample. It can be assumed conservatively be assumed that there is 100% equilibrium. Then for each pCi of uranium measured, about 0.49 pCi is U-234, 0.49 pCi is U-238, and 0.02 pCi is U-235. However, the U-238 portion can then conservatively be assumed to be U-234 as well, so there would be 0.98 pCi of U-234 and 0.02 pCi of U-235.

   Then under the assumption that the daughters of the original U-234 are in equilibtrium with the U-234 (but not the subsumed U-238), there are an additional 0.49 pCi of Th-230 and 0.49 pCi of Ra-226. Additionally; if the daughters of the U-235 assumed to in equilibrium with the U-235 parent, then there is an additional 0.02 pCi of Ac-227. These conservative source terms are summarized in the table below.

   For each pCi of uranium measured in urine:

0.98	pCi	U-234
0.49	pCi	Th-230
0.49	pCi	Ra-226
0.023	pCi	U-235
0.023	pCi	Pa-231

3. Air samples measured gross alpha only. For inclusion of other isotopes, the following may be assumed and should be claimant-friendly.

   For each 1,000 dpm of gross alpha measured in air:

392	dpm	U-234
196	dpm	Th-230
196	dpm	Ra-226
7.3	dpm	U-235
7.3	dpm	Pa-231

4. When intakes from Table 31 or air concentrations from Tables 21-24 are used, they should be prorated over the listed period (e.g., a year) for the time spent in each corresponding occupational activity or area. For example, if bioassay data for a worker is missing for an entire

year and he spent 5 months of that year as an electrician and 7 months as a mechanic, his intake for the year should be assumed to be 5/12 of the annual intake for an electrician plus 7/12 of the annual intake for a mechanic. The appropriate period from Table 32 should be used for this, depending on how many years of data are missing.

5. When air concentrations from Tables 21-24 are used, the prorating for the time spent in each corresponding occupational activity or area should be applied to the entire 2000 hour/year on the grounds of their being claimant-favorable and representatively time-averaged over all activities. That is, no time should be deducted for breaks, etc., since that was included in the time-averaging.

6. For Plants 1 and 2, the most conservative (usually the earliest) applicable data for Plants 4 and 6 should be used, as appropriate for the worker activity.

7. The breathing rate for all workers should be taken to be 1.4 m^3/hr (as shown in Table 6 of ICRP 66 (ICRP 1994)).

8. Radon exposures should be calculated from information taken from Section 5.3.4 and Tables 25 and 27.

9. Ingestion doses are negligible compared to inhalation doses, therefore ingestion can be ignored except in special cases.

3.2 ESTIMATING INTAKE BY USING SURROGATE WORKER OR ESTIMATED THORIUM INTAKE DATA (TABLES 31 AND 32)

Table 31, the surrogate worker annual intake table for uranium inhalation, and Table 32, the estimated intake table for the thorium processing operation, can be used to estimate missed dose or to generate doses for comparison to doses calculated from individual urinalysis and other data.

3.2.1 Using the Surrogate Worker Intake Data (Table 31)

The steps in calculating intake by the use of the surrogate (comparable) worker data table, Table 31, are as follows.

The assignment of job title and if needed, work area should be made on the basis of the claimant's submitted information, urinalysis records, film badge records (if helpful), employment records and other information. Where the job title or work area is not clear, Tables 5, 20, and 21 should be used to help make the selection. The job titles and work areas should then be tabulated by plant and by time period.

A surrogate worker value should be selected from the table(s) according to the appropriate worker classification. If there is no specific worker type or area given in employment or urinalysis records or other sources, then the "generic" or "mixed/miscellaneous" value should be selected, subject to the judgment of the dose reconstructor. For example, if worker is listed in urinalysis records as working in the "Bomb Step" of 6E in 4 out of 5 urinalyses records and only "6E" in the fifth record, it can be assumed that for gaps in this records series that he worked in the bomb step operation during the period covered by the fifth record; thus the "6E Bomb Step" data can be used. However, if the 5 records include "Bomb Step", "Recast", and "6E", then the "6E Generic" data should be used.

The appropriate datum should be selected from the table(s) for each period, as appropriate. If records indicate that the worker spent years in one position instead of skipping around, then the longer period data can be used. This will be representative and since it covers more years, can save calculation time. Where there are occupational changes, the shorter period data should be used. This is especially true for the early period (Period 1), which, as Table 31 shows, usually involved higher exposures for the most exposed workers than the later periods (Periods 2 and 3).

Data for the unmonitored years from 1942-1947 should be taken from Period 1 for Plants 6 and 4, where possible. However, for these years a calculation should also be done using the data from the time-weighted daily average exposure tables, as given in Section 6.3. below, for comparison, to ensure that the intake as inferred from Table 31 does not seriously underestimate the potential intake.

3.2.2 Using the Estimated Thorium Intake Data (Table 32)

The estimated thorium intake data table, Table 32, is applicable only to those workers who were involved in processing thorium (ionium) in Plant 7E during the years 1955-1957. These would be only those workers who have some indication in their records (e.g., urinalysis records) that they worked in Plant 7E, the Minor Elements Production Facility, MEP, the ionium processing plant, or similar.

The appropriate data should be selected from the table for the appropriate periods worked and prorated if partial years were involved. Note that the intakes for 1955 and 1957 have already been prorated for the partial years in the table.

3.3 ESTIMATING INTAKE BY USING TIME-WEIGHTED DAILY AVERAGE EXPOSURE DATA (TABLES 21-24)

The steps in calculating intakes by the use of the time-weighted daily average exposure tables, Tables 21-24, are as follows.

The job title selection from Table 19 and the work category selection(s) from Table 20 should be made on the basis of the claimant's submitted information, urinalysis records, film badge records (if helpful), employment records and other information. Table 5 should be used to help make the selection. The category(-ies) should be tabulated by plant and by time period. .

The air concentrations from Tables 21-24 should be selected to correspond to the work category(-ies), plants, and time periods.

Other assumptions should be made as given in Section 6.1 above. Any necessary adjustments should be made to allow for partial years, overtime, etc.

The intakes, in pCi, should be calculated by multiplying the appropriate air concentrations by the breathing rate(s) and the hours, and dividing by 2.2 dpm/pCi.

For a worker who spent time in an area where radon might present a hazard, the intake, in pCi, should be calculated as in Step 5, except that adjustment should be made for time spent in the area (i.e., the time may typically have been less than a full work day, depending on the job) and the dpm to pCi conversion need not be made although the µCi of the input should be converted to pCi by multiplying by 10^6.

3.4 Calculation of Internal Doses for Missing Periods or for Comparison

Once the intakes in pCi have been determined for each year or subyear period as explained in Sections VI.A-C above, the intakes can be used in the IMBA-NIOSH program (ACJ 2002) to calculate the annual doses for the organ of interest. Reference should also be made to the NIOSH guide on internal dose reconstruction (NIOSH 2002b) and to the dose reconstruction project internal dose procedure (ORAUT 2003 b).

In structuring the IMBA case(s), it should be considered that the annual intakes can be assumed to be chronic and thus, where the intake is much the same for several years running, they can be summed and amortized over those several years without loss of accuracy or conservatism, for the following reasons.

1. The actual intakes were in fact mostly chronic.

2. Because of the typically long lapse of time between exposure and onset of cancer for most Mallinckrodt claimants, whether the intake corresponding to a given year occurred at the beginning or the end of a year or evenly over the year makes little difference.

In selecting the IMBA input parameters, the following should also be considered. As noted earlier, the uranium forms processed at Mallinckrodt all appear to be of the insoluble form. Human and animal studies have indicated that oxides of uranium can be very insoluble (see ICRP Publication 71, pg. 299 (ICRP 1995a)). As noted earlier, ICRP 68 (ICRP 1995b) recommends Type M for UF4. However, to be claimant favorable, the selection of absorption type should depend on the organ of interest. Thus in general, Absorption Type S should be selected for respiratory tract dose calculations and Absorption Type M for all other organ dose calculations. ICRP 66 default parameters should be selected for particle deposition parameters in the IMBA program, unless other information (such as that presented in Table 8) for some overriding reason prompts a different choice.

The annual organ doses produced by the IMBA program (ACJ 2002) can then be entered into the NIOSH IREP program (NIOSH 2002c).

4.0 DETERMINATION OF EXTERNAL DOSES

4.1 GENERAL CONSIDERATIONS FOR MALLINCKRODT EXTERNAL DOSE RECONSTRUCTION

To date, only incomplete dosimetry monitoring records are available for Mallinckrodt employees. As alternatives for dose estimation information, area monitoring data for external radiation is sparse, and though much is known about the process material (source term), considerations of amounts of material and geometry characteristics render any dose estimation with this data subject to a great deal of uncertainty. Thus the approach incorporating the least uncertainty is likely to be based upon existing dose monitoring records.

An external dose reconstruction guideline was formulated for Mallinckrodt claims. Generally, for a given claim, dates of employment are compared to the available dose monitoring information. If dose monitoring records are likely to be available, the dose reconstructor will request project personnel to search the available records and list recorded doses in the external dose reconstruction spreadsheet for the case. Then reconstructed dose is assigned for each weekly cycle worked during the early, unmonitored period. Dose reconstructions are then performed using the Mallinckrodt external dose reconstruction guideline in accordance with the dose reconstruction project external dose procedure (ORAUT 2003a) and with the NIOSH external dose reconstruction guidance (NIOSH 2002a).

Co-worker data, in Mallinckrodt cases, is likely to be a matter of identifying an appropriate worker with a similar work history. Use of "surrogate dose histories" is detailed in the external dose reconstruction guideline for Mallinckrodt, as is the performance of "summary dose evaluations" using only the complete records and neglecting data gaps. Summary dose evaluations are performed for cases where probability of causation greater than 50% may result from this quick estimate. Probability of causation above the criterion allows the dose reconstructor to neglect the underestimating omissions of missing dose data.

Dose incurred during the decontamination and postoperations years (1959-1995) are covered in Section 8.0.

4.2 UNMONITORED WORKERS

Mallinckrodt dose records demonstrate that a substantial proportion of employees had film results recorded as 0-50. From this we infer that the dose-monitoring program was sufficiently conservative that even many individuals who did not receive significant occupational exposure were also monitored. It is further assumed that the converse is true; that individuals who were not monitored were unlikely to receive significant occupational exposure. To account for incidental exposure missed by the monitoring program, these individuals are assigned incidental dose in accordance with Section 7.4.2.4 below.

4.3 APPLICATION OF DOSE DATA

This section defines the use of Mallinckrodt dose monitoring data in performing dose reconstructions.

4.3.1 Incorporation of Available Film Badge Dose Monitoring Data

One reference stated that the same film badge was in use throughout the MCW uranium division operation (MCW 1961). In an unpublished report this was described as follows:

> *The A.M. Samples stainless steel badge holder with open-window and cadmium filters permitting beta and gamma differentiation and measurement. DuPont Type 552 dosimeter film was used in the badge. The film was processed by techniques calibrated and standardized with film exposed to standard gamma and beta radiation sources. Gamma standards were obtained by exposing film to a platinum encapsulated radium needle. Beta standards were obtained using an aged, natural uranium block as a source.*

The foregoing comment does not describe calibration using a phantom, and it is likely that open-air calibrations were performed. Therefore the recommendation is that Mallinckrodt recorded doses be converted using dose conversion factors for Roentgen-to-$H_p(10)$ dose for photons from Appendix B of the NIOSH External Dose Reconstruction Implementation Guideline (NIOSH 2002a).

Work underway for this project at the present time describes the standardization of the film badges used by AEC contractors. A similar badge in use at Idaho National Engineering Laboratory (presently INEEL) is listed as having an open-window density of 0 mg cm^{-2} and a density behind a 1-mm Cd shield of 1000 mg cm^{-2}. This work, to be published as a complex-wide technical basis for external dosimetry, states that MED/AEC/DOE beta/photon dosimeters are generally expected to reasonably measure the $H_p(10)$ dose under most workplace radiation fields, and is claimant-favorable with the single exception of response in workplaces with low-energy photons, such as plutonium facilities. For this reason, no modification is proposed to recorded deep doses, once converted to organ doses using the Roentgen-to-$H_p(10)$ dose conversion factor.

Examination of the results for ‘gamma’ and ‘beta’ in the Mallinckrodt dose records gives the impression that the beta doses are derived by subtracting the optical density for the shielded portion of the film from that of the unshielded part. This is borne out in a series of memoranda between the AEC and Mallinckrodt (AEC 1950e, AEC 1950g, MCW 1950g), where the method of subtracting the two quantities is discussed. For Mallinckrodt, it is assumed that ‘the beta readings are obtained by subtracting the density under the shield from the density under the window and assuming the difference in density is due to beta radiation’ (MCW 1950g). For the purposes of dose reconstruction, the ‘beta’ readings in the Mallinckrodt dose records are assumed to be equal to the shallow dose, $H_p(0.07)$. A claimant-favorable dose conversion factor of one is assumed for application of shallow dose to the skin, testes, and breast.

4.3.2 External Exposure Geometries

Geometry of external radiation exposures varied significantly by job assignment. When job assignments are known in sufficient detail from the individual work history, exact geometries may be applied by specific job title from Table 19. The geometry factors in this table are developed from the time-and-motion studies performed as part of the AEC dust exposure monitoring activities. For dose reconstruction, these may be applied using the "custom geometry" option in the external dose reconstruction spreadsheet calculational tool.

When such detailed individual information is not present in the employee information, assumptions must be made based on the information available. More general categories are available to apply to these cases. These incorporate mixtures of the anterior-to-posterior (AP) and rotational (ROT) geometries.

Exposure geometries for three job categories in uranium facilities are listed in the external dose reconstruction implementation guideline (NIOSH 2002a): "general laborer," "machinist," and

"supervisor". Though these categories are useful when little is known about a given uranium facility, the details of the Mallinckrodt facilities are better understood. Based on the research to date, the following general categories are suggested for use when detail is insufficient to allow use of Table 19.

50% AP/50% ROT
Corresponds to the "supervisory" category in the IG. Should be used for supervisors, foremen, and mechanics assigned to multiple buildings.

25% AP/75% ROT
Corresponds to the "general laborer" category in the IG. Should be used for personnel who are not assigned to specific process equipment.

75% AP/25% ROT
Corresponds to the "machinist" category in the IG. Is applied to most process workers.

90% AP/10% ROT
Is used for Mallinckrodt workers who performed process work and who likely received a majority of their dose in the frontal geometry in a short period of time.

100% ROT
Is used to assign dose to non-process workers.

The most significant adaptation of the categories above from the categories and proportions in Table 4.2 of the IG is that the ROT geometry has been substituted for the ISO geometry. There are several reasons for this change. A survey completed subsequent to the operation of the Destrehan Street plants (MCW 1959) states in the summary that “In general most of the radioactive contamination is located in floors, [and] walls below the six-foot level…Walls, steelwork, and metal platforming…above the six-foot level are usually only slightly contaminated”. It is true that a survey completed after operations ceased would not perfectly reflect operating conditions, especially since the roofs of processing buildings were found to show heavy contamination (MCW 1959). However, review of the process and available floor plans conducted for preparation of this document show little overhead process piping such as would be found in a more recently designed facility such as a commercial nuclear power plant. Further, the early process shows much direct manual handling of the radioactive material. Finally there is the consideration that for the workers receiving the highest doses, higher-dose activities often imparted much of the dose in a short period of time while directly handling the material or equipment. Isometric-geometry exposures are included in the detailed geometries in Table 14 for activities likely to result in overhead dose. Error in these assumptions occurs on the side of claimant-favorability by adoption of the ROT as opposed to the ISO geometry in most cases.

4.3.2.1 Photons in the 50% AP/50% ROT Category

Dose conversion factors in this category represent an even split between the AP and the ROT exposure geometries. Job titles to which this geometry should be applied are supervisors, foremen, and mechanics/maintenance personnel without specific equipment or area assignments.

4.3.2.2 Photons in the 25% AP/75% ROT Category

Dose conversion factors in the tables represent a 25% AP exposure and a 75% ROT exposure. Examples of personnel to whom this general geometry should be applied are warehouse workers, general laborers (personnel not assigned to specific process equipment) in process plants, engineers, fork truck drivers, and instrument technicians.

4.3.2.3 Photons in the 75% AP/75% ROT Category

Exposure geometries for this category of workers reflects a 75% AP/25% ROT geometry. This geometry is appropriate for many process workers.

4.3.2.4 Photons in the 90% AP/10% ROT Category (Process Workers)

Time-and-motion studies document that certain workers received most of their external exposure in a short period of time performing dose-intensive activities. This geometry should be applied to process workers in the higher-dose categories.

4.3.2.5 Photons: Non-Process Workers

These workers are expected to have entered process areas only incidentally and rarely approached process equipment as part of their assigned duties. Examples of these types of workers are clerks, other office workers, and dispensary personnel.

4.3.3 Photon Energy Ranges

Metal plant workers are exposed to natural uranium separated from radium and its progeny, the source of high-energy photons in uranium ore. Workers in the refinery were exposed to uranium in many states, from minimally processed ore through the various stages of uranium separation. Other workers, such as laboratory workers and guards, were exposed to uranium in varying states also.

Photon doses for all workers should be assumed to be evenly divided between the 30 – 250 keV and > 250 keV energy ranges.

4.4 RECONSTRUCTED EXTERNAL DOSE

Some considerations for the reconstruction of external dose in this technical basis document are based on the methodology discussed in Watson et al. (1994). That study utilized external doses for workers at the Oak Ridge National Laboratory (ORNL) and the Y-12 Facility in Oak Ridge, Tennessee to evaluate the accuracy of estimates resulting from the use of the NEARBY procedure, developed by D.J. Strom, as cited in the reference. The procedure is not treated in detail here, due to the ready availability of the reference. The results are significant for this document, however. A statistical test for goodness of fit between estimated doses and actual doses showed the first step (of the 10 ordered steps) of the NEARBY procedure to result in the smallest difference between estimated and actual doses for ORNL. The correlation between estimated and actual dose went down, in general, with increasing step, with exceptions. For the uranium facility, Y-12, the use of department median or mean doses produced as good a fit as use of the NEARBY procedure. Though exact application of the NEARBY procedure is not possible in this case, the methodology is followed to the extent possible with existing dose monitoring data.

4.4.1 Estimating Dose, Unmonitored Period 1942-1945: Workers With Subsequent Dose Monitoring Records

The lack of early external monitoring data for Mallinckrodt likely reflects the novelty of the uranium processing industry, the provisional nature of early uranium activities at Mallinckrodt and the assumption that airborne exposure was the primary hazard. The implementation of a more comprehensive health and safety program in the early post-war period led to questions about external doses that previously had gone unmeasured. This resulted in the publication of the AEC report “An

Estimate of Cumulative Multiple Exposures to Radioactive Materials, Mallinckrodt Chemical Works Plants 4 and 6, July 1942 to October 1949" (AEC 1950a). This study develops cumulative dose data, but unfortunately does not apply it to individual workers. Doses applied to individual workers for dose reconstructions should rely upon recorded doses for actual workers during the monitored period to project doses for the unmonitored period. However, dose reconstructors should be aware of this report in the case of workers who began MED/AEC work before film badges were routinely worn and for whom AEC's "back-calculation" estimate may be found listed in dose records as simply an accumulated dose for the pre-monitoring period of operation.

Because in dose reconstruction different assumptions are made than AEC made and thus these calculations will have to be redone, their results are not repeated here. The cumulative exposure estimates covered workers then employed at Plants 4 and 6 who had been employed in MED/AEC work at Mallinckrodt between July 1942 and October 1949 and who had more than six months of exposure to radioactive materials. AEC's estimates for the dose to the skin were based on film badge data and for the dose to the bone on breath radon analysis (to determine the fixed radium burden) and film badge data. Calculations of lung dose did not include a gamma contribution because AEC deemed it negligible compared to the dose from airborne particle inhalation. It should also be noted that AEC thought that the exposures in the unmonitored years were "at least as severe as they were found to be at the time of our initial studies" (in early 1947); conditions probably were not more favorable and may have been "moderately" more severe. Thus they thought that their extrapolations could possibly be somewhat nonconservative.

For workers whose covered employment took place during 1942-1945 and have dose results from the early monitored period, external dose may be estimated from the total dose listed in the period in the tabulated total doses in the Mallinckrodt Radiation Summary (MCW undated). In this document, only total doses for all weeks worked are listed. For these workers, the average weekly dose is computed by dividing the listed total for gamma and beta each by the number of weeks worked. This average weekly gamma and beta dose is then applied to each week worked during the unmonitored period.

This conforms as closely as possible to Step 8 of the NEARBY procedure, but the lack of data prevents the exact following of NEARBY. Additional sources of uncertainty for this estimate are that the correlation of estimated-to-actual doses decreases with the number of the step; the statistics of applying Step 8 to several years prior to the year for which dose is copied is untested in the reference; and finally, the limitations pointed out at the beginning of this section add to uncertainty also. However, this method seems less inherently uncertain than the application of a simple median from the MCW (undated) data.

This approach appears to be generally consistent with the approach of Dupree-Ellis et al. (2000), who stated that in an Oak Ridge Associated Universities study of Mallinckrodt workers, "for the 20.8% of working years in which doses were not monitored [i.e., 1942-1944], an algorithm was used to assign doses". This author also states that use of 1946 data 'should provide valid exposure estimates for this early period' (Dupree-Ellis et al. 1998). In situations where data for 1946 is incomplete or unavailable, the dose reconstructor should move on to subsequent periods for monitoring data which could introduce additional uncertainty into the dose estimate.

Based on this method, for workers with recorded doses for 1946 (or the nearest time period with recorded doses), the dose reconstructor should assign the same doses for years 1942-1946 when the record indicates the same or similar work assignments. When the record indicates that the work assignment changed, co-worker data should be found that corresponds with the likely work assignment and this dose assigned for the appropriate period.

4.4.2 Estimating Dose, Unmonitored Period 1942-1945: Workers Without Subsequent Dose Monitoring Records

It is assumed that workers without subsequent dose monitoring records either terminated prior to the beginning of dose monitoring or performed work that did not meet later Mallinckrodt criteria for monitoring. For the former, a surrogate dose history is to be formulated based on workers with similar job titles during the period of external radiation dose monitoring. The latter may have had low- or no-dose jobs during the 1942-1945 unmonitored period, in which case assignment of a lower dose based on the median dose from the early monitored period is a claimant-favorable measure.

1. Workers assumed to have terminated prior to the start of external radiation monitoring.

   Doses to these individuals should be assigned based on surrogate dose history estimated from recorded doses of co-workers from 1946, or the closest subsequent period. Dose reconstructors must compare information available from the DOE record and the computer-aided telephone interview (CATI) to the reference documents in order to identify workers with a similar work history, whose recorded doses should then be applied to the worker for whom no doses were found. Care must be exercised to identify the appropriate work history to use as a surrogate for the subject employee, but adequate information is likely in the documents to formulate a reasonably accurate surrogate dose history when the case file contains adequate work history information for the employee.

2. Workers who were outside the uranium division operation during the monitored period.

   For these individuals with no identified records, and work assignments subsequent to the unmonitored period that would probably not result in significant exposure, application of the average doses from the early monitored period provides a claimant-favorable estimate that likely addresses any incidental dose that may have been received from 1942-1945. These are presented in Table 36.

The values in Table 36 were generated from the average doses received by Mallinckrodt "pilot plant" workers during the earliest known period of film badge monitoring, the 15-week program described above (Rochester 1950). It incorporates significant uncertainty due to the following features of the data. Firstly, only total doses were listed for each worker for the number of weeks monitored (n = 1-15). Second, no detail is supplied in the reference as to what activities the workers were engaged in, other than the fact that the location was listed as "pilot plant." The memo, however, states that the doses are from "prior to the operation of the current plant", and is dated around the time that Plant 6 became operational; also, it is known that Plant 4 was called "the pilot plant" after Plant 6 was built and before a pilot plant was established at Plant 6. Thus, though it is unknown whether the listed doses were received at Plant 1, Plant 2, Plant 4, or a combination of plants, the results likely reflect doses received in the early operations prior to the improved control measures presumably implemented in the construction of Plant 6. Further, to what extent early "benchtop" operations may have resulted in doses that differ from the estimates below is not known. Finally, as clear production levels have not come to light for the early period, no attempt has been made to scale the exposures to reflect the quantity of material processed. These factors result in dose estimates that are highly uncertain, but represent the best information at hand.

The methodology used to create Table 36 was compared with the techniques discussed in Watson et al. (1994). Whether it would be a better fit to use the department median or mean, due to the fact that Mallinckrodt was a uranium facility like Y-12, or to use the NEARBY procedure is unfortunately academic in the case of workers without monitoring records subsequent to the unmonitored period, as

insufficient data is available even to approximate the use of NEARBY. Nor is it known how Plants 1 and 2 may have been like Y-12. Additionally, the Mallinckrodt facilities in use from 1942-1945 likely changed significantly over this period, so the dose estimates are applied to plants and equipment with unknown stability in function and arrangement, unlike those used in the study. However, the approach described below resembles the use of a department mean or median dose as closely as possible with the available data.

From total doses in Rochester (1950), the dose distribution of the average weekly dose for the 32 workers considered was evaluated and the values in Table 36 were prepared. Distribution of the data and values for the median and geometric standard deviation were calculated using LOGNORM™ and CrystalBall©.

The median dose is applied to each cycle for which dose is reconstructed during the unmonitored period. For deep dose, the conversion to organ dose for the relevant worker category is accomplished by the use of the energy proportions specified in Section 7.3.3, the geometry proportions listed in Table 19 or Section 7.3.2 (as appropriate), and the energy- and geometry-specific dose conversion factors given in the NIOSH External Dose Reconstruction Implementation Guide (NIOSH 2002a). Shallow dose is assigned as electrons of energy greater than 15 keV (with an implicit dose conversion factor of unity). Integrating the triangular distribution of the energy uncertainty and the lognormal distribution in the table is best done with an appropriate computer application such as CrystalBall©.

4.4.2.1 Dose During the 15-Week Monitoring Period

Dose from this period for listed workers should be estimated from the average dose per week calculated from the listed total dose and the number of weeks the employee participated in the study. Other claimants (not listed in the dose results) are assigned doses from Table 36 in the same manner described above.

4.4.2.2 Gaps in Data

Periods when monitoring records are missing should be filled in accordance with the guidance of NIOSH (NIOSH 2002a) and with the dose reconstruction project external dose reconstruction procedure (ORAUT 2003a). This may involve extrapolation, interpolation, or both.

4.4.2.3 Non-Specific Summary Results

Monitored workers may have received up to 150 mrep in a week without the dose being recorded, if dose summaries are the source of dose information. There is some probability that the dose received was actually zero: dose summaries consistently show a significant number of badges in the 0-50 mrep dose range. For the purpose of dose reconstruction, the most claimant-favorable assumption is that any monitored employee assigned to a given plant but not specifically listed in the dose records for the plant for that week received a dose of 150 mrep that week. Division of the total between gamma and beta components is based upon an average ratio derived from the weeks with specific dose monitoring entries for that employee.

4.4.2.4 Unmonitored Workers

As stated above, most workers who received significant occupational exposure were likely to have been monitored. To account for the possibility of an unmonitored individual receiving incidental exposure to photons, dose will be assigned for unmonitored Mallinckrodt employees.

For the purposes of dose reconstruction, the minimum level of detection was determined to be 50 mrep/week from the fact that Mallinckrodt individual dose monitoring records list many entries in the gamma column as "50*"and the asterisk refers to a footnote that reads "indicates less than." Individuals without monitoring data are to be assigned "incidental dose" for each weekly cycle worked. This is to be assigned as photon dose equal to the LOD (limit of detection) divided by 2 (LOD/2), or 25 mrep, for each weekly cycle worked. This 25 mrep is assumed to be in the form of photons of energy between 30 and 250 keV, and the exposure geometry is assumed to be 100% ROT.

Use of the LOD/2 method results in "slight positive bias" for monitored workers, as stated in the NIOSH external dose reconstruction guidance (NIOSH 2002a). Additional claimant-favorability arises from the fact that as unmonitored workers they are less likely to receive significant occupational dose (see above), and so true doses are closer to zero than "less-than-detectable" or "missed doses" for monitored workers. This overestimating assumption is a claimant-favorable way to account for individuals who may have been incidentally exposed.

4.5 X-RAY DOSE

4.5.1 Mallinckrodt-Specific Information

Employees of Mallinckrodt (cf. Section 5.45) received an annual occupationally related diagnostic x-ray (MCW 1955; Mason 1958a). The annual chest x-rays were taken at the Barnes Hospital (the Washington University School of Medicine) (AEC 1950k; MCW 1955) and the x-ray records remained the property of the hospital (AEC 1950k). There is no evidence so far in the Mallinckrodt documents to indicate when the annual chest x-rays began, although Fleishman-Hilliard suggests that this was done from the start since Mallinckrodt insisted at the outset that the Washington University School of Medicine be engaged to do the physical examinations. A claimant-favorable assumption would be that chest x-rays were performed annually from 1942-1958. Since the radiographs were made at a hospital, and hospital procedures routinely used both PA and lateral chest views much more commonly than non-hospital facilities, the annual dose from chest x-rays for Mallinckrodt workers should consist of the dose from both views. No evidence so far indicates that photofluorographic chest films were performed.

Since no actual x-ray output measurements or x-ray technique factors are available for the Barnes Hospital in Mallinckrodt records, default values for entrance kerma appropriate for this time period will be used in the calculation of organ dose conversion factors for use in dose reconstruction.

4.5.2 General Information

Information to be used in dose reconstruction for the early years for which no specific information is available is provided in the Savannah River Site technical basis document for dose reconstructions (ORAUT 2003c). This information was used to produce Table 37, the organ doses for a generic occupational diagnostic x-ray examination. The important points supporting this table are reiterated below for the convenience of the dose reconstructor, but ORAUT (2003c) should be referred to for complete information.

A source-to-image distance (SID) of 72 inches (183 cm) was standard for the time for both the PA and lateral views. The x-ray machines from this time period (1942-1958) were single phase and typically no air gap was used between the patient and the film. It is assumed that the x-ray equipment was operated at 80 kVp, had at least 1.5 mm Al total filtration (see Table 3.1 of NCRP 102 (NCRP 1989) and that the HVL was approximately 2.5 mm Al equivalent (see Table B.2 of NCRP 102), which are typical machine parameters for chest x-rays performed in this time period.

Specific organ doses for the PA and lateral chest x-rays calculated on the basis of the dose conversion factors found in ICRP Publication 34 (ICRP 1982) are given in Table 37. Doses for organs not listed in ICRP 34 but specified in the IREP code were determined by analogy with anatomical location as indicated below.

Analogues for IREP organs not included in ICRP 34

Anatomical location	ICRP 34 reference organ	IREP organ analogues
Thorax	Lung	Thymus Esophagus Stomach Bone surface Remainder organs
Abdomen	Ovaries	Liver/gall bladder Urinary/bladder Colon/rectum Uterus
Head and neck	Thyroid	Eye/brain

It is assumed that the x-ray beam was not collimated, even though these x-rays were performed at a hospital and collimation practices were generally better in hospitals than in non-hospital facilities. Therefore, organs not normally in the primary beam for a PA and lateral chest were included in the primary beam by using ICRP 34 organ dose conversion factors for procedures where those organs would normally be included in the primary beam.

For any individual entrance skin exposure (ESE) or derived organ dose, an uncertainty of ± 30 % at the 99 % confidence level may be assumed; for further conservatism it may be appropriate to assume that errors are all positive and thus that only the + 30% should be used.

4.6 OTHER DOSE CONTRIBUTIONS

4.6.1 Extremity Dose

Given the relatively small number of claims and the unknown proportion requiring calculation of extremity dose, this subject is not treated in this TBD. Extremity dose estimates, when necessary, will be formulated on a case-by-case basis.

4.6.2 Submersion Dose

Submersion dose is likely to be significant only for the skin, testes, and breast, and is not used when testes dose is used to estimate dose to the prostate. As dose reconstructions are based upon the partial film badge dose monitoring records, submersion doses are not separately calculated.

4.6.3 Shallow Dose

As discussed above, Mallinckrodt dose records contain ‘beta’ values obtained by subtracting the optical density of the film behind the Cd shield from that behind the open window. These recorded values are assumed to be equivalent to $H_p(0.07)$. Work presently underway may result in default assumptions regarding appropriate electron organ dose conversion factors to apply in uranium facilities, but at the present time, for the purposes of dose reconstruction, shallow dose is assigned from the film badge data using a claimant-favorable dose conversion factor of 1.

As noted earlier, work conducted in the early days of the AEC Health and Safety Division dealt with attenuation of beta sources by workplace clothing (AEC 1950h). Attenuation of beta radiation was determined for coverall cloth to be an average of 21.8% (with a standard deviation of 7.5%) for distances between 6 and 36 inches from a sheet of uranium metal in equilibrium with its two major beta-emitting progeny, Th-234 and Pa-234m. Since this study was performed using an appropriate radiation source and the exact material used in the work coveralls, the results may be applied directly to the problem of dose reconstruction. The variability in the mean attenuation 'appeared' to be related to distance from the source, though no pattern could be identified. For this reason, the value proposed for use in dose reconstruction is a constant value of 20% attenuation in shallow dose at cancer sites concealed under clothing.

5.0 DETERMINATION OF EXPOSURES DUE TO RESIDUAL CONTAMINATION REMAINING FROM MED/AEC OPERATIONS

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ATTACHMENT A
TABLES

LIST OF TABLES

Table 1. Plants and buildings used at the St. Louis Downtown Site for AEC/MED uranium processing work.

Plant	Building	Process, function, or area	Notes
1	25	Lab quality control, R&D	Project offices
1	Alley south of 25	Pitchblende R&D extraction	
1	K1E	Temporary pitchblende ore pilot plant	
1	A	General plant maintenance (?)	
1	X	Locker room	
2	38B(?)	Personnel change house	
2	40	Temporary storage of residues	Temporary storage of residues
2	45, 45A	Warehouse	Raw, in-process, and finished materials
2	47	Warehouse	Raw, in-process, and finished materials
2	50	Feed material and product storage, UF_4 experiments, other	Ore concentrates, UO_3 product; tanks of stored process liquids
2	51	U_3O_8 feed preparation (nitric acid dissolution), recovery, other	
2	51A	Denitration of UNH to UO_3, reduction of UO_3 to UO_2	
2	51X	Temporary canopy enclosure outside for extraction of pitchblende liquor	
2	52	Ether extraction to produce uranyl nitrate hexahydrate (UNH)	
2	52A	Miscellaneous(?) re-extraction	Pilot plant for countercurrent ether extraction
2	52X	Canopy, temporary structure	
2	55	Shotgun lab -- temporary structure	
4	400	Production of UF_4, U metal; slag handling, laboratory, change house; metals pilot plant	UF_4 product, U recast
4	400, 401	1st floor: casting pilot plant, slag pilot plant, dingot works	In casting pilot plant: lead man office and saw room; in slag pilot plant, roll mill, chip burning area, and Hoffman cleanup area; in dingot works, blender, saw area, bomb air cooler, bomb cooling room, breakout grate, furnace tank pit, and furnace residue pit
4	400	2nd floor: bomb step area; casting area, laboratory area, ceramic pilot plant	In bomb step area: blending and bomb areas, KB-2 area, bomb tramrail
4	401, 401A	(?) storage, metals and UF_4 pilot plant	
4	402	Warehouse center	
4	403	Machine shop	
4	404	Storage room	
4	405	Part of the lathe and forging area in 408?	
4	406 (A&B)	Magnesium storage	
4	407?	?	
4	408	1st floor lathe & forging areas; storage of slag, dolomite, KOH, NH, HF, etc.	Pilot Lab; furnace; forge press; manipulator; lathe area; slag crushing area; salt bath and quench tanks; slag storage
4	400 Yards	Machine shop (403) yard; guard house and guard tower; incinerator	There were also various production dust collectors in these yards outside 406B and 407
6	100	Electrical substation	Shed attached to the west end of the building was used for storage of uranium materials.
6	101	Research laboratory, decontamination(?) room, receiving offices	Also production offices, shipping & receiving, and decontamination (DX) facilities. Lab had hoods, the DX facility a hood.
6	102	Analytical Laboratory (main chemical lab), Control Lab, Metal Lab, Sample Prep Lab; possibly an additional R&D lab; lab offices	The Control Lab had a hood. There was a dust collector on the roof.
6	103	Refrigeration, spectrographic laboratory	
6	104	Main refinery building: ore to UO_3 to UO_2	Entire building housed wet processes. Barium sulfate cake, raffinate cake were residue products
6	104	Ore Room digest area, feed makeup area, M-20 area, C-3 area	Found to be the most contaminated areas in 1958 due to use when pitchblende was main feed; beta, gamma especially high in Ore Room and M-20 areas (latter up to 12 mr/hr)
6	104	Raffinate area, wet pilot plant, ether pilot plant, pot room, pot room addition, QM-2 packaging, NA recovery area, MGX area	Housed the continuous process equipment
6	104A, AA	Main refinery: ore handling and milling	Pitchblende ore (104A)
6	104B	Main refinery: pilot plant area	
6	105	Main refinery: the " Ether House"	Extraction
6	106	Nitric acid recovery	

Table 1 (continued)

Plant	Building	Process, function, or area	Notes
6	106A	Nitric acid recovery	
6	107	Nitric acid recovery, tank farm pump house	
6	108	Shotgun sample preparation lab	Superseded by lab in Building 102?
6	109	Acid unloading station	Includes 109, 109A, 109B
6	110	Main warehouse for tagged goods, pitchblende area, …, UO_3 product	Pitchblende ore, ore concentrate, UO_3 and UO_2 product. Was the receiving warehouse for pitchblende ore arriving by rail. Found to be moderately and uniformly contaminated (including gamma) in 1958 due to trackage, especially on loading platforms.
6	110A	Main warehouse, part used as Ledoux Lab	
6	110B	….repair	
6	111	Sample preparation, North; Ledoux Lab, South; maintenance shops in the south end	The Ledoux Lab included the main lab room, the oven room, the weighing room, and the dry box room; in these areas were a muffle furnace and dry boxes. It was found to be contaminated in 1958; the main(?) room had a walk-in hood behind which the floor was heavily contaminated.
6	112	Administration, maintenance shop, instrument shop (including a parts room)	This building was 50% offices, uncontaminated, and 50% storeroom and shops, both handling some contaminated materials.
6	113	Paint shed	
6	114	Scale house, temporary storage of residues	For temporary storage of residues, including radium-bearing cake (K-65) in drums. Had interior sampling bays and an exterior conveyor. Found to be heavily contaminated in 1958, including some gamma.
6	115	Boiler house and steam plant	
6	119	Steam plant (?), maintenance storage shed	
6	120 & 121	U metal dissolver (120) with digest and recovery area (pitchblende); pickling building (121)	120 had a sump; 121 had a derby conveyor and pickler. Found to be heavily contaminated in 1958.
6	122	Slag recovery pilot plant	Found to have loose contamination
6	127	…. & dissociator	Ammonia cracking?
6	101 Yard	Loading docks	Used by Shipping & Receiving.
6	104 Yard		Found to be contaminated in 1958. Gamma background from M-20 cell block.
6	105 Yard	Outdoor tanks	Concrete, asphalt, gravel all found to be contaminated in 1958. Tanks, sump in the M-70 pit. Hole by 105 door due to cave-in caused by sump leakage.
6	106 Yard		Found to be contaminated in 1958.
6	NW Yard	Storage yard	Found to be contaminated in 1958, including some high gamma spots.
6	108 Yard	Laboratory site	A laboratory on this site was demolished in 1955, except for the concrete floor. Materials handled contained radium.
6	110 Yard	Boxcar cleaning site	Boxcars that contained pitchblende ore containers were cleaned on the gravel-soil part of this yard; there was a 1.5 mR/hr hot spot between the rails and a 5 mR/hr hot spot under the shipping dock in 1958. A sewer ran under or over the yard.
6	111 Yard		Found to be contaminated in 1958. A sewer ran through the yard.
6	112 Yard	Concrete between 112 and 117	The main gate opened into this yard, as did the dispensary doors and a change room. Some contamination due to trackage
6	115 Yard	Concrete adjacent to the boiler house	Dust collector and incinerator created heavy contamination in yard. An ash silo and the Hoffman drumming station were located here.
6	116 Yard	Storage area	Storage of feed materials. Some contamination, including gamma.
6E	116 (including 116-1 and 116-2)	UF_4-to-metal facility (116-1?) with various operating areas and a maintenance shop, residue recovery area, warehouses (116-1 and 116-2), graphite machining, foremen's office (116-2?), smoking area	Used for manufacturing UF_4 to metal: reduction furnace area (~ 18 furnaces); casting furnace area (with multiple furnaces, 4 hacksaws, Kinney pumps, a crushing station, toilet area); breakout area (with sump, slag conveyor, chipping station, furnace rebuilding station, shop); jolter area (with jolter platform); filling area; center aisle area (with ingot mold station?), generator room, and ingot storage area (with both boxed and finished ingot storage, "pickled derby" shipping enclosure, ingot room with ingot table). Maintenance shop. "F" machine area (2 machines). UF_4 slag residues handled in residue recovery area, which included sump, filter, and recovery pit. Warehouse (blender hopper room, mold outgassing room(?), mold furnace room, loading platforms).

6E	116B	Electrical substation	

Table 1 (Continued)

Plant	Building	Process, function, or area	Notes
6E	116C	Slag recycle building	Magnesium fluoride slag handling and grinding. Had conveyor in (to?) packaging room; ball mill; rolling mill; elevator to C-3, hopper. Light dust contamination found in 1958.
6E	117 (including 117-1 and 117-2)	Service building: clean locker room (117-1?), regulated locker room (117-2?), laundry (117-2), security office (117-1), cafeteria (117-2), other offices and support services	The laundry and the regulated locker room were the only areas found in 1958 to be contaminated. In laundry: lobby, laundry storage room, and small and large sewers in the laundry pit. Locker rooms: turnstiles. Clean locker room: clean clothes room.
7	700	Warehouse, safety office, electrical and carpenter shops, slug machining (fabrication) plant	The slug machining area had lathes and an inspection area. 700 was found in 1958 to be lightly contaminated except for the moderately contaminated slug machining area.
7	701	Slag recovery plant (aka Slag Separation Plant or Slag Processing Plant)	Found in 1958 to be heavily contaminated with loose material, especially with high beta, due to substantial amounts of "aged uranium". It had "Wilfey" tables, pumps, tanks, a ball mill, drum washer w/elevator and sump, and a filter.
7	703	Hydrofluoric acid vaults, HF tank farm	
7	704	HF feed and recovery, HF offgas treatment	704 had sumps, tanks, and a scrubber. 704-707 were all attached and were all found in 1958 to be moderately contaminated.
7	705	Main processing area for manufacturing UO_2, UF_4: packaging station area, maintenance shop, reactor area	Reactor area had UF_4 product hoppers, hydraulic pumps, and access platforms. There were a UO_3 feed station, a Hapman UO_3 conveyor, blenders, a UO_2($_3$?) packaging station(s), and a screw storage area. Localized contamination was found in 1958 around operating stations; green salt was caked on the roof. See also 704.
7	706	Warehouse for U materials (UO_2, UO_3, UF_4)	Had shipping platform. See also 704.
7	707	Ammonia cracking building (manufacturing H_2 and N_2 from NH_3)	See also 704.
7	708	Magnesium storage building	
7	709	HF refrigeration equipment and pump house	Contained refrigeration equipment for the GS(?) pit
7	710	NH_3 tank farm and pump house, ammonia storage	
7	711	Storage shed	
7 (7E)	712	Minor elements production facility	This had a change room, a "cold" (nonradioactive) lab, a "hot" lab (with hoods and a sump), and a production room (with pumper-decanters, mixer-settlers, settling tank, packaging station, sumps). It was used to process residues to obtain an ionium (Th-230) concentrate. Found in 1958 to have high levels of contamination.
7	SW Yard	Storage of drums, feed materials, and contaminated equipment	Moderate contamination was found in 1958, but it was highest where spills had occurred or equipment was stored.
7	700-701 Yard	Secondary gates in 700 yard; conveyor in 701 yard	Found in 1958 to have visible fixed contamination, higher near 701.
7	703(?), 704-707, and 711 Yards	Storage of contaminated equipment in all yards; Th-230 liquor drainage area and boxcar cleaning area in 711 yard	Screws and tubes were stored in the 704-707 yards. Yards were primarily concrete around Plant 7, except gravel around 703. Highest contamination (both alpha and gamma) found in these yards in 1958 was around 711: in 711 yard, Th-230 liquor was drained to the area by the RR tracks.
7	706 Yard		UF_4, scrap (??)
7	712 Yard	Mostly open storage, probably of contaminated scrap	Had lean-tos and an open storage bin. There was also a tank farm on a concrete pad at the south end of 712. The concrete in this yard was found to be heavily contaminated in 1958 from the activity from boxcars and contaminated scrap.

Additional Notes:

The information in this table is drawn from FUSRAP 2003a ; MCW 1958; MCW 1959; and ORNL 1981.

Illegible areas in the references are indicated by dots (…..).

Information regarding contamination levels found in 1958 and 1959 is from MCW 1958 and MCW 1959, which are reports on the results of Mallinckrodt's postoperation survey prior to the start of intensive decontamination.

Buildings that were remained after the general demolishment of 1959-1961 are shown in Table 42.

Plants 1 and 2 were known collectively as “Main Plant”; Buildings 50, 51, 51A, 52, 52A, and 55 were known collectively as Building 51; and all of the Destrehan site was collectively referred to as Plant 6 at times.

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Table 2. Summary chronology of Mallinckrodt site operations.

April 1942	Plant 2 was used to develop a batch process using ether to extract uranium as UO_3 from milled ore and then to convert the UO_3 to UO_2. Plant 1 was used for developmental work.
October 1942	Plant 4 was converted for use in the $UO_2 \rightarrow UF_4 \rightarrow U$ metal process. The ore$\rightarrow UO_2$ operations continued in Plant 2, while miscellaneous activities related to R&D work continued in Plant 1.
April 1943	Production of UF_4 from UO_2 began in Plant 4.
1944	Experimental extraction of uranium using pitchblende ores began in Plant 1.
1945	At some point in 1945, uranium operations at Plant 1 ceased. Plant 2 was apparently still used for some metallurgical-type work. Pitchblende ore began to arrive at the site in greater than research-level quantities in about May 1945.
1946	Plant 6 began operation in early 1946, with all ore$\rightarrow UO_2$ production operations shifted there. Uranium operations at Plant 2 ceased in early 1946, the work (including UO_3 milling) apparently shifting to Plant 6. Only Plants 4 and 6 were in operation.
1949–1950	In 1949-1950, major improvements were made in dust control at Plants 4 and 6, with the latter shut down during part of 1949-1950 for this. Ore milling at Plant 6 stopped in 1950.
October 1950	Plant 6E operations began. The $UF_4 \rightarrow U$ metal work shifted there from Plant 4, with the $UO_2 \rightarrow UF_4$ work remaining at Plant 4. Plant 4 was also modified for metallurgical-R&D work and became known as the Pilot Plant; some metal production (derbies, dingots) continued to take place there for experimental purposes.
1951	Plant 7 operations began in the first half of 1951. At that time, some UF_4 production work continued until perhaps 1952 at Plant 4, while the UO_3-to-UO_2 production at Plant 6 seems to have ended completely. Instead, UO_3 was sent to Plant 7 to be converted in a continuous process to UF_4. Some recovery and storage operations also shifted to Plant 7.
1952-1953	At some point, the continuous UO_3-to-UF_4 process began in Plant 7, after which time Plant 6 made only UO_3.
1954	The Ore Room and K-65 sampling operations in Plant 6 appear to have ended by about August 1954, possibly with the shipment of the last of the pitchblende ore (which would have been processed into at least 1955). It is not clear when the various Plant 6 pilot plant(s) began, but a 1954 start appears reasonable. Also, the Plant 6E Slag Separation Plant started in the first half of 1954. Some reversion of UF_4 to UO_2 and UO_3 was done in Plant 7.
1955	In 1955, thorium extraction from AM-7 residue began in Plant 7E and slag processing began in the Slag Separation Plant (Bldg. 701, part of Plant 7). Also, processing of residues to extract thorium began in early 1955 and the processing of a small amount of "enriched uranium" was done at Plant 7 early in 1955. Predigestion ore grinding ceased.
1955 or 1956	In late 1955 or early 1956, dingots began to be produced in Plant 4, with derby production only intermittent; both were for experimental purposes.
Late 1956	All operations at Plant 4 ceased..
1957–1958	In 1957, all regular site operations ceased, except for some Plant 7 activities that continued until July 1958. Other postprocessing and shutdown-related activities may have continued into 1958.

Table 3. Principal changes made in sites, processes, and equipment (e.g., AEC 1949, Miller 1953).

Year	Plants	New method or form	Purpose(s)
1942-1943	4	Converted Plant 4	U metal production from UF_4; UF_4 production from UO_2
1946	6	Began operation of Plant 6	Increase production, reduce all types of exposures from processing of pitchblende ores
1948	4, 6	Start of formal health program	Track and reduce exposures
1948	6	Used ventilated ore railcars	Reduce radon exposures
1949	4	Added ventilation to bomb step and recasting furnaces	Reduce deposition of volatiles and thus reduce beta exposures; reduce airborne dust levels
1949	4	Redesigned UO_2 and UF_4 handling methods	Reduce airborne dust levels, eliminate hand scooping
1949	6	Added ore room shielding	Reduce gamma exposures
1949	6	Added remote control for filters	Reduce gamma exposures
1949	6	Added K-65 centrifuge shielding	Reduce gamma exposures
1949	6	Added shield tanks	Reduce gamma exposures
1949	6	Added C-3 cell block shielding	Reduce gamma exposures
1949	6	Revised ore house weighing process	Reduce gamma exposures
1949	6	Redesigned ore room dust control (drum weighing and deheading)	Reduce airborne dust levels
1949	6	Revised UO_2 handling (pneumatic unloading and conveying systems)	Reduce airborne dust levels, eliminate hand scooping
1949	6	Revised UO_3 handling (pneumatic unloading and conveying systems)	Reduce airborne dust levels; eliminate hand scooping
1950	6E	Began operation of Plant 6E	Increase production, reduce all types of exposures
1951?	6, 6E?	Centralized exhaust ventilation	Reduce airborne dust levels
1951	7	Began operation of Plant 7	Increase production, reduce all types of exposures
1953	6	Mechanical conveyor facilities provided in the Ore Room Addition for handling ore drum lids	Decrease airborne dust levels
1953	6	Increase in capacity of pneumatic gulping system in the Pot Room	Lower breathing zone and general area airborne dust levels
1953	6	New Ledoux sampling labs with better ventilation	Lower airborne dust levels
1953?	4	Enclosure around upper part of casting furnace	Reduce dust levels and beta radiation levels when furnace lid is removed
1953	4	Enclosure around blender and charging pit	Reduce dust levels in general area
1955	6E	All-purpose dust hood in the area adjacent to the smoking and maintenance areas	Reduce dust levels in breaking out ruptured derby furnace shells, rebuilding recast furnaces, dumping waste into drums, and dumping out drum to sort

1 Table 4. Types and quantities of material produced in association with Mallinckrodt uranium refining.

Material	Process or operation	Content and form notes	Amount
ORES AND OTHER FEEDS			
All ores	Eldorado processed all the Canadian and part of the Congo pitchblende; Vitro, all the vanadium tailings and some Congo ore (Eisenbud 1975). Some milled ore also came from Linde. Mallinckrodt would have received most of the Congo only during and just after the war; Canadian pitchblende and domestic ores were used after that. Pitchblende ores were apparently used exclusively until early 1955.		Mallinckrodt processed up to 50,000 tons of ore from 1942-1957 (DOE 1996). Typical amounts in 1945: Eldorado black oxide, 60,000-160,000 lbs/month, average 80,000 lbs/month; Vitro black oxide, 30,000 lbs weekly; Vitro soda salt, 20,000 lbs per 10 days (MED 1945a)
Belgian Congo ore (Q-11)	Most of the pitchblende processed by Mallinckrodt was obtained as a concentrate from the Belgian Congo in 1944 and shipped to St. Louis in 55-gal drums (AEC 1978).	Pitchblende ore, up to 65% (DOE 1997, MED 1949) or 70% (Dupree-Ellis et al. 2000) U_3O_8 by weight; up to 100 mg Ra/ton (Dupree-Ellis et al. 2000); averaged 135 mg Ra/ton (AEC 1949); 0.185 ppm equilibrium Ra for Q-11 (60%) ores (AEC 1949); 0.1 Ci/ton (total?), up to 70% U, average U concentration >25%, about 100 mg/ton ore for 25% U (Eisenbud 1975)	3400 tons U produced during wartime (through 1944) (Eisenbud 1975)
Canadian pitchblende ores (Great Bear Lake, Port Hope)		Ores at perhaps 10% U (Eisenbud 1975); ores and U_3O_8 concentrate	850 tons U produced from Canadian ore in wartime (through 1944) (Eisenbud 1975)
Domestic ore and tailings: Uravan, Durango, Grand Junction, Naturita (Col); Monticello (Utah)		During wartime (through 1946?) vanadium tailings were used, not fresh ore (Eisenbud 1975); <1% U (Eisenbud 1975); shipped as a 20% ore sludge (Eisenbud 1975). The US stimulated domestic production from 1948 on; ores and lower-grade concentrate (DOE 1997). Colorado ores were carnotite type (Eisenbud 1975); N. American ore contained less than 1% U_3O_8 (AEC 1978)	850 tons U produced from the vanadium tailings (through 1944) (Eisenbud 1975). It is not clear how much if any of this was used by Mallinckrodt, except such as came as soda salt, etc.
U_3O_8 (milled ore or black oxide)	Ore usually arrived at Mallinckrodt in milled or concentrated form, as black oxide. However, DOE 1997 stated that Mallinckrodt produced black oxide, presumably at Plant 6.	Originally, (wooden?) beer barrels were used to transport the Congo ore from Eldorado, with wooden bracing in the railcars. This was unsatisfactory so metal containers (barrels) were used. The metal containers weighed about 100 lbs each when full. (MED 1945a)	Normal in-process inventory circa 1945 was about one month's production (MED 1946a).
Sodium diuranate (soda salt)	Packed in fiber containers (MED 1945a)	Vitro converted U ores to sodium diuranate (DOE 1997); some apparently also came from Anaconda, Durango, and Fernald (AEC 1956c). Fiber containers weighed about 75 lbs each when full (MED 1945a).	

Table 4 (Continued)

Material	Process or Operation	Content and Form Notes	Amount
REFINING PRODUCTS			
UO_3 (orange oxide)	Feed digested in nitric acid; precipitation of Ra-Pb w/ sulfuric acid (pitchblende ores); filtration to remove acid-insolubles; sulfate removal w/ Ba salt; centrifuging of solution; boiling of "liquor"; double extraction of U w/ diethyl ether; water wash to remove uranyl nitrate from ether; dewatering in Sperry press; boiling of molten salt to "hex liquor"; decomposition in pots to form UO_3; UO_3 "gulped" out of pot using vacuum system, packed in fiber containers for shipment.	Digestion took 4-8 hours (MED 1946a). Various solid and liquid wastes were produced, including most of the residues listed below. 2.5-gal fiber containers weighed about 75 lbs each when full (MED 1945a).	Sent to Clinton Engineer Works: 30,000+ lbs monthly prior to 15 DOE 1944 but 15,000 lbs weekly after that. (MED 1945a)
UO_2(brown oxide)	UO_3 was transferred from fiber containers into stainless steel drums, then weighed out on monel trays; reduced with cracked ammonia in batch electric (muffle) furnace to form UO_2 (MED 1949a); scooped from trays into fiber containers for transfer elsewhere (MED 1945a). Packed in fiber containers for transfer elsewhere.	This step took about 7 hours (I). 2.5-gal fiber containers weighed about 75 lbs each when full (MED 1945a). There was 349 lbs on a 4-tray charge (MED 1944a).	By DOE 1942 Mallinckrodt was producing a ton a day (DOE 1996). Per MED (1944a), Mallinckrodt used 32,000 lbs weekly. Per MED (1949a), Mallinckrodt produced 2/3 of the US total; 64% of what it made stayed at Mallinckrodt, 20% went to Harshaw, and 16% went to Linde. Per MED (1946a), in 1944-45, 20,000 lbs monthly went to Linde; 10,000 lbs/week went to Harshaw from Sept-Oct 1944, 28,000 lbs in DOE, and 13,000 lbs/week after that.
UF_4 (green salt)	UO_2 placed on graphite or nickel trays in graphite or nickel boxes in the hydrofluorination reactor (furnace); HF gas passed over it to form UF_4; UF_4 removed from furnace and put through pulverizer; UF_4 packed into fiber containers (MED 1945) or 5-gal containers for transfer to Plant 4 or 6E or another site (AEC 1949).	Fiber containers weighed about 75 lbs each when full (MED 1945a). In 1944, one control sample was taken per charge; there were 107 runs per week; 535 lbs per week was sent to a recovery tank; and there were 135 lbs per drum and 3375 lbs per lot (MED 1944a).	Mallinckrodt was the major producer of UF_4; up to 1949, some UF_4 came from ElectroMet (DOE 1997). Normal in-process inventory circa 1945 was 2 days' production (MED 1946a). In 1944, 37,000 lbs weekly was produced, of which 11,000 lbs was used at Mallinckrodt to make metal (MED 1944a). In 1945, 8000 lbs/week was being sent to Harshaw and 20000 lbs/week to Iowa State (MED 1945).
U metal in derby form	Reduction with magnesium in furnace to U metal (slag + derby); slag chipped off to leave derby	In 1944, there was 135 lbs of UF4 per bomb, along with 55 lbs of liner and 24 lb of magnesium; a biscuit weighed 92 lbs and was associated with about 122 lb of slag, of which 10 lb was metal; about 80 lbs of sawdust a week was produced; 15 and 2 lbs of samples were sent (weekly?) to plant and outside labs respectively (MED 1944a).	In 1944, there were 7500 lb of biscuit produced weekly (MED 1944-TTTTT). Normal in-process inventory circa 1945 was one week's production (MED 1946a).
U metal in billet form	Derby was vacuum recast to form the billet		Normal in-process inventory circa 1945 was one week's production (MED 1946a). In 1945, billets were being shipped out every other week to Hanford in a carload lot of about 30,000 lbs, from a weekly production of 13,000-15,000 lbs (MED 1945a).
U metal in dingot form	A dingot was a single massive ingot needing no recasting. The dingot-making operation was most similar to the regular derby-making operation. After the chipping step, the dingot was pressed into a slab. (AEC 1956b)	In late 1955 or early 1956, this replaced the derby-billet operation, except for occasional experimental derby production in Plant 4, per AEC (1956b). But AEC 1956d reports that in mid-1956 (all?) billet recasting was being done in 6E, using new graphite molds. A dingot weighed about 3300 lbs (AEC 1956b).	

Table 4 (Continued)

Material	Process or Operation	Content and Form Notes	Amount
Radioactive metal samples	"Small" samples were sent to Clinton Engineer Works (Y-12) packed in glass tubes and packed into cardboard boxes. "Eggs" were sent to the Chicago Area Engineer (MED) packed 8 to a box in wooden cardboard boxes. (MED 1945a)		A "small sample" was sent daily to Y-12; eggs were sent in 2-3 lots daily, 63 lbs to a lot. (MED 1945a)
"Tubealloy"	Early synonym for uranium (Fleishman-Hilliard 1967), but in what form is unclear. Manufactured by Mallinckrodt and shipped to the Chicago Area Engineer (of MED).		150 lbs shipped daily to Chicago (MED 1945a)
RECYCLED AND RECOVERED MATERIALS			
Organic solution of $Th(NO_3)_4$	AM-7 residue was processed via a nitric acid strip to concentrate Th-230 in Plant 7E; solution was sent to Mound, residue (AM-9) returned to storage.	Concentrate had about 1 kg of Th-230, 0.7% alphas from Th-227 & daughters, <0.03% from Th-228.	350 tons of AM-7 processed for Th- 230 (FUSRAP Undated a, AEC 1959); 3600 gal (13,630 l) of Th-230 solution sent to Mound (DOE 2002).
U slag (derby)	Derby slag was scalped or cut off derby and separated into a MgF2 part and a C-liner part; the MgF_2 part was sent to Vitro for recovery; the C-liner part was stored as waste. Eventually both parts were processed at Mallinckrodt.	Some of the C-liner slag was apparently reprocessed to recover U from about 1953 on (AEC 1954f). In 1955, an interim pilot plant at Plant 7 was built to scalp off most of the U-bearing segment of the MgF_2 part.	
U slag (recast)	Recast slag was recovered as residue from the recast furnace.	Recast furnace slag was highly concentrated in UX1-UX2 (beta emitters) (AEC 1949, Eisenbud 1975) .	
U slag (dingot)	Dingot slag was broken off and swept down through a floor grill, collected on a conveyor, put through a grinding series, drummed, and sent to the Slag Building (701) for reprocessing. (MCW 1949c)		
U scrap	Miscellaneous material, including some residues, ash from incinerating the UO_3 fiber containers, and metal; some oxide and nitrate scrap was sent from the Chicago Area Engineer (MED); some scrap was sent to Du Pont. C-2 scrap was packed in 50-gal whiskey barrels; C-1, C-3, C-4, C-5, and D-2 scrap was packed into 5-gal containers with a steel clamp top. (MED 1945a)		Scrap from Chicago Area Engineer, 1945: 1500 lbs oxide type per 2 months, 1500 lbs nitrate type per 4-5 months. Scrap shipped to Du Pont as follows. C-1, C-3, C-5, D-2: 80,000-90,000 lbs total per 4-6 weeks; C-2: 80,000-90,000 lbs per 5-6 weeks; C-4: 100,000-120,000 lbs per 4 months. (MED 1945a)
K-65	One source suggests that this residue was "reworked to recover additional uranium values" (i.e., reprocessed?) before transfer to Lake Ontario.	Radium-bearing residue	
Sawdust and fiber containers	Fiber containers were incinerated and processed to recover uranium; sawdust was apparently processed similarly.		

Table 4 (Continued)

Material	Process or Operation	Content and Form Notes	Amount
RESIDUES AND OTHER WASTES			
Pitchblende raffinate (AM-7)	"Airport cake"; produced as part of the digestion process	0.2% U (U, pg 48)); 29 ppm Th-232, 3.8 ppm Th-230 (11.6 isot %) (Figgins and Kirby 1962). Pitchblende residues:Th-232/Th-230 ~ 8.	33000 lbs/day (AEC 1949); 74K tons total, 113 tons U stored through about 1953
De-thoriated pitchblende raffinate (AM-9)	Residue after processing AM-7 for ionium (Th-230)		
Domestic ore raffinate (AM-10)	"Airport cake" (different from AM-7); produced as part of the digestion process	Carnotite residues: Th-232/Th-230 ~ 15-20	32.5K tons total, 48 tons U stored through about 1953 (AEC 1959)
Pb-Ra precipitate (K-65)	"Lead cake"; appears to be a subset of AM-7; a Ra-bearing residue produced as part of the digestion process (first precipitation)	750-900 mg Ra/ton (AEC 1949); 750 mg/ton Ra and 0.2% U (AEC 1949); up to 300 Ra mg/ton (Eisenbud 1975)	8000-12000 lbs/day (AEC 1949); K-65 part of the AM-7 (AEC 1959)??
Ba sulfate cake (AJ-4)	Produced as part of the digestion process	1 mg Ra/ton, 0.1% U (AEC 1949)	6800 lbs/day total AJ-4 (AEC 1949); stored: 1.5K tons total unleached (wit 22 tons U), 8.7K tons total leached (with 7 tons U) (FUSRAP Undated a), i.e., 10.2K tons total (with 29 tons U (AEC 1959)
Sperry cake	Produced in Sperry press from aqueous tails from the ether extraction step; some later sent to Mound for extraction of Pa	Good source of Pa-231 (2 g/20 tons); per Salutsky (1956), this was a cake @ 50% solids, 1.6 g/cm^3 density, 0.1-0.3 ppm Pa-231	20 tons (AEC 1959)
Vitro residues (C-6)	Sent from Vitro (?) for storage at the airport		290 tons total, 1.9 tons U (AEC 1959)
Bomb furnace residue (C-Special)	This was from the Mallinckrodt and ElectroMet bomb furnaces and appears to be the same as the "C-liner slag" below. (AEC 1949)		
U-containing sands, precipitates (V-10)	Captured from the Japanese		60 tons total, 0.2 tons U (AEC 1959)
Dolomite liner (C-liner or C-liner slag)	Slag material, mainly dolomite, remaining after the derby slag was separated from the derby and the top (MgF_2) part of the slag was detached.	This remainder slag was produced until early 1953, when dolomite was replaced by recycle magnesium fluoride. Some was reprocessed to recover U from about 1953 on (AEC 1954e). U content: <2%.	7800 tons, 122 tons U (1959)
Interim Residue Plant Tailings (C-701)	Resulted from scalping the U content from the Mg fluoride slag from 1955 on; 701 apparently refers to Bldg 701		7K tons total, 144 tons U (AEC 1959)
30- and 55-gallon drums	Empty drums, stored as contaminated waste		55000 (AEC 1959)
Metal and alloy scrap	Stored as contaminated waste		3500 tons (AEC 1959)
Aqueous tails	From the ether extraction step		

NOTE: See the text for process details. See the keywords table (Table 5) for other code numbers and terms.

Table 5. Functional and process keywords and codes.

Plant	Keyword	Note
7	7E	7 East (Building 712), where the processing of AM-7 to extract thorium was done
7	7W	7 Warehouse? 7 West?
6	Acid	Acid addition: in ore digestion (nitric) or Pb-Ra precipitation (sulfuric)
6	AEC	Atomic Energy Commission
6	Airport	The former airport site later used for waste storage by the AEC
4,6,6E,7	Area M	Area mechanic
6	Assist LO	Assisting the lead operator, assistant lead operator
4	Ballard	Vertical turret lathe (manufactured by Ballard) used to scalp the dingot
6	Barium	Barium salt addition
6	Bird centrifuge	Solid-bowl centrifuge (manufactured by Bird) used to separate liquids and solids or heavier and lighter liquids in the digestion process
	Black oxide	U_3O_8
4, 6	Blender	Apparently ore in Plant 6; UF_4 + Mg in Plants 4, 6E; slag in Plant 6E
6	Boildown	A step between digestion and ether extraction
4	Bomb	Container for Mg-UF_4 in the metal reduction process
4, 6E	Bottom	Lower (furnace or F machine)
4	Box	Crucible holder (external assembly)
6E	Breakout	Removal of the derbies from the bombs
	Brown	Brown oxide, i.e., UO_2
----	Brushing	Same as chipping
6E	Burnout, burn	Crucible burnout (heating)
6	C-	When followed by a number, denotes material collected by a given dust collector or filter press or a type of scrap
6	C-3 (C-3A, etc.)	C-3 cell block operations (e.g., packing, centrifuging) related to dust or cake collection
	C-liner	Refers to the slag left after the bomb is opened and the derby removed
4, 6E	Cage	Scrap area
6E	Cap	Putting the top on the crucible assembly
6	Centrifuge, CEN, Cent, Furn Cntr	Also abbreviated CNF?
---	Change Room	Locker room, where clothes were issued by the porters
6E	Charge Room, Charging Room	Area where bomb was loaded ("charged")
4	Chipping	Removal of the slag from the derbies using a manual or power hammer
---	CL	Cleanup? Cell?
---	Cleanup	Generic for area or item cleanup: see associated process keyword (e.g., TA-7)
6	Cloth	Cloth (actual or metal) used to filter solids from liquid streams
6	CM	Cloth man?
4, 6	Continuous furnace, Cont furn	Unclear which furnace (probably the recast furnace) (6 should probably be 6E)
---	CROM	Cloth Room?
	Croppings	Chips or pieces taken off derbies, billets, and dingots
6E	Crucible, Cruc	Crucible and/or assembly (if 6 shown, probably a typo -- should be 6E)
6	D-	When followed by a number, denotes a given dust collector or filter press OR the material collected there or a type of scrap
7	D-30	Dust collector for the FMFL product (dust is the product)
6	DA	Dissociated (cracked) ammonia
6,6E, 7	Decontamination	Generic
	Deheading	Removing the lid of a drum, usually of ore
---	DEN	Probably same as DEV
---	DEV	Development, as in PRO (product) DEV and MET (metallurgical) DEV
6	Digest, DIG	Digestion process (ore dissolution by acid)
4	Dingot	Extra-large ingot produced instead of derbies and billets
6	Diuranate	Sodium diuranate (sodium salt), also called soluble feed
	DR	DX?
---	DX	Probably decontamination
	Egg	Piece of U metal in the shape of an egg, produced for external assays
6	Ether, Ether House, EH	Ether storage, handling for U solvent extraction process
---	Exp, Expansion, Exp Eng, Exp Off	Expansion -- apparently plant expansion or modification work (Expansion Office)
---	Expeditor, construction expeditor	Possibly related to Expansion (q.v.); apparently a coordinator or engineer
4, 6	Extra, Extra Man	Extra (floater) for a process or area (4, 6); possibly "extraction" (6)
6	Extraction	Extraction of U in ether extraction process
6	FE	Feed? Feinc?
6	Feed	Ore or other feed material; also could indicate main stream of process (i.e., not residue)
6	Feinc	String discharge rotary vacuum filter (manufactured by Feinc) used to separate solids from liquids
6	FH	Feed hopper?

Table 5 (Continued)

Plant	Keyword	Note
6	Filter press	Press type of filter for separating solids from liquids and leaving a dewatered cake
6E	F Machine	UF_4-to-Derby bomb filling ("F") machine: the top is used for the UF_4, Mg mixing, the bottom for filling the bomb
7	FMFL	Fluorinated MgF_2 liner, used as a low-hydrogen liner in dingot bombs
4, 6	FR, Furnace, Furn	Furnace Room
---	FTO	Fork truck operator
6	GLC	Gangue Lead Cake, i.e., the Pb-Ra cake
	Green	Green salt, i.e., UF_4
6	Gulping	Vacuum-sucking UO3 out of the pot it was produced in into drums
	H-20	??? (H_2O, i.e., water?)
7	Hapmann	Conveyor for loose material; typically discharges into a feed hopper
6	Hex, hex liquor	Uranyl nitrate hexahydrate in an aqueous solution
6E	Hoffman	Dust collector (manufactured by Hoffman)
All	House	Generic for dedicate additive handling and storage building or area
6	Instrument, Instru, Instr	Instrument Shop
4, 6E	Jolter, jolting	Jolter-filling machine in UF_4-to-U metal production, also the operator; the operation
6	K-65	K-65 (Ra-Pb) residues (in the ore-to-UO_3 process)
4	Label	Apparently labeling product containers
6	Laboratory, Lab, LAB	Unclear which lab is meant (Analytical, Shotgun, Ledoux, Research, etc.)
6	Laundry	One each for contaminated and uncontaminated clothing; Mallinckrodt had own contaminated laundry from at least 1948 on
6	Leach Oliver Cell	Leaching cell in the extraction process
6	Ledoux (LeDoux) Laboratory, LL	The raffinate and U assay laboratory in Plant 6
	LG	Lead gangue? See GLC
---	Lime	In the derby production process, lime or dolomite (i.e., calcium or dolomitic quicklime)
6	Liquor	Extracted liquid concentrate, usually after removal of undesirable materials as solids
4, 6	Loading, Load, Ld	Generic: see associated process keyword, e.g., TA-7
---	M	Apparently generic for maintenance
6	M-20 Process	???
---	MFG	Manufacturing: generic for production processes, as opposed to development
---	MGH	Same as MGX?
6	MGX, MgX, MGX Process	Unclear: Milling & Grinding × (uranium)? Manufacturing × (i.e., uranium products)?
4	Mag Room	Magnesium [Storage] Room
6, 6E	Maintenance, M, MNT	Maintenance, presumably process maintenance
---	ME	(1) Mechanic, mechanical work (often with location designation: e.g., ME Powerhouse) (2) Minor Elements (see MEP)
7	MEP	Minor Elements Production Facility (Building 712, where, e.g., AM-7 was processed to extract thorium)
7	MFL	MgF_2 liner (for use in dingot bombs)
---	Mtns	Maintenance
---	Mtrs	Typo for maintenance (Mtns)?
4	Muffle	Batch electric furnace used to reduce UO3 to UO2
6	NA, NAH	Nitric Acid House
6	Neutral	Neutralizing uranium solution (in acidification step?)
6	Niagara, Nia	Pressure leaf filter (manufactured by Niagara) used to separate solids from liquids
6	NOK(?)	HOK? $H_2$0-uranyl-nitrate-hexahydrate is called "OK hex liquor" (I) -- ???
6	Ntns	Typo for Mtns?
4	Office, OFF	Generic for office
6	Oliver	Filter press (manufactured by Oliver)
	Orange	Orange oxide, i.e., UO_3
6	Ore, Ore Room, OR	Ore processing, storage before use; also handling of residues
4, 6, 7	Pack, packing, packaging	Appears to be generic for packaging of uranium products
---	PEW	Powerhouse
---	PH	Probably Powerhouse
6E	PLO	Process Lead Operator
4	Pole, poling	Pushing the charge down into the dingot bomb with a steel rod
6	Pot, Pot Room	Denitration pot room (producing UO_3)
6E	Pouring	Part of the recast process, possibly the extraction of the stop to allow the molten metal to flow into the mold
6E	Pickling	Soaking derbies in acid to remove surface impurities (scale, oxides)
4, 6	Pilot Plant, PP	Plant 4's name (for metallurgical research and UF_4 work), after metal production moved to 6E; also, a slag recovery pilot plant in 6E and an unspecified pilot plant at 6
4	Pl.7	Plant 7 (apparently Plant 4 person detailed to Plant 7)

Table 5 (Continued)

Plant	Keyword	Note
6	Powerhouse	Power-generating or distribution area; may be same as Boiler House
6	Press	Filter press
6	Production Engineering, Prod Eng, Prod Off Eng	Generic for production/process engineering work
6	Production Office, PO	The MCW [Main] Production Office
6	Raffinate, Raff	Residues (mainly the cakes)
4,7	Reactor	Reaction vessel/heater in which UO_3 is converted to UO_2 with cracked ammonia
4	Recast, Recasting, Recast Furnace	Where derbies are recast into billets
4	Receiving & Shipping	Generic? The main Receiving & Shipping area was in Plant 6
6	Recovery, REC	Nitric oxide recovery (6); other types of recovery at other plants
6	REF	Refinery (i.e., Plant 6)
	Regulated	Refers to radiologically controlled areas, e.g., the regulated locker room versus the general (clean) locker room
6	Reverter (riverter?)	Unclear. Appears to be a type of pump or processor used in the recycling (reverting) of dust collector material, probably to convert UF_4 back into UO_2 or UO_3
7	RMF	Recycle magnesium fluoride (from bomb liner residue)
6E	Rockwell	Rockwell furnace (UF_4-Mg reduction to derby metal)
6	Rover	Extra pair of hands?
6E	Ruemelin	Exhaust hood (from the name of its manufacturer)
6E	RUNOUT	Could be a typo of "Burnout"
4	Salt bath	Bath in which a dingot is put to heat it
---	SAM, SAMPLING PLAN	Late 1950's: apparently general sampling but may have been a special project
---	Sample Room	Any of several sample rooms, e.g., the K-65 Sample Room
6	Sampler, Spl	Generic for sampling or work in a sample room
6E	Saw	Sawing off a portion of the metal billet as a sample
6E	Scalping	Mechanically slicing off slag from the external surfaces of a billet
6	Scrap	Usually, scrap left over after cleaning the derbies; miscellaneous scrap
7	Slag Processing Plant	Same as Slag Separation Plant
[4]	Slag Shed	Storage of the chipped-off bits of slag?
6E	Slye	Dust collector (manufactured by Slye)
6	Shotgun Laboratory	Shotgun sample preparation laboratory
6	Shotgun Samp Prep, SSP	Shotgun sample preparation (lab)
6	Soda salt	Sodium diuranate ($Na_2U_2O_7$, from Vitro or another site)
6	Soluble feed	Usually sodium diuranate (see Soda salt)
	Spec Anal Lab	Spectrographic Analysis Laboratory
6	Sperry	Filter press (manufactured by Sperry); also, the cake produced
6	Storeroom, SR	Generic; the main storeroom was in Plant 6
6	Stripper	Unclear; probably piece of equipment rather than operator name
6	T-3	Typo for C-3?
6	Thawhouse	Building where ore was thawed in winter before undrumming
6	THP	THP ether?
---	Tinner	Worker with tin and sheet metal (presumably in the tin shop)
4, 6E	TM	Top man, Top-off man, etc.
4, 6E	Top	Refers to the upper or top recasting furnace or the top F machine
4, 6E, 7	Topping	Refers to the operation of adding material to ensure proper fill
6	UNH	Uranyl nitrate hexahydrate
6E	Utility	Utility man or "floater" who filled in as needed
All	Warehouse, WH	Generic: various warehouses were used, with the main one in Plant 6 and later in Plant 7
6	Wash Oliver Cell	Wash cell in the extraction process
4	Weigh, check weigh	Generic: feed and products were weighed at various points
6?	Weighmaster	Apparently the "official" certifier of weights of uranium products and possibly ore
6E	Wilfey	Shaker table (manufactured by Wilfey) used to separate high-U slurry from low-U material

Codes:

Pitchblende ore	Q-11 (high-grade); AQ-4
Black oxide (U_3O_8)	162, 172, or 182; Chemical A (not of spec grade), K-35, C-55, or K-82; GY-3
Sodium salt ($Na_2U_2O_7$)	Chemical S
Magnesium uranate	MgX
Calcium uranate	CX
Miscellaneous feed	F
UNH (U nitrate hexahydrate)	SC-5
Orange oxide (UO_3)	QM-2; 264 or 272
Brown oxide (UO_2)	LF-9; 306

Brown oxide (UO_2)	YB-1 (when produced from UO_3 in the experimental continuous reactor)

Table 5 (Continued)

Codes: (Continued)

Green salt (UF_4)	TA-7
Green salt (UF_4)	TZ-7R (when produced from UO_2 in the experimental continuous reactor)
Derby (rough U metal form)	KB-2
Billet (finished U metal form)	YM-5
Uranium metal (generic)	Tubealloy
Magnesium metal	M
Magnetically fused dolomite	OZ
Uranium metal scrap	ST
"Radium element"	D
Plants 1 and 2	Project 89
Plant 4 green salt operation	Project 90
Plant 4 derby production	Project 91
Plant 4 recast operations	Project 92
The Mallinckrodt St. Louis site	Location E

Table 6. Thorium and daughter content of the AM-7 residue ("airport cake").

Material	Concentration, ppm	Mass, grams	Specific activity, Ci/g*	Total curies in ore	Notes
Ore	---	3.18×10^{8}	---	---	350 tons processed (see Table 4)
Th-230	3.8	1,208	0.0202	24.4	Concentration: Figgins and Kirby 1962
Th-232	29	9,222	1.09×10^{-07}	0.00176	Concentration: Figgins and Kirby 1962
*From Shleien 1992					
Isotope	**Half-life**		**Activity after 15 years, Ci**	**Percentage of original**	**Notes**
Th-230 Chain					
Th-230	77,000 years		2.44×10^{1}	~100%	
Ra-226	1,600 years		1.58×10^{-1}	0.65%	Ignoring Ra-226 decay
Rn-222	3.82 days		1.58×10^{-1}	0.65%	Ignoring Rn-222 decay
Po-218	3.05 minutes		1.58×10^{-1}	0.65%	Ignoring Po-218 decay
Pb-214	26.8 minutes				
Bi-214	19.9 minutes				
Po-214	164 microsecs				
Pb-210	22.3 years				
Bi-210	5.01 days				
Po-210	138 days				
Th-232 Chain					
Th-232	1.41 × 1010 years		1.01×10^{-3}	~100%	
Ra-228	5.75 years		8.46×10^{-4}	84%	Ignoring Ra-228 decay
Ac-228	6.13 hours		8.46×10^{-4}	84%	Ignoring Ac-228 decay
Th-228	1.91 years				
Ra-224	3.66 days				
Rn-220	55.6 seconds				
Po-216	0.15 seconds				
Pb-212	10.6 hours				
Bi-212	60.1 minutes				

Notes

Fifteen years is assumed to be the maximum decay time (1942-1957).

As the second part of the table shows, in 15 years secular equilibrium has not been reached for either the Th-230 chain or the Th-232 chain, although Th-232 is almost there. Thus only the activities of the first few members are shown.

Table 7. Airborne uranium particle size in process areas (Sanders 1975, Table 2).

Area and U type	Mass median diameter, µm	% Activity from <7 µm particles
Foundry		
Depleted U	2.8 ± 2.7	88
Enriched U	3.3 ± 2.2	
Enriched U	2.1 ± 2.0	
Machining		
Depleted U, milling dry	3.0 ± 2.3	---
Extruding		
Depleted U	3.2 ± 2.7	---

Table 8. Uranium dust concentrations by process, Plant 4, 1943–1952 (Mason 1958a, Table 2).

	Concentration, multiple of 70 Alpha dpm/m^3				Concentration, alpha dpm/m^3			
Year	UO_2 handling	UF_4 production	KB-2 production	YM-5 production	UO_2 handling	UF_4 production	KB-2 production	YM-5 production
1943	30	34	17	36	2,100	2,380	1,190	2,520
1944	30	34	17	36	2,100	2,380	1,190	2,520
1945	30	34	17	36	2,100	2,380	1,190	2,520
1946	30	34	17	36	2,100	2,380	1,190	2,520
1947	30	34	17	36	2,100	2,380	1,190	2,520
1948	30	34	17	36	2,100	2,380	1,190	2,520
1949	6	4	4	11	420	280	280	770
1950	4	2	3	11	280	140	210	770
1951	4	3			280	210		
1952	4	3			280	210		

Note: The last two processes were moved to Plant 6E in 1951, the first two to Plant 7 in 1953.

Table 9. Uranium dust concentrations by operation, Plant 6, 1946–1957 (Mason 1958a, Table 1).

				UO_3 production			UO_2 production		
Year	Warehousing	Ore grinding	Feed digest	Milling	Pot room	Packaging	Load	Unload	Packaging
1946	3	190	6	180	111		76	45	161
1947	3	195	6	180	111		76	45	161
1948	3	195	6	180	111		76	45	161
1949	1	5	1	180 0	111 60	10	20	10	5
1950	0.4	5	1	*	11 5	10	10	5	5
1951	0.5	5	2		2	1	6	3	5
1952	0.5	3	5		3	2	6	3	5
1953	0.9	2	0.7		3	2	**	**	**
1954	0.3	2	0.6		2	2			
1955	0.3	*	0.8		2	2			
1956	0.3		0.4		3	4			
1957	0.3		0.8		3	1			

Notes
Units are multiples of 70 alpha dpm/m^3.
The above operations were done in Building 51 (Plant 2) up to 1946, then moved to Plant 6.
Various significant improvements in dust control were made in Plant 6 in 1949-1950.
Milling of UO_3 was discontinued in 1950 (*).
UO_2 production work was transferred to Plant 7 in October 1952 (**); the rest remained at Plant 6.
All work was transferred to Weldon Spring in March 1957 and all remaining plants were closed.

Table 10. Uranium dust concentrations by process, Plant 6E, 1950–1958 (Mason 1958a, Table 4).

Year	KB-2 production			YM-5 production		
	Average	High	Source of high	Average	High	Source of high
1950	0.1	0.3	Charging	1.0	1.8	Crucible assembly
1951	0.3	0.8	Residue	1.1	1.8	Top furnace
1952	0.4	1.0	Residue	1.2	2.3	Burnout
1953	0.3	1.2	Charging	0.5	0.7	Top furnace
1954	0.5	3.0	Residue	0.9	1.7	Bottom furnace
1955	1.6	4.0	Residue	0.6	1.5	Bottom furnace
1956	0.4	1.6	Capping	0.5	0.6	Bottom furnace
1957	0.4	1.5	Burnout	0.7	1.2	Bottom furnace
1958	0.8	2.1	Breakout	1.2	2.1	Bottom furnace

Notes
Units are multiples of 70 alpha dpm/m^3.
KB-2 is the derby form and YM-5 the billet form of uranium metal.

Table 11. Uranium dust concentrations by process, Plant 7, 1952–1958 (Mason 1958a, Table 3).

Year	Average	High	Source of high
1952	0.5	1.6	UO_2 dumping
1953	0.4	1.7	Furnace operation,TA-7 packaging
1954	0.5	7.0	Sampling and cleanup
1955	0.3	1.1	UO_2 dumping
1956	0.4	0.8	UO_2 dumping
1957	0.3	0.8	UO_2 dumping
1958	0.5	1.4	TA-7 packaging

Notes
Units are multiples of 70 alpha dpm/m^3.
Operations were moved to Weldon Spring in 1958.

Table 12. Airborne uranium dust concentrations in Plant 4 Areas, 1948: AEC versus Mallinckrodt measured data (AEC 1949, Table 3).

Activity	Multiple of "Preferred Level"		ug/m^3		Adjusted to dpm/m^3	
	AEC	Mallinckrodt	AEC	Mallinckrodt	AEC	Mallinckrodt
LF-9 Loading						
Operator A	47.7	29.7	2.39E+03	1.49E+03	1.99E+03	1.24E+03
Operator B	47.7	30.7	2.39E+03	1.54E+03	1.99E+03	1.28E+03
Furnace Tending						
Operator A	7.5	5.7	3.75E+02	2.85E+02	3.13E+02	2.38E+02
Operator B	9.1	6.1	4.55E+02	3.05E+02	3.79E+02	2.54E+02
TA-7 Unloading						
Operator A						
- Manual	186	66.8	9.30E+03	3.34E+03	7.75E+03	2.78E+03
- Semi-mechanized		16.4		8.20E+02		6.83E+02
Operator B						
- Manual	186	57.2	9.30E+03	2.86E+03	7.75E+03	2.38E+03
- Semi-mechanized		20.7		1.04E+03		8.63E+02
TA-7 Mixing & Packing						
Operator A	63	13.1	3.15E+03	6.55E+02	2.63E+03	5.46E+02
Operator B	57	24.6	2.85E+03	1.23E+03	2.38E+03	1.03E+03
Bomb Charging	51	42.4	2.55E+03	2.12E+03	2.13E+03	1.77E+03
Topping	10.4	32.4	5.20E+02	1.62E+03	4.33E+02	1.35E+03
Jolting	51	7.5	2.55E+03	3.75E+02	2.13E+03	3.13E+02
Charge Firing	13.3	13.8	6.65E+02	6.90E+02	5.54E+02	5.75E+02
Derby Unloading						
Operator A	5	9.1	2.50E+02	4.55E+02	2.08E+02	3.79E+02
Operator B	5	18.7	2.50E+02	9.35E+02	2.08E+02	7.79E+02
Chipping	26.3	11.5	1.32E+03	5.75E+02	1.10E+03	4.79E+02
Slag Handling	1.6	2.2	8.00E+01	1.10E+02	6.67E+01	9.17E+01
Top Furnace Tending						
Operator A	61	36.5	3.05E+03	1.83E+03	2.54E+03	1.52E+03
Operator B	61	23.2	3.05E+03	1.16E+03	2.54E+03	9.67E+02
Bottom Furn Tending	73	59	3.65E+03	2.95E+03	3.04E+03	2.46E+03
Sawing	15.8	5.4	7.90E+02	2.70E+02	6.58E+02	2.25E+02
Cage Handling	2.7	52	1.35E+02	2.60E+03	1.13E+02	2.17E+03
Office	0.6	4.1	3.00E+01	2.05E+02	2.50E+01	1.71E+02
Shipping & Receiving	1.6	6.8	8.00E+01	3.40E+02	6.67E+01	2.83E+02
Mechanics	5	10.7	2.50E+02	5.35E+02	2.08E+02	4.46E+02
Carpenter	2	4.6	1.00E+02	2.30E+02	8.33E+01	1.92E+02
Porters	0.8	2.9	4.00E+01	1.45E+02	3.33E+01	1.21E+02
Guards	0.4	1.4	2.00E+01	7.00E+01	1.67E+01	5.83E+01

Notes

At the time of this report, AEC's "preferred level" for U dust in air, 50 µg/m^3, was based on an assumption of exposure 8 hrs/day, 6 days/week (AEC 1949). Columns 2 and 3 are based on this.

Columns 4 and 5 represent the values in Columns 2 and 3 respectively multiplied by 50 µg/m^3 and adjusted to 40 hours per week.

Table 13. Plant 4 measured daily weighted average exposure concentrations.

Occupation	Weighted average concentration, alpha dpm/m^3								
	5/56	11/53	3/53	6/50	10/49	9/48	5/48	AEC 1949	AEC 1951
Magnesium operator				35	70				
Lime blender				35	70				
Slag man				70	105	210	140		
Derby unloader				175	245	1,260	280		
Bomb topper				210	280	2,310	840		
Charge firing				140	350	980	910		
Derby chipper				140	350	910	1,890		
Jolter				70	140	490	3,500		
Bomb charger				210	490	3,010	3,640		
Green lead man				70	140				
Cleanup man				140	140				
Furnace tender				70	70	350	560		
Furnace box puller				35	140	560	630		
TA-7 Pilot Plant				980	175				
Brown loader				280	350	2,240	3,360		
Green packer				245	210	1,750	3,990		7,210
Green miller and mixer				70	140	980	4,690		
Green unloader				210	490	1,540	13,020		
Plant superintendent	7.3								
Technical supervisor	6.6								
Engineers	7.3	9.8	14						
Chief chemist	5.9								
Vacuum fusion chemist	39								
Vacuum fusion technician	59								
Microscopist	18.4								
Chemist	10								
Chemical technician	10	4.6	7						
Foreman	22.5	6.7	12	35	70	175			
Shift foremen	12.4			56	98	175			
Lead operator	25	8.2	19	119	63	---			
Dingot/bomb, slag grinding oper	85	33	64	X	X	X		X	
Furnace and saw man	17.5			X	X	X		X	
Casting furnace operator	10.8	110	480					5110	
Furnace operator (UF_4-derby?)				91	70	570			
HF operator				91	70	570			
UO_3 & Brown packer				217	322	2,730		4200	2,730
Green packing operator				196	315	7,210		4,000; 13,000	
Asst green packing operator				112	133	2,800			
Residue	27.4								
Ceramic	14.8								
Vertical lathe	28.5								
Forge press lead operator	22								
Forge press salt bath man	21.5								
Forge press manipulator (oper'r)	22.6								
Forge press operator	21.9								
Clerk	5							42	
Guard	7.1							28	
Porter	40	2.7	5.8					56	
Area mechanic	---	22	15	84	112	350		350	

Notes

Data from the surveys of 6/50, 10/49, 9/48, and 5/48 is from AEC 1950m; data from the surveys of 3/53 and 11/53 is from AEC 1954b; and data from the survey of 5/56 is from AEC 1956b. Other data is from the references given in the column heading.

Table 14. Plant 6 measured daily weighted average exposure concentrations.

Occupation	Weighted average concentration, alpha dpm/m^3								
	5/56	**5/54**	**10/53**	**1/53**	**1/52**	**1950**	**1949**	**1948***	**1948****
Digest area lead operator	6	60	36	62	140	84		686	
Digest operator	7.3	37	41	52	370	77		77	
U-con man #1	7.3								
U-con man #2	14								
Feinc operator	6.2	96	38	110	175	154		980	
Barium operator			38	130	144	126		1.8	
Feed operator	40.8	23	100	150	110	126		910	
C-3 wash filter operator		79	32	48	120	116		497	
C-3 adjustments operator			22	420	120				
C-3 centrifuge operator		42	630	52		140		567	
Ore Room operator			140	170	370	392	350	13,720	
Extraction area lead operator	34	5.4	4						
Ether House operator	11					40		46	
Ether House lead operator						66		154	
Sump recovery operator			8.5	100	76	126		273	
Raffinate operator	216	11	8	170	68	154		273	
Reduction area (furn room) lead oper'r	22	25	28	69	54	147		686	
QM-2 (Orange) packager	268	1,961	120	130	130				
LF-9 (Brown) packager						364		38,990	2,730
Nitric acid recovery operator	20	9.6	19	44	35	99		46	
Pot Room operator	234	113	45	190	100	336	770	7,770	
Metal dissolver #1	204								
Metal dissolver #2	21								
MGX operator		29	68	52	94				
Utility operator	88	129	94	97					
Furnace operator	12	33	55	96	150	1,400		24,780	
Miller (Mill Room)						X	X	12,600	
Pilot Plant group leader	7.5	6.9	3.1			105		245	
Pilot Plant lead operator	7.7	8.8	6.1	77	116	105		245	
Pilot Plant technician	1,940	9.2	6	77	116	105		245	
Production superintendent	7.7	8.8	56	25					
"Experimental continuous furnace"?						8,540		122	
Asst. production superintendent	18	21	26						
General foreman	14	18	30	50					
Foreman	17	21	29	58		52		161	
Technical supervisor	18	21	25	33		52		161	
Production Office clerk	9.1	12	18	17		27		161	
Production Office secretary	3.4	3.4				27		161	
Shift foreman	19	25	27	81	96				
Cloth & Training Grp Lead Operator			23	25					
Cloth operator		18	19	92		245		665	
Trainers						231		2,520	
Decontamination man	17	22	19	60	99				
Decontamination man	3.5	2.7	2.8	29					
Receiving clerk	5.2	19	4.5	10	99	28			
Cleanup man	22								
Production Research Lab personnel	3.7	2	5	13	30	12		84	
Ledoux Lab asst technician (raffinate)	15.2	8.1	39						
Ledoux Lab technician (raffinate)	12.9	8.1	39	140	420	91		189	
Ledoux Lab technician (K-65)	21	7.5	27	440	1,900	1,400		2,100	
Ledoux Lab technician (MgF_2)	21	7.5	27						
Shotgun Lab analyst	24.1	10	27	23	25	24		238	
Laboratory personnel	42	2.9	30	23	21				
MCW Laboratory west section						21		245	
MCW Laboratory east section						13		245	
Powder sample technician	56.5					217?		3,150	
Metal room sampler	420								
Outside sampling man	22.5								
Sample Room supervisor	41					245		448	
Laboratory Office personnel	42	2	5.6						
Truck operator	16	19	20	63	75				
Truck operator	20	19	20	63	75				
Warehouse foreman & Asst Foreman	4.2	2.9	6.2	17		70		161	

Table 14 (Continued)

Occupation	Weighted Average Concentration, alpha dpm/m^3								
	5/56	**5/54**	**10/53**	**1/53**	**1/52**	**1950**	**1949**	**1948***	**1948****
Warehouse man -- K-65 sampler			350	270	230	84		196	
Warehouse man	5.8	10	20	38	46	84		196	
Boiler House operator	9.3	7.3	7.5	8.9	2	36		44	
Laundry operator	6.2	19	11	19	4.5	13			
Porter	3.9	17	14			39			
General cleanup						39			
Change room						48			
Lunch room						5.6			
Clothes issue man	18	19	9.4	92					
Chief guard	1.7	14	16	14	1.8				
Security Office						6.3			
Guard	10	13	15	22	1.8	32			
Health Office - personnel (office)	1.6	6.7	15	14	0	11		14	
Health Office - personnel	8.1	11	15	14	0				
Health Office personnel (plant monitor/health surveyor)	10	15	15	14	0	46			
Health Office person'l (plant monitor)	15	16	15	14	0				
Medic	1.3	3.5	6.3						
Nurse		3.5	6.3	42	99				
Dispensary & Safety						56		175	
Instrument Shop technician	12	33	17	40	60	51		252	
Instrument Shop machinist	5.5	44	17	27	60	51		252	
Maintenance/mechanical supervisor	140	13	10	42	38	50			
Maintenance Office clerk	6.5	12	7.7	39					
Area mechanic	24	29	28						
Ore & Furnace Room AM						2.7		189	
Digest & feed AM						1.9		133	
Raffinate and C-3 AM						2.3		161	
Ether & NA House AM						1.1		77	
Welders, pipefitters, etc.						98		126	
Carpenters						66			
Stock Room (Storeroom) foreman	3.7	14	22	13	33	21			
Stock Room clerk	2.6	9	34	15	33	21			
AEC Office personnel		2.2	1.8	6.7	0	Non-det		33	
AEC Engineer		19	9.9	31	7				
MCW Office personnel	1.5	2	2.9	0.7	0			50	
MCW engineer	4.2	4.5	5.4	10	7	15			
MCW Office messenger	15	14	15	40					
MCW Office maintenance	7.5	12	20	10					
MCW Office construction expeditor			9.6	29					
Overall average weighted exposure	41	24	25	56	63				

Notes

The first set of 1948 data (Column 9) is mostly Mallinckrodt values from MCW 1949a (repeated in AEC 1949) and MCW 1950i, but AEC values from AEC 1949 are used where available (they are almost always higher). The second set of 1948 data is from AEC 1951 (it is the daily weighted average for packaging UO_2 at Plant 4, for comparison). The 1949 data is from MCW 1950i ; the 1950 data is from MCW 1950i and AEC 1953; the 1/52, 1/53, and 10/53 sets of survey data are from AEC 1954c; the 5/54 survey data is from AEC 1954d; and the 5/56 survey data is from AEC 1956c.

Table 15. Plant 6E measured daily weighted average exposure concentrations.

Occupation	Weighted average concentration, alpha dpm/m^3					
	7/56	3/55	6/54	11/53	4/53	10/52
Lime blender/Slag blender	5.7	11	13	8.9	19	8.9
Jolter	15	79	18	8.9	17	25
Utility operator	50	38	33	32	56	37
Top/Upper "F" machine operator	23	100	46	12	85	25
Bottom/Lower "F" machine operator	29	52	24	13	17	23
Top(ping)-off man	24	113	17	13	17	28
Reduction furnace operator	7.2	20	7.4	6.8	17	14
Breakout operator/man	23	42	28	23	42	25
Residue man	24	300	115	210	80	66
Reduction (KB-2) lead operator	21	36	26	24	36	45
Furnace loaders				23	16	15
Crucible loader	60	19	49	43	130	28
Burnout man	39	31	23	26	26	160
Crucible assembler	42	32	31	58	43	81
Upper/Top furnace operator/man	26	28	30	23	16	21
Bottom furnace operator/man	41	107	118	34	28	68
Saw operator/man	13	425	34	49	17	30
4th or cage saw man		38	21	66	94	17
Cage/cage grinding man	349	35	20	55	166	55
Billet grinder	668	425	34			
Brushing man		47				
Brushing man/chipper	19	2,110				
Recast furnace (YM-5) lead operator	71	30	47	21	19	49
Production machinist	7	11	7.5	10	17	380
Mechanic	73	36	23			
Millwright	14	36	23			
Maintenance man	27	36	23	53	26	45
Porter	15	23	12	19	8.8	42
Production clerk	9.5	14	7.8	18	13	13
Technical superintendent	4.4	24	15			
Technical/Chemical engineer	5.7	24	15	11	16	27
Shift foreman	12	31	23	17	17	44
Foreman/General foreman	6.1	27	19	12	13	20
Lift truck driver	8	22	17	14	15	30
Electrician		35	14	43	34	
Decontamination man	15	34	24	21	21	
Slag building operator	18	224	110			
Average of all personnel	44	113	30	33	43	55

Table 16. Plant 7 measured daily weighted average exposure concentrations.

	Weighted average concentration, alpha dpm/m^3						
Occupation	**7/56**	**3/55**	**6/54**	**11/53**	**4-5/53**	**10/52**	**9/51**
Utility operator/man	17	18	23	77	14	28	9
Area mechanic	12	12	6	11	63	14	37
Welder	14	13	7	10	14	14	
Porter	32	25	13	6	14	14	
Lift truck operator/driver	41	26	14	6	14	14	
HF operator	5.3	5	5	4	14	14	8
TA-7 hoisting operator	17	11	13	11	14	14	
Furnace operator	14	16	10	120	14	21	25
Sampler and cleanup man	9.1	8	8	530	42	28	
36' Level operator	19	6	5	20	14	14	
Panel board operator	16	30	16	7	21	21	
TA-7 packager	24	49	68	150	56	28	242
QM-2 dumper/hoister	56	74	48	42	63	112	107
Magnesium Room operator	4.5						
Foreman	15	16	7	6	14	21	28
Assistant foreman					8	21	22
Asst plant superintendent	32	70	7				
Technical supervisor	18	15	6				
Engineer		70	7	13	7	14	
Lead operator	30	17	9	12	14	21	38
Clerk/Record Clerk	20	32	8	6	14	21	
Decontamination/-ator	18	17	9	10	14	21	
Safety inspector		9	12	16	28		
Fire marshal		9	12	16			
Safety clerk		14	9	17			
Average for all personnel	19	19	13	57	22	21	

5/53 data includes screw-pulling operation

Table 17. Plant 7E measured daily weighted average exposure concentrations.

Occupation	**Weighted average concentration, alpha dpm/m^3, 3/55**
Ionium plant operator	0.06
Ionium plant lead operator	0.1
Overall average	0.07

Note that the ionium plant was the thorium processing plant, in operation from 1955-1957.

Table 18. Average and highest airborne dust concentrations in the laundry (alpha dpm/m^3) (Utnage 1958b, Table 2).

	Concentration	
	Average	**Worst**
Operation		
Load washer with coveralls	560	820
Load dryer with coveralls	50	140
Unload dryer with coveralls	20	70
Press white coveralls	40	55
Repair white coveralls	60	90
Sorting to wash	20	870
Weighted average by job		
Washer operator	50	
Presser	40	
Repairman	40	
Sorting and handling	30	140
Average general air in laundry	20	110

Notes

"Worst" measurements for sorting and handling were taken with no ventilation; "Worst" measurements for the general air case were taken with ventilation turned off for 4 hours.

"Average" measurements were taken with ventilation on. The worst "average" air in the general area case was found in the vicinity of handling and loading into the washer.

Table 19. Job titles and classifications, with function class codes and geometry factors.

Plant	Job Title or Classification	Class Code	Notes	Geometry Classification, %		
				AP	ROT	ISO
7	36' Level operator	D2	Subclassification of 7 Furnace operator (rotating jobs): mainly the UO_2-to-UF_4 reactor area	---	---	---
6E	4th saw man	F	Mostly same as Saw man	90	10	
6	AEC engineer	Z1	Spent time in Plants 4, 6, 6E, and 7 but office was in 6	10	90	
6	AEC Office personnel	Z2	Spent time only in AEC office in Plant 6		100	
4,6,6E,7	Area mechanic	P	May have worked in all buildings, not dedicated to one	50	50	
6E	Asst foreman	N3	See Shift foreman	50	50	
7	Asst plant superintendent	N1	May have been in charge of only Plant 7 or of the whole site	10	90	
6	Asst production superintendent	N2	Assumed to have spent time in Plants 6, 6E, and 7 production areas as well as Plant 6 offices, as the production superintendent did	50	50	
6	Asst warehouse foreman	S2	Worked in the U products warehouse, apparently	25	75	
6	Barium operator	B4	Worked in the barium salt addition phase of digestion	50	25	25
6E	Billet grinder	F7	Cleaned and finished billets after recasting and before shipping	90	10	
4,6E?	Blender	E1, G1	See Lime blender	50	50	
6	Boiler House operator	Q1	Presumably worked to provide steam for the boildown processes		100	
4	Bomb charger	E1	Loaded MgF_2, UO_2 into bomb and sealed it; may have blended them	75	25	
4	Bomb makeup operator	E1, G1	Blended UF_4, Mg; charged bomb; dumped out dust collectors	75	25	
4	Bomb makeup/deslagging (slag grinding) operator	E1, G1, I1	Performed combined functions of Bomb makeup operator and Slag grinding operator	75	25	
6E	Bottom "F" machine operator	E3	Charged bomb (using F machine): UF_4-Mg mixture, Mg	75		25
4,6E	Bottom furnace operator/man	F5	Removed assembly from recast furnace, removed mold, put in new assembly	75	25	
6E	Breakout operator/man	E7	Removed (broke out) derby from bomb	75	25	
6	Brown furnace operator/unloader/ packager		See UO2 operator/unloader/packager	75	25	
6E	Brushing man	E8	Same as Chipper	75	25	
6E	Burnout man	F5	Removed broken crucible, knocking lid off	80	20	
6	C-3 adjustments operator	B5	Cleaned wash precipitate filter press; other duties	50	25	25
6	C-3 centrifuge operator	B6	Operated and "plowed off" Bird(?) centrifuge (digestion process)	50	25	25
6	C-3 wash filter operator	B8	Operated and cleaned the wash precipitate filter press	50	25	25
6E	Cage grinding man	F7	Mostly same as Saw man	90	10	
4,6E	Cage operator/man	F7	Cleaned and finished billets after recasting; handled scrap in cage	90	10	
6E	Cage saw man	F7	Mostly same as Saw man	90	10	
4	Carpenter	Q2	May have worked in all buildings, not dedicated to one	25	50	25
4	Casting operator/man	F2	Operated the billet casting furnace	75	25	
6	C. Eng	O1	See Chemical engineer	25	75	
4	Ceramic (technician?)	L4	Split time: ceramic lab (Ceramic Pilot Plant), Production Research Lab	50	50	
4	Charger	E1	Same as Bomb charger	75	25	
4	Charge firing (man)	E2	Furnace operator for bomb furnace	75	25	
6E	Chemical engineer	O1	Worked in production aspects; had production area access	25	75	
4	Chemical technician	L3	Did chemical analyses in Analytical Lab; possibly some assays	90	10	
4	Chemist	L3	Did chemical analyses in Analytical Lab; possibly some assays	90	10	
4	Chief chemist	L3	Did chemical analyses in Analytical Lab; possibly some assays	90	10	
6	Chief guard	Y1	Spent time in Plants 4, 6, 6E, and 7 but base was in Plant 6		100	
4,6E	Chipper	E8	Deslagged and cleaned derbies (and dingots?)	75	25	
4,6	Cleanup man	B12, E9	Miscellaneous cleanup activities	50	50	
4,6E,7	Clerk	X1	Plant 7 clerk worked in Plant 6E as well as inventorying in the Plant 7 production area; Plant 4 clerk may have been same person(s)		100	
6	Cloth operator/man	B3	Cut and replaced filter cloth for Feinc and similar filters	50	25	25
6	Cloth & Training Group lead operator	B3	Apparently dual position: coordinated cloth ops, headed Training Grp	10	90	
6	Clothes issue man	U2	Issued work and protective clothing in the locker rooms		100	

Table 19 (Continued)

Plant	Job Title or Classification	Class Code	Notes	Geometry Classification, %		
6E	Crucible assembler	F1	Assembled crucible and mold assembly in billet production process	75		25
6E	Crucible loader	F3	Loaded the crucible assembly into the recast furnace	75		25
6,6E,7	Decontamination man	T	Did decontamination in all plants, on boxcars, in Plant 6 Decon Room	50	25	25
7	Decontaminator	T	Same as Decontamination man	50	25	25
6E	Derby chipper	E8	Same as Chipper	75	25	
4	Derby unloader	E6	Unloaded bomb from furnace	75	25	
6	Digest area lead operator	B1	Worked on the digestion process (up to extraction)	50	25	25
6	Digest operator	B1	Worked on the digestion process (up to extraction)	50	25	25
4	Dingot operator	G2	Prepared, loaded, removed dingot bomb; probably operated furnace	50	25	25
6	Dispensary (personnel)	W	Medical-pharmaceutical personnel; no prod area access assumed		100	
6E	Electrician	P2	May have worked in all buildings, not dedicated to one	25	50	25
4,6E,7	Engineer	O1	Assumed to be the process engineer assigned to individual plant; may have worked in all; had production area access	25	75	
6	Ether House operator	Q1	Worked in the ether house (operating tanks, valves, etc.)	50	50	
6	Experim'rntal Continuous Furnace	D	Pilot Plant project? May have been pilot for eventual Plant 7 use	25	50	25
6	Extraction area lead operator	B7	Worked on the extraction process (up through UO3 production?)	50	25	25
6E	Extra man	*	Presumably a "floating" worker (cf. Utility man)	50	50	
6E	F (machine) charger	E3	Loaded MgF_2, UO_2 into bomb and sealed it; may have blended them	75		25
6E	F machine operator	E3	Charged bomb (using F machine): UF_4-Mg mixture, Mg	75		25
6	Feed operator	B1, B2	Loaded black oxide and other feeds for digestion; washed out feed Niagara; may have handled other aspects of the ore-to-UO_3 process	50	25	25
6	Feinc operator	B2, B5	Operated Feinc filter; cleaned out cake; washed out feed Niagara	50	25	25
7	Filter operator	I3	Operated solids-removal(?) filters in Slag Separation Plant (Bldg 701)	50	50	
7	Fire Marshall	V1	Did inspections in Plants 4, 6, 6E, and 7, but base was in Plant 6		90	10
4,6,6E,7	Foreman	N3	Apparently dedicated to individual plant, but may have worked in more	50	50	
4	Forge press lead operator	G5	Operated the forge press in dingot finishing	75		25
4	Forge press manipulator	G5	Same as Forge press operator	75		25
4	Forge press operator	G5	Operated the forge press in dingot finishing	75		25
4	Forge press salt bath man	G4	Operated the salt bath segment of dingot finishing	75	25	
4,6	Fork truck operator/driver	Q2	Same as lift truck driver	25	75	
4	Furnace and saw man	E5, F7	Divided duties: see Furnace operator and Saw man	75	25	
4,6E	Furnace loader	F3	Loaded bomb or crucible assembly into furnace, depending on plant	75		25
4,6E	Furnace operator	F4	Operated recasting (billet) furnace	75		25
6	Furnace operator	C2	Operated the UO3-to-UO2 (Rockwell) furnace	75	25	
7	Furnace operator	D2, H2, D5	Job (Plant 7) rotated 36' Level, Panel Board, and Sampler & Cleanup tasks: see individual job titles	75	10	15
4	Furnace puller	F4	Unloaded UO_2-to-UF_4 furnace?	75	10	15
4	Furnace tender	E5	Tended UO_2-to-UF_4 furnace	75		25
6E	Furnace unloader	E6	Unloaded bombs from furnace, cleaned out residue(?)	75		25
6,6E,7	General foreman	N3	UF_4 production (for Plant 6E); or may have spent time in all plants	50	50	
6E	Graphite shop personnel	R1	Assumed to be doing only clean work manufacturing graphite molds		100	
7	Green packager	D6	Packaged UF_4 (green salt)	75	25	
4,6	Guard	Y1	Spent time in Plants 4, 6, 6E, and 7 but base was in 6		75	25
6	Health Office -- office personnet	V5	Assumed to spend all time in Health Office		100	
6	Health Office -- other personnel	V2	Spent time in Plants 4, 6, 6E, and 7 but base in 6; assume no production area access		100	
6	Health Office -- plant monitor	V3	Spent time in Plants 4, 6, 6E, 7 but base in 6; production area access	50	50	
6	Health Office -- health surveyor	V4	Spent time in Plants 4, 6, 6E, 7 but base in 6; production area access	50	50	
4,7	HF operator	B6, J1, Q1	Spent some time at Bird centrifuge (7), in recovery areas (7), as well as in providing HF for the hydrofluorination process (UO_2-to-UF_4)(4,7)	10	90	
7	Hoisting (slag) operator	I1	Worked in the Slag Separation Plant (Bldg 701)	50		50
6	Instrument Shop machinist	P3	Worked only in Instrument Shop; some equipment contaminated	10	90	

Table 19 (Continued)

Plant	Job Title or Classification	Class Code	Notes	Geometry Classification, %		
6	Instrument Shop technician	P2	Spent time in Plants 4, 6, 6E and 7 but base in 6 (Instrument Shop); production area access	25	75	
7E	Ionium plant lead operator	K	Th-230 processing (mostly operating chemical tanks and filters)	75	25	
7E	Ionium plant operator	K	Th-230 processing (mostly operating chemical tanks and filters)	75	25	
4,6E	Jolter	E2	"Jolted" (air hammer?) bomb liner, other material to compress, remove	75	25	
6	K-65 sampler	S2	See Warehouse man: K-65 sampler	90	10	
4,6E	KB-2 lead operator	E	Handled all aspects of derby (KB-2 production)	75	15	10
6	Laboratory Office personnel	L3	Worked in the Analytical Lab (Building 102)		100	
6	Laboratory personnel	L3	Worked in the Analytical Lab (Building 102)	90	10	
6	Laundry lead operator	U1	Handled operations at the laundry (incl contaminated items)	10	90	
6	Laundry operator	U1	Laundered work and protective clothing (incl contaminated items)	10	90	
4,6,6E,7	Lead Operator	*	Generic: see specific titles; otherwise, (default) geometry factors at right may be used	75	25	
6	Ledoux Lab asst tech (raffinate)	L1	Worked in the Ledoux Lab pulverizing, prepping, assaying raffinate	90	10	
6	Ledoux Lab technician (raffinate)	L1	Worked in the Ledoux Lab pulverizing, prepping, assaying raffinate	90	10	
6	Ledoux Lab technician (K-65)	L1	Worked in the Ledoux Lab assaying K-65 residue	90	10	
6	Ledoux Lab technician (MgF_2)	L1	Worked in the Ledoux Lab assaying MgF_2, incl recycle MgF_2	90	10	
4	LF-9 (furnace) loader	D1	See Furnace loader, Furnace operator for Plant 4 (UO_2-to-UF_4)	75	25	
6	LF-9 unloader/packager		See UO_2 operator/unloader/packager	75	25	
6E,7	Lift truck driver (operator)	Q2	Drove lift truck, handling miscellaneous materials, possibly at all plants	25	75	
4,6E	Lime blender	E1	Charge blender for derby production	50	50	
4	Magnesium operator	Q1	Handled magnesium storage and disbursal; limited exposure potential?	75	25	
7	Magnesium Room operator	Q1	Handled magnesium storage and disbursal; limited exposure potential?		100	
6E	Maintenance man	P2	May have worked in all buildings; assume production area access	50	50	
6	Maintenance Office clerk	R3	Worked only in Maintenance Office		100	
6	Maintenance supervisor	N3	Spent time in Plants 4, 6, 6E and 7 but base was in 6 (same person?)	25	75	
6	MCW engineer	O1	Spent time in Plants 4, 6, 6E and 7 but base was in 6	10	90	
6	MCW Lab (personnel)	L3?	This lab was not the Ledoux, Shotgun, or Research Labs, which were listed separately in the records; perhaps the Analytical Lab	25	75	
6	MCW Office construction expeditor	X2	Spent time in Plants 4, 6, 6E, and 7, but probably only in office and construction areas		100	
6	MCW Office maintenance	X2	Spent time in Plants 4, 6, 6E, and 7, but apparently only in office areas		100	
6	MCW Office messenger	X2	Spent time in Plants 4, 6, 6E, and 7, but probably only in office areas		100	
6	MCW Office personnel	X2	Spent time only in MCW offices in Plant 6 (Bldg 112?)		100	
4,6,6E	Mechanic	P1	See Area mechanic	50	50	
6	Mechanic supervisor	N3	See Maintenance supervisor	50	50	
6	Medic	W	Worked in dispensary presumably, but may have gone into production areas on occasion		100	
6	Metal dissolver (#1, #2)	I6	Dissolved scrap U metal in acid for recycling as feed? Also spent up to half time in Pot Room	75	25	
6	Metal room sampler	I7	Sampled scrap and other metal for U or content?	75	25	
6	MGX operator	B	Unclear -- may be Milling & Grinding uranium (operator) since U=X	25	50	25
4	Microscopist	L5	Worked full-time in the Microscopy Room, probably on U specimens		100	
4, 6	Miller	D4	Performed the UF4 pulverizing (4)? Milled UO_3 (orange oxide)(6)	50	50	
6E	Millwright	N3	May have worked in all buildings, not dedicated to one	25	50	25
6	Nitric acid recovery operator	P2	Worked in the nitric acid recovery area (several buildings)	50	25	25
6	Nurse	W	Worked in dispensary presumably, but may have gone into production areas on occasion		100	
4,6E	Office employees	X2	Assume they are Plants 4 and 6E production(?) office-only personnel		100	
6	Ore Room operator	A1, A2, H4	Handled ore, residue: storage, lidding, delidding, cleaning drums	70	20	10
6	Outside sampling man	H2, H4	Sampled dust collectors; sampled drums (incl. opening and sealing)	50	50	
7	Panel board operator	H2	Subclassification of 7 Furnace operator (rotating jobs): vacuuming C-3 into reverter, sampling D-30 material, replacing D-30 drums, work at panel board area including reverter operation	---	---	---
6	Pilot Plant engineer	M2	Participated in experimental extraction processes and like activities	25	75	
6	Pilot Plant group leader	M2	Participated in experimental extraction processes and like activities	75	25	
6	Pilot Plant lead operator	M2	Participated in experimental extraction processes and like activities	75	25	

Table 19 (Continued)

Plant	Job Title or Classification	Class Code	Notes	Geometry Classification, %		
6	Pilot Plant technician	M2	Unclear what activities this Pilot Plant was carrying on	75	25	
6	Pipefitter	N3	May have worked in all buildings, not dedicated to one	50		50
4	Plant superintendent	N1	May have been in charge of only Plant 4 or of the whole site	10	90	
4,6,6E,7	Porter	R2	Worked in a janitorial capacity, likely in all buildings or rotating among them; entered only office areas, not production areas		100	
6	Pot Room operator	B9	Worked in the denitration (UO_2-to-UF_4) pot room	50	25	25
6	Powder sample technician	L5	Assume mainly did sampling and worked with small samples	75	25	
6E	Production clerk	X1	Kept records and did inventories; assumed to spend some time in production area		100	
6E	Production machinist	R1	Spent all time in graphite shop machining molds and the like		100	
6	Production Office clerk	X1	Kept records and did inventories; assumed to spend some time in production area		100	
6	Production Office secretary	X2	Assumed spent all time in office		100	
6	Production Research Lab personnel	L4	Worked in the Production Research Lab in Building	90	10	
6	Production superintendent	N2	Spent time in Plants 6, 6E, and 7 production areas and Plant 6 offices	50	50	
7	QM-2 dumper	C1	Loaded UO_3 into trays for the UO_3-to-UF_4 conversion	75	15	10
7	QM-2 hoister	C1	Same as QM-2 dumper	75	15	10
6	QM-2 loader		See UO_3 loader	75	25	
6	QM-2 (orange) packager	B11	"Gulped" (vacuum-extracted) UO_3 out of the pot and into drums; weighing and making up (weight) in drums, emptying dust collectors	75	15	10
6	Raffinate operator	B5, B9	Handled the various residues from the filters (drummed, sampled); spent up to half time in Pot Room	75	25	
6E	Recast furnace lead operator	F4	Operated the billet casting furnace	50		50
6	Receiving clerk	S1	Recorded and inventoried incoming shipments of ore and U products	50	50	
7	Record clerk (A, B)	X2	Kept records of receipts, production, and shipments; some entry into production areas and outside areas for inventory and like purposes		100	
6	Reduction (area) lead operator	C2	Operated UO_2 (Rockwell) furnace; assumed to load UO_3, unload UO_2	75	25	
6E	Reduction (area) lead operator	E5	Operated the bomb (UF_4-to-U metal) furnace	50	25	25
6E	Reduction furnace operator	E5	Operated the bomb (UF_4-to-U metal) furnace	50	25	25
4,6E	Residue man	H2, H3	Changed derby chip drums and Hoffman and Mikro dust collectors; cleaned residue from the plate and frame press; picked out KB-2	75		25
7	Safety clerk	V6	Worked full-time in the Safety Office		100	
7	Safety inspector	V5	Did inspections in Plants 4, 6, 6E, and 7 (production area access)	10	80	10
4	Salt bath man	G4	Same as Forge press salt bath man	75	25	
7	Sampler and cleanup man	D5	Subclassification of 7 Furnace operator (rotating jobs): sampling UF_4, cleanup of furnace platforms	---	---	---
6	Sample Room supervisor	A2, A4?	Supervisor operations in the Sample Room (probably in Bldg 111)	75	25	
4,6E	Saw operator/man	F7	Removed billet from quench tank; ground, sawed, and weighed it	90	10	
6	Security office (personnel)	Y2	Assumed to be other than guards (e.g., clerical)		100	
6,6E	Shift foreman	N3	Assumed to be generic, although may have covered several plants; default geometry factors at right may be used	50	50	
4	Shipping & Receiving (personnel)	S1	Handled the receipt and shipment of U products	50	50	
6	Shotgun Lab analyst	L2	Worked in Shotgun (sample assay) Lab, first in Bldg 55 in Plant 2, then Bldg 108 in Plant 6, then Bldg 102(?) of Plant 6	90	10	
6E	Slag blender	I5	Blended C-liner and other slag from Plants 4 and 6 for use in bombs	75	25	
6E	Slag building operator	I3	Ground C-liner and other slag, sorted it via shaker tables, drummed it	75	25	
4	Slag man, slag grinding operator	E8	Mostly the same as Chipper	75	25	
6	Soluble feed operator	B1	Loaded soda salt ("diuranate") at appropriate point in digestion process; see also Feed operator	75		25
6	Stockroom clerk	S1	Stockroom possibly in Bldg 112. Spent time in Receiving (Bldg 101)		100	
6	Stockroom foreman	S1	Stockroom possibly in Bldg 112. Spent time in Receiving (Bldg 101)		100	
6	Sump recovery operator	J2	Worked on U recovery from sump fluids	25	50	25
6E	Supervisor	O2	Probably same as Technical supervisor	50	50	
7	TA-7 hoisting operator (hoister)	D1	Hoisted and loaded UO2 into reactor for conversion to UF_4 (TA-7)	25	50	25

Table 19 (Continued)

Plant	Job Title or Classification	Class Code	Notes	Geometry Classification, %		
4,7	TA-7 packager	D6	Packaged UF_4 (green salt)	75	25	
4	TA-7 Pilot Plant (personnel)	D	Assumed to be technicians and operators producing UF_4 (green salt)	50	50	
4	TA-7 unloader (operator)	D3	Unloaded UF_4 (green salt) from hydrofluorination reactor	50	50	
7	Tables operator	I3	Worked in the Slag Separation Plant (701) operating shaker tables	25	75	
6E	Technical engineer	O1	Same as Chemical engineer or (Process) Engineer	25	75	
6E	Technical superintendent	O2	May have spent time in all the plants	25	75	
4,6,6E,7	Technical supervisor	O2	Unclear what duties were; probable frequent production area access	50	50	
4	Top cleaner	F2	Cleaned top furnace in billet (YM-5) production; not Top seat man	75	25	
6E	Top "F" machine operator	E3	Charged bomb (using F machine): UF_4-Mg mixture, Mg	75		25
6E	Top furnace operator/man	F4, F5	Operated recasting (billet) furnace, removed crucible parts	50		50
6E	Top-off operator/man	E3	"Topped off" bomb with slag, bolted on lid	75	25	
4	Topper	E3	Same as Top-off operator?	75	25	
4	Top seat man	E3	Involved in billet production, furnace area; same as Top-off operator?	75	25	
6	Trainer	B2, B3	Duties not clear. Assumed to train operators, especially in filter work	10	90	
6	Truck operator/driver	Q3	Spent time in Plants 6, 6E, and 7 areas; radiation most likely from the back in hauling, the front in loading: * 50 AP, 25 PA, 25 ROT	*		
6	UO_2 (furnace) operator		Operated the UO_3-to-UO_2 (Rockwell) furnace	75	25	
6	UO_2 unloader/packager		Unloaded UO_2 from the Rockwell furnace, packaged it	75	25	
4	UO_3 & brown packer		Loaded UO_2 into Rockwell furnace; unclear regarding UO_2	75	25	
6	UO_3 loader		Loader UO_3 onto trays and into the Rockwell furnace (may have been collateral duty of the UO_2 furnace operator)	75	25	
6E	Upper furnace man	F4	Same as top furnace man	50		50
6	U-con man (#1, #2)	I3	Handled U-containing slurry from Slag Sep Plant that went to Plant 6	50	25	25
7	Utility operator/man	*	Worked on various production jobs	50	25	25
6,6E	Utility operator	*	Average of all production jobs for the respective plant	75	25	
4	Vacuum fusion chemist	L5	Worked in office and vacuum fusion area; did some hands-on U work	90	10	
4	Vacuum fusion technician	L5	Worked in office and vacuum fusion area; did some hands-on U work	90	10	
4	Vertical lathe (operator)	G6	Scalped dingot after casting and before forge-pressing	75		25
6	Warehouse foreman	S3	Handled storage of ore and U products	25	75	
6	Warehouse man: K-65 sampler	S2	New job, 1953: sampled K-65 residue, plus typical warehouse duties	90	10	
6	Warehouse man (other)	S3	Handled storage of ore and U products	25	75	
6	Weighmaster	A2, S4?	Duties not clear. Assumed to perform or approve ore, K-65 weighings	25	75	
6,7	Welder	N3	May have worked in all buildings, not dedicated to one	10	90	
6E	YM-5 lead operator	F	Worked on billet (YM-5) casting	80	20	

*Note
Since these classifications are mostly based on later records (after the UO_3-to-UF_4 direct process was established at Plant 7), UO_2 (brown oxide, LF-9) unloading and packaging classifications and UO_3 (orange oxide, QM-2) milling and loading classifications have been added for Plant 6.

1

1 Table 20. Relationship between major processes and job functions.

General code	Operational/functional area	Item code											
		1	2	3	4	5	6	7	8	9	10	11	12
A	Ore handling	Thaw, delid, clean	Weigh, sample	Milling									
B	Digestion to UO_3	Feed loading and operations	Feinc/Niagara operations	Cloth	Barium addition	Residue removal	Centrifuge	Extraction	Postextraction filter operation	Pot Room	UO_3 unloading	UO_3 packaging	Clean-up
C	UO_3 to UO_2	UO_3: loading	Furnace ops	UO_2: unloading	UO_2:weighing, sample, pkg'g								
D	UO_2-UF_4, UO_3-UF_4	UO_2 loading	Furnace (reactor) opers	UF_4 unloading	UF_4:milling, pulverizing	UF_4:weigh, sample	UF4 packaging	UO_3 loading (UO_3-UF_4)					
E	UF_4 to Derbies	UF_4+Mg mixing	Charge jolting	Bomb:chrg, top, seal	Bomb loading	Furnace ops	Bomb unloading	Derby removal	Chipping, grind, pickling	Clean-up			
F	Derbies to Billets	Crucible assembly	Furnace preparation	Crucible loading	Furnace ops	Crucible unloading	Billet removal	Billet: crop, grind, saw	Billet: package, weigh				
G	UF_4 to Dingots	UF_4+Mg mixing	Mold handling, furnace oper	Chipping	Salt bathing	Forging	Scalping						
H	Residue/Waste handling	Cake ops (exc removall)	Dust: collect, sample	Slag, chip handling	Store, sample								
I	U recovery operations	Slag loading	Slag grinding	Slag processing	Slag filter operations	Slag blending	Metal dissolving	Metal Room sampling					
J	Other recovery ops	Nitr ox recovery	Sump recovery										
K	Th processing	All phases											
L	Laboratory ops	Ledoux	Shotgun	Analytical	Prod Resrch	Other							
M	Process/metallurgical devel	Pilot Plant 4	Pilot Plant 6										
N	Process mgt & supervision	Infrequent PAA	Frequent PAA	Routine PAA									
O	Tech. supervision & supp	Engineer	Tech. supervisor										
P	Process, area maintenance	Mechanic	Other PAA craft, technicians	Contaminated equip shop									
Q	Process support	Supply facilities	Fork/Lift driver	Truck driver	PAA constr.								
R	Nonprocess maintenance, support	Graphite Shop	Clean maint/ support	Office only									
S	Ship'g & Rec'g/Warehouse	Ship & Rec	Warehs - –K-65	WH - Other	Weighing								
T	Decontamination												
U	Laundry/Clothes handling	Laundry	Clothes issuing										
V	Safety & Health	Fire marshal	Health-other	Plant monitor	Health, med	Safety insp	Office only						
W	Medical												
X	Office personnel	PAA Clerk	Office only										
Y	Security	Guard/chief	Office only			Note: PAA stands for production area access, indicating potential for exposure.							
Z	AEC	Engineer	Office only										
*	Generic -- ID process												

Table 21. Uranium dust daily weighted average exposure levels, Plant 4.

Job title	Airborne dust exposures, alpha dpm/m^3								
	Oct 1942 - 1946	1947	1948 - 1949	1950	1951	1952 - 1953	1954 - 1955	1956	1957
Mechanic/Area mechanic	350	350	350	84	15	15	22	22	X
Blender/Bomb charger/ Charger/Bomb makeup/ Dingot operator/Slag grinding operator	3,010	3,010	3,010	210	64	64	33	85	X
Cage operator/man	190	190	190	190	X	X	X	X	X
Carpenter/Other craft	140	140	140	84	15	15	22	22	X
Casting operator/Furnace operator/Top seat man	5,100	910	980	140	480	480	110	11	X
Lab: ceramics/microscopy	X?	X?	X?	X?	18	18	18	18	X
Charge firing (man)	931	910	980	140	X	X	X	X	X
Chemist/Chief chemist/Chemical technician	40	40	40	40	7	7	10	10	X
Chipper/Cleanup man/Saw operator/man	1,890	1,890	910	140	140	140	140	140	140
Derby unloader	350	280	1,260	175	X	X	X	X	X
Foreman/Shift foreman/Engineer/Technical supervisor	175	175	175	56	12	12	10	23	X
Forge press operator/lead operator/manipulator*	X	X	X	X	X	23	23	23	X
Furnace and saw man	X	X	X	X	18	18	18	18	X
Furnace loader (UF4-derby)	3,360	3,360	2,240	280	X	X	X	X	X
Furnace tender	560	560	350	70	X	X	X	X	X
Guard/Chief guard	28	28	28	28	28	5.8	2.7	7.1	X
HF (fluorination) operator	570	570	570	70	X	X	X	X	X
Jolter	3,500	3,500	490	70	X	X	X	X	X
KB-2/YM-5/Dingot lead operator/Furnace puller	931	630	560	35	19	19	8.2	19	X
UO2/LF-9 loader/packer	4,200	3,360	2,240	280	X	X	X	X	X
Lime blender/Magnesium operator	70	70	70	35	X	X	X	X	X
Miller-mixer (UF4/TA-7)/Top cleaner	4,690	4,690	980	70	X	X	X	X	X
Office: Plant superintendent/Clerk/Other	42	42	42	42	42	5.8	2.7	7.3	X
Porter	112	112	112	56	56	5.8	2.7	40	X
Residue man/Salt bath man/Vertical lathe operator	X	X	X	X	X	X	28	28	X
Shipping & Receiving	126	126	126	126	15	15	22	22	X
Slag man/Slag grinding operator	140	140	210	70	X	X	X	X	X
TA-7 packager	7,210	7,210	7,210	245	X	X	X	X	X
TA-7 unloader (operator)	13,000	13,000	1,540	210	X	X	X	X	X
Topper	840	840	2,310	210	X	X	X	X	X
Vacuum fusion*: chemist/technician	X?	X?	X?	X?	X?	59	59	59	X

Notes

An “X” indicates that the job title did not exist during the indicated period. An “X?” indicates that it is uncertain if the job title existed, i.e., it is not certain when that job began.

* Work started in 1953

Table 22. Uranium dust daily weighted average exposure levels, Plant 6.

Job title	Airborne dust exposures, alpha dpm/m3							
	1946 - 1948	1949	1950	1951	1952	1953	1954	1955 - 1957
AEC engineer	X?	X?	X?	7	31	9.9	19	19
Barium operator	1.8	1.8	126	144	130	38	X	X
C-3 centrifuge/wash filter/adjustments operator	567	567	140	140	420	630	79	79
Cleanup man/utility operator	X	X	X?	97	97	94	129	88
Cloth operator	665	665	245	245	92	19	18	18
Cloth & Training Group lead operator/trainer	2,520	2,520	231	231	23	25	18	18
Clothes issue man	92	92	92	92	92	9.4	19	18
Crafts: Carpenter/Pipefitter/Welder	126	126	98	28	28	28	29	24
Decontamination man/U-con man*	99	99	99	99	60	19	22	17
Cloth/Digest/Reduction operator, Outside sampling*	686	686	245	370	92	41	60	22
Dispensary: Nurse/Medic/Other (personnel)	175	175	56	99	42	6.3	3.5	1.3
Boiler/Ether House/Extraction /Nitric acid recovery operator	46	46	99	50	44	19	11	34
"Experimental Continuous Furnace": Pilot Plant project**	X?	8,540	8,540	X?	X	X	X	X
Feinc/Feed/Soluble feed operator	980	980	154	175	150	100	96	41
Foreman/General foreman/Shift foreman/Technical supervisor	161	161	161	96	81	30	25	19
Furnace operator	24,780	24,780	1,400	150	96	55	33	12
Guard/Chief guard	32	32	32	1.8	22	16	14	10
Health/Security Office personnel; Engineer (MCW, chemical)	15	15	15	7	14	15	11	8.1
Health Office: health surveyor/plant monitor	46	46	46	42	14	15	16	15
Instrument Shop machinist/technician	252	252	51	60	40	17	44	12
Laboratory Office personnel	100	100	10	5.6	5.6	5.6	2	42
Laboratory personnel - generic/MCW/Shotgun	245	245	24	25	23	30	10	42
Laundry operator/lead operator	X?	X?	X?	4.5	19	11	19	6.2
Ledoux Lab technician/assisstant technician - raffinate, MgF2	189	189	91	420	140	39	8.1	27
Ledoux Lab technician (K-65)	2,100	2,100	1,400	1,900	440	27	7.5	21
LF-9/brown/UO2 packager/unloader	38,990	38,990	364	350	350	X	X	X
Maintenance supervisor	50	50	50	38	42	10	13	140
Mechanic/Area mechanic: ore & furnace room, digest & feed, raffinate & C-3, Ether House, Nitric Acid House	189	189	2.7	28	28	28	29	24
Metal dissolver (#1, #2)	X?	X?	X?	204	204	204	204	204
Metal room sampler	X?	X?	X?	420	420	420	420	420
MgX operator	94	94	94	94	52	68	29	29
Miller (UO_3/QM-2)***	12,600	12,600	X	X	X	X	X	X
Office: MCW - Clerk/Maintenance/Messenger/Porter/ Expeditor	50	50	50	48	48	20	17	15
Office: MCW - Other, AEC - all AEC except Engineer	50	50	50	0	6.7	2.9	2.2	2.2
Office: Production - Clerk/Secretary, Receiving - Clerk	161	161	52	99	17	18	19	9.1
Ore Room operator***	13,720	350	392	370	170	140	140	X
Pilot Plant engineer	123	123	53	58	39	3.1	6.9	7.5
Pilot Plant lead operator/group leader	245	245	105	116	77	6.1	8.8	7.7
Pilot Plant technician	245	245	105	116	77	6	9.2	1,940
Pot Room operator	7770	770	336	100	190	45	113	234
Powder sample technician	3150	3150	217	217	57	57	57	57
Prod Research Lab personnel	84	84	12	30	13	5	2	3.7
Production superintendent/Asst production superintendent	25	25	25	25	26	56	21	18
QM-2 (orange) loader	5,320	5,320	1,400	420	420	420	X	X
QM-2 (orange) packager	1,400	1,400	1,400	420	130	130	120	*****
Raffinate/Sump recovery operator	273	273	154	76	170	8.5	11	216
Sample Room supervisor	448	448	245	245	245	41	41	41
Stockroom foreman/clerk	21	21	21	33	15	34	14	3.7
Truck/forktruck operator/driver	75	75	75	75	63	20	19	20
Warehouse foreman/Assistant foreman/Warehouseman	196	196	84	70	38	20	10	5.8
Warehouse K-65 sampler/Weighmaster****	196	196	84	230	270	350	350	X?

Notes

An “X” indicates that the job title did not exist during the indicated period. An “X?” indicates that it is uncertain if the job title existed, i.e., it is not certain when that job began.

Table 22 (Continued)

* Outside sampling and U-con positions began in 1955.
** Pilot Plant work began in 1948.
*** Milling work ended by June 1949.
**** These jobs appear to have ended in 1954, or to have been subsumed in other job titles.
***** 1961 dpm/m3 in 1955, 268 in 1956-57.

Table 23. Uranium dust daily weighted average exposure levels, Plant 6E.

Job Title	Airborne dust exposures, alpha dpm/m^3				
	Oct 1950 - Dec 1952	1953	1954	1955	1956 -1957
Area mechanic	23	23	23	36	73
Billet grinder	34	34	34	425	668
Blender; Lime/slag blender	8.9	14	13	11	5.7
Bottom/Lower "F" machine operator	23	15	24	52	29
Breakout operator/man	25	33	28	42	23
Brushing man	X	X	X	47	47
Burnout man	160	26	23	31	39
Cage grinding/cage operator/man	55	111	20	35	349
Cage/4th saw man	17	80	21	38	38
Capping man/Crucible assembler	81	51	31	32	42
Chipper/Derby chipper	2,110	2110	2,110	2,110	19
Crafts: Maintenance/Electrician/Mechanic/Millwright; Graphite Shop	45	40	23	36	73
Crucible loader	28	87	49	19	60
Engineer/Chemical engineer/Technical engineer; Superintendent/Supervisor	27	14	15	24	5.7
F (machine) charger/Extra man/Utility operator	37	44	33	38	50
Foreman/Assistant foreman/General foreman	20	13	19	27	6.1
Furnace loader; Reduction furnace operator	15	20	23	23	23
Furnace operator/unloader; Bottom furnace operator; Generic lead operator	68	31	118	107	41
KB-2/Reduction lead operator; Shift foreman; Porter	45	40	26	36	27
Lift truck driver (operator)	30	15	17	22	8
Office employees/Clerk; Production clerk	13	16	7.8	14	9.5
Production machinist	380	14	7.5	11	7
Recast furnaceYM-5 lead operator	49	20	47	30	71
Residue man	66	145	115	300	24
Saw operator/man	30	33	34	425	13
Slag building operator	110	110	110	224	18
Top/Upper/Generic "F" machine operator; Top(-ping) operator; Jolter	28	49	46	113	24
Top/upper furnace operator; Decontamination man	21	21	30	34	26

Notes

An “X” indicates that the job title did not exist during the indicated period. An “X?” indicates that it is uncertain if the job title existed, i.e., it is not certain when that job began

Table 24. Uranium dust daily weighted average exposure levels, Plant 7 (including the Slag Separation Plant) and Plant 7E.

Job title	Airborne dust exposures, alpha dpm/m^3					
	1951	1952	1953	1954	1955	1956 - 1957
Plant 7						
Area mechanic; Welder	37	14	37	7	13	14
Asst foreman/Plant superintendent/Engineer	22	21	10	7	70	32
Clerk/Record clerk; Porter	22	21	10	13	32	32
Decontamination man/Decontaminator	161	21	12	9	17	18
Filter/Tables operator*	X	X	X	X	9	9
Foreman/Technical supervisor; Safety inspector/Fire marshal	28	28	22	12	16	18
Furnace operator/Utility operator	25	28	67	23	18	17
HF/Magnesium Room operator	8	14	9	5	5	5.3
Hoisting (slag) operator*	x	X	X	X	15	15
Lead (UO_3-to-UF_4, TA-7) Operator; 36' Level/Panel board operator**	38	21	17	9	30	30
Lift truck driver (operator)	14	14	10	14	26	41
QM-2 dumper/hoister	107	56	61	42	63	112
Safety clerk	17	17	17	9	14	14
Sampler and cleanup man	X	28	286	8	8	9.1
TA-7 hoisting operator (hoister)	121	14	13	13	11	17
TA-7 (green/UF4) packager	242	28	103	68	49	24
Plant 7E (thorium/ionium) process)						
Ionium plant operator/lead operator***	X	X	X	X	0.1	0.3

Notes

An “X” indicates that the job title did not exist during the indicated period. An “X?” indicates that it is uncertain if the job title existed, i.e., it is not certain when that job began.

Plant 7E was in its startup phase when the only known measurements were taken in March 1955. Thus as AEC (1955c) noted, the full processing figures would likely be higher. Thus figures for 1956 and 1957 have been tripled to allow for full processing. Processing ceased at some point in late 1956 or very early 1957, so a end date of March 1957 should be taken.

* These positions began after July 1955.

**The 36' Level operator position began in 1953, the panel board operator position in 1952.

***The ionium plant work began after July 1955 and continued until March 1957.

Table 25. Measured radon concentrations at various indoor and outdoor areas, in units of 1 x 10^{-10} Ci/L.

	1947	1948					1949				1951			1952	
	Med/ Mean	No.	Min	Med/ Mean	Max	GSD	No.	Min	Med/ Mean	Max	No.	Med/ Mean	GSD	No.	Med/ Mean
INDOOR AREAS															
Scalehouse/Ore Storage/Warehouse (1)	0.10	27		0.46		3.28					35	0.09	5.91	95	0.09
Scalehouse/Ore Storage/Warehouse (2)		193	0.03	2.02	32.8		158	0.03	1.03	13					
Digest/Feed (1)											2	0.05	10.6		
Digest/Feed (2)		57	0.03	0.39	7.82										
Extraction Cells (1)											33	0.36	5.89	92	0.37
Extraction Cells (2)		14	0.03	1.08	4.14										
Centrifuge Area (1)											35	0.06	4.77	95	0.12
Centrifuge Area (2)		141	0.03	1.13	11.7		48	0.03	1.55	12					
Feinc/Filter/C-3/Raffinate/ Cloth Storage (1)		9		0.18		1.98					34	0.18	3.65	94	0.14
Feinc/Filter/C-3/Raffinate/ Cloth Storage (2)		186	0.03	12.3	894		172	0.03	0.75	468					
Orange Packing															
Pot Room															
Ledoux Lab (!)															
Ledoux Lab (2)		30	0.03	0.08	0.37										
Shotgun Lab															
Other Lab (Research/Control/ X-ray/MY)															
6E Breakout Area															
6E Recast Area															
Recovery area	0.21														
Decontamination Room															
Metal Dissolver Bldg															
NA House															
Ether House															
Refrigeration Room															
Receiving															
Welding Shop															
Millwright Shop															
Electric shop															
Maintenance Shop	0.09														
Smoking Room															
Production Office Area															
Dispensary	0.11														
YARDS AND OTHER OUTDOOR AREAS															
General Plant 6 (1) General Plant 6 (2)		35	0.03	0.19	2.06										
Bldg 104/Scalehouse	0.07	9		0.07		1.47									
Bldg 104 (Pilot Plant) (1) Bldg 104 (Pilot Plant) (2)		7	0.03	0.15	0.6										
Warehouse		17		0.10		2.05									
Warehouse exhaust (1) Warehouse exhaust (2)		33	0.06	0.91	3.3										
Near warehouse during K-65 drum welding		8		0.11		2.84									
Labs, guard office		8		0.06		1.38									
Ether House/ Bldg 109															
Parking lot area		9		0.13		1.56									
Scalehouse intake/ exhaust		3		0.12		2.06									
Scalehouse exhaust (1)		18		0.13		3.08									
Scalehouse exhaust (2)		24	0.04	2.2	48.7										
Ore Storage intake/ exhaust		6		0.68		2.44									
Ore Storage exhaust		2		0.31		1.77									
Outdoor drum storage, Bldg 115/ Plant 6E															

Table 25. (Continued)

	1952	1953			1954					1956			1957		
	GSD	No.	Med/ Mean	GSD	No.	Min	Med/ Mean	Max	GSD	No.	Med/ Mean	GSD	No.	Med/ Mean	GSD
INDOOR AREAS															
Scalehouse/Ore Storage/Warehouse (1)	6.04	66	0.01	4.99	74		0.01		5.45	5	0.01	1.00			
Scalehouse/Ore Storage/Warehouse (2)															
Digest/Feed (1)		17	0.12	5.20	57		0.03		3.85	18	0.01	5.06	3	0.03	5.46
Digest/Feed (2)															
Extraction Cells (1)	5.31	59	0.28	3.79	101		0.26		5.82	33	0.01	7.00	3	0.01	8.65
Extraction Cells (2)															
Centrifuge Area (1)	4.96	55	0.05	5.59	51		0.07		6.46	7	0.01	5.18	3	0.01	1.00
Centrifuge Area (2)															
Feinc/Filter/C-3/Raffinate/ Cloth Storage (1)	4.10	60	0.10	4.80	114		0.14		6.22	41	0.07	5.76	5	0.01	6.82
Feinc/Filter/C-3/Raffinate/ Cloth Storage (2)															
Orange Packing					1	0.12	0.12	0.12							
Pot Room					2		0.02		2.17						
Ledoux Lab (!)		6	0.10	1.33	10		0.02		3.38						
Ledoux Lab (2)															
Shotgun Lab					2		0.04		5.80						
Other Lab (Research/ Control/ X-ray/MY)					3		0.01		1.00				2	0.04	8.02
6E Breakout Area					3		0.01		1.00						
6E Recast Area					4		0.01		1.00						
Recovery area					1	0.11	0.11	0.11							
Decontamination Room					1	0.01	0.01	0.01							
Metal Dissolver Bldg					4		0.01		2.65						
NA House					3		0.01		16.0						
Ether House					2		0.02		2.67						
Refrigeration Room					1	0.01	0.01	0.01							
Receiving					1	0.01	0.01	0.01							
Welding Shop					1	0.01	0.01	0.01							
Millwright Shop					1	0.01	0.01	0.01							
Electric shop					3		0.01		1.00						
Maintenance Shop					3		0.04		6.95						
Smoking Room					1	0.01	0.01	0.01							
Production Office Area					1	0.01	0.01	0.01							
Dispensary					2		0.04		6.13						
YARDS AND OTHER OUTDOOR AREAS															
General Plant 6 (1) General Plant 6 (2)															
Bldg 104/Scalehouse															
Bldg 104 (Pilot Plant) (1) Bldg 104 (Pilot Plant) (2)															
Warehouse															
Warehouse exhaust (1) Warehouse exhaust (2)															
Near warehouse during K-65 drum welding															
Labs, guard office															
Ether House/ Bldg 109					1	0.01	0.01	0							
Parking lot area															
Scalehouse intake/ exhaust															
Scalehouse exhaust (1)															
Scalehouse exhaust (2)															
Ore Storage intake/ exhaust															
Ore Storage exhaust															
Outdoor drum storage, Bldg 115/ Plant 6E					3		0.30		8.62						

Notes

Values are taken from (1) AEC 1948b, MCW various, and MCW 1951b and (2) AEC 1949.

Where there was only a single measurement for the time period, the value is given above in the Median/Mean column. Where there were only a minimum, average, and maximum reported, the three values are given above in the Min, Median/Mean, and Max columns. Where there were two or more measurements and the data was given in full, a lognormal distribution was used for the analysis and the geometric mean and geometric standard deviation (GSD) are given

above in the Median/Mean and GSD columns. In each case where the number of measurements was given in the reference, the number is given above in the No. column

Table 26. Middlesex ore storage worker radon exposures, January 1944–January 1949 (AEC 1949, Table 1).

Area	Level		
	Min	Avg	Max
Railcar unloading	200		250
Drying room	1	6.7	21.7
Storage area	0.1	0.8	2.9
Sampler rooms	0.1	0.2	0.5
Crushing area	0.1	0.2	0.9
Crusher pit	0.3	0.8	1.3
Sampling lab	<0.1	<0.1	<0.1
Weigher's booth	<0.1	<0.1	<0.1

Notes

Radon levels are given in multiples of the radon MPC/preferred level of 10^{-10} Ci/L. New blower-equipped railcars began to be used in about early 1949, which reduced levels to below the MPC.

Table 27. Potential radon exposures from thorium processing.

Isotope	Maximum Ore Content, Ci	Emanation per Working Hour, Ci	Average Concentration, Ci/L
Rn-220	3.29×10^{-3}	7.31×10^{-7}	1.62×10^{-12}
Rn-222	$<1.30 \times 10^{-12}$	2.89×10^{-16}	6.42×10^{-22}

Notes

The maximum ore content is from Table 6.

Emanation is based on an assumption of 10% outgassed to the room (this is conservative, since most would have been vented when the cake containers were opened in a well-ventilated area, as for ore, or when the cake was in the digestion vessels). The total number of working hours is 2000 per year for 2.25 years (1955-March 1957). Thus the emanation per hour is 10% of the maximum ore content, divided by 4500 hours.

The average concentration is based on a conservative assumption of 2 air changes per hour (i.e., minimal ventilation) in a room measuring 3 m × 3 m × 2.5 m (about 10 ft × 10 ft × 7.5 ft), a conservatively small process area. This gives an air volume of 22,500 liters in the room and an air change volume of 45,000 liters. The emanation per working hour is divided by the air change volume to produce the average concentration.

Table 28. Ratio of alpha airborne activity to surface contamination (Becher 1958, Table 2).

Source of Data	Ratio*
Two operating areas having the highest contamination levels (1953)	
Shift-length air samples	0.64
Spot air samples	1.9
Plant-wide operations (415 surveys over 9 months in 1958)	
Shift-length air samples	0.36
Spot air samples	5.05
Special test conditions (1953)	
Simulated conditions	13
Worst possible conditions (short periods)	20

* Units of the ratio are dpm/m^3 of air per dpm/cm^2 of surface

Table 29. Contamination levels on various surfaces and pieces of equipment in the laundry (Utnage 1958b, Table 1).

Unit	Beta + Gamma, cpm
Presser pad surface	2,000
Cloth hamper surface	5,000
Wooden hamper surface	1,000
Work tables and surfaces	200-1000
Lint ball/dryer lint trap/roof lint trap	4,000/2,000/3,000
Inside washer	300
Inside dryer	1,000-4,000
Under washer	20,000-60,000
Under dryer	100-40,000
Floors, average	300-500
Walls	100-300
Overhead pipes, etc.	300-1000

Table 30. Contamination levels and associated dose rates from work clothing (Utnage 1958b).

Item	Spot		Whole Garment or Group		Contamination Notes
	Max	Average	Max	Average	
Regulated coveralls	80% have ≥ 1-2 in^2 spot >3000 cpm	Most coveralls have ≥1 spot >1 mr/hr	60% have ≥ 1 mrep/hr over whole garment	1.5 mrep/hr; range, 0.2 to 12; 100% have avg >100 cpm per 2 in^2	Apparent U spots on 70%; area is from 10 cm^2 to 30% of total area
Nonregulated coveralls	30% have ≥1 spot >1000 cpm		100% <3 mrep/hr	80% <1 mrep/hr; 0% with avg <100 cpm	5% visibly contaminated
Handkerchiefs	>1,000 cpm			<300 cpm	10% visibly contaminated
Socks			800 cpm	200 cpm	
Underwear			800 cpm	200 cpm	
Caps				300 cpm	Low to moderate
Blue smocks	>1,000 cpm			200 cpm	Low to moderate
White smocks	>1,000 cpm				More than blue smocks (more spots)
Lab smocks	>1,000 cpm			<300 cpm	Low (few spots)
Gloves				~5,000 cpm per 2 in^2	All: heavy
Shoe covers				>90% have >1,000 cpm	"Destrehan": "high"

Note: Measurements were taken after wearing but before washing.

1

Table 31. Surrogate (comparable) worker inhalation intake values, in pCi/yr.

Category	Type	Median or *Actual	GSD	No. Cases	Median or *Actual	GSD	No. Cases	Median or *Actual	GSD	No. Cases
Plant 6		Period 123			Period 1			Period 23		
	Generic (mixed, miscellaneous, or unknown)	2.51 x 10^4	0.482	21	8.29 x 10^4	0.626	13	2.12 x 10^4	0.574	7
	Mostly Cloth, Raffinate, Feinc	--	--	--	5.61 x 10^4	0.997	3	2.87 x 10^4	0.146	3
	Mostly Digest	2.10 x 10^4	0.529	3	4.45 x 10^4	0.933	3	*1.98 x 10^4	--	1
	Mostly Ether House	2.19 x 10^4	0.493	5	3.08 x 10^4	0.200	4	2.32 x 10^4	0.0016	3
	Mostly Packaging	--	--	--	1.28 x 10^5	1.636	3	--	--	--
	Mostly Pot Room, Orange Oxide	--	--	--	1.80 x 10^5	0.697	5	2.26 x 10^4	0.843	5
		Period 12			Period 1			Period 2		
	Mostly Ore Room	*2.45 x 10^5-4.96 x 10^4	--	2	*4.83 x 10^4 - 5.96 x 10^4	--	2	*3.84 x 10^4	--	1
Plant 6E		Period 123			Period 1			Period 23		
	Generic (mixed, miscellaneous, or unknown)	2.98 x 10^4	0.450	12	4.79 x 10^4	0.831	4	3.12 x 10^4	0.439	13
	Bomb Step (UF4→Derby)	3.19 x 10^4	0.335	3	2.30 x 10^4	0.410	4	2.59 x 10^4	0.665	6
	Recast (Derby→Ingot)	*2.49 x 10^4 - 2.02 x 10^4	--	2	4.71 x 10^4	0.575	3	3.44 x 10^4	0.507	4
		Period 12			-		-			-
	Graphite Shop	1.56 x 10^4	0.450	3						
Plant 4		Period 123			Period 1			Period 23		
	4 Metal (Derby, Ingot)	--	--	--	1.24 x 10^5	0.931	11	--	--	--
	4 Pilot Plant (Dingot, Metallurgical, etc.)	*1.65 x 10^4 - 1.04 x 10^4	--	2	2.29 x 10^4	0.874	3	2.92 x 10^4	0.484	8
Plants 4 & 7		Period 123			Period 1					
(Green Salt)	UF4 Production Work, First at 4, Then at 7	1.81 x 10^4	0.449	8	1.18 x 10^5	1.499	7			
Plant 7		Period 23			Period 2					
	Generic (mixed, miscellaneous, or unknown)	1.67 x 10^4	0.408	16	2.18 x 10^4	0.624	7			
Multi-Plant		Period 123			Period 1			Period 23		
	AEC	*7.20 x 10^3 - 6.94 x 10^3	--	2	1.96 x 10^4	0.465	5	*6.01 x 10^3 - 1.60 x 10^4	--	2
	Decon/Cleanup	1.44 x 10^4	0.209	3	--	--		--	--	--
	Boiler House/Power House	1.11 x 10^4	0.203	6	1.73 x 10^4	0.439	6	*1.23 x 10^4	--	1
	Engineering	1.08 x 10^4	0.336	7	3.38 x 10^4	0.436	10	9.71 x 10^3	0.222	10
	Instrument Shop	1.26 x 10^4	0.263	6	2.13 x 10^4	0.647	7	--	--	--
	Laboratories (Anal., Research, Ledoux, etc.)	1.11 x 10^4	0.406	24	2.30 x 10^4	0.742	22	1.17 x 10^4	0.352	23
	Laundry	1.10 x 10^4	0.360	6	1.73 x 10^4	1.036	8	*9.06 x 10^3 - I72.20 x 10^4	--	2
	Maintenance									

	Carpenter	*9.17 x 10^3	--	1	--	--	--	--	--	--
	Electrical	1.66 x 10^4	0.438	7	5.19 x 10^4	0.487	7	--	--	--
	Insulator/Pipe Coverer	*3.25 x 10^4	--	1	--	--	--	--	--	--
	Machinist/Machine Shop	*4.17 x 10^4	--	1	--	--	--	--	--	--
	Mechanic/Millwright	1.75 x 10^4	0.544	10	7.05 x 10^4	0.580	9	2.40 x 10^4	0.507	4
	Miscellaneous/Mixed	1.46 x 10^4	0.372	12	3.57 x 10^4	0.799	12	--	--	--
Multi-Plant, continued	Oiler	*1.76 x 10^4	--	1	--	--	--	--	--	--
	Painter	1.49 x 10^4	0.349	5	1.70 x 10^4	0.446	6	--	--	--
	Pipefitter	2.42 x 10^4	0.693	7	2.65 x 10^4	0.845	9	--	--	--
	Rigger	*3.24 x 10^4 - 1.48 x 10^4	--	2	--	--	--	--	--	--
	Tinner	*2.49 x 10^4	--	1	*3.23 x 10^4	--	1	--	--	--
	Welder	2.62 x 10^4	0.433	7	3.30 x 10^4	0.298	6	*6.63 x 10^3 - 9.43 x 10^3	--	2
	Office Workers	9.74 x 10^3	0.310	23	1.98 x 10^4	0.507	15	1.10 x 10^4	0.592	6
	Porter/Custodian	1.12 x 10^4	0.260	7	2.94 x 10^4	0.895	9	8.55 x 10^3	0.213	3
	Safety & Health, Fire	8.23 x 10^3	0.314	3	2.06 x 10^4	0.669	6	1.35 x 10^4	0.625	5
	Shipping & Receiving, Warehouse, Storeroom, Fork Truck Operator	1.11 x 10^4	0.380	22	1.52 x 10^4	0.843	20	9.63 x 10^3	0.180	3
	Supervision & Management (where not specified by plant)	1.95 x 10^4	0.394	7	3.46 x 10^4	1.059	7	--	--	--

Notes

A lognormal distribution was used. The geometric median and the geometric standard deviation (GSD) are shown. However, where only one or two suitable cases were found for a category and time period, no distribution could be formulated. For these cells, only the one or two actual results from IMBA are given; this is indicated by an asterisk (*). The non-distribution case results thus indicate what may be known regarding the exposure of a comparable worker.

The sample size was assumed to be 1.4 liters; the assumed activity equivalence is .676 pCi per µg nat U (or 676 pCi/mg); the sample data was in mg U/l; and IMBA uses 365 days of exposure per year. Hence the conversion factor for input data in mg U/l was 676 x 1.4 = 946, to give pCi; the conversion factor for IMBA output data in pCi/day was 365, to give pCi/year; and the overall conversion factor was thus 517.90.

Period 1 is from 1948-1951; Period 2 from 1952-1955; and Period 3 from 1956-1958. Period 123 includes all three periods, Period 23 includes only the last two periods, and so forth. Major improvements were made in 1949-1951. Thus after this period, exposures went down in many areas and for some occupations. Increases in exposures in other areas and for other occupations are likely due to increases in production.

In IMBA, the assumption was made that all of the uranium measured was U-234. The daughters assumed to be in equilibrium in the U-238 and U-235 chains must be added by the dose reconstructor when appropriate (see Section 6.1 of the text).

Table 32. Estimate of annual intake of thorium dust during Plant 7E operation.

	Jul-Dec 1955	1956	Jan-Mar 1957
Alpha dpm/m^3	0.1	0.3	0.3
pCi/m^3	0.0450	0.135	0.135
pCi inhaled in the period	63.1	378	94.6

Notes

All of the source is assumed to be Th-230 (with negligible build-in of Ra-226, etc.)

The breathing rate is taken to be 1.4 m^3/hr and the working time to be 2000 hours per year, ratioed as necessary to correspond to the fraction of a year.

Table 33. Exposure rates (mR/hr) from drums of K-65 and Q-11 residue in a railcar (AEC 1949, Figure 21).

Source	Position	Distance, feet	Dose rate	Dose rate A	Dose rate B	Dose rate C
96 drums of K-65, along the full width of a railcar and ~46 ft along its length (57 ft)	Drum group centerline perpendicular to long side of railcar, 4 ft from ground	1	85			
		3	72.5			
		5	50			
		8	37.5			
		12	27			
		18	19			
		24	12.5			
		30	9.4			
	Top of railcar	Contact	104			
87 drums of Q-11, distributed in two groups at ends of boxcar	One drum group centerline perpendicular to long side of boxcar (A); at center door (B); at end (C)	2		37	7.75	24
		4		24	8.75	
		6		18	9	9.5
		8		16	9.5	
		10		14	9.7	6.6
		12		12	9.7	
		14		10.5	9.5	5.5
		16		9	8.5	
	Top of car, over one group (A); over empty center (B)	Contact		21	11	
5 boxcars in a row containing unspecified amount of K-65	Along a line perpendicular to the axis of the line of cars, even with the center of the middle car	10	50			
		25	22			
		43	13			
		50	10.2			

Note

The total length of a car is given as 57 feet.

Table 34. Middlesex ore storage worker gamma-beta doses, 1944–1949 (AEC 1949, Figure 3)

Worker type	Number of workers	Weekly gamma-beta dose, mrep
Guard	11	150
Laborer	20	500-600
Labor Foreman	1	250
Laboratory Technician	2	300
Maintenance	10	150-500, avg 300
Office	---	100
Timekeeper	1	250

Note: Doses were 65% gamma. K-65 residue was still coming here at this time.

Table 35. Measured dose rates at various positions in Plant 6 (MCW 1946).

Location	Exposure, % tolerance
Center of 4 barrels of GLC (3 days old)	150
Between 2 barrels of GLC (3 days old)	120
Under M-3 containing GLC	120
Operator position while filling drums of GLC	110 (2)
Operator position while milling GLC - Sample Prep Room	130
Near drying oven -- Sample Prep Room	20
Skids of acid press cake (2-3 days old)	200 (5)
Floor surface under Feinc platform	30 (8)
In front of Feinc filter while filtering reslurry batch	210 (2)
Fork truck driver position while loading GLC(rail?)car	140
By M-1: on platform, about 250 gal GLC (3 days old)	90
By M-2 on platform, 5 hrs after addition of 6000 lbs ore	100
By M-3 on platform while adding ore (2000 lbs in tank)	70
On platform at M-19 while reslurrying skid cake batch	120
At operator position between skid and M-14 on platform	120
Above skid of GLC on M-14	280
By M-72, containing wash water	50
By M-83, 3/4 full of GLC (2 days old)	220
Floor around Feinc filters	110 (7)
Sump recovery skids, all full	80 (5)
Dempster body of Chemical 6BC	30
Dempster body of Chemical 6BP	40
Laboratory sample room, center	0
Laboratory sample room, in vault	80
Sample Prep Room, 1 foot from pile of K-65 in hood	60
Sample Prep Room, 1 foot from a 3-gal bottle of K-65 at equilibrium	160
Sample Prep Room, 1 foot from 3 2-qt bottles of K-65 at equilibrium	100
Sample Prep Room, operator position at Ro-Tap	50

Notes

Data is based on measurements taken in July and August 1946 at one foot from the source.
Figures are given in units of per cent of tolerance, where tolerance is defined only as the "amount of exposure that a person can receive 8 hrs/day for an indefinite period of time", presumably corresponding to 500 mrep/ wk at this time.
Parentheses indicate the number of measurements used to form the average.

Table 36. Weekly external dose values, April 1942–December 1945.

Lognormally-distributed doses (rem)			
Median weekly photon dose	**GSD**	**Median weekly electron dose**	**GSD**
0.1	1.85	0.124	1.79

Table 37. Organ doses (rem)[a] for a beam quality (HVL) of 2.5 mm Al and 80 kVp (1942-1958)

	PA Chest	**Lat Chest**	**Total [(b)]**
Entrance Air Kerma (cGy)	**0.20 [(c)]**	**0.50 [(c)]**	
Thyroid	7.5×10^{-2} [(f)]	3.8×10^{-2}	1.1×10^{-1}
Ovaries	3.4×10^{-2}	2.8×10^{-2}	6.2×10^{-2}
Testes	1.8×10^{-3}	1.7×10^{-3}	3.5×10^{-3}
Lungs (male)	8.4×10^{-2}	9.7×10^{-2}	1.8×10^{-1}
Lungs (female)	9.0×10^{-2}	1.1×10^{-1}	2.0×10^{-1}
Breast	9.8×10^{-3}	1.3×10^{-1}	1.4×10^{-1}
Uterus	3.0×10^{-2}	2.2×10^{-2}	5.2×10^{-2}
Bone Marrow (male)	1.8×10^{-2}	1.9×10^{-2}	3.7×10^{-2}
Bone Marrow (female)	1.7×10^{-2}	1.5×10^{-2}	3.2×10^{-2}
Total Body (male)	2.6×10^{-2}	3.2×10^{-2} [(e)]	5.8×10^{-2}
Total Body (female)	2.4×10^{-2}	3.0×10^{-2} [(e)]	5.4×10^{-2}
Thymus	9.0×10^{-2}	1.1×10^{-1}	2.0×10^{-1}
Liver/Gall Bladder	3.4×10^{-2}	2.8×10^{-2}	6.2×10^{-2}
Eye/Brain	4.6×10^{-3}	6.9×10^{-2}	7.4×10^{-2}
Esophagus	9.0×10^{-2}	1.1×10^{-1}	2.0×10^{-1}
Stomach	9.0×10^{-2}	1.1×10^{-1}	2.0×10^{-1}
Urinary Bladder	3.4×10^{-2}	2.8×10^{-2}	6.2×10^{-2}
Colon/Rectum	3.4×10^{-2}	2.8×10^{-2}	6.2×10^{-2}
Bone Surface	9.0×10^{-2}	1.1×10^{-1}	2.0×10^{-1}
Skin [(d)]	2.7×10^{-1}	6.9×10^{-1}	9.6×10^{-1}
Remainder	9.0×10^{-2}	1.1×10^{-1}	2.0×10^{-1}

(a) For organs listed in ICRP 34 (1982) and proximal organs for input to IREP

(b) Sum of dose from the PA and lat views

(c) Kathren et al, to be published

(d) Skin dose is entrance skin exposure calculated from air kerma, multiplied by a backscatter factor of 1.35 from NCRP 102, Table B-8

(e) The ICRP 34 DCFs appear to have been switched male/female

(f) The DCF for the AP cervical spine was used, corrected by a 43% depth dose factor (NCRP 102, Table B-8)

Table 38. Decontamination and decommissioning years, 1959-1961: maximum annual doses (rem).

Exposure Potential	Exposure Mode	Plant			
		4	**6**	**6E**	**7**
High	Inhalation	4.73×10^{-1}	1.61×10^{0}	9.39×10^{-1}	3.08×10^{0}
	Radon	2.13×10^{-2}	7.77×10^{-2}	4.52×10^{-2}	1.48×10^{-1}
	Direct gamma	1.60×10^{-3}	1.18×10^{-2}	1.12×10^{-3}	2.00×10^{-4}
	Total	4.96×10^{-1}	1.70×10^{0}	9.86×10^{-1}	3.23×10^{0}
Moderate	Inhalation	2.39×10^{-1}	6.73×10^{-2}	7.25×10^{-2}	7.52×10^{-2}
	Radon	1.07×10^{-2}	3.23×10^{-3}	3.49×10^{-3}	3.62×10^{-3}
	Direct gamma	2.40×10^{-4}	2.00×10^{-4}	8.00×10^{-5}	8.00×10^{-5}
	Total	2.50×10^{-1}	7.07×10^{-2}	7.61×10^{-2}	7.89×10^{-2}
Low	Inhalation	1.22×10^{-1}	3.09×10^{-3}	1.07×10^{-2}	2.28×10^{-3}
	Radon	5.71×10^{-3}	1.48×10^{-4}	5.17×10^{-4}	1.10×10^{-4}
	Direct gamma	6.40×10^{-5}	8.00×10^{-5}	0.00×10^{0}	4.00×10^{-5}
	Total	1.28×10^{-1}	3.31×10^{-3}	1.12×10^{-2}	2.43×10^{-3}

Notes

Data in this table was calculated using the RESRAD-BUILD computer code (ANL 2003) and measured data from Refs. MCW 1958 and MCW 1959.

Both surface contamination and bulk (floor and wall contamination were taken into account in calculating the inhalation and radon contributions.

"High" exposure potential represents those working in the most contaminated areas, i.e., the former process areas; "moderate" represents those accessing the less contaminated areas or infrequently accessing the former process areas; and "low" represents those accessing the uncontaminated areas.

Table 39. Postoperations years, 1962-1995: maximum annual doses (rem).

Former Plant 6E Buildings			Former Plant 7 Buildings		
Exposure Potential	Exposure Mode	Annual Dose (rem)	Exposure Potential	Exposure Mode	Annual Dose (rem)
High	Inhalation	3.74×10^{-3}	High	Inhalation	6.08×10^{-3}
	Radon	6.09×10^{-3}		Radon	1.01×10^{-2}
	Direct gamma	1.29×10^{-4}		Direct gamma	8.00×10^{-4}
	Total	9.96×10^{-3}		**Total**	1.70×10^{-2}
Moderate	Inhalation	2.40×10^{-3}	Moderate	Inhalation	2.31×10^{-3}
	Radon	4.06×10^{-3}		Radon	3.79×10^{-3}
	Direct gamma	4.29×10^{-5}		Direct gamma	4.00×10^{-4}
	Total	6.50×10^{-3}		**Total**	6.50×10^{-3}
Low	Inhalation	9.56×10^{-4}	Low	Inhalation	8.00×10^{-4}
	Radon	1.62×10^{-3}		Radon	1.36×10^{-3}
	Direct gamma	0.00×10^{0}		Direct gamma	2.00×10^{-4}
	Total	2.58×10^{-3}		**Total**	2.36×10^{-3}

Notes

The data in this table was calculated using the RESRAD-BUILD computer code (ANL 2003) and measured data from MCW (1961). Both surface contamination and bulk (floor and wall contamination were taken into account in calculating the inhalation and radon contributions.

"High" exposure potential represents those working in the most contaminated areas, i.e., the former process areas; "moderate" represents those accessing the less contaminated areas or infrequently accessing the former process areas; and "low" represents those who accessing the uncontaminated areas.

Table 40. Summary of postoperational years exposure data as measured by two survey groups.

		1981	1986	1990		Overall Averages, 1981		
Plant	Bldg Remaining	Radon daughters (WL)	Radon Yearly Avg, WLM/yr	Radon Yearly Avg, WLM/yr	Source	BG	Average Measured Levels at St. Louis Site
1	K1E	0.009-0.02	0.05	0.12	Radon in air	<1 pCi/L	0.4 – 37 pCi/L, avg daytime; 69 pCi/L max
1	25-1	0.001		0.01	Radon daughters in air	<0.01 WL	0.0009-0.07 WL, avg daytime conc
1	25-2	0.0009		0.01	Gamma from Ra, U daughters	8 uR/hr	8-290 uR/yr @ 1 m above floor
1	38						
1	40						
2	50	0.0003					
2	51	0.0005	0.02	0.01			
2	51A		0.02	0.01			
2	52A	0.07					
2	52	0.0007-0.001		0.00			
6	100			0.02			
6	101		0.10	0.01			
6E	116-1		0.00	0.04			
6E	116-2			0.00			
6E	116B			0.01			
6E	117-1			0.00			
6E	117-2			0.00			
7	700			0.00			
7	704		0.03	0.00			
7	705			0.00			
7	706			0.00			
7	708			0.01			

Measurements are from ORNL (1981) and Applied Nuclear Safety (1986; 1990)

APPENDIX A

Notes on How the "Tolerance" or "Preferred" Level for Insoluble Uranium Compounds in Air Was Calculated in 1948

(From AEC 1949)

Assumptions

1. The "tolerance" alpha radiation level to the lung is 30 mrep/week or 4.3 mrep/day.
2. The fraction of inhaled material retained in the lungs and pulmonary lymphatic tissue is 0.25.
3. The biological half-life of insoluble uranium compounds in the lung is 90 days.
4. The weight of a pair of lungs is 1000 grams.
5. An individual inhales 10 cubic meters per 8-hour working day.

Calculations

1. µCi in lung required to deliver 4.3 mrep/day: $= \frac{(5.2 \times 10^7)\ (0.0043)}{2.2 \times 10^6 \times 60 \times 24 \times 8.86}$

where

5.2×10^7	=	number of MeV/g in one rep
0.0043 rep/day	=	daily acceptable dose rate
2.2×10^6	=	number of dis/min per µCi
60×24	=	number of minutes per day
8.86	=	sum of energies of alpha radiation from U-238 and U-234 in equilibrium, in MeV

$= 8 \times 10^{-6}$ µCi/g

2. Total µCi in lungs for 4.3 mrep/day:

$= 1000 \times 8 \times 10^{-6}$
$= 8 \times 10^{-3}$ µCi

3. µCi per 10 m^3 (inhaled in 8 hours) which will give 8×10^{-3} µCi to the lung at equilibrium (assuming exposure every day)

where

8×10^{-3}	=	µCi in lungs at equilibrium
0.25	=	fraction of inhaled material deposited in the lung
90	=	assumed biological half-life in the lungs, in days
	=	2.54×10^{-4} µCi per 10 m^3
1.4	=	factor to convert half-life to mean life

4. µCi per m^3:

$= 2.54 \times 10^{-5}$
= 56 dpm per m

5. Adjustment for actual exposure occurring up to 6 days a week, when 7 days was assumed:

   56 dpm * (7 days/6 days) = 65 dpm)
   (i.e., 5-6 days per week actually, since 56 dpm * (7 days/5 days) = 78 dpm

   and

   = **70 dpm per m^3**
   = **50 µg per m^3**

Note: As AEC 1949 states, these calculations use no factor to account for nonuniform distribution in the lungs. It is also stated that the acceptable weekly dose rate for alpha dust exposures was going to be changed (presumably by AEC) to either 30 mrep/week or 15 mrep/we

1