

<p><b>ORAU Team</b>  <b>Dose Reconstruction Project for NIOSH</b></p> <p>Basis for Development of an Exposure Matrix for the Mallinckrodt Chemical Company St. Louis Downtown Site and the St Louis Airport Site, St. Louis, Missouri, Period of Operation: 1942–1958</p>	<p>Document Number:  ORAUT-TKBS-0005  Effective Date: 03/10/2005  Revision No.: 01  Controlled Copy No.: _____  Page 1 of 248</p>
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### RECORD OF ISSUE/REVISIONS

<b>ISSUE AUTHORIZATION DATE</b>	<b>EFFECTIVE DATE</b>	<b>REV. NO.</b>	<b>DESCRIPTION</b>
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.
Draft	10/17/2003	00-B	Draft revision to incorporate NIOSH review comments. Initiated by Janet L. Westbrook.
10/24/2003	10/24/2003	00	First approved issue. Initiated by Janet L. Westbrook.
Draft	03/04/2004	01-A	Revision to incorporate comments on Section 8.0 and to incorporate additional lately captured information. Initiated by Janet L. Westbrook.
Draft	02/16/2005	01-B	Revision to incorporate comments on Sections 7.0 and 8.0; to incorporate additional lately captured information regarding site work and external and radon exposure rates; to incorporate neutron exposure information; to incorporate information about the St. Louis Airport Site (SLAPS); and to provide additional guidance to dose reconstructors. Section 7.0, regarding external dose, remains on hold. Initiated by Janet L. Westbrook.
Draft	03/08/2005	01-C	Incorporates NIOSH comments. Initiated by Janet L. Westbrook.
03/10/2005	03/10/2005	01	Approved Issue of Revision 01. Initiated by Janet L. Westbrook.

## ACRONYMS AND ABBREVIATIONS

AEC	Atomic Energy Commission
AP	anterior-to-posterior
Ci/L	curies per liter
D&D	decontamination and decommissioning
DCF	dose conversion factor
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)
HVL	Half-value layer
LOD	limit of detection
MAC	Maximum Allowable Concentration
ME or MEP	Minor Elements Production
MED	Manhattan Engineer District
MFL	MgF <sub>2</sub> liner
MgX	magnesia concentrate feed
MPC	maximum permissible concentration
mR	milliroentgen
mrاد	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 <sub>2</sub> 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.



## 1.0 PURPOSE AND SCOPE

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

In this document the word "facility" is used as a general term for an area, building or group of buildings that served a specific purpose at a site. It does not necessarily connote an "atomic weapons employer facility" or a "Department of Energy facility" as defined in the Energy Employee Occupational Illness Compensation Program Act of 2000 (42 U.S.C. § 7384l (5) and (12)).

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, and for the St. Louis Airport Storage Site, which was received residues from Mallinckrodt operations from 1946 until 1958, after which it was used until about 1967 for residue storage and burial of some material. 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 during and after decontamination and decommissioning is considered for the period 1959-1995 for workers who began work at Mallinckrodt during the period of operations.

This document also covers Mallinckrodt workers who performed operations at the St. Louis Airport (Storage) Site (SLAPS or SLAPSS), the waste repository site north of the former St. Louis Municipal Airport in Robertson, Missouri, from 1946 to 1958. Additionally, exposure due to residual contamination left at the site and during further work at the site is considered for the period 1959-1962.

## 2.0 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-Hilliard 1967; FUSRAP undated b). The work began immediately and by July 1942 Mallinckrodt was producing almost a ton of  $UO_2$  per day (Fleishman-Hilliard 1967; Mallinckrodt 1994; FUSRAP undated b). Later in 1942, Mallinckrodt started production of  $UF_4$  and in July 1943, it started the first uranium metal plant (Fleishman-Hilliard 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 2002).

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. Like most of the early MED plants, the early Mallinckrodt facilities were large-scale expansions of laboratory processes and techniques and were designed without pilot plant studies or any special provision for health and safety (AEC 1951b). Also, temporary types of construction methods were used; even Plant 6, which was completed in mid-1946 and did have the benefit of an engineering pilot plant study, was of temporary-type construction because it was to process only high-grade pitchblende and the available supply was thought to be limited (AEC 1951b). The permanent status of the Mallinckrodt site was not established until 1946 (AEC 1951b; Mason 1958a). Engineered and administrative provisions for health and safety were instituted as high exposures were found in the course of monitoring (Hickey and Dupree 1984). 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 (except possibly for a pilot project starting in mid-1945) and urinalysis in the summer of 1948 (MCW 1950c) (some urinalysis was done earlier, but there was some question about its validity – see Section 5.3.6). 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 1955d; 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, except for some special cases. 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 for a time (MCW 1955d), but eventually Mallinckrodt did its own urinalyses again (ORAU 1983b). It appears that most of the records of this monitoring are available. The external dose records needed for dose reconstruction are mostly available from 1946 on, but are missing for the period 1942-1944 and for most of 1945, and are also missing for the period of some time in 1954 to the end of operations; the internal dose records (as bioassays) are mostly available from 1948 to the end of operations, but are missing for the period 1942-1947. Records for the postoperations decontamination and decommissioning should be found with the Weldon Spring records since film badges were issued from Weldon Spring (MCW 1961b), but to date the Weldon Spring records are not available except by request for individual claim subjects.

The St. Louis Airport Storage Site (SLAPS or SLAPSS) was acquired by AEC in 1946 for use in storing residues arising from pitchblende ore processing (AEC 1959; ORNL 1979). Later, it was also used to store other types of residues and some ore (AEC 1956d; Mallinckrodt 1994). Although

MED/AEC operated the site itself from 1946 until July 1953, it appears that Mallinckrodt and perhaps some Ledoux Company workers actually did the work (MCW 1949d; MCW 1949p; ORAU 1989); Mallinckrodt ran the site under contract to AEC from July 1953 to 1958 and possibly until 1962, when control of the site passed to a private concern that was given a license to take over the stored residues (AEC 1959; ORAU 1989; AEC 1972). Thus the film badge records for airport workers from 1946 until at least 1958 should be found among the Mallinckrodt film badge records; film badge records after that may possibly be among the Weldon Spring records.

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.

### **3.0 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.

MED was required to store some of the residues produced from the pitchblende ore (AEC 1959) because the ore supplier, the African Metals Company, retained ownership of the radium and valuable metals remaining in the residues. Because of the volume of the residues and the high gamma and radon exposures associated with storage at the Mallinckrodt site, MED acquired a tract of land located in Robertson, Missouri near the St. Louis Municipal Airport (Labert Field) (AEC 1959) to use to store the residues and some of the pitchblende ore (AEC 1959). This storage area was formally called the St. Louis Airport Storage Site (SLAPS or SLAPSS), but in Mallinckrodt and MED/AEC documents it was often referred to simply as "the airport".

#### **3.1 HISTORY OF USE OF THE ST. LOUIS DOWNTOWN SITE (SLDS)**

Plants 1 and 2 were already in existence and used for other operations by Mallinckrodt at the time uranium-refining operations started in 1942 (Mason 1977). MED (1944p) states that as of November 1944, MED operations occupied a small part of Plant 1, part of Plant 2, and all of Plant 4.

Laboratory development work started in April 1942 in Plant 1's Building 25 (second floor) and in the alley on the southwest side of the building (Mason 1977). (Mallinckrodt 1994 states that work began in Plant 2 in uranium-refining operations began at Plant 2 in April 1942, but the Mason 1977 chronology appears to be more plausible.) Additional laboratory and 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).

In Plant 1, Building 25 contained the project offices, while Building P contained the engineering office. MED (1944p) states that Building Z contained other offices; Mason (1977) specified that the early uranium project was a semi-works operation for which administrative services were furnished from Mallinckrodt headquarters in Building Z. Building A in Plant 1 was the base for the plant mechanical department, which provided general maintenance services (Mason 1977; MED 1944p). Mason (1977) states that the laboratory in Building 25-2W provided quality control services.

Facilities for batch production were installed in Plant 2's Buildings 50, 51, 51A, and 52 to produce uranium trioxide ( $UO_3$ ) from ore concentrates (Mason 1977; Hickey and Dupree 1984; Mallinckrodt 1994). The concentrates were "digested" (dissolved) in nitric acid in Building 51 to produce uranyl nitrate (Mason 1977; ORNL 1981; Mallinckrodt 1994; Fleishman-Hilliard 1967). The digested liquid was then transferred to Building 52 to be purified by ether extraction to uranyl nitrate hexahydrate (UNH) (MED 1944p; Mason 1977; ORNL 1981; Mallinckrodt 1994); however, sources such as ORNL (1981) suggest that an area outside of Buildings 51 and 52, referred to as 51X and 52X, was covered with a canopy and used temporarily for extraction. The UNH was converted in Building 51A first to  $UO_3$  and then to  $UO_2$  (Mason 1977; ORNL 1981; Mallinckrodt 1994). The  $UO_2$  was apparently packaged in Building 51A (Mason 1977). By July 1942 Mallinckrodt was producing approximately a ton of uranium oxide ( $UO_2$ ) per day (Mason 1977; Mallinckrodt 1994).

Part of Building 38 was used as the change house for the uranium project workers (Mason 1977). Buildings 40, 45, 45A, and 47 were used as warehouse buildings for raw, in-process, and finished

materials (MED 1944p). Building 50 was also used as a utility area, as a tank storage area for liquids to be used in Building 51, as a storage area for incoming feed materials and packaged products, and as a mechanical repair area (Mason 1977; Mallinckrodt 1994).

Building 55 contained the “shotgun” laboratory that tested  $UO_3$  samples (MED 1944I; Mason 1977; ORNL 1981) and also operated as a pilot plant from 1943 until some time in 1947. The shotgun laboratory was designated as a special restricted area because of the RaBe source used for the sample testing (Mason 1977).

Work began in 1942 on production of  $UF_4$  by the high-temperature gas-solid reaction of  $UO_2$  with HF; for a short time, one corner of Building 50 (the “sulfur burner room”) was used for development work on this process (Mason 1977; ORNL 1981).

Experimental processing of high-grade pitchblende ores began in Plant 1 in about July 1944 (Mason 1977; Mallinckrodt 1994). Because of the high radium content of these ores and the residues resulting from the processing, Mallinckrodt wanted to confine the materials to a limited area and to prevent their spread into other plant areas (Mason 1977). Mallinckrodt therefore instituted strict controls of the developmental work and also decided to do pilot-scale work to obtain design data for eventual construction of a production-level refinery (Mason 1977). The laboratory for the testing of radium extraction methods was set up in Building 25-2 and the pilot plant in Building K-1E (Mallinckrodt 1994; ORNL 1981; Hickey and Dupree 1984 (which states that the pilot plant was in Building 25-2)) and in the alley (Fleishman-Hilliard 1967). The radium-free feed liquor that resulted from the Building K-1E digestion and precipitation processes was conveyed in containers by hand cart to Building 52, where it was first treated in vessels outside the building (presumably in the alley) (Mason 1977). The liquid was then taken into Building 52 for conversion as usual to  $UO_3$  and then to  $UO_2$  (Mason 1977). By the end of 1944, Mallinckrodt had obtained sufficient data to begin the engineering design of a pitchblende ore refinery (Mason 1977). Mason (1977) states that “radium-bearing materials were not processed or stored at any time in the Plant 2 buildings”, but consistent with the usage of the term “radium-bearing materials” in various documents from the 1940’s and 1950’s, it may be the high-radium-level residues that are being referred to. Mason (1977) also states that solid residues from the extraction were drummed, stored temporarily, and transferred from Plant 2 to other government sites for scrap recovery.

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). It is not clear where it is this plant or the Building K-1E plant that is the one referred to as the “Pilot Plant” in early film badge records; perhaps the term included both. Work at Plant 2 continued until 1946, when the plant was closed in preparation for the startup of the newly built Plant 6 (Mason 1958a; Mason 1977; Eisenbud 1975; ORNL 1981; Mallinckrodt 1994). Mason (1977) also states that when Plant 6 started up, all uranium work at Plants 1 and 2 stopped and the buildings were sealed to await further cleanup (but see below).

Plant 1 was not used after about 1945 (ORNL 1981) or early 1946 (Mason 1977); the offices and laboratories apparently moved to Plant 6. In particular, administrative and related services moved from Building Z to Plant 6 at this time; however, the quality control services moved to a laboratory in Building 400 of Plant 4 (Mason 1977). Although as noted above the Plant 2 operating area was said to have been closed in 1946 when production moved to Plant 6, Mason (1958a) states that milling of  $UO_3$  and unloading of (some) pots was not discontinued at Building 51 (Plant 2) until about 1947 and ORAU (1977) states that this building was closed about January 1947. Thus it can conservatively be assumed that Plant 2 was in limited operation through 1946.

From late November 1942 through April 1943, Plant 4, a lumber sash and door works, was hastily converted for uranium processing (AEC 1951b; Mason 1958a) and dubbed "the metal plant" (AEC 1949b; AEC 1951b). It replaced the uranium metal production work done in Building 25-2 (Hickey and Dupree 1984). Production of uranium tetrafluoride ( $UF_4$ ) began in Building 400 in April 1943 after the process had been scaled up from the early work in Building 50 of Plant 2 (AEC 1951b; Mason 1977; Fleishman-Hilliard 1967). Production of uranium metal began in Buildings 400 and 401B in July 1943 (AEC 1951b; Mason 1977; Mallinckrodt 1994). Magnesium metal for the process was stored in Building 406, while the residues from the process (e.g., slag) were stored in Building 408 (Mason 1977). The principal production of metal moved from Plant 4 to Plant 6E in 1950 (Mallinckrodt 1994) although some metal was still produced in Plant 4 (AEC 1951b; Hickey and Dupree 1984) and some  $UF_4$  was still produced there until perhaps early 1953 (Hickey and Dupree 1984). After the development of a continuous furnace process,  $UO_2$ -to- $UF_4$  production moved to Building 705 of Plant 7 (7N) in late 1951 (overlapping Plant 4's production) (AEC 1951b; Fleishman-Hilliard 1967; Mason 1977 (which says that Plant 4  $UF_4$  production was completely shut down in 1951); Hickey and Dupree 1984; Mallinckrodt 1994). In about 1950 or 1951 (ORNL 1981 says 1956, but this is evidently incorrect), 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" (Mason 1977; ORNL 1981). The "dingot" metal production process was developed and conducted at Plant 4 in the mid-1950's (AEC 1956a; Fleishman-Hilliard 1967), along with sporadic ordinary metal "derby" production on a developmental basis. Plant 4 was used until 1956 (Mason 1977; ORNL 1981; Mallinckrodt 1994; FUSRAP 2003c).

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; ORAU 1983a; Mallinckrodt 1994)), Plant 6 was built in 1945-46 on a large site fronting on Destrehan Street (Mason 1958a; Fleishman-Hilliard 1967; Mallinckrodt 1994); it began operation in July 1946 and was then referred to as "the refinery" (AEC 1949b; AEC 1951b). Mason (1977) states that the choice of this site was based on proximity, security considerations, and space availability for constructing administrative and other support buildings that would enable the uranium operations to function as an independent unit. Most of the administrative offices, laboratories, and support facilities for the uranium refining operations were in fact located there. In early 1946, the ore-to- $UO_2$  part of the refining process was moved to Building 104 of Plant 6 from Plant 2 and apparently the laboratory work moved to Building 102 from Plant 1, while the  $UO_2$ -to-metal production remained at Plant 4 (FUSRAP 2003c; Hickey and Dupree 1984; AEC 1949b; 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 (1950c). Mason (1977) states that expansion of Plant 6 (new construction and production increases) continued through 1954.

In November 1947, Mallinckrodt cast 100 special billets for use by Hanford in an alpha extrusion experiment (AEC 1949d). These special billets contained higher nickel levels than usual and were prepared as part of the research into green salt production, in the belief that the new continuous green salt production reactor might give a product with higher levels of nickel than usual (AEC 1949f). From late 1947 to early 1948, Mallinckrodt was engaged in producing natural uranium castings for the Schenectady zero power pile (AEC 1949d). Also from late 1947 to early 1948, several tanks and centrifugal filters were added to the digest process line to allow the reprocessing of the radium (K-65) and barium sulfate residues and recovery of 95% of the 2% of the original uranium from the ore that was in these two residues (AEC 1949d; AEC 1948g). The K-65 and barium sulfate residues already stored in the St. Louis area were then returned from storage and processed. Subsequently this so-called C-3 process was used on all the K-65 residues produced and the companion process on all the barium sulfate residues produced (AEC 1949d).

The incoming ore arrived by rail and was stored in Building 110; however, in late 1950 or early 1951 an outdoor onsite ore storage area was added for pitchblende ore (Q-11) (AEC 1950i). 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). The new refinery process was designed to include the new operations developed in the laboratory and pilot plant, i.e., to recover radium and raffinates as separate residues and to remove sulfate as a barium sulfate cake (Mason 1977). In 1949, following laboratory and pilot-scale studies, a second digest line was added to Building 104 to process uranium ore (mill) concentrates (Mason 1977; Mallinckrodt 1994). This appears to have included a magnesia concentrate designated MgX or MGX and a calcium uranate concentrate designated CX, both of which were prepared in the Congo from low-grade tailings (AEC 1951b; AEC 1949f). Building 114 was used for temporary storage of residues until they could be transferred elsewhere (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 1949b). Pitchblende ore use was phased out over the period 1952-1954, after which the pitchblende digest line was placed on standby (Mason 1977). Feed concentrates were used exclusively from 1955 through the end of production in 1958 (Hickey and Dupree 1984).

When equipment was added to Plant 7 to allow continuous  $UO_3$ -to- $UF_4$  conversion, Plant 6 continued to produce  $UO_2$  until early 1953 and then began to produce only  $UO_3$  (Hickey and Dupree 1984; Mallinckrodt 1994). Milling of  $UO_3$  at Plant 6, milling of ore at Plant 6, and pre-digestion ore grinding, conducted initially at Plant 4 and later at Plant 6, were discontinued in 1950, mid-1949, 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 had become clear to AEC that process improvements to Plants 4 and 6 were not enough to bring about satisfactory control of dust and other hazards (AEC 1949b; AEC 1951b). As Mallinckrodt reminded AEC, Plant 6 had been built as an ordinary processing plant with no special provisions for health hazards because it was not expected to be used more than eight months (AEC 1951b; MCW 1950t). AEC 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 (MCW 1950e; AEC 1951b). Mallinckrodt and AEC agreed to build a new pair of plants that were located at the Destrehan Street site (AEC 1949b; Mason 1958a). The first was Plant 6E, the new metal plant, which was constructed from early 1948 to June 1950, began startup operations in June 1950, and went into operation in July 1950 (AEC 1949e; AEC 1951b; Mason 1977). Note that there was a laborers' and hod carriers' strike from 28 March into early April 1949 that slowed construction of Plant 6E (AEC 1949e; AEC 1949d). 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 (Mason 1977; Mallinckrodt 1994). An expansion project was started in March 1951 and finished in about September 1951 (AEC 1951b). 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 was constructed from November 1950 to March 1951 and was turned over to Mallinckrodt for operation in March 1951 (AEC 1951b). Note that AEC (1949b) appears to indicate that Plant 7 operations began in late 1952, while Mason (1958a) indicates a 1948 start date and Mason (1977) indicates a 1951 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. The buildings involved at first were Buildings 703 through 708 (Mason 1977). At Plant 7, a continuous process replaced the batch-type process used at Plant 4 and the  $\text{UO}_3$ -to- $\text{UO}_2$  production process at Plant 6, although  $\text{UO}_2$  could still be produced as needed (AEC 1951b; Mason 1977); however, Mallinckrodt (1994) states that it was only later that equipment was added to allow the continuous production of  $\text{UF}_4$  from  $\text{UO}_3$  directly.

Uranium metal recovery and some storage operations were moved to Plant 7 in late 1951 (AEC 1951a; AEC 1951b; Mallinckrodt 1994) or early 1952 (Mason 1958a). Some reversion of  $\text{UF}_4$  to  $\text{UO}_2$  or  $\text{UO}_3$  was done in 1953 and perhaps into 1954 (MCW 1953c). Building 700 was placed in service in 1954 to serve as a warehouse (Mason 1977). A new wet slag (interim residue) recovery operation was added in late 1955 in Building 701 (Mason 1977; Mallinckrodt 1994); this was apparently what was referred to as Plant 7W and may have been a pilot plant (Hickey and Dupree 1984). Some time in 1954 (Mason 1977) or in the late 1950's (Mallinckrodt 1994) machining of (nuclear) reactor core (elements) was done on a temporary basis in a fabrication facility in Building 700. In 1955, very low enrichment uranium (probably only a small amount) as  $\text{UF}_4$  was processed at Plant 7 (AEC 1955d) and in August 1956, about 5.5 kg of 20%-enriched uranium was processed, presumably in Plant 7 (MCW 1956e).

Plant 7E, whose sole building (712) was constructed as a temporary facility in 1954-1955 and which was 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; Mason 1977 says from 1955-1956) by an acid digestion process similar to the uranium ore digestion (AEC 1955e). The concentrate was sent to the Mound site for further processing.

A new facility to replace the so-called "Ledoux Laboratory" was completed in November 1952 (MCW 1953a). The purpose of this was to provide improved dust control for the sampling and processing of K-65, the radium-containing solid waste. Further improvements were made in 1953 (MCW 1953a). Other sampling and assay work was done, such as the evaluation of slugs produced by National Lead Company of Ohio from extruded rods that had been manufactured by the Bridgeport Brass Company from dingot billets apparently produced by Mallinckrodt (MCW 1956d).

In 1957 or 1958, all uranium refining operations ceased at all the plants (FUSRAP 2003c; 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  $\text{UO}_3$  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 already 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; Mason 1977, which says the work began in 1949); contaminated materials and some contaminated equipment were collected and delivered to AEC for disposal, while the rest of the contaminated equipment was transferred to Plant 6 (Mason 1977). After AEC was satisfied as to the completion status of the decontamination, AEC performed a final survey (Mason 1977), with presumably some touchups by Mallinckrodt and resurveys by AEC. In 1951, AEC released these plants to Mallinckrodt for unrestricted use and no further AEC work was performed there (Mason 1977; DOE 1981). Mallinckrodt (1994) states that further decontamination took place in 1954 and 1970. Some of these buildings were still extant as late as 1990 (Applied Nuclear Safety 1991). Plants 4, 6, 6E, and 7 were surveyed by AEC and Mallinckrodt in 1958-1959



and were decontaminated or taken down in 1959-1961 by Arch Wrecking Company (under contract to AEC), with safety and health coverage by Mallinckrodt (Mason 1977). Mallinckrodt performed a final decontamination survey for AEC during 1960-1961 (Mason 1977). The buildings removed during the takedown included all of the Plant 4 buildings and all wet-process buildings in Plant 6 (ORNL 1981; Mallinckrodt 1994) (see Table 1 for details). The site was released to Mallinckrodt without restriction in 1962 (ORNL 1981). These decontaminations were done to the AEC standards then in force, i.e., not to background levels (ORNL 1981; DOE undated). The remaining Plants 6, 6E, and 7 buildings were decontaminated to modern standards in the 1990's and demolished in 1997 (FUSRAP 2002).

Note that the term "Destrehan Street site" seems to have been used in documents 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. In distinguishing between these plants and the SLAPS airport site (see Section 3.2), these plants as a group will be referred to in this technical basis document as the Mallinckrodt St. Louis main site.

To summarize, work performed at the Mallinckrodt St. Louis main site 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  $UO_3$  coming from Hanford and other sites in the 1950's (DOE 1997; Mallinckrodt 1994; MED 1946a)
2. Production of  $UF_4$ , with some being shipped to Harshaw and K-25 (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 (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 or small-batch basis included the following.

1. Production of dingots using a thermite reduction process (Mallinckrodt 1994; Fleishman-Hilliard 1967; AEC 1956a)
2. Machining of metal rods for reactor fuel slugs (Mallinckrodt 1994; FUSRAP undated b)
3. Casting of special billets (ingots) and other special uranium castings (AEC 1949d)
4. 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)

5. Production of  $\text{UO}_2\text{F}_2$  (FUSRAP undated b)
6. Reprocessing of pitchblende residues to recover uranium (AEC 1949d; AEC 1951b)
7. Recycling of slag for use as liner material in the processing of uranium metal
8. Extraction and concentration of Th-230 from pitchblende raffinate (FUSRAP undated a; FUSRAP undated b; Mallinckrodt 1994; AEC 1955e)
9. Experimental processing of very low enrichment  $\text{UF}_4$  (FUSRAP undated b; Mallinckrodt 1994; ORNL 1981) and some 20% uranium metal (MCW 1956e)
10. Production of small research quantities of uranyl nitrate hexahydrate (UNH)(AEC 1951b); conversion of small research quantities of aqueous uranyl nitrate hexahydrate to  $\text{UO}_3$  (DOE 2000)
11. Production of  $\text{U}_3\text{O}_8$  and  $\text{UO}_2$  using an experimental continuous denitration furnace (Mallinckrodt 1994)
12. Experimental extraction of uranium using tributyl phosphate (TBP) to replace ether (Mallinckrodt 1994), apparently in a pilot plant circa 1950-1951
13. Miscellaneous analysis and assay work (e.g., MCW 1956d)

DOE (2001b) states that from 1946-1955, personnel provided by Ledoux and Co. of New York performed uranium ore assays at the Mallinckrodt St. Louis main site and FUSRAP (2003b) states that this work was done in the "Ledoux Laboratory" located in Buildings 110A and 111 of Plant 6. However, from MCW (1954a) and other contemporary references, it appears that only the K-65 residue assays were done in the Ledoux Lab, which work had been contracted to Ledoux by African Metals (ORAU 1989a), which retained the rights to the radium in the residue. 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 (1944p) 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), soda salt (sodium diuranate, or  $\text{Na}_2\text{U}_2\text{O}_7$ ),  $\text{UO}_3$  (orange oxide), and  $\text{UO}_2$  (brown oxide) was done under AEC/MED Contract W7401-Eng 1;  $\text{UO}_2$  and  $\text{UF}_4$  (green salt) under Contract W7405-Eng 29, 1st Phase; and  $\text{UF}_4$ , biscuit metal (uranium derbies), slag processing, ingots (billets), croppings, sawdust processing, and other metal production under Contract W7405-Eng 29, 2nd Phase (MED 1945a; MED 1944p).

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 1949h); 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. Because this work was done commercially and not for the AEC (FUSRAP 2003a), it is not considered to fall in the category covered by EEOICPA.

### **3.2 HISTORY OF USE OF THE ST. LOUIS AIRPORT STORAGE SITE (SLAPS OR SLAPSS)**

The main supplier of the pitchblende ore to MED, the African Metals Company, retained ownership of the radium and valuable metals remaining in the residues after the ore was processed (AEC 1959). Thus by contract, MED was required to store the radium-bearing residue (K-65 or gangue lead cake) and the metal-rich barium sulfate cake residue until they could be transferred to African Metals (AEC 1959). From 1942 to 1945, the residues and other solid wastes were stored temporarily at the Mallinckrodt site and then shipped to the Lake Ontario Ordnance Works. Because of the volume of the residues and the high gamma dose rate and radon emanation rate of the K-65 residue, MED obtained consent in March 1946 to use for residue storage purposes a 21.7-acre tract of land located in Robertson, Missouri north of the former St. Louis Municipal Airport (also known as Lambert Field) (AEC 1959). In January 1947, MED obtained title to the property by condemnation (AEC 1959). This storage area was formally called the St. Louis Airport Storage Site (SLAPS or SLAPSS), but in Mallinckrodt and MED/AEC documents it was often referred to simply as "the airport". The SLAPS site was operated by MED/AEC from 1946 until July 1953 (AEC 1959; ORNL 1979), when the operation was turned over to Mallinckrodt (AEC 1959); Mallinckrodt then ran the site under contract to AEC from July 1953 to 1958 and possibly until it was turned over to a private concern that assumed control of it under an AEC license (AEC 1959; ORAU 1989; AEC 1972). Although AEC owned SLAPS, Mallinckrodt workers appeared to have been doing the residue delivery and placement work even in 1946-1953 (MCW 1949d; MCW 1949p).

Initially, it was only the radium-bearing waste residues (K-65), the barium sulfate residues (AJ-4), and the pitchblende raffinates (AM-7 or "airport cake") produced at Mallinckrodt that were stored at SLAPS (Mallinckrodt 1994). Later, SLAPS was also used to store other types of residues and wastes and some ore and to serve as a storage and burial site for contaminated objects and debris (AEC 1959; AEC 1956d; Mallinckrodt 1994; AEC 1948e; AEC 1949m). The ore was stored there as part of AEC's strategic stockpiling program (AEC 1949d). The other types of residues included the residue left after reworking of the AM-7, called AM-9; Colorado (domestic non-pitchblende) ore raffinate; and a residue formed from the precipitate of the first-phase ether extraction columns ("Sperry cake", apparently a synonym for or subset of the AM-7) (AEC 1956e; AEC 1964; Mallinckrodt 1994). Metal scrap, dolomite slag ("C-liner" or "C-oxides"), and tailings of uranium scalping operations from magnesium fluoride slag (the latter two from the derby metal production) were also sent to SLAPS (Mallinckrodt 1994). Some of the debris buried at the site appears to have been from the decontamination and decommissioning of the Plants 1 and 2 area in 1948-1950. From perhaps mid-1948 on, pitchblende ore (Q-11) was stored at SLAPS (MCW 1949p).

In 1948 and 1949, the K-65 residue was brought back from SLAPS in lots to be “reworked” (reprocessed to recover more uranium) (AEC 1959), after which it was sent to the Lake Ontario Ordnance Works (AEC 1959). The drums in which it had been stored were returned to SLAPS for storage. From 1955-1957, most of the AM-7 was brought back from SLAPS to be processed to recover Th-230 as a solution that was sent to Mound; the resulting residue, AM-9, was sent back to SLAPS (AEC 1959). Also in 1955, the tailings (D-701) from the processing of the magnesium fluoride slag produced in the metal plant were stored at the site (AEC 1959) or at SLAPS (AEC 1956d; Mallinckrodt). The barium sulfate cake remained at SLAPS because eventually African Metals relinquished ownership of it (AEC 1959).

In 1952, some of the western part of the SLAPS plot, where contaminated metal and debris was buried (presumably from the decontamination of Plants 1 and 2), was filled in deeply with earth (AEC 1964). In April 1959, a railroad siding and loading facilities were installed (AEC 1959), apparently in preparation for moving out the residues and other material (AEC 1959); the tailings from the magnesium fluoride slag processing were then sent to the Fernald site (AEC 1959). In about 1959-1960, some of the scrap and rubble from the demolition and decontamination of the Mallinckrodt St. Louis site facilities was buried at the west end of the site (AEC 1972; ORNL 1979). At some point, a building consisting of a changeroom, a shower, and office space was moved to the site (AEC 1959; AEC 1964); it is not clear when this occurred, but since earlier references mention only a truck wash pad as a cleanup area, the building was likely not installed until the burial activities of 1959-1960 took place.

In March 1962, AEC issued an invitation to bid on the residues and on September 1962, AEC issued a license to the successful bidder, a commercial entity, to possess and remove 125,000 tons of uranium and thorium residues stored at SLAPS and at the licensee’s processing facility. Although this is taken to be the end point for dose reconstruction purposes, some further history of the site will be given below in case it is later necessary to choose a different end point.

The 1962 license was terminated in February 1966. This was possibly due to the licensee’s going out of business (AEC 1967). A new license was issued to a new purchaser in 1966. In 1966-1967, this purchaser moved the residues from SLAPS (AEC 1967, FUSRAP 2004a) to a site at Latty Avenue in Hazelwood, Missouri (AEC 1967); this was said to have required ten dump trucks operating for five months to move a total of 100,000 tons of residue (AEC 1967).

AEC apparently proposed to the City of St. Louis that the city take over the site, specifically the city-owned airport management organization. Thus in 1969-1970, under a November 1969 acquisition permit from AEC and with some radiological support from the City of St. Louis Health Department, the St. Louis (Lambert) Airport Authority demolished the structures on the site and excavated some of the contaminated earth (AEC 1969; AEC 1972; ORNL 1979; FUSRAP 2004a). Excavated material, including some residual barium sulfate residues, was trucked to the AEC quarry at Weldon Spring (AEC 1969; AEC 1972), while the demolished structures, including the concrete floors and pads, were buried at the site and clean fill was placed over the entire site (AEC 1972). More fill was placed over several areas following a radiation survey performed in December 1969 to meet the requirements of the permit (ORNL 1979). In November 1971, AEC representatives performed a satisfactory final radiological survey of the site (AEC 1972; ORNL 1979).

In 1973, AEC relinquished ownership of the site to the St. Louis Airport Authority by quit claim deed (FUSRAP 2004a). After that, access was controlled by the St. Louis Airport Authority and casual entry was precluded (ORNL 1979). Over the period from about 1972 through 1978, the site served as an isolation or buffer space on the side of a runway approach at the adjacent airport and it was also used as a dump site for nonradioactive rubble from the airport; the fence remained in place, but the

area was not patrolled (AEC 1979). Without maintenance, the site deteriorated, in that erosion occurred and minor contamination was transported to the drainage ditch that surrounded the site outside the fence and to the creek that traversed the lower end of the site (AEC 1979). This was shown in the radiological characterization surveys performed by Oak Ridge National Laboratory (ORNL) for AEC in November 1976 and August 1978 (ORNL 1979; AEC 1979). On the basis of these surveys, it was decided that remedial action was required (AEC 1979; FUSRAP 2004a) and in 1981 the drainage ditches along the north side of the site were designated for remedial action under FUSRAP (2004a).

The residues that had been sold and taken out of the site went to the Latty Avenue (St. Louis) site to await processing by the purchaser; however, the purchaser went bankrupt before processing actually began. Under a Nuclear Regulatory Commission (NRC) license, the Cotter Corporation then dried the residues in a kiln at the Latty Avenue site and sent them off to their Colorado facility. However, the Latty Avenue site was not properly decontaminated before the NRC license was terminated and the site was sold to a private purchaser. After an ORNL survey at the Latty Avenue site, the owner was advised by NRC to stop property development and the NRC asked the Department of Energy (DOE) to allow materials from the future decontamination of the site to be taken to the Weldon Spring Plant (AEC 1979). However, DOE considered the Weldon Spring raffinate pit to be unsuitable for permanent disposal of these materials. NRC then suggested that the material be returned to SLAPS and DOE agreed, providing that this could be done in an environmentally acceptable manner (AEC 1979).

Eventually, the US Congress, via the Energy and Water Development Appropriate Act of 1984 (Public Law 98-360), directed DOE to reacquire and stabilize the SLAPS site and to use it as a storage and disposal site for the Latty Avenue materials (Bechtel 1987; DOE 1986). Although it postponed acquisition of the site even after being directed to do so by Congress, DOE had begun to have routine monitoring of SLAPS done by Bechtel National Incorporated in 1983 and as of 1987 was planning to dispose of the waste materials from the Hazelwood Interim Storage Site (including the Latty Avenue materials) at SLAPS eventually (Bechtel 1987). In October 1989, the Environmental Protection Agency (EPA) placed SLAPS on the National Priorities List, which meant that the cleanup would proceed according to the guidelines of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) (FUSRAP 2004a). DOE then began to work with EPA to determine how to clean up the site and where to put the contaminated soil (FUSRAP 2004a). The two agencies signed an agreement establishing an environmental review process and remediation schedule, with one of the options to be considered being storage of the SLAPS and HISS materials at SLAPS; DOE declined to accept SLAPS back from the City of St. Louis until the CERCLA review process was completed (FUSRAP 2004a).

In 1990, the St. Louis Board of Aldermen approved a plan to transfer SLAPS to DOE on condition that a permanent disposal cell for radioactive wastes would not be constructed on the site (FUSRAP 2004a). In 1994, DOE formulated a remediation plan and presented it to the St. Louis community. The community rejected it because it included a disposal cell at SLAPS, contrary to the terms of transfer enacted by the board of aldermen; the site was therefore never transferred to DOE and it appears unlikely that it will ever be (FUSRAP 2004b). However, as of July 2004, FUSRAP was working to develop a Record of Decision to document the final cleanup remediation plan for the North County sites, including SLAPS – a plan that did not include a disposal cell at SLAPS (FUSRAP 2004b).

#### **4.0 DESCRIPTION OF THE MALLINCKRODT URANIUM REFINING PROCESS, OTHER PROCESSES, AND SLAPS STORAGE AND DISPOSAL ACTIVITIES**

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.

It is also important to understand the nature of the work performed at SLAPS in order, again, 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 discussion of SLAPS work is included in the discussion of Mallinckrodt-produced residues (Section 4.7 below).

#### **4.1 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 in nitric acid in a digestion vessel or tank (MED 1946a; AEC 1949b; AEC 1967; Fleishman-Hilliard 1967). Sulfuric acid was added to the solution in the vessel to precipitate the radium and lead as sulfates (MED 1946a; AEC 1949b; AEC 1951b; AEC 1967; Fleishman-Hilliard 1967). The uranium was left in solution as uranyl nitrate and the precipitate was filtered out (MED 1946a; AEC 1949b; Fleishman-Hilliard 1967) using a string-discharge rotary vacuum filter (AEC 1967) referred to as a Feinc because of the name of its manufacturer (Federal Engineers Incorporated or FE Inc). The filtered solids formed a radium-bearing residue referred to as the K-65 residue (AEC 1949b; AEC 1967) 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 1949b; AEC 1951b; AEC 1967; 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 1949b; AEC 1967). 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 to concentrate it (MED 1946a; AEC 1951b). 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 1967; Fleishman-Hilliard 1967).

Second, uranium oxide as  $UO_3$  was produced from the solution, as follows. In the two-step ether extraction process, diethyl ether was added to the solution in extraction columns; the double extraction was to remove the acid-insoluble molybdenum (AEC 1951b). 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 1949b; AEC 1951b; AEC 1967; Fleishman-Hilliard 1967). Eisenbud (1975) stated 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 1949b; Fleishman-Hilliard 1967). The molten salt was then directed in batch form to gas-fired denitration "pots" or boil-down vessels, which were continuously heated and agitated so as to produce the dissociation of the hexahydrate and the formation of  $\text{UO}_3$  (also called orange oxide or QM-2) (MED 1946a; AEC 1949b; Fleishman-Hilliard 1967). The  $\text{UO}_3$  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 1944o).

Third, the  $\text{UO}_3$  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  $\text{UO}_2$  (also called brown oxide or LF-9), a step that took about 7 hours (MED 1949b; MED 1946a; AEC 1949b; Fleishman-Hilliard 1967). Usually the  $\text{UO}_2$  was further processed at Mallinckrodt, but some was shipped to non-Mallinckrodt sites such as Harshaw (DOE 1997).

Fourth, the  $\text{UO}_2$  was converted to  $\text{UF}_4$ , as follows. The  $\text{UO}_2$  was removed from the fiber containers and placed into large stainless steel drums for temporary storage (AEC 1949b). As needed, it was removed onto steel (later monel) trays and weighed (MED 1946a; AEC 1949b; Fleishman-Hilliard 1967). The trays were then set into airtight graphite or nickel boxes and placed in a hydrofluorination reactor (MED 1946a; AEC 1949b; 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 (HF) was passed over the  $\text{UO}_2$ , forming  $\text{UF}_4$  (also called green salt or TA-7) and water (MED 1946a; Fleishman-Hilliard 1967). The  $\text{UF}_4$  was unloaded and put through a pulverizer or mill and then a blender, followed by packing into metal containers (AEC 1949b). Most of the  $\text{UF}_4$  was further processed at Mallinckrodt, but some was regularly shipped to non-Mallinckrodt sites (DOE 1997; AEC 1949b); MED (1946), however, implies that all of the  $\text{UF}_4$  produced at Mallinckrodt was also further processed there. Excess HF was neutralized with lime or potassium hydroxide solution to recover uranium (Mason 1977).

Fourth, the  $\text{UF}_4$  was converted to uranium metal, as follows. The  $\text{UF}_4$  was blended with magnesium powder and mixed in a tumbler (AEC 1949b; Fleishman-Hilliard 1967; Mason 1977). A special firing container (the "bomb") was lined with a refractory material, variously reported to be lime (1945, per MED 1946a); dolomite (from 1946 on, per FUSRAP undated a, or 1942 on, per Fleishman-Hilliard 1967); or recyclable magnesium fluoride from about 1954 on (FUSRAP undated a; Fleishman-Hilliard 1967). The bomb was "jolted" (shaken) on a mechanical jolter until the liner was packed sufficiently hard. 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  $\text{UF}_4$  to uranium metal in this process (MED 1946a; AEC 1949b; Fleishman-Hilliard 1967). The molten mass formed a "derby" or "biscuit" of solidified metal as it cooled (MED 1946a; AEC 1949b; Fleishman-Hilliard 1967). (The derby form was also called KB-2 and there were subtypes of derbies called Number 1 Number, etc.) After the bomb cooled, the derby was taken out by "breaking out" the bomb shell (Mason 1977) and the slag on the derby was chipped off pneumatically, crushed, and sent to uranium salvage (recovery), first to Vitro and eventually to onsite recovery (MED 1946a; AEC 1949b; Fleishman-Hilliard 1967; Mason 1977).

Finally, the metal derbies were remelted and cast in an induction-heated, high-vacuum furnace (a process 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

1949b; 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 1949b; Fleishman-Hilliard 1967). A sample was taken from the billet by power hacksaw (AEC 1949b) and the billets were sawed to suitable lengths (presumably only when necessary) (Mason 1977). The billets were then packed, stored temporarily in Building 400 (Mason 1977), and shipped to the appropriate non-Mallinckrodt site for further processing (MED 1946a; AEC 1949b; Mason 1977).

The nitric oxides produced as offgasses in the pots were sent to a recovery system (MED 1946a; AEC 1949b; 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 1967).

The precipitate from the first extraction column was on occasion dewatered using a Sperry filter press, producing a supernate and a batch of cake called Sperry cake (AEC 1967). The supernate from the press and the aqueous uranium tails from the wash were de-etherized and treated with a hydrated lime slurry (AEC 1967). 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 AM-7, called "airport cake" (AEC 1967), from its being stored for several years at the AEC's SLAPS site that had been an airfield. Note that the Sperry cake appears to be a subset of the AM-7 or perhaps synonymous with it. Also, several other types of cake (e.g., the barium sulfate cake) were also referred to loosely as "airport cake" due to their being sent there for storage.

#### **4.2 THE WARTIME PERIOD (APRIL 1942– APRIL 1945)**

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 (DOE 1997; AEC 1967; 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, during the same month (Fleishman-Hilliard 1967). Mason (1977) stated that there were no wet processes in Plant 4 (ever).

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). The ore had to be ground to "four mesh" size for optimum digestion as well, if the ore particle size was larger (MCW 1947). Little information is available as to how or where the early milling and grinding operations were performed, but it was apparently in Plant 2 (see Table 1), later in Plant 4 (AEC 1945f; AEC 1945h; AEC 1945i), and still later in Plant 6 (e.g., MCW 1950e). Some soda salt was also used as feed material (DOE 1997). Note that the radium-lead precipitation step was necessary for the high-radium pitchblende ores, but not necessarily for other types of ore.

Plant 4 began production-level  $UO_2$ -to- $UF_4$  conversion in April 1943 and production-level  $UF_4$ -to-metal production in July 1943. The ore→ $UO_3$ → $UO_2$  conversion continued to be done in Plant 2. MED (1942) stated that the ether extraction was done by a completely enclosed process of "recirculating" and that a solution of purified uranyl nitrate was boiled in large open receptacles to decompose the



nitrate and produce the  $\text{UO}_3$ . The  $\text{UO}_3$  was then ground and sifted to yield the appropriate size for “roasting” in a furnace to produce the  $\text{UO}_2$ .

AEC (AEC 1951b) stated the following. The process of refining pitchblende ore by using nitric acid, including the radium removal technique and acid extraction were developed by Yale University but expanded to production scale by Mallinckrodt during this period; also, double extraction to remove molybdenum when pitchblende ores were processed and the balance of the processing to  $\text{UO}_3$  were developed by Mallinckrodt. The  $\text{UO}_2$  hydrofluorination process was developed by DuPont and Harshaw, while the process for reduction of  $\text{UF}_4$  to uranium metal was developed by Iowa State College at Ames. The research for the continuous  $\text{UO}_3$ -to- $\text{UF}_4$  process was done by Mallinckrodt.

### **4.3 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 4 (AEC 1945f; AEC 1945h; AEC 1945i) and then to Plant 6 after the latter began operation in 1946. Because of the dust hazards of the pitchblende ore, AEC had Mallinckrodt develop a method to permit automatic unloading and loading of the pitchblende ore in the grinding operation (AEC 1948f). 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 after that apparently still had to be ground to some extent (e.g., AEC 1947a).

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. There was apparently still some possibility of “splatter or slopping over” at some point if the chemical reaction was too violent, but this would not be true of the column extraction process because it was completely enclosed (AEC 1949e). The sulfur removal step was added when ores containing high levels of sulfur were used. However, the removal of products such as  $\text{UO}_3$  and  $\text{UO}_2$  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 ( $\text{UO}_2$ ,  $\text{UO}_3$ , and  $\text{UF}_4$ ) produced as particles and chunks of material. Also, during the first year of operation (1946-1947), it had become apparent that not all of the uranium in the pitchblende ore was being dissolved in the nitric acid step, but was remaining in the “K-65” or gangue sludge residue that was to be stored and returned to African Metals Company; a process was developed and installed in 1948-1949 to allow greater capture of the uranium from the ore (see Section 4.7).

It was realized that the  $\text{UO}_2$ -to- $\text{UF}_4$  production in Plant 4 was particularly problematic from a dust point of view and AEC therefore had Mallinckrodt embark on an experimental program to produce a continuous-process reactor for the production of  $\text{UF}_4$  (AEC 1948f).

#### 4.4 THE LATER POSTWAR PERIOD (1950–1958)

Milled ore was sent from Middlesex to Mallinckrodt up to 1955, when the Middlesex work was transferred to the Fernald plant, which thereafter was the sender of milled ore to Mallinckrodt ((DOE 1997). An Ore Room and addition were added by 1950 to Plant 6. Early on, there was grinding of ore in a rod mill and opening, dumping, cleaning, and closing of drums (MCW 1950u); later, the duties of the operator included opening (deheading) and cleaning ore drums (AEC 1953). Hence this was not simply a storage area. During 1950, the average concentration of raw materials arriving at Mallinckrodt dropped to less than 50% (as  $U_3O_8$ ), compared to ~65% during 1947-1949 (AEC 1951b). This was due to a gradual decrease in the content of the pitchblende and to the introduction of the magnesia concentrate MgX, which was produced from low-grade tailings. The new feeds had higher impurity content and the MgX contained 25-30% moisture compared to the normal pitchblende content of less than 3%. In order to maintain the production level, a new extraction column was designed and installed by Mallinckrodt in December 1950 to permit direct solvent extraction of the MgX slurry without prior filtration.

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. In late 1950 or 1951, in order to increase production, Plant 6E was placed in six-day, three-shift operation as quickly as new crews could be trained (AEC 1951b), while Plant 7 was designed to operate on a six-day, three-shift schedule.

AEC (AEC 1951b) stated the following. In 1951, the Plant 4  $UO_2$ -to- $UF_4$  conversion equipment consisted of six large gas-fired furnaces containing five reactor banks each. The individual reactors were composed of a graphite tray assembly inside of a steel shell. The Plant 4  $UF_4$ -to-biscuit equipment included six individual gas-fired furnaces, and the biscuit-to-ingot conversion equipment included four high-vacuum induction furnaces. The Plant 6E  $UF_4$ -to-biscuit equipment included 16 electrically heated induction furnaces and the biscuit-to-ingot equipment included six ultrahigh-vacuum furnaces. In Plant 6E, operations were mostly remotely controlled and/or totally enclosed, for health and safety reasons. In Plant 7, there were three parallel reactor banks, each made up of one  $UO_3$ - $UO_2$  reactor tube and three  $UO_2$ - $UF_4$  reactor tubes, with the four reactors making up the bank operated in series. Each reactor tube was equipped with a ribbon screw that moved the material continuously through the reactor into the feed area for the next tube. A single  $UO_3$ - $UO_2$  tube was installed to provide for the production of  $UO_2$  alone. The later expansion called for additional  $UO_2$ - $UF_4$  tubes to be added.

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 1956b). 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).

The Plant 6E operations became more enclosed and more mechanized over the years. In 1955, the billet (ingot) postprocessing grinding and inspection method in Plant 6E was described as follows (MCW 1955q); it is likely that this was the method used from the start but with the addition, over time, of the grinding enclosure for operation. The operator moved the billet from the water cooling tank into grinding position by means of a remote-controlled hoist. Through canvas gloves installed in the enclosure wall, he ground off the fin (raised line) from the mold joint. Using a remote-controlled piston, he then ejected the billet from the grinding rollers on the scale through a small opening in the enclosure. Using a rag, he wiped off the excess black oxide as he rotated the billet slowly, checking it for defects. He then moved the billet by hoist onto the billet cart to move it to the saw for a sample to be taken.

An alternative method of producing the metal form was developed at Plant 4 in the mid-1950's. This process (AEC 1956a; Fleishman-Hilliard 1967) took the  $UF_4$  to the final cast (ingot/billet) form in one step instead of two, eliminating the need for recasting and the associated impurity contamination. 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  $MgF_2$  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 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 to have 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.

Feed forms and quantities used for a period in 1955.

	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

A list of process cells, dust collectors, and tanks appears in MCW (MCW 1955g).

#### 4.5 OTHER PROCESSES

Some uranium recovery operations consisted 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 (from the sawing of uranium metal billets) was stored under oil until it could be processed in this way and converted to ingots (Fleishman-Hilliard 1967; MED 1944o; MED 1944p); the sawdust was also recovered by oxidizing it at high temperature to  $U_3O_8$ , and was then sending it back to Plant 6 as a feed material (AEC 1949g). As mentioned earlier, some uranium was recovered from neutralizing excess HF in the  $UF_4$  production process (Mason 1977).

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 on 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 (1956d), 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" or "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.

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). See Sections 5.2.1-5.2.3 for more details. The ore areas and residue storage areas appeared to be separate from the product warehouse areas, 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 in an AEC Plant 7 air dust study report (AEC 1954g) to the work of a panel board operator's work: 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 often the "C-" designated scrap material or waste material captured in a dust collector. Later such AEC reports also mention that the reverter was being used by this operator (AEC 1955d, AEC 1956b) but not an earlier report (AEC 1952a), 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 1955e). 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 have been of a routine process nature.

There was no information at all about the production of  $UO_2F_2$  or the processing of (supplied) uranyl nitrate hexahydrate, both 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 1955d) regarding an 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 thermally, resulting in a better separation of slag and metal.

An experimental permit was issued in July 1956 that allowed the pickling of 14 tons of high-carbon scrap metal in Plant 6, which was done on 29-30 July 1956 without the health and safety department's knowledge (MCW 1956f). It is not known if any more of this work was done.

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.

Regarding specific laboratory sampling and assay processes, there is limited information available. This is given in Section 5.2.4.

#### 4.6 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 ( $Na_2U_2O_7$ ), also called soda salt, some of which was sent to Mallinckrodt for refining to  $UO_2$  and  $UO_3$  (DOE 1997, MED 1945a; MED 1943e); other soda salt may have come from Belgium and Port Hope, Ontario (MED 1943e). 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 1956e; AEC 1959), when the plant switched to processing various types of concentrates. However, MED (1943e) 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 1967), the so-called African ore. There is some disagreement as to how it came to St. Louis. DOE (1997) states that from 1943 on, the receiving and storage facility operated at Middlesex, New Jersey (DOE 1997) assayed, crushed, riffled, and redrummed the ore as it came into the United States, then sent it to the various refineries, including Mallinckrodt (AEC 1949b, Eisenbud 1975). MED (1945n) states that the African ore came through the Eldorado (Port Huron, Canada) area for processing before being sent on to the US refineries. AEC (1967) states that the concentrate was shipped from the Belgian Congo to St. Louis in 55-gallon drums (but this could mean that it came by way of Middlesex). Whatever the case, it was not likely that significant milling of this ore (as opposed to simply grinding to somewhat smaller size) was done at Mallinckrodt. In any case, it arrived by rail in carload lots and was stored in Building 110, the warehouse (Mason 1977).

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. The ore was usually stored in the warehouse or in another dedicated area on site, but presumably because of the volume of the pitchblende ore (Q-11) and its hazards, from about mid-1948 on at least some of it was stored at SLAPS (AEC 1949d) in a dedicated shed or shack (MCW 1949g; AEC 1949d, which states that ten 25-ton lots were shipped to Mallinckrodt in May 1949 and an additional twelve lots were sent to SLAPS).

From 1955 on, ore concentrates were mostly used. This included some Belgian Congo ore tailings concentrates (resulting from the leaching of raw ore during pre-processing in the Belgian Congo in previous years before the ore was shipped as a concentrate) (AEC 1951b). Soda salt 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 1956b) and as noted Vitro also supplied soda salt until it was shut down.

#### **4.7 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 1967); thus the external exposure implications of handling residue waste depended on what kind of waste it was.

From 1942-1945, MED solid wastes were stored temporarily at the Mallinckrodt site and then shipped to the Lake Ontario Ordnance Works in Lewiston, New York (Mallinckrodt 1994). The radium-bearing pitchblende residues (K-65 or gangue lead cake) were shipped by rail to the Middlesex, New Jersey repository for storage for a time, up to 1946 (AEC 1949b). But from the time AEC acquired the SLAPS site in 1946 and up through 1948, all residues produced at Mallinckrodt were stored temporarily in Building 114 of Plant 6 until they were shipped by truck to SLAPS (MCW 1949p; AEC 1967; Mason 1977; Mallinckrodt 1994). From 1948 to at least 1949, the K-65 residues were shipped to Middlesex (AEC 1949b) or to the Lake Ontario Ordnance Works (AEC 1959) after being drawn back from SLAPS and reprocessed. After about 1949, K-65 was shipped to the Lake Ontario Ordnance Works (FUSRAP undated a; AEC 1959; AEC 1949b); although Mallinckrodt (1994) says that these were still sent to SLAPS up to 1956, it was clearly only the other types of residues and wastes that were sent after 1949, not the K-65. Some uranium scrap, including the mainly magnesium fluoride

slag immediately above the derby (in the metal reduction step) was sent to the Vitro Manufacturing Company for uranium recovery (AEC 1949b).

Initially, it was only the K-65, the barium sulfate residues (AJ-4 or "airport cake"), and the pitchblende raffinates (AM-7) produced at Mallinckrodt that were stored at SLAPS (Mallinckrodt 1994). The K-65 was trucked in drums (AEC 1947a), while the barium sulfate (AJ-4) and pitchblende raffinate (AM-7) cakes were collected in dumpster-type containers, loaded into AEC dump trucks, and transported on a daily basis to SLAPS (Mallinckrodt 1994). The K-65 drums were stored in a dedicated shed structure (AEC 1947a), but the other residues were simply dumped on the ground in piles (AEC 1947f; AEC 1947a; AEC 1947e; AEC 1949b) because they were insoluble in water and were thus regarded as fairly immobile (AEC 1947a).

Later, SLAPS was also used to store other types of residues and wastes and some ore and to serve as a storage and burial site for contaminated objects and debris, such as empty drums, Rauschig rings from the ether extraction columns, bituminous floor materials, and some materials from the decontamination and decommissioning of Plants 1 and 2 (AEC 1959; AEC 1956d; Mallinckrodt 1994; AEC 1949m). As noted earlier, the other types of residues included the AM-9 residue left after reworking of the AM-7 to recover thorium; Colorado (domestic carnotite and other low-grade non-pitchblende) ore raffinate (AM-10); and the precipitate residue of the ether extraction columns ("Sperry cake", apparently a subset of the AM-7) (AEC 1956e; AEC 1967; AEC 1964; Mallinckrodt 1994). There were also small amounts of other raffinates present at the SLAPS waste storage site from the processing of lower-grade uranium ores (AEC 1967). The material obtained from processing carnotite and other low-grade domestic ores was kept separate from the K-65 (AEC 1967).

Metal plant waste, such as metal scrap, dolomite slag ("C-liner" or "C-oxides"), and tailings of uranium scalping operations from magnesium fluoride slag were also sent to SLAPS (Mallinckrodt 1994). The C-liner consisted was mainly used and nonrecyclable dolomite liner with less than 2% uranium content (FUSRAP undated b; AEC 1949b) and 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 1949b), 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).

Within the Mallinckrodt plants, most "product" ( $\text{UO}_3$ ,  $\text{UO}_2$ , and  $\text{UF}_4$ ) 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 1944o). Also sent to a recovery system were floor sweepings and spillages, swept into sumps; scrapings off the walls and equipment; and dust collected in collectors, usually by vacuum systems (MED 1944o).

Some reprocessing of residues was also done to recover uranium. AEC (1951b) states that following the development and installation of a sodium carbonate/sodium bicarbonate leach process in 1948-1949 to recover more of the uranium, the K-65 produced up to that point was brought out of storage at SLAPS in lots and reprocessed in about 1949 (MCW 1949o and AEC (1959) imply 1948-1949), resulting in a final uranium content in the residue of 0.05%. This was apparently done in the same vessels and in the same general manner as ore would be processed, including heating the K-65 drums in the thawing oven used to thaw ore drums (MCW 1949o). The new residue was sent to the Lake Ontario Ordnance Works (AEC 1959) to await return to African Metals and the corroded drums in which the K-65 had been stored were returned to SLAPS for storage (AEC 1949m). At least some of the barium sulfate cake was reprocessed similarly (AEC 1951b; AEC 1948g); however, the



resulting barium sulfate residue was taken back to SLAPS because (eventually) African Metals relinquished ownership of it (AEC 1959). Some of the Sperry Cake, a good source of protactinium-231, was brought back from SLAPS and shipped to Mound, which processed approximately 20 tons (about eighty 55-gallon drums) of it and obtained approximately two grams of protactinium-231 (AEC 1967).

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 1967; FUSRAP undated b). Starting in 1955, the thorium-bearing AM-7 raffinate residue was brought back from storage at SLAPS, stored at Plant 6, and conveyed by dumpster from Plant 6 to Plant 7E as needed (AEC 1955b). The processing was first done on a crash basis in early 1955, apparently on a laboratory level (AEC 1955c; ORAU 1991), to produce a solution containing several hundred grams of thorium. Mallinckrodt later undertook the process on a pilot scale, but insisted on only a limited number of workers and strict safety precautions (ORAU 1991). The resulting residue, AM-9, was sent back to SLAPS (AEC 1959).

AEC (1955b) described the thorium solution extraction process as follows. The AM-7 was first digested in nitric acid in a tank and filtered. The resulting "liquor" was then processed in a TBP (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 (apparently in solution). The thorium fluoride was sent to the Hot Lab in Plant 6, where it was treated with aluminum nitrate ( $\text{Al}(\text{NO}_3)_3$ ) and a pentaether-ether mixture, forming thorium nitrate ( $\text{Th}(\text{NO}_3)_4$ ) 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-9, was sent back to storage at SLAPS. From the beginning of 1955 into 1957, a total of 350 tons of the AM-7 was processed (AEC 1959; AEC 1967). (ORAU 1991 says the processing was performed in 1958, but this seems unlikely). Note that the Th-230 was also called "ionium" and was referred to that way in Mallinckrodt records.

As noted earlier, significant earthmoving operations to cover buried contaminated items were done in 1952 (AEC 1964); the tailings from the magnesium fluoride slag processing were sent to the Fernald site in 1959 (AEC 1959); and in 1959-1960, some of the scrap and rubble from the demolition and decontamination of the Mallinckrodt St. Louis site facilities was buried at the site (AEC 1972; ORNL 1979). 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 1949b). A small additional amount of acid waste flowed to the Mississippi via an acid sewer (AEC 1949b); Mason (1977) states that excess HF (from  $\text{UF}_4$  production) was neutralized with lime or potassium hydroxide and sent to process sewers, so it is unclear what the acid referred to by AEC (1949b) might have been. 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).

## 5.0 RADIOLOGICAL CHARACTERISTICS, CONDITIONS, CONSIDERATIONS, AND AVAILABLE DATA

As AEC (1950a) observed, radiation measurements or evaluations of dust exposure for the purpose of dose determination were not 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. Thus only a few instantaneous measurements were made and time-weighting was generally not considered. 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" with respect to the long term (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 1945 and a formal dust measurement program in 1948 (AEC 1950a). Although urinalysis for uranium was done as a "screening experiment" in acute and chronic exposures as early as 1944 (MED 1944j), a routine urinalysis program appears to have begun only in 1947 also or possibly 1948 (MCW 1950c) (see Section 5.3.6).

Since little individual monitoring data are 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  $\mu\text{g}/\text{m}^3$ , or 70 dpm/ $\text{m}^3$  (AEC 1949b). AEC was also expected that construction of a new metal plant (Plant 6E), in which  $\text{UF}_4$  would be reduced to metal as was currently done at Plant 4, would produce satisfactory (occupational) environmental conditions (AEC 1949b). It was also expected that in 1951, the new  $\text{UO}_2$ -to- $\text{UF}_4$  plant (Plant 7) would further reduce exposures (AEC 1949b). 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.

An AEC effort in evaluating dose to workers is documented in AEC (1950a), which is a report of an attempt by AEC in late 1949 to estimate the cumulative exposures of Mallinckrodt workers at Plants 4 and 6 who were working at any time between July 1942 and 1 October 1949 and who had more than six months of exposure to radioactive materials. The base data came mostly from Mallinckrodt through its health physics staff, who did some calculations and sent them to AEC (e.g., MCW 1950c). This study is important because it was apparently AEC's first large-scale study of chronic exposure to all types of workers; ORAU (1977) commented that this was the best information available about individual employment dates, jobs, and dust concentration during the period since more than 90% of all full-time uranium workers were included; also, the exposures were chronic and potentially sizeable -- production was in thousands of tons per year and the Mallinckrodt main facilities were "factories, not laboratories" (ORAU 1977). Of the 650 workers included in the study, 99 were working in Plant 4, 294 were working in Plant 6, and about 250 had previously terminated (ORAU 1977).

However, the potential usefulness of this data is lessened by the fact that the Plant 4 work records were somewhat deficient and Mallinckrodt was thus not able to evaluate past dust exposures for workers who had terminated employment or who had transferred out of the AEC project work prior to 1 October 1949 (MCW 1950c). Also, some of the estimates were difficult for Mallinckrodt to do because the particular type of work was variable (e.g., maintenance work) (MCW 1950c). Mallinckrodt used the data of 1948 to calculate exposures prior to 1948 although they thought that many of the exposures were likely somewhat higher (MCW 1950c). Finally, since reported dust concentrations were based on a gross alpha measurement rather than on a chemical (element-specific) basis, the reported concentrations and the doses calculated from them might not always indicate a strictly uranium exposure; it was known that some workers, such as those working with K-65 residue, were exposed to radium dust (beyond that normally present in uranium dust as per uranium-radium parent-daughter ratio) (MCW 1950c). Still, correlation of the urinary uranium concentrations with calculated dust exposures was considered to be good for Plant 6, although poor for Plant 4 (MCW 1950c).

AEC's estimates for the dose to the lung were based on air samples of alpha-emitting dusts (translated to a daily weighted average exposure level); to the bone, on breath radon analysis (to determine the fixed radium burden); and to various organs, on film badge data (AEC 1950a). ORAU (1977) stated that there was a Mallinckrodt lifetime tolerance dose exposure level, but did not state what the level was; however, it did report that by October 1949, 52 employees had accumulated 100% of this level, with 45 exceeding 100% of it and 10 exceeding 200% of it.

Plant 6 was the most hazardous area in terms of dust levels, radon levels, and external gamma dose. Both Mallinckrodt and AEC made periodic studies of the various areas and continuous incremental improvements were made over the years of operation. An AEC consultant noted in 1949 that film badge records were well kept and the external exposures could be seen to correlate with the amount of radium in the plant (in ores and residues); despite problems with airbornes, progress had been made in reducing external dose and airborne dust levels (AEC 1949k). However, in October 1955, a Mallinckrodt health and safety official was asking an operations manager what had happened to Plant 6, listing in detail the many areas that were dirty and had leaking or nonfunctional equipment and the many questionable practices and violations of requirements (e.g., doors left open and respirators not being worn) that were resulting in unnecessary exposures to workers, particularly dust exposures (MCW 1955d). This official stated that many of these items had been pointed out repeatedly, to no avail. It appears that by this time it was clear that Plant 6 production would be moved elsewhere within a few years and either Mallinckrodt or AEC felt that it was not worthwhile to make improvements in the plant or even to maintain it adequately. Thus although the various hazards were progressively identified and addressed over the course of the years of operation and exposure levels did go down significantly, in the last few years some hazards were allowed to continue for extended periods before being addressed and some exposures were seen to go up. Even so, it appears that some studies and improvements were made very late in the life of the plant (e.g., the cleanup following the January 1957 study of radon and gamma levels in the Cloth Storage Room (MCW 1957)). Because of this somewhat up and down safety history, it is important to consider what was going on at the plants in any given year in order to assess the dose to an individual.

## 5.1 UNITS, LIMITS, AND RECOMMENDATIONS

The external exposure (dose) units used by MED/AEC during most of the relevant period were milliroentgen (mR) for gamma doses and millirep for beta doses, with the rep being equal to 0.93 rad; the abbreviations in the film badge and other records were mr and mrep respectively. Air exposures were expressed as disintegrations per minute per cubic meter sampled or inhaled (dpm/m<sup>3</sup>), while radon exposures were usually given in units of 10 x 10<sup>-10</sup> pCi/L. AEC also expressed exposures in

terms of “tolerance” levels set on the basis of assumed safe levels; a tolerance level was equal to a given external dose level in mR per week, mrep per week, dpm/m<sup>3</sup>, etc., but the given value changed with time as AEC set the safe levels lower and lower. The tolerance was regarded as a recommendation rather than a rigid limit, but AEC pressed the contractors to get and keep exposures to below the tolerance level. The units and the tolerances are further explained below.

In the early days of the war, MED decided that its tolerance levels of external exposure for uranium processing would be 0.1 R per eight-hour day or 0.6 R per week for gammas and 0.5 R per eight-hour day or 3.5 R per week for betas (MED 1943c, MED 1945b). This was based on the findings of the University of Chicago that the gamma dose rate from an infinite plane source (a 2- $\pi$  geometry) of uranium metal was 0.04 R per eight-hour day and for a room of uranium metal (a 4- $\pi$  geometry) it was 0.09 R per eight-hour day (MED 1943c). Later in the war, the limits were set at 700 mR per week to the whole body and 3500 mrep per week to the hands (MED 1945b, AEC 1949b; AEC 1950b). MED (1945b) stated that the entire dose for one week of either type of radiation could be received in one day or less; AEC (1950b) stated that the limit 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). MCW (MCW 1950f) states that the tolerance level as 12.5 mR/hr, i.e., the hourly average for the 0.1R per eight-hour day; presumably this was according to AEC usage as well.

At some point, when NYOO had assumed the job of reading the film badges, the tolerance level appeared to have been lowered again 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. In 1947, the basic dose limit was said to be 0.1 rep/day and the relative biological effectiveness (RBE) for alphas to be 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 1949b). An AEC internal memo dated January 1949 (AEC 1949c) states that the Plant 6E design by Singmaster & Breyer was intended to meet the following AEC-specified criteria: whole-body beta dose less than 250 mrep per week (based on a maximum permissible (tolerance) level of 500 mrep per week) and beta dose to the hand less than 500 mrep/week (based on a maximum permissible level of 1500 mrep per week). It was noted that AEC considered these criteria to be the minimum requirements and did not include any factors of safety beyond the “acceptable” (i.e., tolerance levels). New shielding added in 1948-1949 was designed on the basis of 50 mR per day of gamma radiation (MCW 1950e; AEC 1947b).

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 a 1950 letter to AEC, Mallinckrodt summarized AEC’s tolerance levels in the postwar era, as given in the table below (MCW 1950t). In MCW (MCW 1950l), Mallinckrodt suggested that AEC use

absolute units instead of tolerance units to report exposures because the tolerance values were apt to change with time and this lead to confusion in interpreting older records.

Summary of AEC tolerance levels in the postwar years.

Date	Beta tolerance level, mrep/week	Gamma tolerance level, mR/week	Total beta + gamma tolerance level, mrep/week
Before June 1948	700	700	1,400
June 1948 - August 1949	500	500	1,000
August 1949 - January 1950	300	300	600
January 1950 on	---	---	300

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 1950e); this was apparently based on the fact that Mallinckrodt was already using a system of personnel rotation to reduce doses (MCW 1949p; 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). Subsequently, Mallinckrodt 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).

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  $\mu\text{g}/\text{m}^3$  for insoluble uranium salts and 150  $\mu\text{g}/\text{m}^3$  for soluble salts (AEC 1949b). In 1944 MED determined that a standard was needed for uranium dusts and adopted the air maximum permissible concentration (MPC) level for lead, 150  $\mu\text{g}/\text{m}^3$ , as the interim standard (Hursh 1975).

In 1949, a University of Rochester scientific group suggested an air MPC of 50  $\mu\text{g}/\text{m}^3$  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  $\mu\text{g}/\text{m}^3$  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" (also referred to as a tolerance level) of 50  $\mu\text{g}/\text{m}^3$  for uranium dust, assuming a routine exposure of 8 hours a day, 6 days a week (AEC 1949b). This was taken to be equivalent to 70 dpm/ $\text{m}^3$  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/ $\text{m}^3$  for alpha, as AEC (1955e) 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  $5 \times 10^{-11}$   $\mu\text{Ci}/\text{ml}$  for 40 hours/wk (i.e., occupational) and  $1.7 \times 10^{-12}$   $\mu\text{Ci}/\text{ml}$  for continuous occupancy (AEC 1958, Table I). In 1959 the AEC also recommended against respirator use except in emergency situations (AEC 1949b), 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  $500 \mu\text{g}/\text{m}^3$ , agreeing with the information above, the “present MAC” (i.e., in 1958) was said to be  $110 \text{ dpm}/\text{m}^3$  instead of the  $70 \text{ dpm}/\text{m}^3$  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  $110 \text{ dpm}/\text{m}^3$  was based on a 48-hour week, this would be equivalent to  $65 \text{ dpm}/\text{m}^3$ , or about  $70 \text{ dpm}/\text{m}^3$ , 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  $6 \times 10^{-11}$  “special”  $\mu\text{Ci}/\text{cm}^3$ , which agrees with the value of  $5 \times 10^{-11}$  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.

The “generally accepted level” for radium fixed in the body (as a body burden) was taken to be  $0.1 \mu\text{Ci}$  (MED 1946c). In the highest concentrations handled by Mallinckrodt (i.e., of the pitchblende ores),  $0.1 \mu\text{Ci}$  corresponded to about 0.5 g of ore (MED 1946c). Since the radium was present in insoluble or only slightly soluble form, the original MED value for allowable dust concentrations of ore was  $150 \mu\text{g}/\text{m}^3$  (MED 1946c) (as mentioned above). When the tolerance for other kinds of dust was raised to  $500 \mu\text{g}/\text{m}^3$ , MED apparently did not mean for the ore and radium-bearing waste dust tolerance level to rise to  $500 \mu\text{g}/\text{m}^3$  as well, but Mallinckrodt apparently assumed so, based on the statement in MED (1946b) that the maximum allowable concentration for chronic exposure for  $\text{U}_3\text{O}_8$ ,  $\text{UO}_2$ , and  $\text{UF}_4$  had been raised from  $150 \mu\text{g}/\text{m}^3$  to  $500 \mu\text{g}/\text{m}^3$ , effective June 1945. Thus in late 1946, a Mallinckrodt manager told MED that they were using  $150 \mu\text{g}/\text{m}^3$  as the tolerance level for (apparently unground) ore dust, but  $500 \mu\text{g}/\text{m}^3$  for  $\text{U}_3\text{O}_8$ ,  $\text{UO}_3$ ,  $\text{UO}_2$ , and  $\text{UF}_4$ ; MED (1946c) soon told them to return to using  $150 \mu\text{g}/\text{m}^3$  for uranium compounds and “ $5 \times 10^{-11}$  grams radium per cubic meter [sic]” for ore residues with the uranium removed. As noted, above the tolerance level was raised to  $50 \mu\text{g}/\text{m}^3$ , equivalent to  $70 \text{ dpm}/\text{m}^3$ , by 1949; this is also the figure given as the tolerance level for the radium-bearing residue in 1953 (MCW 1953b).

There was a separate tolerance level of  $40 \mu\text{g}/\text{m}^3$  set for the “shotgun” residue dust (i.e., for sampling and work done in the shotgun laboratory), according to MED (1945d); this applied only if the concentration of the Th-234 and Pa-234 decay products (called T11 and T12 in the reference) had not been increased by concentration to more than 400 times the equilibrium value (presumably secular equilibrium).

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 1949b) 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  $1 \times 10^{-12}$  Ci/L was also mentioned as the tolerance level in 1950 (AEC 1950k). A ventilation design contractor stated in 1953 that the radon design criteria limit for work for Mallinckrodt and Harshaw was  $10^{-8}$  Ci/ $\text{m}^3$  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 1949b). 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 1949b). No information is available as to Mallinckrodt's approach to effluent control, e.g., whether it followed the AEC recommendation.

For workers employed in years during which no (radiological) urinalysis was done, reference may be made to AEC (1950a), which was a cumulative exposure estimate study done by AEC of Mallinckrodt workers who had been employed between July 1942 and October 1949. AEC's estimates for the dose to the lung were based on air samples of alpha-emitting dusts (translated to a daily weighted average exposure level); to the bone, on breath radon analysis (to determine the fixed radium burden); and to various organs, on 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 but the tabulations that produced the bottom-line figures for the report may be available by worker name in dose reconstruction project files.

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 AEC did not include radon dose because they could not estimate an average concentration and they assumed that airborne particle inhalation would dominate; that AEC assumed all the uranium to behave like  $UO_2$  in the lung; and that AEC 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). They stated that conditions probably were not more favorable and may have been "moderately" more severe. Thus they thought that their extrapolations could possibly be somewhat nonconservative.

## **5.2 RADIOACTIVITY CONTENT AND HANDLING OF THE ORE, URANIUM PRODUCTS, AND RESIDUES**

### **5.2.1 Ores and Other Feeds and the Initial Process Steps**

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, with the radon releases again being highly correlated to the radium content. Since the concentration of radium and other daughters present in the ore, processed uranium, and processing residue at any given time depended most strongly on the concentration of uranium in the

ore, on a per-ton-of-ore-processed basis (ignoring process differences), the various 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% (Eisenbud 1975) or 30% (Mason 1977) uranium by weight, up to a maximum of 65-70% (DOE 1997; Dupree-Ellis et al. 2000). 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). (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.)

Ores from the Belgian Congo had average concentrations of 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 1949b). (Mason (1977) gives 300 milligrams per ton, but this appears to be in error.) 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. A 1947 study done for AEC by the University of Rochester evaluated the relative amounts of uranium and radium in ore (see Section 5.3.1). The radon in the Belgian Congo ore 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.

As stated earlier, most of the pitchblende processed by Mallinckrodt was obtained as a concentrate from the Belgian Congo by AEC in 1944 and was shipped to St. Louis in 55-gallon drums from whatever North American receiving point was distributing it at a given time. 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.

In 1942, there was some contact (i.e., it was open to the air and potentially could be touched) with non-pitchblende uranium in the form of  $U_3O_8$  when it was mixed with nitric acid for digestion (MED 1942). As noted earlier in Section 3.1, the pilot plant operations in Building K-1E yielded a liquor that was conveyed by hand cart to vessels outside Building 52 and as suggested by Mason (1977), the further transfers also appear to have involved some closeup, manual handling. But when the pitchblende ore began to be used, contact was reduced as much as possible. To minimize personnel exposure, the ore (storage) room (addition) was divided by brick piers into corridors, with each corridor being wide enough to hold four drums of ore side by side, with a layer of four more drums stacked on top of them (MED 1946c). It was thought that this design would eliminate the need for workers to pass between or close to stacks of ore during the ore storage and transfer operations. However, due to the blocking of some corridors and the filling of others because of the volume of ore drums, it was after all necessary for workers to pass (close) by the ore drums stored in the partly filled corridors (MED 1946c). As of at least 1947, barrel handling of ore barrels was done with a forktruck, thus eliminating nearly all of the necessity of manual handling of the barrels (AEC 1947a).



In 1948-1949, ventilation and remote control systems were installed in the Ore Room and its addition. This helped to reduce the radon concentrations in the operating areas, except for a point in the Ore Room at the junction of the two conveyor systems: radon levels were found to be high and to remain high for nearly half an hour after pitchblende drums were opened (MCW 1949m). Operators were not supposed to be near the drums after they were opened, but operators sometimes still had to enter the Ore Room or the conveyor alleys while drums were standing open on the conveyor because of operating difficulties. These difficulties included the need to make frequent visual inspections of the flow through the Syntron feeder mechanism into the rod mill, incorrect placement of a drum on the conveyor, failure of conveyor stops, and the jamming of some fiber (cardboard) drums on the conveyor. In the case of the second and third items, the operator had to crawl into the conveyor alley to remedy the problem and in the case of the fourth item, had to go into the Ore Room to remove the open drum manually.

In February 1950, a study was done of gamma and radon exposure to three workers conducting a special pitchblende ore inventory (MCW 1950g). This included moving 1.5 lots (probably a total of 9 drums) by forklift, weighing the ore drums, checking the numbers, and counting all the ore drums present (not just the checked drums). They received gamma doses of 45-75 mR, compared to the then-tolerance dose of 60 mR per day. Radon exposures averaged  $1.02 \times 10^{-10}$  Ci/L, which was higher than normal because the ventilation system was operated in a special mode to facilitate radon sampling for the study. It was concluded that these exposures were acceptable if the special inventory was done monthly, but if more extensive inventories were done, rotation of personnel and extra planning would be necessary.

In 1950, it was observed during a study that it was very dusty in the Ore Room proper and that while the rod mill (grinder) was running it was necessary for the operator to enter once for 1.5 minutes to go to the top of the skip hoist and dislodge the ore stuck in the supply drum; this was done using a hammer (AEC 1949e). Other than that, the operator's time in the Ore Room was spent opening, dumping, cleaning, and closing the drums, with the average number handled being 22 per shift over about four days (MCW 1950u). In 1954, it was noted that operators were still being forced to enter the Ore Room frequently, due to the ineffective drum-handling system: drums would hang up on the conveyor and have to be pushed free manually (MCW 1954c). Also, large drums had to be removed from the skip hoist by hand because the system could not handle large drums (MCW 1954c).

Contamination control instructions were not always enforced in these known dusty operations. For example, in 1954 operators in the Ore Room were observed to be loosening lids on the ore drums on the conveyor before moving the drums to the skip hoist, which allowed dust to come out under the lids as the drums were moved; similarly, these operators took drums from the skip hoist and placed them on pallets with the lids positioned only loosely and without the clamps being fastened on (MCW 1954c). Drums of ore were also observed to be sitting in the Scale House without lids on, with the lids and clamps being put on in the open area of the Scale House or even outside and not on the conveyor as procedure required (MCW 1954c). The reason for the irregularities with the drum lids and clamps was that by this time many of the drums, having been used and re-used, were old and slightly out of true, so that the lids had to be beaten on and the clamps were fastened on only with great difficulty (MCW 1954c). When the feeder (conveying) screws that removed the ore from the hopper became blocked, ore had to be scooped from the hopper by hand; it was noted at least once in 1954 that this was done without respirators (MCW 1954c). The dust released was not confined to the ore area, since the doors to the Ore Room and Ore Room addition were often left open through negligence or for convenience (MCW 1954c).

Similar issues arose in the MgX area, used from 1949 on. Various memos and an August 1953 report (MCW 1953d) expressed concern about the MgX area, in particular the inadequate design and

maintenance of the conveying facilities that created dust levels in the breathing zone and general area up to 300-350 dpm per m<sup>3</sup>. This report noted that the drum washer was not working properly, so that there were high levels of dust when the workers hammered the ring clamps onto the drum; the airflow into the exhaust on the operator's platform was so inadequate that dust often came out of the opening when the operator released the mechanical "grab"; the operator had to go to the top frequently to push the feed material down the hopper into the screw feeder with a paddle, with dust coming out of the hopper opening as he did so. Also, the housing was warped, the gasketing material was loose, and there were broken windows in the drum washer housing (MCW 1953d). The problems had still not be solved in 1954, when leakage was observed coming from the feed hopper to the tanks at the feeder screw housing because of flanges that were not securely fastened and from loose packing at the screw shaft; the tops of the digestion tanks were thus covered with this dust (MCW 1954c).

In 1947, apparently after some months of experience in working with the high-level pitchblende ores, Mallinckrodt wanted to install steel shielding around several of the digestion tanks along the catwalks (platforms) and around the Feinc press filters that produced the K-65 waste (AEC 1949f). However, AEC rejected shielding around Tank M-14 because sludge was shoveled into the tank from the platform and the shielding would impede the shoveling (AEC 1949f). AEC apparently rejected all of the extra shielding eventually (MCW 1947). Mallinckrodt protested, stating that they had agreed to fewer provisions for health protection than they thought advisable in the design of Plant 6, on condition that the provisions would be added "if trouble later developed"; the difficulty was that after the plant was built and high-level pitchblende ores were being handled, AEC and Mallinckrodt disagreed as to what constituted "trouble developing" (MCW 1947). Thus although some shielding appears to have been added in 1948-1949 (AEC 1949b, MCW 1950e), notably for the ore grinding and C-3 filtration operations, the relatively high dose rates from the digestion tanks and the Feinc "bowls" were a continuing personnel protection problem at Mallinckrodt. This was noted on an inspection of the Mallinckrodt facilities by an AEC consultant, who stated that shielding was reaching a practical limit because with the tanks and vessels being shielded, the existing piping had become an important source of dose and the piping was not easily shielded (AEC 1949k). Further, rearranging the piping was not an option because the pitch and length of the sections was important to the process (AEC 1949k).

Dust and radon could be a continuing problem even in some of the "wet" areas. It is known that one reason for the spread of dust and radon was that doors to the cells containing the process equipment were often left open through negligence or for convenience; as late as 1954, a Mallinckrodt internal safety report gave as examples the leach and wash (Oliver) cells, the Feinc cells, and the M-14 cells (MCW 1954c). Tank lids were also left open unnecessarily, most notably the centrifuges, which were sometimes opened on one shift for cloth changing and not closed until the next shift (MCW 1954c); this allowed K-65 residue to dry out and drift out of the centrifuge and onto its outer surfaces and the floor. Also, as equipment became worn, there could be substantial leakage out various openings. In the case of the centrifuges, leakage was observed around the shaft, plow, and scoop openings at the top; this leakage was often allowed to collect and dry out (MCW 1954c).

From about mid-1948 on, at least some pitchblende ore (Q-11) was stored at SLAPS (AEC 1948e, MCW 1949p). Apparently at least one forktruck driver (to move the drums) and one truck driver were required; possibly a sampling worker was needed at times. Guards were said to have been "maintained" at the site from 1946 to 1951 (AEC 1959), apparently constantly; after that, it appears that guards were present only for routine patrols and actual worker entry into the site for deliveries or removals of ore. It is not clear whether the storage workers and guards were always Mallinckrodt employees or not; e.g., Mason (1977) states the raffinate cake and barium sulfate cake collected in dumpsters in Plant 6 were taken away in dump trucks "which AEC operated". However, Mallinckrodt warehouse workers and guards appeared to have been doing the residue delivery and placement

work even in 1946-1953 (MCW 1949d; MCW 1949p), when AEC was running the site. There are notations of "airport" in urinalysis and film badge records, so it may be possible to determine from such records whether and when a particular individual did work at the site.

Material was taken between the main Mallinckrodt site and SLAPS by truck (Mallinckrodt 1994; AEC 1947a; MCW 1949p), so it can be inferred that ore drums were received by rail at Mallinckrodt and then trucked to SLAPS. The ore drums were stored on a concrete pad next to the K-65 shed (the pad also formed the floor of the shed) (AEC 1948j). Mallinckrodt (MCW 1949p) restricted the time that warehouse workers spent at SLAPS because of the hazards from the K-65 drums and because of other ore work at the main Mallinckrodt site, such as unloading ore drums from railcars. The task of obtaining ore drums from the airport pad involved three trips per week (MCW 1949p) from Plant 6 (where the warehouse and yard workers were based) to SLAPS; apparently at least one forktruck driver (to move the drums) and one truck driver were required. Because of the proximity to the K-65 storage in the enclosed shed, it appears that the K-65, with its much higher content of Ra-226 than the ore, may have contributed non-negligibly to the exposure of the ore workers.

It should be noted that in the later years, many booths or walk-in areas were called "enclosures". These were generally not entered bodily by the operator, unless there was a malfunction of the equipment; rather, he inserted his arms into such enclosures through openings or used remotely operated devices to perform work within the enclosure. Some "stations" were actually enclosures such as this, some were hoods, and some were semi-enclosed booths.

### **5.2.2 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 in processing (except for the radium-bearing residue). Radium and radon would again build up to significant levels from the uranium parent, but this took more time than the apparent typical digestion-to-shipout time at Mallinckrodt. The principal hazard was thus the uranium-bearing dust.

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); in 1942, it was noted that contact could be made with  $UO_3$  when removing it from the open receptacles (boilers) to transfer it to the furnaces, and with  $UO_2$  when packing it. 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 by hand-scooping (Mason 1958a), i.e., manually using handheld scoops. The  $UO_3$  was scooped into a drum through a grated funnel that had a vacuum connection on it to draw the  $UO_3$  dust out of the drum (MCW 1956c) (the vacuum connection was probably in use only from the late 1940's on). The large pieces caught in the grated funnel were broken up by hand, which was always recognized as being a particularly dusty step operation and a principal reason why respirators were supposed to be worn during the operation. In 1954, there was a temporary top that was supposed to be used during the filling of the  $UO_3$  drums to keep the dust down, but since it did not allow the operator to see when the drum was full, it was usually left off (MCW 1954c). The dust on the outside of the drums was supposed to be vacuumed off, but the operators often used a rag to do it (MCW 1954c), which meant that much of the dust went into the air and onto the floor or the conveyor. When the dust collection bag for the  $UO_3$  area was changed, a spool piece was supposed to be installed in the ductwork, presumably to allow for an alternate suction source to keep the dust from coming out, but this was not done even through many bag changes (MCW 1954c).

The drums of  $UO_3$  were taken to the loading area and trays were filled with the material. After being weighed, the trays of  $UO_3$  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. This was described in Rochester (Rochester 1948b) as follows. In the tumbling area, the newly formed and cooled  $UO_2$  was placed in tumbling drums and rotated on a tumbler to break up clumps; the drums were taken to the skip hoist, where the tumbling drums were opened and transferred to the hopper of the Fiberpack loader; at the Fiberpack loader, a vibrating chute fed the material into 75-lb containers and the containers were sealed on a roller conveyor; and from the  $UO_2$  production area, the  $UO_2$  containers were trucked to the warehouse for storage.

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  $UO_3$  "gulpers" (AEC 1954d; AEC 1956b). A 1956 Mallinckrodt report (MCW 1956c) explained why: when the pneumatic system was not operational when the  $UO_3$  was ready to be unloaded from the pots, the unloading could not be postponed because acid would condense in the ducts and run into the pot, ruining the batch of  $UO_3$ . So it was recommended that while the pneumatic system was out of order, the exposure be reduced somewhat by collecting the large pieces caught in the funnel grate and waiting until the pneumatic system was back in order before breaking them up (MCW 1956c).

$UO_2$  produced at Plant 6 was trucked over to Plant 4 in small fiber containers (AEC 1949b); 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). AEC (1947a) states that the  $UO_2$  was hand-scooped into trays and leveled off with a stick; the gloved hand thus came into direct contact with the material. Manual handling 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 Plant 4 and part of Plant 6. 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 1955d), this was not always so. AEC (1955e) even reported in 1955 that a Plant 7 operator used a piece of cardboard in lieu of a conventional metal scoop to make up  $UF_4$  weight (in loading a container), with the operator's (presumably gloved) fingers dipping into the material frequently.

In 1955, a new derby "pickling" facility went into operation in Plant 6. The derbies made in Plant 6E were transported to this facility to be pickled – i.e., cleaned in a dilute acid bath – and then returned to Plant 6E in baskets of eight or metal boxes of twelve (AEC 1955e, MCW 1955p). Prior to being processed in the recast step, the derbies were dried with a flame in a hood, if necessary (AEC 1955e). Some chipping in the chipping enclosure was still necessary (AEC 1955e) because during the drying (whether by air or flame), the surface of the derby would oxidize to black oxide ( $U_3O_8$ ). Thus the dust in the chipping operation was at least partly  $U_3O_8$ . Although the use of the flame for drying was supposed to be discontinued (MCW 1955o), it appears that it did continue (MCW 1955p).

The billet (ingot) was initially low in beta activity because during the melting in the vacuum furnace (i.e., in vacuo), the dross and slag floated to the top of the crucible and the beta-emitting UX1 and UX2 (Th-234 and Pa-234) sublimed and cooled on the underside of the furnace lid (Mason 1977). The dross from the crucibles and the other furnace residues was packaged separately from the slag and the billet (Mason 1977). However, as the billet aged, the UX1 and UX2 started to build up again.

In November 1953, a study was done of Plant 4 recast operation to determine the cause of high film badge readings (MCW 1953e); although Plant 6E made most of the metal, some metal was still produced on a pilot or experimental basis in Plant 4. The following dose-producing practices were found. The furnace jack was warped, so the operator had to enter the furnace enclosure to guide the jack with his foot each time the furnace was loaded. After unloading the furnace, the operator had to weigh the crucible and put it into a drum by hand. The crucible dose rate varied with the number of times used and the type of metal; the crucible in the study read almost 400 mrep/hr (beta plus gamma) before it was loaded because it had been used before (and would read more after the recast was done). Aged metal billets were stored on the floor beside the operator's desk and were left there until the lead operator or the engineer examined and approved them, a period of one to three days. The operator spent four to six hours sawing "betatron slices" (samples to be sent to Granite City Steel (aka General Steel Castings) in Granite City, Illinois for testing) because the shape of the slices required the operator to spend several minutes setting the metal on the saw. The slices were stored on a table in a storeroom until enough had accumulated for shipment, a period of three to four weeks. When enough slices had accumulated, the operator would examine each closely to determine the weight and lot number stamped on it, which took a total of 30 to 45 minutes.

Besides these practices, MCW (MCW 1953e) noted that in their one run per shift, the same two Plant 4 recast operators had to load the crucibles, clean the furnace, saw the metal, degrease the metal (by hand until some time in late 1953), and load the betatron slices. There was no mechanical method to move the crucible from the furnace to the scale, so one of the operators had to climb physically into the furnace bottom and attach a chain to the billet, remove the fire brick from the billet, remove the empty crucible, and weigh the crucible. Meanwhile, at Plant 6E there were separate groups for each step, i.e., saw operators, furnace operators, crucible loaders, and cage men (who ran the degreasing machine). At Plant 6E, after the metal was sawed, it was kept covered and was stored away from contact with workers. Also, the metal at Plant 6E read fairly low compared to the aged Plant 4 metal. Thus as MCW (MCW 1953e) pointed out, the hazards faced by the Plant 4 recast workers were not being considered to the same degree as the Plant 6E recast workers. It is not clear whether the subsequent film badge readings went down because changes were made or because the type of operation was reduced or discontinued, but it appears that the handling of the crucible was minimized thereafter.

### **5.2.3 Residues and Other Wastes and Reprocessing**

Because of the splitting of chemical forms in the course of processing, the various wastes had content that was concentrated or depleted in particular isotopes, depending on where in the process the wastes were formed. Details are given in Table 4 and in the text as specific isotopes are discussed. But in general, it can be stated that the waste was disposed of promptly because otherwise storage space would have been exhausted. Thus once the waste was taken out of the process equipment or area, exposure to the waste was limited to the radioactivity existing in it at the time it was created or collected, with the exceptions of the K-65 drums that might be stored until they were transported to SLAPS, the slag that was recycled in the later years, the low-level solid wastes (such as rags) that might be accumulated prior to incineration; and the residues brought back from SLAPS for reprocessing. In the case of the K-65 drums, the exposure would be to radon emanating from the drums and to the gamma radiation from the radium; in the case of the slag, the exposure would be to dust and mostly beta radiation; in the case of the low-level solid wastes, which were probably kept in dumpsters or similar large bin-type containers, the exposure would be dust and external radiation; and in the case of the reprocessable residues (e.g., the AM-7), the exposure would be to dust and external radiation. It does not appear that any of the wastes had before disposal sufficient time to build up daughters much beyond what was already in the waste, except to some extent the residues brought back from SLAPS.

The residues dumped on the ground or stored in drums at SLAPS are a special case, since they sat there for a number of years, with only a few workers entering the storage area intermittently. In the case of the residues dumped on the ground, the exposure would be to dust and to some degree from external radiation and in the case of the drummed K-65 residue, it would be to radon and gamma radiation.

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 1967; AEC 1949b). 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, also called gangue lead cake or GLC. K-65 and other wastes were trucked to SLAPS but sent by train to sites outside Mallinckrodt. Radiation levels from the K-65-containing 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 1949b).

A 1947 dust study done for AEC by the University of Rochester evaluated the relative amounts of uranium and radium in the K-65 residue (see Section 5.3.1). It was reported in February 1948 that the K-65 contained about 600 mg of radium per ton and about 0.2% uranium; at that time it was being sent to the Lake Ontario Ordnance Works at an estimated rate of 6000-12000 pounds per day (AEC 1949m). AEC (1949b) stated that as much as 100 grams of Ra-226 contained in the K-65 residues was produced per month at the Mallinckrodt facilities. This was in fact the quantity produced in December 1948 (AEC 1949b). It was reported that 200 grams had been transported at one time to Middlesex (AEC 1949b), meaning that up to this quantity had been in storage at the Mallinckrodt site or at SLAPS and had had to be loaded for transport at one time.

In addition to the K-65 residues, there were other solid and liquid residues and wastes, as reported in February 1949 (AEC 1949m). The other two major solid refinery residues were the barium sulfate or AJ-4 residues and the pitchblende raffinate or AM-7 residues. The barium sulfate contained about  $4 \times 10^{-9}$  grams of radium per gram of residue and about 0.1% uranium; because of the low radioactivity content, it was being dumped on the ground at SLAPS at the rate of about 6800 pounds per day. The AM-7 consisted of various metal hydroxides with about 0.1% uranium; it too was dumped on the ground at SLAPS at an estimated rate of 23,000 pounds per day. The liquid wastes (from the refinery processes) contained about 0.002% uranium; they were discharged through a sewer to the Mississippi River at an estimated rate of 3000 gallons per day, with about 12 pounds per day of it being uranium. Miscellaneous waste byproducts of the  $UF_4$  production process were sent to Vitro for recovery of uranium, but in relatively insignificant quantities, while the slag from the uranium metal production process contained about 0.3% uranium and was stored at the airport. All of the various processes generated contaminated scrap metal, with the most problematic, in terms of quantity and degree of contamination, being Raschig rings from extraction columns, corroded drums in which K-65 had been stored before reprocessing, and floor materials (such as bituminous floor coverings being replaced).

The K-65 residues were stored in drums. Some of the waste sent to SLAPS was said to have been hand-packed by Mallinckrodt workers into barrels (drums) (Eisenbud 1975). A concrete-lined pit ("the swimming pool") was constructed to store the drums in, but was never used "due to health reasons" (i.e., the dose rates and perhaps the radon concentrating in the pit would be at excessively high levels) (AEC 1959) and because the corrosion of the K-65 drums would have made retrieval from a pit difficult (MCW 1949g). However, (AEC 1959) states that the pit was used to store tailings from the slag reprocessing operation from 1955 on. The same storage design and precautions as for the ore were followed for the radium-containing waste (MED 1946c), except that the drums may have been

kept in the open until the storage shed was built in about August 1947 (AEC 1947a). (See also Section 5.2.1. above.) Shield walls were included in this to divide it into smaller areas (AEC 1947a). Workers who performed operations where the K-65 and ore were stored at the Mallinckrodt main St. Louis site and at SLAPS (i.e., the warehouse/yard workers) were placed on a rigid time schedule to keep them from exceeding the tolerance dose (MCW 1949g; MCW 1949s; MCW 1949p; MCW 1950v). For example, MCW (1949s) states that a warehouse worker (including forktruck drivers) could, in one week, unload one ore car and make one trip to SLAPS involving K-65 handling and other duties within 50 feet of the K-65/ore pad or he could work loading one railcar with K-65 drums and make one trip to SLAPS ditto; an additional restriction was that no more than 2 hours per week could be spent at SLAPS, with only one hour per day actually working at the pad. As Mallinckrodt and AEC recognized (MCW 1949g), prior to the reprocessing of the K-65, corrosion of the drums was a severe problem: although the K-65 was insoluble, stream pollution at SLAPS was a possibility, but repackaging the K-65 would involve significant worker dose. MCW (MCW 1949g) suggests that some of the "sand" (inferentially, the AM-7 residue, as furnace sand with the radioactivity deposited on it) was being put into the K-65 drums, presumably to lower the dose rate from individual drums.

Concern was also expressed in 1949 about the bulldozer and crane operators working at the fresh and aged raffinate (AM-7) heaps at SLAPS (MCW 1949g). This was studied and it was found that the beta dose rate at the cab of a bulldozer pushed all the way into a heap of raffinate was considerably below tolerance. Since the bulldozer operator averaged less than 8 hours per week on the raffinate heap work, this operator's exposure was a small fraction of tolerance. These workers were thus not issued film badges.

As noted in Section 4.7, most or all of the K-65 was brought back in drums from SLAPS and reprocessed starting in early 1948. In January 1949, the gamma dose to the hands of operators opening drums of return K-65 was studied by placing film badges on their wrists (MCW 1949e). See Section 5.4.1 for results. No correction of the high hand dose situation was made, however, because the K-65 drum opening was done over a limited period of time (i.e., once all the K-65 stored at SLAPS had been brought back and reprocessed, the operation was over) and it was not realized how high the doses were until the study was done late in the reprocessing campaign (MCW 1949e).

The K-65 waste residues included not only the residues themselves, but also the used cloths from the Feinc press filters; drum disposal was the only solution for disposal of the cloths, since (1) they were impregnated with the radium-lead salt sludge and thus would not burn and (2) they were made of plastic fibers and thus would not dissolve in acid (AEC 1949f). It was reported that three used filter cloths, stored in two 55-gallon drums, produced 30 times the tolerance level dose rate at contact with the drums (AEC 1949f). Thus the cloths and the operations associated with them were of major concern with respect to external exposures in Plant 6.

In 1949, a study was done of the beta and gamma exposures associated with preparing, repairing, cleaning, and changing Feinc filter cloths by the cloth operators (MCW 1951g). Due to the recent reduction in the external dose tolerance levels by AEC, it had been recommended that an additional (third) worker be added to the rotation schedule for this job. Major revisions as a result of the 1949 study were that a basket was provided for carrying the used cloths in, that the filters were partly cleaned by the area operator before the cloth operator began work, and that a fourth worker was to be added to the rotation schedule in May 1950. However, the cloth operators did not like to use the basket because it was hard to haul it up the stairways of the filter platforms and they still had to spend some time cleaning the filter. Also, during the summer of 1950 several dozen workers were transferred from Plant 6 to Plant 1 (see Section 5.0) and this disruption of operations and the need to retrain new workers delayed the assignment of new people to the rotation, which was not done until

November 1950. This also increased the two principal cloth operators' doses significantly over the other cloth operators' doses.

As a result, it was agreed in 1950 that the area operators would better clean the filters and blankets in preparation for the cloth operators' work, the cloth change interval would be increased from two days to three, and a fifth worker would be added to the rotation (MCW 1951g; MCW 1951a). In January 1951, a new study was done of beta and gamma exposures associated with preparing, repairing, cleaning, and changing filter cloths (MCW 1951a); this included cloths for the Feinc, C-3, and Recovery filters. Dose rates measured with instruments were combined with time measurements to estimate doses; the gamma doses were said to agree well with film badge readings but not the beta doses, due to the technical difficulties of field measurements of beta radiation. These results were said to be comparable to those found in the 1949 study, although some of the tasks the cloth operators were doing in 1949 had been given to the area operators to do (MCW 1951a), but clearly the weekly doses had increased at the time of the 1951 study. Also, the operators were still not using the basket provided because of its bulkiness. But waiting in the cell for work to start and other work practices that increased the "close to Feinc" (distance of less than three feet) time had been changed and the cloth change interval was increased from two days to three (MCW 1951a), so the doses were expected to decrease.

There were varying quantities of miscellaneous waste arising from various sources. For example, rags and paper with small amounts of uranium forms and residues were created from cleaning and wiping procedures, such as the black oxide from wiping derbies, billets, and mold strips and the residue from wiping the outsides of drums before transport. Other types of contaminated materials included packaging, sweeping compound, old uniforms and gloves, and like items that were used in the process areas or were in contact with radioactive matter. All of these types of materials could be burned in an incinerator outside Building 115 at Plant 6 or outside Building 403 in Plant 4 (Mallinckrodt 1994) and the ash could be processed or sent elsewhere for recovery. The filter cloths were also incinerated (MCW 1951a), at least at some periods of operation.

Dust from the various processes was collected mostly in bag-type filters, although some was collected with a rotoclone (a water spray type of collector) and run into a recovery tank (MED 1944o). Dumping these filters, i.e., dumping the bags of dust into drums, was recognized as a high-dust operation (e.g., AEC 1954a, AEC 1954d, AEC 1954c). Mallinckrodt estimated that bags were changed about every six weeks for the Plant 6 Pot Room dust collector and that it took 1.5-2 hours per bag change, for an downtime percentage of 0.4% (MCW 1955r). Occasionally a bag would break, obviously resulting in even higher dust levels. For these reasons, respirators were supposed to be worn but were not always (e.g., AEC 1954e). There was also a possibility of increased external dose from dealing with the collectors. For example, in 1956 a maintenance worker received an external dose higher than usual, as shown by his film badge reading; this was found to be mostly due to the eight hours he spent repairing one of the Hoffman collectors that served the recast (YM-5 or billet) area (MCW 1956j). This collector handled the beta-active black oxide that resulted from the recast activities (MCW 1956j).

Dust was a problem even with empty drums. Mallinckrodt reported to AEC in 1950 that used K-65 drums being returned to Mallinckrodt in ATMX railcars did not always have lids and were not always cleaned (MCW 1950n). This resulting in dispersal of the residual dust throughout the car during shipment, to such an extent that Mallinckrodt collected 100 pounds of it in one railcar after it was unloaded; there was contamination of the receiving dock as well. Dust concentrations in the railcar were in excess of 250 times tolerance (i.e., more than 17,500 dpm/m<sup>3</sup>) were found in the general area of the railcar and about 27 times tolerance in the worker's breathing zone, but the radon concentrations did not exceed 20% of tolerance and the gamma radiation did not exceed 15% of



tolerance. AEC appears to have resolved this by directing the drum sender (presumably Lake Ontario Ordnance Works) to correct the situation.

It was noted in January 1955 that for a considerable period, radon concentrations of  $1-8 \times 10^{-10}$  Ci/L had been detected in the Plant 6 Cloth Storage Room (MCW 1955j). After much detective work, it was found that the wall near the M-50 (tank) sump was saturated with "material" that had come from the sump and from the Wash Oliver cell (presumably by liquid leakage and/or by deposition via air currents). Holes in the wall and ceiling of the Cloth Storage Room created a draft from the sump area across the accumulated material and up into the upper area of the room. This situation appears to have been remedied once discovered. However, in December 1956, the Cloth Storage Room was again studied because of the wide variation in the radon readings taken during weekly checks; Over 1 August to 31 December 1956, the 18 weekly measurements of radon level varied from less than  $1.0 \times 10^{-12}$  Ci/L (i.e., nondetectable by Mallinckrodt methods) to  $1.11 \times 10^{-10}$  Ci/L, with the average being  $0.5 \times 10^{-10}$  Ci/L and the median being 0.265 Ci/L (MCW 1957). It was found that there were two major radium-containing deposits in the floor and a wall of the room. While the highest gamma reading was only 2 mR/hour, in accessible areas, it was thought that the reading would be higher in the nonaccessible areas behind equipment. Thus the migration of material from adjacent areas appears to have been a continuing phenomenon.

It was recognized that radon levels at the K-65 and ore storage area at SLAPS were high also; along with the gamma problem, the radon problem necessitated restrictions on the time a worker could spend there (MCW 1949g). Mallinckrodt was supposed to be taking radon samples at SLAPS, but after one set had been taken someone mistakenly stopped taking them (AEC 1949j). An AEC safety representative then averaged the sixty-plus samples taken up to then to produce results that could be graphed so as to see the rough falloff with distance (AEC 1949j).

The ore drum thawing and drying oven – apparently a large walk-in room with steam coils for heating – was used to thaw the K-65 drums before processing and even for temporary storage of dozens of these drums (MCW 1949o). Not only did radon emanate from the drums during heating, but because the drums were apparently opened for the heating, K-65 had been spilled onto the coils and was contributing radon on a continuing basis. This could not all be cleaned off by a vacuum cleaner. High radon levels were seen outside the oven during the heating, so a fan and stack were installed in the back of the thawing oven to draw away the radon from the drums during thawing (MCW 1949o). However, this produced no improvement. It was discovered when the heating coils were turned off, even when the fan was on, air was drawn in under the oven door and forced out over the top of the door, where it eddied in front of the oven before being drawn in again under the door. This phenomenon kept radon concentrations up inside and outside the oven. Although the time spent by workers in the oven was short and their daily weighted exposure was below the radon tolerance level, it was believed that it was not safe to operate at tolerance levels for extended periods (MCW 1949o). Thus the thawing oven ventilation had to be revised and the coils taken apart for cleaning.

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 1967; DOE 2002). AEC (1967) 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 grams 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.

When AEC asked Mallinckrodt to establish a pilot plant to process more of the thorium-bearing residue, Mallinckrodt refused, on the basis that the health hazards of thorium were not well understood (AEC 1955c). One concern was that because the process involved only solutions (i.e., the liquid form), exposures would mainly arise from accidental releases or leaks, which would not be easily detectable by ordinary industrial hygiene measures; hence Mallinckrodt wanted some way to detect exposure via urinary or other biological measurements (AEC 1955c). AEC agreed to study the biological half-life of thorium in the lung and bone following inhalation of thorium fluoride and nitrate salts; they were also to study the urinary clearance rate (AEC 1955c). Mallinckrodt approached the Los Alamos site because it would be receiving the thorium, but could elicit only the information that thorium could be considered equivalent to plutonium on a curie basis (ORAU 1991). AEC agreed that the pilot plant would be built and operated as if it were to process plutonium (AEC 1955c) and the pilot plant began operation at MEP on 25 February 1956 (ORAU 1991). Because the health hazards were on a "speculative level", Mallinckrodt restricted the number of workers on the project and took strict precautions as to handling, contamination control, and access (ORAU 1991). However, there does not appear to be any information available as to how the urinalyses were analyzed.

The "breathing zone" operations in the thorium processing were the removal of the raffinate cake (formed in the processing) in dumpsters and the opening of the contactor tank to adjust the concentration of the process material and to add laboratory waste materials (AEC 1955d). While AEC (1955d) found that exposures of the Plant 7E workers were always below the MAC (note that since gross alpha was measured, the thorium and its alpha-emitting daughters were in fact measured in air sampling), it was also pointed out that the pilot plant was then in the startup phase of operations and that thus the 1955 air survey was possibly not representative of mature operating conditions (AEC 1955d).

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 cake used had been processed in any way at the St. Louis downtown site; 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.

AEC (1960) states that the SLAPS waste, also called the airport residue, was evaluated for sale or disposal in about 1960 and were sampled even before that. The pitchblende (K-65) residues were auger-sampled in June 1953; barium sulfate cake, Colorado raffinates (from domestic ores), and miscellaneous ores were also considered. See Table 4 for quantitative information.

It is not clear whether the storage workers and guards were always Mallinckrodt employees or not, but Mallinckrodt workers appeared to have been doing the residue delivery and placement work even in 1946-1953 (MCW 1949d; MCW 1949p) and there are mentions of "airport" in urinalysis records. ORAU (1989) suggests that Ledoux Company laboratory workers also worked there, probably doing

sampling. Material was taken to and from the Mallinckrodt St. Louis site by truck (Mallinckrodt 1994; AEC 1947a; MCW 1949p). Guards were maintained at the site from 1946 to 1951 (AEC 1959); after that, it appears that guards were present only for routine patrols and actual worker entry into the site.

At the time that planning for SLAPS decontamination was being planned in about 1964, the residues still stored on the site were the pitchblende raffinate (AM-7), Colorado ore residues, leached and unleached barium sulfate cakes (AJ-4), miscellaneous residues (but not K-65), and the C-oxides (AEC 1964). The C-oxides were then begin shipped to Fernald for reprocessing and the rest were to be offered for sale. In addition, there were several hundred tons of contaminated metal and debris at the site (AEC 1964).

#### **5.2.4 Sampling and Laboratory Activities for All Forms**

As noted earlier, other feeds besides ore were used from the mid-1950's on. The drums of these alternative feeds were usually sampled (e.g., for oil analysis) in the Plant 6 warehouse by either Analytical Laboratory workers (MCW 1956h) or warehouse workers. The process as performed by the laboratory workers was described in December 1956 as follows (MCW 1956h). Three drums were opened and a small amount was scooped out of each and put into a bottle, which was labeled and taken to the laboratory. Air samples of this activity were taken with the warehouse exhaust fan running and the large doors (panels) to the outside open. Air movement was found to be almost nil and the dust created by the sampling lingered in the air for an extended period. The average airborne level during sampling was 18,000 alpha dpm per cubic meter. A recheck of sampling was done under the same conditions but from the residue drum where the samples taken at the origination point were put after analysis there; this drum held the samples from the entire lot shipped and so could be assumed to be representative of the lot. Readings during the residue drum sampling showed an average level of 8530 dpm per cubic meter. Using the all-purpose hood in the Old Boiler House showed levels of 3460 and 584 dpm per cubic meter respectively for the two types of drums. Since the residue drum was at most half full and was a single dust source, it was clearly preferable to sample that way. It is not clear whether the change to sampling the residue drum and using the Old Boiler House hood was made, but it is likely that it was.

In 1955 feed material had come from or was expected to come from Beaver Lodge, South Africa, and Portugal (the latter as a concentrate) (MCW 1955m). A problem identified with this material was that it contained scrap iron, cake materials, and large pieces of uranium. Obtaining a representative sample of the feed would thus require preliminary separation of the extraneous material. It was necessary to process this feed and more like it at the rate of 200 drums per day, hence construction of a suitably ventilated sampling station was not an option in the short term. It appears that at least in the short term Mallinckrodt sampled these drums with an auger in the ventilated sampling bays of the Plant 6 warehouse.

In the early days of the project, the shotgun laboratory in Building 55 of Plant 2 used a 100-mg RaBe source to test  $UO_3$  samples using neutron absorption techniques; hence it had to be designated as a special restricted area for access control purposes (Mason 1977). It appears that the RaBe source was not used after some early point, since (MED 1944m) and other documents state that such samples were prepared at Mallinckrodt and then sent elsewhere for analysis. It may therefore be assumed that use of the RaBe source for this purpose had ended by September 1944 (the date of MED 1944m).

MED (1944m) stated that  $UO_2$  shotgun samples (possibly the reference meant  $UO_3$ ) were prepared by dissolving 25 lbs of  $UO_2$  in acid and extracting uranium nitrate hexahydrate in a four-step ether process; the remaining water layer, which also contained nearly all of the Th-234 and Pa-234 (UX1

and UX2), was run through a separating funnel, then evaporated to dryness in a dish, first by the chemist using a handheld blast burner, then in a muffle furnace. The sample remaining, which averaged 3-5 grams, was ground by hand in a mortar and poured into a bottle. The accumulation of sample bottles, usually three to twelve per day, was sent away daily for analysis. In 1954, the shotgun samples were made up in the Dry Material Sample Room (or Powder Sample Room), apparently because of equipment availability, but the work was performed by the Shotgun Sample Lab personnel and not the Dry Material Sample Room personnel (MCW 1954b). There was also a Metal Sample Room (MCW 1954b), presumably for assaying the finished metal forms.

Prior to August 1955, an average of two Mallinckrodt  $\text{UO}_3$  samples were run daily in the Shotgun Laboratory and film badge readings were under the applicable limits (MCW 1955e); usually only one worker was needed for this. However, from August 1955 into October 1955, a campaign was performed to run  $\text{UO}_3$  samples from other sites as well; these other-site samples constituted more than half of the total and were mostly from Fernald but also from Beaver Lodge, Port Hope, "Canada", and "Pilot Plant" (apparently not a Mallinckrodt pilot plant). The workload increased by a factor of three and temporary workers were hired for a few months to do the work. With one Mallinckrodt worker and one temporary per shift to do two Mallinckrodt samples and four other-site samples per day, film badge readings went up significantly – one badge read 5810 mrep in one week in August and another read 2040 mrep in September, mostly beta. The hot plate hood, the muffle furnace, and the evaporating dish in the cooling and scrapedown hood were found to be contaminated with material producing mostly beta radiation, while a can of pellets under the sample press was giving off a significant gamma dose rate.

The situation was studied (MCW 1955e). It was found that there was no significant radiation reading in the laboratory assay of  $\text{UO}_3$  until the laboratory crucible containing the sample was placed on the hot plate; as the sample was evaporated, the reading rose rapidly. The source of the radiation was the dried residues on the crucible. For the Mallinckrodt-produced samples, the average reading of 10 samples was 1500 mrep/hour at 1" above the top of the crucible and 1000 mrep/hour at 2"; the respective averages for the four "Pilot Plant" samples checked were 1800 and 1200 and for the ten Fernald samples they were >12,500 and 12,000 mrep/hour respectively. (Apparently the maximum that the Zeus instrument could read was 12,500 mrep/hour, so the Fernald 1" readings were undoubtedly much higher.) A film badge set at 2 feet over the scale on the main work bench and about 5 feet from the boildown and crucible cooling hoods for a week read 1000 mrep beta and 50 mR gamma. A time-and-motion study showed that a laboratory worker handled the sample in some way for a total of 11 minutes after boildown, i.e., after significant readings could be expected to appear.

The Shotgun Laboratory was decontaminated by the Mallinckrodt decontamination group, with the contaminated items either cleaned or disposed of; a Lucite shield was provided to put in front of the crucibles during cooling and a steel box was provided to put the crucibles in during cooling and storage (MCW 1955e). Respirators were required to be worn during the scraping, grinding, and palletizing of the samples. A film badge placed in the same area as the first one had been read 1500 mrep/hour beta and 95 mR/hour gamma after two weeks, indicating that the cleanup and other corrective measures had been only partly successful.

K-65 sludge was sampled to determine its radium content 24 hours after it was produced, put into metal drums and stored in an adjacent warehouse (AEC 1949f). The sampling appears to have been done in the warehouse by the warehouse workers in the early years, but in a sampling room in the Scalehouse in later years; the assay was done in the Ledoux Lab by Ledoux company workers (MCW 1954a, ORAU 1989a).

In March 1955, a survey of the Scalehouse Sampling Room was made to evaluate dust, radon, and external exposure hazards from sampling K-65 drums (MCW 1955n). At this time, drums of K-65 were sampled once a day. Approximately 24 drums were moved, four at a time on a pallet, by forktruck from the storage bay to one of the K-65 sampling bays. Two samples were taken from each drum using a thief sampler inserted by means of the sampling holes (as described above); after the sample was deposited in a pan, the thief was cleaned by scraping it and knocking it against the sample rack, putting dust into the air. The pans of material were accumulated inside the sampling area until all the drums had been sampled, after which the pans were taken into the Scalehouse area and put on a rack to await transport to the Ledoux Laboratory. The operator then cleaned the floor of the sample room. It was found that during the 80 minutes of the sampling work period, the total external exposure to an operator from sampling a lot of 24 drums was 3.4 mR gamma and 3.8 mrep beta; the average total beta-gamma dose rate was 5.5 mrep/hour, the peak radon level was less than  $0.5 \times 10^{-10}$  Ci/L and the average was less than  $0.25 \times 10^{-10}$  Ci/L; and the average dust level was 1870 dpm per cubic meter, with both the general area and the operator breathing zone concentration during the actual sampling being about 2300 dpm per cubic meter. It was also found that air was frequently forced into the Sampling Room through the sampling holes in the floor, especially with a north or west wind. This air carried with it dust from its passage across the stored drums of K-65 and thus contributed strongly to the dust concentration in the room despite the nominal adequate exhaust flow, which was exhausted at floor level to draw down the dust from the sampling pans. It was recommended that respirators be worn, which apparently was not being done previously.

In 1953, the Ledoux Lab technician spent three whole days and two half days in the Ledoux Lab and two half days in the shotgun (assay) lab (MCW 1953b). At this time, the K-65 (radium-bearing) residue testing work in the Ledoux Lab consisted of compositing residue, drying it in an oven, blending it in a blender, redrying it in a dry box, mixing it in a tumbler, and then presumably testing it. The sources of dust in this operation were identified as using the grinding hood, when dumping pans of K-65 for grinding; weighing out (since there was some spillage and some need to scrape off the bottoms of the pans); cutting the sample (ground K-65 was cut through a riffle); screening (on the "Ro-tap"); and using the jaw crusher (for AM-7 residue only), for which there was no hood (MCW 1954a). The sink used for washing pans had no sump, so the wash water went to the sewage; splashing from the sink was viewed as a source of the contamination on the floor (MCW 1954a). At one point, the exhaust fan door was locked closed until the chain assembly could be repaired, hence ventilation was impaired (MCW 1954a). The cabinets interiors were found to be very dusty and the hood bases and walls, which were made of transite, had visible signs of absorbing K-65 (MCW 1954a). There was an associated Furnace Room, presumably for drying, in which respirator wearing was recommended (MCW 1953b) and the K-65 was said to be weighed on a pan on a scale "through the hole in the Furnace Room wall" (MCW 1953b). However, the heat from the ovens (furnaces) created enough draft to draw the radon up out of the lab and out over the roof (MCW 1954a). All of this information suggests a significant amount of manual handling of the residue and uncertain control of contamination, even after a new laboratory was built in 1952 and improvements were made in 1953 (MCW 1953a).

When the "U-Con" process was set up to recover uranium as a slurry from reject  $MgF_2$  material, the U-Con began to be sampled in the Slag Separation area of Plant 7 and the samples processed in a minimal preliminary fashion in the Analytical and LeDoux Laboratories (MCW 1955L). Four samples per day were taken and transported together in open stainless steel pans in a coaster wagon to the Shotgun Laboratory. They were processed in a hood with a left-right sliding panel, the purpose of which was to keep dust out of the laboratory technician's breathing area. The technician reached around the panel and used a small hand scoop to remove some of the U-Con and place it in a grinder in the hood. After the sample was ground the grinder pan was emptied back into the sample pan. Then the sliding panel was moved to allow the dust in the grinder to be brushed out into the grinder

pan. Finally the panel was slid back and the grinder pan was re-emptied back into the sample pan and the sample pan was removed from the hood. The grinding and grinder brushing took a total of 8.7 minutes and was repeated for each of the four samples per day. With preparation work, the technician thus spent about an hour per day in the Shotgun Laboratory. A dust study showed the average breathing zone concentration to be 20 dpm per cubic meter and the general area concentration to be 23 dpm per cubic meter over the entire four-sample operation, indicating that the open pans were more of a problem than the grinding itself, because of the hood.

A check of the Shotgun grinding hood was also performed. This showed that the flow volume was 234 cubic feet per minute and the air velocity averaged 75 linear feet per minute over the face of the hood, only somewhat under the 100 linear feet per minute that might be typical of such a hood today.

### **5.2.5 Safety, Health, Decontamination, and Laundry Facilities**

A respirator decontamination facility was added, presumably in Plant 6, in April 1950 (MCW 1950e). It is unclear where this was done previously.

Although most contaminated equipment could be repaired in situ or in the Mallinckrodt repair shop -- which was not dedicated to AEC work but served the entire Mallinckrodt general site -- some equipment had to be sent out to other companies' facilities for repair (AEC 1948h). AEC approved this practice based on its requirement that all items should be decontaminated if possible to "zero wipe" (i.e., no detectable removable contamination) and on the assumption that any resulting contamination on floors and machines would not be significant. AEC also stated that air samples should be taken of representative repair operations in the Mallinckrodt shop and that areas immediately adjacent to the Mallinckrodt shop should be monitored for contamination in order to verify that surface contamination was not being tracked out (AEC 1948h); it is not clear if this was done or not.

MED (1942) stated that both contaminated and clean clothing were laundered on the premises, in separate laundries; however, AEC (1947a) stated that contaminated protective clothing from all areas was sent to public laundries, contrary to other AEC sites' practice. Use of public laundries appears to have ceased at AEC direction (as suggested by AEC 1947b). An onsite laundry with "clean side, dirty side" flow was installed some time prior to April 1950 (MCW 1950e).

## **5.3 INTERNAL DOSE CONSIDERATIONS**

The primary route of internal exposure was via inhalation of airborne particulates, although radon was a considerable problem in some areas. It was noted in December 1942 (MED 1942) that the primary precautions taken against radiological hazards were against inhalation of the dust. 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. 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, although some dose calculations were apparently

done by AEC for study or verification purposes. 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.

### **5.3.1 Particle Size, Solubility, and Composition Considerations; Air 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.,  $\text{UO}_2$ ,  $\text{UF}_4$ , and uranium metal (Lippmann 1958, regarding solubility); no patently soluble forms, such as  $\text{UF}_6$ , 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  $\text{UF}_4$  show behavior consistent with Type F in some cases and Type M in other cases, while ICRP 68 (ICRP 1995b) recommends Type M for  $\text{UF}_4$ . 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.

A study of air dust particle sizes in the  $\text{UO}_3$ -to- $\text{UO}_2$  area was done in 1948 for AEC by the University of Rochester (1948b). Both filter paper dust samples and cascade impactor samples were taken at the tumbling area (where the newly formed and cooled  $\text{UO}_2$  was placed in tumbling drums and rotated on a tumbler to break up clumps); at the skip hoist (where the tumbling drums were opened and transferred to the hopper of the Fiberpack loader); at the Fiberpack loader (where a vibrating chute fed the material into 75-lb containers and the containers sealed on a roller conveyor); and at the warehouse (where the  $\text{UO}_2$  containers were stored). The sampling rate of the cascade impactor was 14 liters per minute; it is unclear what the filter paper sampling rate was. All samples were analyzed for uranium by the fluorometric method and the results were found to be well within the accuracy range of the method. Particle size distributions showed normal curves and to be in excellent agreement with the theoretical curves. The results are shown in Table 7.

Also shown in Table 7 are some measurements reported by Sanders (1975). 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 ( $\text{UF}_4$  to metal) have the smallest percentage.

Eisenbud (1958) reported that "It has been shown that in these [uranium processing] plants [the uranium processing plants] the mass median diameter was about 2  $\mu$  [microns]". But he also noted that while the peak for alveolar retention is 1-2  $\mu$  for dust of unit density (i.e., 1 g/cm<sup>3</sup>), uranium oxide dust has a density of 9 or 10 g/cc, so that a 1-2  $\mu$  particle would behave as though it were a 3-6  $\mu$  particle of unit density. An AEC report on uranium mills stated that ore concentrates (the form that arrived at uranium refineries such as Mallinckrodt) had a "mass medium [sic] size" of 2.5  $\mu$  (AEC 1958). Some uranium refinery workers were said to have been exposed to  $\text{UO}_3$  dust with a mass

median diameter of 2  $\mu$ ; however, with a density for U compounds in the range of 9-10 g/cm<sup>3</sup>, the effective aerodynamic diameter was much larger than 2  $\mu$ , possibly in the range of 5-6  $\mu$  (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 two-stage setup: following a cyclone separator, the first stage collected 100% of particles  $\geq 10 \mu$  AED, 75% of those  $= 5 \mu$ , 50%  $= 3.5 \mu$ , 25%  $= 2.5 \mu$ , and 0% of those  $\leq 2 \mu$ , while the second stage, a filter, collected the rest of the particles. They found that less than 15% of the airborne material collected on the second (the respirable-particle) filter. Schwendiman et al. (1975) noted that this agreed 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<sub>3</sub>O<sub>8</sub>, UO<sub>3</sub>, UO<sub>2</sub>, ore concentrate, and mixed scrap.

Because of the lack of specific information regarding all types of particle sizes at the Mallinckrodt plants, the ICRP 66 default deposition parameters (ICRP 1994) should 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 should be of general application even when the listing is for depleted or enriched rather than for the natural uranium used at Mallinckrodt.

Regarding the isotopic and chemical composition of the dusts, there is only a little Mallinckrodt-specific information. In 1947 AEC had the ore and residue dust studied by the University of Rochester, which investigated the uranium and radium content of filter paper after use in air sampling (Rochester 1948a); it was stressed in the University of Rochester's report on the results that the samples were taken not to determine health hazards directly (i.e., by inferring the air concentration from worker positions) but rather to obtain a heavy concentration of each material so as to compare the relative concentrations in the dust. Thus each concentration was taken at the maximum emission point (in fact the centrifuge was partially opened for the sample-taking), without reference to actual worker position or breathing zone. The precision of the measurements was said to be better than +/- 10% and each figure in the given represented at least three analyses. See the table below for the results and the inferred curie ratios. As can be seen, the U/Ra ratio was approximately 1 in the ore, indicating equilibrium of the uranium and at least its first few daughters; 0.01 in the gangue (GLC or K-65) residue, indicating removal of most of the uranium; and intermediate during the centrifuging of the residue to separate the liquid and solid (Ra-bearing) fractions.

Comparison of the uranium and radium content of ore and gangue (K-65) residue samples.

Compound	Area	Operation	Uranium		Radium		U-238 Ci/ Ra-226 Ci
			ug of sample	u/m <sup>3</sup>	ug of sample	u/m <sup>3</sup>	Ratio
Ore (U <sub>3</sub> O <sub>8</sub> )	Ore Room	Crushing and milling ore	540	2,540	182	850	1.0
			520	2,440	184	860	0.95
			260	1,220	102	480	0.86
			1,010	4,750	307	1,440	1.1
			760	3,560	220	1,030	1.2
Gangue residue	Scalehouse	Sampling residue	21	148	665	4,700	0.011
	Sampliing Room		17	120	555	3,920	0.010
	Centrifuge	Centrifuging residue	10	71	25.5	180	0.13
			11	78	18	130	0.21



The precision of the measurements was better than +/-10%. Each figure above represented at least three analyses.

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<sub>3</sub>O<sub>8</sub>, the ratio was 1:0.01:0.001, indicating that these products were removed in the processing (Wilde 1975). However, as discussed in the paragraph above, at least the one study of what was probably Belgian Congo ore at Mallinckrodt showed that secular equilibrium down to just above radon had been re-established by the time of processing at Mallinckrodt. Thus it seems best to assume that equilibrium did exist in the ore.

AEC began taking air dust samples for particulate alpha emitters in 1943 and Mallinckrodt appears to have been taking dust samples and sending them to NYOO for evaluation from about 1943 on (MED 1944j). The various AEC air dust study reports state that an established AEC protocol was followed, but the documentation for what the protocol was is lacking. However, some information is known about Mallinckrodt's and AEC's methods. MED (1943d) stated that the sample rate for measurements in the second quarter of 1943 was 3 ft<sup>3</sup>/min, with either 30 or 120 ft<sup>3</sup> sampled, depending on the area. Mallinckrodt (MCW 1946g) stated that dust was measured with a "precipitron and ion-meter". For the data reported by MCW (1949d), dust samples were collected on 1-1/8" Whatman #41 filter paper disks, using a modified Fischer pump, at 0.5 ft<sup>3</sup>/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%. Data from 1946 lectures by A. A. Jarrett of Clinton Laboratories were used in the error calculations. AEC (1949g) also states that Mallinckrodt was using a flow rate of 0.5 ft<sup>3</sup>/min, with a Fisher and Porter rotometer. AEC (1950a) stated that it was using 1-1/8" Whatman filter paper disks and a handheld air sampler with a collection rate of 15-20 lfm to take its samples at Mallinckrodt.

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 (usually Whatman #41, widely used in the time period) and counted on an alpha scintillation counter (e.g., the laundry samples of Utnage 1958b). 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<sup>3</sup> (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). In 1958 at the Oak Ridge Gaseous Diffusion Plant, the Whatman #41 paper was used with fixed counting equipment, for a counting and collection efficiency of 30% (Becher 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.

In 1948, some filter paper samples were taken at Mallinckrodt, conveyed by an AEC inspector to Clinton Laboratories in Oak Ridge to be counted for alpha and beta-gamma activity, and then returned by the inspector to Mallinckrodt to be counted for alpha activity there, apparently as a comparison test (AEC 1948a). The samples were taken in the ore milling area, where ore drums were opened and the ore was ground to the desired consistency for later digestion; thus it can be inferred that the samples showed uranium in equilibrium with its daughters down to radon (as suggested by the results of Rochester 1948a – see table above). The counting equipment was said to be a parallel plate counter at Mallinckrodt, but was unspecified for Oak Ridge. For both the Oak Ridge and Mallinckrodt alpha counting conditions (with identical geometries), the absorption loss was assumed to be 30% and the geometry factor to be 52% (with the extra 2% above the 50% being ascribed to backscatter of the alpha particles). For the Oak Ridge beta-gamma counting conditions, the absorption loss was assumed to be 30% and the geometry factor to be 10%; the beta-gamma counting apparatus at Mallinckrodt was being repaired, so no beta-gamma measurements were made there. The (alpha?) background at Oak Ridge was 4 cpm, while the background at Mallinckrodt was 20 dpm. The conversion factor for alpha was given as 2.75 dpm per cpm and for beta-gamma as 14.3 dpm per cpm. (Although these figures were backward in the text of the reference, the data sheets show the correct correspondence.) In 1949, Mallinckrodt (MCW 1950g) stated that it was assuming the counter geometry to be 52% and the filter paper absorption to be 30%.

AEC (AEC 1948a) noted that the samples taken could not be read at Mallinckrodt for several days after they were brought back from Oak Ridge because the parallel plate apparatus and the counting room had to be decontaminated and the background reduced from 110 cpm to 20 cpm. The agreement for the alpha samples was fairly good, in general mostly within 25% and in many cases much better. For a subsequent set of samples counted at Mallinckrodt (with the background now down to 6 cpm), the same AEC inspector reported (AEC 1948b) that the formula used to convert from alpha cpm to microcuries per cubic meter was as follows, with the 0.3 and the 0.52 being the absorption and geometry factors respectively and the 0.5 being the intake rate of the sampling pump:

$$\# \mu\text{Ci}/\text{m}^3 = \frac{\# \text{ cpm} \times 35.3 (\text{ft}^3/\text{m}^3)}{(1 - 0.3) \times .52 \times 3.7 \times 10^{10} (\text{dis}/\text{sec}-\text{Ci}) \times 60 (\text{sec}/\text{min}) \times .5 (\text{ft}^3/\text{min}) \times 1 \times 10^{-6} (\text{Ci}/\mu\text{Ci})}$$

A report issued about the same time by AEC to Mallinckrodt gives the results of dust samples taken in an unspecified Mallinckrodt location and counted apparently at NYOO (AEC 1949i). Counts are given in dpm per cubic meter, with alpha counts given for all samples and both alpha and beta-gamma counts given for about half the samples. These latter show alpha-to-beta-gamma ratios ranging from 0.98 to 6.44, with most values in the range 2.5-3.4.

John Harley, former director of HASL, told an epidemiological studies group (ORAU 1983b) that the equipment used to do the air dust surveys was not very good. He said that HASL had confidence in readings greater than or equal to 25 ug/m<sup>3</sup>, but in the range of 10 ug/m<sup>3</sup>, the results were thought to be “shaky”. He added that although most of the production sites did not do breathing zone sampling (only general air sampling) and some even resisted it, Mallinckrodt did do breathing zone sampling (e.g., MCW 1949d).

The AEC's HASL staff was committed to the time-weighted average as being most representative of total exposure. As Glauber 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. Besides that, AEC was interested in using the feasibility of the levels of urinary excretion of uranium as a control metric in production and processing facilities (AEC 1949d); to do this, it was necessary to correlate the urinary measurements with the dust exposures, which could not be done if only general, instantaneous dust levels were used. The time-weighted averages for Mallinckrodt are documented in a series of AEC air dust study reports (e.g., AEC 1954b) and in some Mallinckrodt reports (e.g., MCW 1949d).

### **5.3.2 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  $\mu\text{g}/\text{m}^3$  were measured in poorly ventilated processing areas. An industry-wide survey showed the average concentration to be 5000 dpm/ $\text{m}^3$ , 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/ $\text{m}^3$  were not uncommon, and that some operations produced concentrations up to 1000 MAC for a few minutes at a time. AEC also stated many employees were exposed to elevated dust levels for years (AEC 1949b); AEC estimated that the inhalation of many Plant 4 operators involved in  $\text{UF}_4$  production was 27 grams or more of uranium, as compared to what it termed a "life tolerance" of 6 grams, and that an additional two years' of exposure would add about 2 more grams (MCW 1949b).

The high levels were of concern to both MED and Mallinckrodt. MED (1944h), in transmitting to Mallinckrodt the results of dust samples taken in June 1944 in the bomb and furnace areas, noted that the results were high and that either ventilation in those areas should be improved or respirator use should be required. Mallinckrodt too was concerned by the high levels, for example the fact that dust concentrations around the various crushing, grinding, and packaging operations consistently exceeded the tolerance levels by a factor of 1-300 (MED 1944k). As a result, Mallinckrodt hired a consulting engineering firm to put together a re-design proposal for dust control (MED 1944k).

MED (1944n) stated the following. In September 1944, MED and Mallinckrodt representatives met to discuss proposals for ventilation improvements in the green salt and metal production areas. It was decided that the ventilation in the green salt furnace room did not need improvement because there were 30 air changes per hour and because the "smell of HF [hydrogen fluoride] was faint". But on the other hand, the green salt unloading, grinding, milling, and blending operations were so dusty that it was decided to do them henceforth under hoods in a continuous sequence, instead of as separate operations, and the blending would be done mechanically instead of manually. Also, the bomb loading, jolting, unloading, and charge blending and the biscuit chipping, all of which were carried out in close proximity, would be provided with separate, localized ventilation. Finally, the green salt blending operation would be redesigned to use a tumbler-type mixer instead of manual mixing, after which time the blender table would no longer be used. Thus in about 1944-1946, significant

incremental improvements in dust control were made that reduced initial production-level dust concentrations in the green salt area.

Respirators were said to be required “for practically all plant operations” in 1946-1948 (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  $\text{UO}_3$  (Mason 1958a). In 1950, for example, it was reported that the air supply system in the Ore Room was such that there was a significant outward flow through the drum opening/closing area shield (MCW 1950u); in 1953, an AEC inspector reported that there were many small openings between the operating area and 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  $\text{UO}_3$  on supposedly clean drums and that as cans of  $\text{UF}_4$  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 1948-1950, tighter administrative controls were instituted and much of the manual handling of  $\text{UO}_2$ ,  $\text{UF}_4$ , 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  $110 \text{ dpm/m}^3$ , although AEC (1954f) indicates that it was  $70 \text{ dpm/m}^3$  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  $1800 \text{ dpm/m}^3$  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 and 9 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  $70 \text{ dpm alpha per m}^3$ . It appears from the reference that they represent typical or representative 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 1950c; MCW 1955d); also, beta-gamma activity analysis was not routinely done (MCW 1955d). Thus Tables 8-16 must be assumed to be gross alpha measurements, whoever took the measurements. There were no continuous air monitors at the Mallinckrodt site, at first because there was no commercial monitor available (MCW 1950e) and later because the results were thought to be of doubtful value (MCW 1955d).

Table 10 presents some early air sampling data taken by MED. The samples represent single point measurements and no correction was applied for exposure time. Thus unless some assumptions are made as to time spent in the given area performing the given operation, only a bounding or

conservative dose calculation can be performed with this data. However, there are some after-operation or “not in operation” measurements among the data that could help to characterize an average level, if needed.

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 are 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 comparative form in Table 11 and in comprehensive form in Tables 12 through 16.

Table 11 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 11 shows that AEC and Mallinckrodt’s data were in general agreement (AEC (1949b) termed it “excellent agreement”), although there were some differences. Mallinckrodt (MCW 1949d) stated that while the Mallinckrodt and AEC results did differ significantly in some instances, it was thought that none of the differences was highly significant except in the case of the office workers; Mallinckrodt (MCW 1949d) also noted that the (overall) lower results of the Mallinckrodt studies were due to Mallinckrodt’s taking more control samples and counting low-activity samples for longer times to reduce statistical error.

One notable difference is for “Cage handling”, where the AEC-measured level is given as 2.7 times the tolerance level and the Mallinckrodt-measured level is given as 52 times tolerance, or 189 and 3640 dpm/m<sup>3</sup> respectively. The ratio of these two values is about 20. In the original report in which AEC reported its values (AEC 1848I), the job description and summary listing of job categories and DWEs does not include a mention of the cage handling function; there is only a mention of the “Saw man” as taking billets to the cage area. However, in the original report in which Mallinckrodt reported its values and where the comparison table (assembled by Mallinckrodt) first appears (MCW 1949c), there is a category called “Cage man”. Thus it appears that the job category of cage man did not exist until mid-1948 or after, i.e., after the AEC study was made. Mallinckrodt seems to have put together an estimate for the “Cage handling” category from the AEC data as some sort of composite of the values for two or more of the other categories, probably including the slag handler (1.6 times the tolerance level). However, given the general functions of the cage man as later described in other dust studies, the cage man’s exposure was more likely to be similar to that of the saw man (15.8 times tolerance according to AEC) and the chipper (26.8 times tolerance according to AEC).

Further, an inspection of the detailed job sheet for “Cage man” in the Mallinckrodt report shows that about two-thirds of his dust exposure was due to a single activity, “Dumping D-7”. What D-7 was is not defined in any available Mallinckrodt document but it appears to be a form of slag dust.

Dumping D-7 is again mentioned in the Mallinckrodt dust study done in December 1949, but the average levels reported here were reduced by a factor of about 1000 from those of the earlier Mallinckrodt study. This reduction is most likely attributable to administrative measures taken in 1949 to reduce dust levels in the highest-level activities, but it could also have been due to malfunction of the sampling apparatus in the earlier study, as explained below.

Also, the high value listed in the 1948 Mallinckrodt study (MCW 1949c) for “Dumping D-7” appears to have been thrown out in the calculation of the DWE by Mallinckrodt. This may have been due to a belief that the sampler malfunctioned in taking that sample. It should be noted that the average level in the next highest area of Plant 4 as measured in this study was less than half this value and that the

known highly dusty operations reported on by Mallinckrodt (MCW 1949d) for Plant 6 for October-November 1948, such as ore room, pot room work, and UO<sub>2</sub> handling activities, typically had highest-sample levels that were lower by 50% or more than the MCW (1949c) "Dumping D-7" value. (The pot room and UO<sub>2</sub> handling had only single samples.) Because Mallinckrodt did not include this value in the calculation of the average, probably because they thought it suspect, it is possible that the other D-7 measurements apparently taken at the same time may also have been higher than the true values. Thus the value for "Cage handling" attributed to AEC by Mallinckrodt may in fact be more correct.

Thus the AEC-Mallinckrodt discrepancy in the "Cage handling" category may be due to the job's being new with the Mallinckrodt study, to a mis-estimation of the cage man's exposure from the AEC data, or to a malfunction of the sampler. AEC and Mallinckrodt obviously did not think this discrepancy was significant at the time. However, because it is not possible to determine this from the information available (including missing pages in the project copy of the AEC report (AEC 1948I)), the claimant-favorable assumption is made that the Mallinckrodt value was the more correct for 1948 and the cage man's exposure value was used in Tables 29B and 31B to calculate inferred intakes.

An additional note about the dust levels measured in 1948-1949 and their applicability to previous years is in order. It is clear from the inclusion in Table 1 of Mason (1958a) of 1946 through 1950 figures (repeated in this technical basis document as Table 8) that 1946 and 1947 data was available that Mason thought appropriate for comparison to 1948, 1949, and 1950 data, or at least that Mason believed (by his repetition or plateauing of the same values throughout 1946-1948) that the 1948 data was representative of the 1946 and 1947 operations as well. This can be inferred for Plant 4 as well from Table 2 of Mason (1958a) (repeated in this technical basis document as Table 8). Thus although the report argues from the paper's Table 1 that significant improvements were made by late 1948 through 1950 that reduced dust levels considerably, this is irrelevant to a significant conclusion that can be drawn from Mason's tables: that the 1948 data was representative of the 1946-1947 data.

This is also borne out by other information from Mason (1958a). This paper states that the dust concentrations "in some operations" in 1942-1943 "were considerably higher than present standards". However, the paper was likely written in 1958 (the conference at which the paper was given took place in October 1958), so the "present standards" were those of the late 1950's. Mason might arguably have made the same comment about 1946-1948 since he also stated of the 1946-1948 operations in Plant 6 that "during initial operations dust control was minimal, and it can be seen that air concentrations were high during the period 1946 through 1948, when respirators were required for practically all plant operations". While Mason stated that the new health program was authorized in 1947 and got under way in 1948, he also said that one of the first projects of the new Mallinckrodt Health Department was "a thorough analysis of the dust data already accumulated and the immediate collection of additional data to enable an estimation of dust exposure already received by operation and maintenance personnel". Thus even in 1948, apparently no immediate engineered improvements were undertaken. Mason went on to say that only in 1949, under the new health program, "immediate steps were taken to install good ventilation and dust control and to initiate process improvements". This implies that the point at which dust levels began to go down significantly in Plant 6 was in 1949, as is also shown from Mason's (1958a) Table 1. Regarding Plant 4, Mason stated that mechanization was installed in 1948 and 1949, but since he gave the same figures for 1943-1947 as for 1948, it must be concluded that either he considered the 1948 values to bound the 1943-1947 ones or the values he used for 1943-1948 (from whichever year) corresponded to those that were representative of the entire period.

Mason (1958a) referred to his Tables 3 and 4, showing Plants 7 and 6E values respectively (repeated in this technical basis document as Table 9), as showing an improvement of "a factor of 60 compared

to 1943 figures and by a factor of 8 compared to 1950 figures” for Plant 7 versus Plant 6 and a reduction factor “of about 20 compared to 1943 figures and 8 compared to 1950 figures” for Plant 6E versus Plant 4. These explicit comparisons too suggest that Mason had information as to the early (1943) dust levels and that his tables reflect that. Mason also plotted his data from 1943 on, again typically showing a plateau for the years 1943-1947.

Mason (1958a) noted that “no regular dust sampling program was in effect during 1943 through 1947, but sufficient samples were collected to show that airborne uranium concentrations were high by present standards; concentration of 50 to 100 times the present MAC [70 dpm/m<sup>3</sup>] were not uncommon, and some operations produced concentrations up to 1000 MAC for a few minutes”. However, such levels were also measured in the later dust studies, e.g., near the end of the paper, Mason commented that it was “evident that personnel did work in fairly high concentrations in the early days of the operation, and that the exposures received depended partly on the effectiveness of the respirator program”. However, he appears to consider the early days to be 1942-1947 or (by his tables) 1942-1948.

This does not mean that the dust exposures in about 1949-1951 were not also high (above the preferred level), although not usually as high as in 1948, as was shown by the following table of data. Some dust sample measurement data from 1948 and 1950, in multiples of the PL\*.

Survey date	May 1948	Nov 1948	Jul-Aug 1950
Survey performed by	AEC	Mall	Both
General information about the studies			
Number of workers in areas studied	170	279	406
Percent at less than the PL*	31	43	61
Percent at 1-3 PL	20	32	31
Percent at 3-5 PL	23	3	5
Percent at 5-10 PL	13	13	0.7
Percent at 10-15 PL	2	0	0
Percent over 15 PL	12	9	2.5
General Categories (in multiples of the PL)			
Average exposure	53	12	2.1
High exposure	660	195	20**
Ore Room operations	71	195	4.9
Digest/Feinc/feed makeup/C-3, centrifuge operations	3.4 - 12	9.8	1.1 - 2.2
Pot Room operations	460	111	4.8
Raffinate and recovery operations	5.2	3.9	1.8 - 2.3
Rockwell (brown) furnace operator	350	76/45	20/3.1
Brown oxide packer	560	161	5.2
Warehouse worker	3		1.4
General maintenance and mechanics	1.8		1.3
Boiler House		0.63	0.62
Digest pilot plant	3.5	1.3	1.5
Experimental continuous furnace (pilot plant)	Not in operation yet	Not in operation yet	122
Ledoux Lab K-65 sampler		30	20
Shotgun Lab		0.34	3.4
Production offices		1.4	0.2
MCW offices	0.7	0.08	0.013
AEC offices	0.5	0.11	0.013
Guards	1.1		0.5
Health office	0.2	0.1	0.16
Other Information			
Ore Room: cleaning ore drums, dpm/m <sup>3</sup>	Range 1710-127000, avg 64400, for 30 min	---	Range 253-496, avg 374, for 64 min
Ore Room: general air, operating, dpm/m <sup>3</sup>	Range 275-8920, avg 2590, for 125 min	---	Range 700-5750, avg 1954, for 20 min

Figures are from AEC (1948i), MCW (1949d), and AEC (1950o). Dashes in the table above indicate the range given in AEC (1950o), while slashes indicate two types of workers of the same title, e.g., day shift versus night shift workers.

\* The PL is the preferred level, equal to 70 dpm/m<sup>3</sup>. All dust sample measurements are in multiples of the preferred level (PL, or 70 dpm/m<sup>3</sup>), except as indicated.

\*\* This figure does not include the exposure of the three Experimental Continuous Furnace workers' exposure at 122 PL, although their exposures were included in the calculation of the percent over 15 PL.

Here we see that in 1948 there were areas where the exposures were indeed “50 to 100 times the present MAC [i.e., 50-100 times the preferred level of 70 dpm/m<sup>3</sup>, or 3500-7000 dpm/m<sup>3</sup>]” and that some operations, e.g., the ore room drum cleaning, clearly did produce concentrations up to 1000 MAC (70,000 dpm/m<sup>3</sup>) for periods of minutes at a time. Thus it appears that the 1948 figures do fit Mason’s description of what “high” was.

Some comparisons were made between spot dust levels measured in 1943-1946 (Table 10) and the corresponding ones measured from 1947 on, with the point being to verify that for the presumably peak or near-peak points of individual operations, the 1943-1946 dust levels were generally no greater and were usually less than they were later, after Plant 6 was in full operation. This too supports the conclusion that the 1948 figures, prior to installation of significant upgrades in Plant 6, would bound the experience in the earlier years.

Data similar to that in the table above can be shown to exist for Plant 4 (i.e., for 1948 and before), so that the “50-100 times” quotation appears to apply for Plant 4 as well. Also, in AEC (1949c), a memorandum from early 1949, an AEC official summarized the hazards in Plant 4, which he said were to be solved by the completed designs for Plant 6E, including dust levels of up to 186 times the preferred level. This suggests that the 1948 figures for Plant 4 are also indicative of the exposure levels of earlier years. The spot dust levels for the early years, when compared to those of about 1947-1948, also appear to show that the 1947-1948 levels bound the early years.

It can be concluded that Mason (1958a) and the references supporting the table above show that the 1948 figures did bound or were representative of the figures of the earlier years. Comparisons with the data from earlier years are consistent with this conclusion.

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 17; some information about the laundry 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 5.3.5 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.

No information is available regarding dust exposures at SLAPS. This was likely due to low radioactive dust levels in this open area (i.e., most of the dust collected would have been nonradioactive even in the dump pile areas, except possibly when the dumping was actually taking place) and to the contained nature of the K-65 residue. Because the SLAPS workers likely were subject to higher dust levels in their regular work at the main St. Louis site (e.g., in the warehouse or loading the dumpsters with barium sulfate residues or doing guard rounds in the plant), their dust exposures are based on their main St. Louis site plant exposure and thus are expected to be conservative.

The reported air concentrations generally pertain to those workers directly and continuously involved in uranium refining work. However, Breslin (1958) defined “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<sup>3</sup> at that time) and more than 1% to concentrations greater than 440 dpm/m<sup>3</sup> (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.

The case of the maintenance and craft worker requires special consideration. Area mechanics were assumed to be dedicated to the particular process area or plant, with their work time being mostly spent in and around process areas, and thus their daily weighted average inhalation exposures should be considered to be representative of their residence time in the process areas. Similarly, their radon exposures can be taken to be those representative of their process areas. However, it is more difficult to determine inhalation and radon exposures for maintenance and craft workers who spent part of their time in their shop areas, where contaminated equipment might be brought to them to work on at irregular intervals, and part of their time working on equipment in process areas. As Hickey and Dupree (1984) pointed out, Mallinckrodt Uranium Division maintenance and craft workers were not usually assigned to a particular process (with the exception of area mechanics, which Hickey and Dupree do not note) but served the entire division. Not only Breslin (1958, quoted above) but also MCW (1950c) pointed out the variability of exposure of these workers as compared to the process area workers.

AEC and Mallinckrodt dust studies from 1948 on list at least some maintenance workers besides area mechanics as a category and tabulate the time spent in various activities and areas in some detail (e.g., MCW 1949c; MCW 1949d). However, AEC (AEC 1954b) and MCW (MCW 1949d) stated that the studies they described used only general area samples to estimate the exposures of maintenance workers and not breathing zone samples while they were performing specific operations (unlike the case with the process workers). MCW (1950c) made a similar point with regard to the AEC-directed back-calculation of dust exposures to Plant 4 employees in 1949. Although it is not possible to determine what the temporarily elevated levels in the shops and the resulting somewhat higher exposures were, it can be concluded from the data in the various dust studies that the shop area dust levels were lower than the process area levels, usually decidedly so, and that thus the most significant contribution to the exposures of these workers most likely came from their time spent in process areas. It is assumed that from 1948 on, this time is factored into the exposures of these workers (as part of the daily weighted averaging calculation). However, for the years from 1942-1947, it is appropriate for the purposes of dose reconstruction to determine from the dust study tabulations reasonable and conservative percentages of time spent by the maintenance and craft workers in process areas and to use the percentages to determine the potential exposures during the time spent in the process areas. The table of these percentages and an explanation of their use are given in Section 6.1, Item 11 rather than here (for the convenience of internal dose reconstructors).

Relatively high potential for dust exposure applied not only to those actually present in the dusty buildings and to some extent to those working elsewhere in the plants, but even to those 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 1955d). 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 Weinstein 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  $1.7 \times 10^{-12}$   $\mu\text{Ci}/\text{ml}$  air for continuous exposure, or  $2.5 \mu\text{g}/\text{m}^3$ , 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, Table 18 was set up to help dose reconstructors interpret claimant submissions and the Mallinckrodt records. Table 18 lists job titles obtained from AEC and Mallinckrodt reports and from film badge and urinalysis records; in addition, it gives a geometry factor set appropriate for each job title (for later use as described in Section 7).

Table 18 is to be used with Tables 19 through 22 and later tables 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 19 through 22 were derived from condensing Tables 12 through 16 and from other sources; the data they contain thus represents average daily weighted air concentrations in nearly all cases. Additional data for individual sampling and laboratory operations is given in Section 5.2.4. All of the data in the tables mentioned are based on a natural uranium mixture, with the exception of thorium processing, as discussed below.

The process in which AM-7 residue was converted into a concentrated thorium nitrate solution, as explained in Section 4.7, 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. The processing appears to have been entirely of liquids (AEC 1955c). Besides the AEC-measured data given in Table 16, 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  $48.1 \times 10^{-10}$  and  $16.3 \times 10^{-10} \mu\text{Ci}/\text{cm}^3$  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  $38.8 \times 10^{-10} \mu\text{Ci}/\text{cm}^3$  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 weight 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 a Th-232 source to be added to the Th-230 source term (see Table 6). Although the internal dose per curie intake is generally somewhat higher for Th-232 than that for Th-230, the specific activity (Ci per g) of Th-230 is over  $10^5$  times that of Th-232. Thus the Th-232 contribution to the dose is likely to be negligible.

### **5.3.3 Respirator Use**

An undated MED reference that is assumed to be of 1942-1944 vintage (MED undated a) stated that respirator use was mandatory when the process required; MED (1942) and MED (undated a) stated that this was especially necessary for the  $\text{UO}_3$  and ore grinding and sifting operations respectively.

An MED reference from May 1945 shows layouts indicating the areas of required respirator wear (MED 1945n). A Mallinckrodt manager stated in 1946 (MCW 1946g) that although dust levels had been high, exposures were being reduced not only by improving the dust systems but also by having workers keep their respirators on all the time that they were working in high-dust areas (thus implying that this may not always have been the practice). An AEC inspector noted in 1947 that although respirators were supposed to be worn in high-dust areas such as the ore grinding and orange production area, they were seen to be worn around the neck or even not at all in areas immediately adjacent to the cited areas; these adjacent areas were visibly covered with finely divided particles that could clearly be made airborne when swept off the floors and walls by drafts (AEC 1947a). 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. 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 1955d). The requirements for them were spelled out in standard operating procedures (MCW 1955d). 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 1955e).

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) stated 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 asserted 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.

MED (1946b) gave acceptable types of respirators for use in uranium processing work, as follows. For use in  $U_3O_8$  dust, the MSA "Comfo" 2101 with the All Dust 2133 filter was acceptable; for use in  $UO_2$  dust, the MSA "Comfo" 2101 with the Dust & Mist 2130 filter, the MSA Dustfoe 2147 with the Dustfoe 2138 filter, or the Willson 770 2119 with the Fume 2123 filter; and for use in  $UF_4$  dust, the Duper 46 2111 with the 2124 filter or the MSA "Comfo" metal frame 2101 with the Dust & Mist 2139 filter. A 1955 list of Plant 6 process cells, dust collectors, and tanks, together with the then-current uses of the tanks, appears in MCW (MCW 1955g); maximum emergency nonsurvey stay times (i.e., for urgent access and not inspections) and the general respiratory protection (mask) types are also given in this reference. It appears that the stay times are based on external dose rate, not on inhalation considerations.

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

#### 5.3.4 Radon

As noted earlier, radon levels could be significantly elevated in enclosed areas where material containing uranium daughter products was stored. ORAU (1989a) stated that a short burst exposure was more typical than a sustained exposure and this appears to be borne out by contemporary descriptions of the various operations in which radon might be released.

Radon measurements by Mallinckrodt and AEC were reported in units of  $10^{-10}$  Ci/L. It is clear from MCW (MCW 1955k) (which, despite its lack of company heading and date, is assumed to be a Mallinckrodt procedure circa 1955) that for both the "environmental" radon measurements and the breath radon measurements, it was just the radon and not the radon daughters in the air that was counted. That is, the procedure specifies that the air sample be alpha-counted for 14 hours, i.e., allowing the radon to come to equilibrium with its daughters Po-218 and Po-214, and that the first two hours of counting are to be discarded, i.e., discarding the contribution of the radon daughters already in the air at the time of sampling. The data from 2 to 14 hours is then extrapolated back to zero. As also stated by MCW (MCW 1955k), the chamber standardization value is given as a theoretical 266 counts per hour per pCi of "radon in equilibrium with its daughters", with half the counts due to the radon and the other half due to the two daughters. The radon decays are assigned a counting efficiency of 100% in the ionization chamber, but the daughters are assigned an efficiency of only 50% because they deposit on the walls of the chamber. Thus in that laboratory and with that type of chamber, the count rate was actually 220 counts per hour per pCi of radon in equilibrium with its daughters, for an effective total efficiency of 83%. However, because the net counts per hour is divided by the chamber standardization value, the result is in pCi of radon alone, not radon and its daughters.

Operations involving radon potential were examined by the Mallinckrodt health physicist and supervision to determine if there was any step in which transient exposure to flood (sudden high) radon concentrations were a possibility (MCW 1950e). From perhaps the mid-1940's on, radon samples were taken once a week in high-radon areas (MCW 1950e). This included the outdoor yard areas, from which measurements Mallinckrodt concluded that some outdoor area was always downwind and that the Plant 6 outdoor background (based on "ordinary" emissions to the outdoor plant atmosphere) was on the order of  $1 \times 10^{-11}$  Ci/l. (MCW 1949n). AEC (1949g) stated that Mallinckrodt had constructed several radon measuring devices for its own use and were in fact in the process of constructing one for NYOO. The standard used by Mallinckrodt was made up by the National Bureau of Standards (AEC 1949l). AEC (1949g) also reported that the author of the reference, an AEC inspector, had visited the airport (SLAPS) with Mallinckrodt health personnel and had assisted them in taking radon samples by using an extension pole device designed by Mallinckrodt; samples could thus be taken at levels as high as 20 feet above the ground. It seems clear that based on (1) the long history of radon sample taking at Mallinckrodt, with the start preceding by some years the processing of high-radium and thus high-radon pitchblende ores, and (2) the apparent competence of the Mallinckrodt health and safety and instrument people at developing and using radon-measuring instruments, the radon measurements taken can be regarded as reasonably representative of the conditions.

Some early radon measurements from 1945 are shown in Table 23. The principal locations where difficulty was found in 1946 in keeping radon concentrations below tolerance levels were the railcars during unloading of ore drums and in the ore and residue storage area (MED 1946c).

MED (1946c) noted that a railcar could be unloaded fast enough that the then-current ventilation methods and restrictions spent on time in the railcars were usually sufficient to keep below tolerance levels. Still, the radon problem became more acute with the heavy use of pitchblende ore and in 1948 AEC provided or arranged for new railcars to be used that could accommodate installation and de-

installation of fans at the ends of the cars at the delivery points (MCW 1948h). Presumably the openings were covered with panels while the railcar was in transit. In October 1948, Mallinckrodt tested the efficiency of the ventilation in one of these new railcars (MCW 1948h). The door was left open two feet overnight, then closed for three hours until the start of the test. The fans were started and at subsequent intervals the radon level was measured at two points at the center of the car halfway between the door and either end. The result was that the radon level fell from an average of  $7.03 \times 10^{-10}$  Ci/L at time zero to about  $0.5 \times 10^{-10}$  Ci/L after about 3.5 hours, reaching the  $1.0 \times 10^{-10}$  Ci/L point some time around 20 minutes, although the levels fluctuated at and between points. While the ventilation was seen to be effective, two drawbacks were noted. First, the gamma dose rate at the top and side of the car was 20-32 mR/ hr and it took two or three workers about 1.5 hours to install the fans, so that the workers who installed the fans received 30-50 mR, according to pocket chamber readings. Second, because the total time to unload a car increased to more than two hours with the addition of the fan installation step, the car could be on the siding for an extra day before being unloaded and thus people passing by and working near the car received extra exposure. Hence Mallinckrodt recommended that the fans be left permanently installed in the railcars (MCW 1948h). It is not known if AEC allowed this.

The problem was more complicated in the storage area because worker occupancy times were of necessity longer. There was no forced-draft ventilation in the ore storage area at that time, only a natural exchange of air provided mostly by a four-foot opening on either end of the building. The result was that radon samples likely averaged on the order of the maximum permissible concentration ( $1 \times 10^{-10}$  Ci/L) or higher. These openings appear to have been permanent, since AEC (1947e) states that the (each) whole end of the building could be removed, but if not, a large opening still remained.

In the Scalehouse Sampling Room, samples of K-65 residue were taken from open K-65 drums sitting in the sampling bays on the level below the Sampling Room (MCW 1948j). This was done with a thief sampler through holes in the Sampling Room floor. Although there were several small exhaust fans that were supposed to draw the radon away from the sampling workers, the turbulence caused by a unit heater resulted in the radon being distributed throughout the room. Also, although most of the time the exhaust fans maintained adequate control over the open pans into which the drawn samples were deposited, at times the turbulence also drew radon from the thief and the pans as the sample was being dumped out. The concentrations found in the Scalehouse itself were very erratic, showing that here too the radon was being carried in momentary eddy currents about the room. High concentrations usually coincided with the pulling out of the drums on pallets from the storage bins and the removal of the drum lids. It was noted that a worker could be present in the Scalehouse and the Sampling Room for up to 4 hours on some days.

Besides the ore and residue handling and storage areas, some processing equipment was also associated with elevated radon levels. In August 1948, a ventilating fan was installed in the wall of the K-65 centrifuge room to exhaust thermally hot air (MCW 1948l). However, this created a suction from the neighboring Wash Oliver (filter press) room into the centrifuge room, drawing appreciable quantities of radon off the Wash Oliver filters and into the centrifuge area. To solve this problem, a door was installed between the two rooms. Prior to the installation of the fan, the overall average radon concentration in the centrifuge room was  $0.83 \times 10^{-10}$  Ci/L; after the installation of the fan, it was  $1.25 \times 10^{-10}$  Ci/L; and after the installation of the door it was  $0.62 \times 10^{-10}$  Ci/L. Further ventilation improvements were apparently made in the centrifuge area.

A significant short-term exposure to radon would occur when the Feinc Niagara filter press, which was used to produce the high-radium K-65 residue, was opened for the washing of the plates (MCW 1950b). This occurred about 12 times a day when the processing was "operating on digest" because the plates could not effectively be washed down by remote control in this regime. It was necessary for

a worker to open the press and hose down the cake. Approximately once a week, the plates became “blinded” (clogged) and had to be manually removed for cleaning with caustic (MCW 1950b). When the Niagara was opened, the radon concentration in the near area would suddenly go up to as high as 34 times tolerance, then went back to tolerance level over about 5 minutes. As the last of the cake was washed into Tank M-289, the radon concentration would double again because of the venting of M-289 as the pipe cleared and air from the tank was displaced back to the open Niagara and thus to the room. The concentration fell back quickly to nondetectable levels when the line to M-289 was closed. Radon levels at the small tank where the plates were cleaned, however, showed low or nondetectable levels.

Radon concentration in enclosed spaces in MED/AEC 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 (drying) oven, the ore thaw house, and the Wash Oliver cell, as shown by some of the results in Tables 24 and 25 which cover the years 1947-1949 and 1950-1957 respectively. However, Mallinckrodt (MCW 1949m) reported the results of measurements taken in the Ore Room and its addition soon after ventilation and remote handling equipment was installed; some of these results are shown in Table 24. The improvements significantly reduced radon levels in most areas, but there were still some operational problems (see Section 5.2.1). Because as MCW (MCW 1949m) states the radon hazard was greatest near newly opened drums and because the ventilation system apparently was not very effective at taking care of this hazard for close approaches to the drums (i.e., the radon die-off to less than  $1 \times 10^{-10}$  Ci/L after a drum was opened took 25 minutes), radon was a continuing concern in the ore drum storage and handling areas. The operational problems that forced operators to approach open drums appear to have been corrected thereafter.

Most of the information regarding radon levels from 1947 on comes from the weekly “MZ” radon reports (Mz was a code for radon) (MCW 1955d; MCW 1947-1957). Additional data are shown in the table below (from AEC 1949b, Table 1), which gives typical radon exposures for different areas at the Middlesex facility over the years 1944-1949 (covering the early years of pitchblende use). These would be comparable to the railcar unloading and Ore Room operations at Mallinckrodt.

Middlesex ore storage worker radon exposures, January 1944–January 1949.

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

Radon levels are given in multiples of the radon MPC or preferred level of  $10^{-10}$  Ci/L. Use of blower-equipped railcars starting in about early 1949 reduced levels to below the MPC.

Tables 24 and 25 also give information that 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) and in SLAPS the levels were lower than tolerance ( $1 \times 10^{-10}$  Ci/L) in all but very enclosed areas and

because the thorium and radium were removed in the production of UO<sub>3</sub>, it can be assumed that the radon levels were well below the tolerance level in areas where ore and pre-UO<sub>3</sub> residues were not present.

A further item regarding radon content of the residues was noted by AEC (1947e). A certain percentage of the radon produced during decay would be adsorbed on the surface of the ore particles (the percentage depending on the particle size of the ore, the temperature, the moisture level in the ore, etc.). When the ore was digested in acid, the adsorbed radon was released and the gamma activity of the ore would drop. But when the radium was precipitated as a sludge, as was done at Mallinckrodt, the precipitate would adsorb some of the radon and there would thus be an increase in gamma activity as the precipitate "aged". This meant that the radon content of the digest vent exhaust, the residue, etc., could be variable depending on process conditions.

Regarding the processing of residues to concentrate thorium, it is clear from the data in Table 26 that the average concentration of radon (Rn-220 and Rn-222), under process-applicable and claimant-favorable assumptions, was about eight times the AEC "preferred level" of 10<sup>-10</sup> Ci/L. It was also well above the 3.0 x 10<sup>-12</sup> Ci/L that represented an "undetectable" amount for the AEC during the relevant period of time (as per Eisenbud 1975).

ORAU (1989a) estimated the radon exposures of approximately 184 Mallinckrodt Plant 6 workers as part of a larger study. They calculated the working level (WL) for each job title using the mean radon concentration value from all available surveys in 1946-1957 for each job title's assigned work area; exposure estimates were then calculated in units of working level months (WLMs) for each job title. It was assumed that an equilibrium factor of 0.25 applied for radium and its daughters, based on plant and memoranda, other documents, and findings from uranium mine and residential radon studies. Their approach of assigning a WLM value for each job title for a single grouped period of years (rather than breaking it down by years) was due to the lack of survey data for many of the years. The "roving operator" and the production/processing/manufacturing operators were assigned the average area radon levels for the entire Plant 6 area and the highest daily work time breakdowns of all the production processes. Weekly rotation as practiced at Mallinckrodt was handled by assigning an average radon level of all available survey data from those work areas in the rotation plan for that job title. Pertinent results are shown below for information. These results are for the years of pitchblende processing and so would presumably be conservative for the pre-pitchblende years.

Exposure rates of 184 Mallinckrodt workers, based on surveys done in 1946-1957 (ORAU 1989a).

Job title	No. of workers	WLM per month worked
Manufacturing operator	3	.138
Operator, process develop	1	.138
Production operator	2	.138
Roving operator	3	.138
Cleanup operator	8	.127
Maintenance (general)	1	.111
K-65/GLC sampler	1	.102
Pot Room operator	14	.097
K-65/AJ-4 sampler	4	.096
Raffinate operator	9	.092
Barium operator	6	.091
C-3 (Centrifuge) operator	18	.084
Feinc operator	12	.084
Director, technical	1	.077
Mail boy (office)	2	.057
Porter, Production	6	.056
Ore Room operator	16	.055

Job title	No. of workers	WLM per month worked
Recovery operator	13	.052
Guard	3	.047
Porter, Lab	1	.044
Digest operator	2	.042
Pilot Plant operator	4	.041
Clerk, Manufacturing Office	1	.040
Clerk, Production Office	8	.040
Feed operator	2	.038
Filter press operator	3	.038
Plant monitor	1	.030
Health office	2	.020
Engineer, senior mechanical	1	.018
Furnace operator	12	.010
Industrial relations (office)	1	.010
Ether House operator	17	.008
Machinist (instrument)	2	.008
Chemist	4	.003

Note that for use in dose reconstruction, radon concentrations reported in units of Ci/L must 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 reported results are given in Tables 23-25 of this technical basis document in the original units so that the dose reconstructor can readily use whatever equilibrium factor appears to be most appropriate if the factors used in the conversions to annual intakes in this technical basis document (see Section 5.3.8) need to be re-examined for whatever reason.

### 5.3.5 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. Little surface contamination measurement data appears to have survived, presumably because it could vary so much and because excessive levels, when found, were cleaned up but not necessarily documented.

Mallinckrodt (MCW 1958; MCW 1959) gave the results of a plant-wide surface contamination and external dose rate study that Mallinckrodt did after some preliminary 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<sup>2</sup> and average beta activity of 2 mrep/hr; high spots of 35,000 dpm/100 cm<sup>2</sup> alpha and 15 mrep/hr beta were not unusual. High spots of up to 20 mR/hr gamma were found west of the UF<sub>4</sub> loading dock where ore cars were 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<sup>2</sup> 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., the study partly documented in MCW 1958 and MCW 1959, quoted by Utnage (1958a)), also showed fixed floor surface contamination levels of greater than 10,000 alpha dpm/100 cm<sup>2</sup> 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<sup>2</sup> and the center of the maintenance cage (where there was no uranium processing) measured 1200 dpm/100 cm<sup>2</sup>. Other stations in the "pitchblende (ore) area" (Plant 6) showed levels of 1000-60,000 dpm/100 cm<sup>2</sup>; in the uranium products warehouse, 4500-21,500 dpm/100 cm<sup>2</sup>; and in the metal plant (6E), 1000-9000 dpm/100 cm<sup>2</sup>. The UF<sub>4</sub> production plant (Plant 7) had no reading higher than 1200 dpm/100 cm<sup>2</sup>. 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 transferable activity was measured with a Samson alpha survey meter, with an overall counting and efficiency factor of 20%. The data, shown in the table below, indicate that the airborne concentrations ranged from 0.36 to 5.05 dpm/m<sup>3</sup> for every dpm/cm<sup>2</sup> of surface contamination, or an air concentration of 3.6 to 50.5 dpm/m<sup>3</sup> for every 1,000 dpm/100 cm<sup>2</sup> of surface contamination.

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<sup>3</sup> of air per dpm/cm<sup>2</sup> of surface

Other fixed surface contamination data are given below for various surfaces and pieces of equipment in the laundry (from Table 1 of Utnage 1958b).

Contamination levels on various surfaces and pieces of equipment in the laundry.

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

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 recommended AEC limits on hand contamination and on ingestion as a result of smoking.

A 1947 AEC letter to Mallinckrodt (AEC 1947b) stated that surfaces in the lunchroom should show less than 100 dpm alpha on a smear test and less than 500 dpm alpha per 100 sq cm (fixed plus removable); the maximum hand count should be equivalent to no more than 0.35 mg of uranium on either side of the hand. In 1949, dust samples taken in the lunchroom at various times over one lunch period, showed that the level ranged from 6 dpm per cubic meter with only 7 workers present to 57 dpm per cubic meter when the room was full; the level was 12 dpm per cubic meter at the start of the post-lunch cleaning and then went up to as high as 65 dpm per cubic meter following the cleaning due to dust suspended in the air (MCW 1949d). The same sampling study showed that levels in a conference room in association with a service group (operators') meeting were 4, 22, and 30 dpm per cubic meter respectively before, during, and just after the meeting. In both the lunchroom and conference room, the workers wore cover clothing over their work clothing. In 1951 it was reported that the average dust level in the Plant 6 lunchroom (MCW 1951b) was 1.3 dpm/m<sup>3</sup>. Thus although it was stated in MCW (1949d) that the sub-tolerance levels reported were acceptable, clearly the lunchroom levels were reduced over time by better clothing change and contamination control practices.

Smoking areas were typically adjacent to the working areas. In 1951, in response to AEC's pointing out that Plant 6 workers entering the smoking room habitually slapped their dusty gloves and brushing material from their clothing after they entered the smoking room, Mallinckrodt agreed to provide improved ventilation in the smoking room and to put a small vacuum cleaner inside the smoking room for workers to use to vacuum their gloves and clothing after they entered but before they smoked (MCW 1951d). Mallinckrodt also agreed to have greater enforcement by supervisors of the requirement that gloves be removed before smoking (MCW 1951d).

These findings may explain the observation by AEC (1951a) that in a majority of the jobs evaluated at Mallinckrodt, 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. In 1951 it was reported by Mallinckrodt that air samples taken in the smoking room in Plant 6 were always above tolerance, even after UO<sub>2</sub> production had moved to Plant 7 (MCW 1951b); the average dust level was 116 dpm/m<sup>3</sup>, versus 1.3, 4.2, and 66 for the lunchroom, locker room, and change room respectively, and the typical daily individual occupancy of the smoking room was 60 minutes. This all 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.

Tests done in about 1958 at the Oak Ridge Gaseous Diffusion Plant with UNO<sub>4</sub>, UF<sub>2</sub>, and UF<sub>4</sub> (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  $2.5 \times 10^5$  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  $2.5 \times 10^5$  dpm on each hand would correspond to the maximum permissible ingestion; and that a maximum of  $2.5 \times 10^5$  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  $8.6 \times 10^4$  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.). This suggests that ingestion is a negligible source of internal dose during operations, compared to inhalation.

Regarding clothing, Table 27 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 almost 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). Gloves were discarded when soiled and were treated as contaminated clothing (MCW 1950e).

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<sup>2</sup> to be equivalent to 9700 cpm/100 cm<sup>2</sup> 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<sup>2</sup> after unloading uranium oxide, UF<sub>4</sub>, or uranium metal at uranium processing plants, even though the sites made an effort to decontaminate them (AEC 1949b). AEC advised that strippable coatings would eventually need to be used (AEC 1949b), 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.

Monitoring for surface contamination was done using portable alpha and gamma-beta survey meters and smear tests (MCW 1950e). Tools to be moved from contaminated areas were to be cleaned to a stated level (MCW 1950e), given in 1947 as 100 cpm, presumably beta-gamma (AEC 1947b). If the article could not be decontaminated, it was to be securely wrapped in paper or placed in a clean container and marked with handling instructions. However, these checking and control requirements did not apply to tools belonging to outside contractors, who presumably could take away tools contaminated to any level (MCW 1950e). Alpha hand counting devices were not used after some time prior to 1950, supposedly because AEC-NYOO requested that their use be discontinued (MCW 1950e). As of at least 1950, hands and feet were not checked when workers exited a process area to go to the lunchroom to eat or smoke (MCW 1950e; AEC 1947a), but they had to go through the personnel decontamination cleanup in the change room area, with a strict "clean side, dirty side"

regime maintained (MCW 1950e) (see Section 5.5.3). Visitors were not checked for contamination before leaving the plant, at least through about 1950 (MCW 1950e).

### **5.3.6 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 (MED 1942) and they were given an annual physical that included a routine urinalysis and a blood count (MED 1942 (which says it was a "followup" examination); MCW 1955d; Mason 1958a). From about the summer of 1948 on (MCW 1950c), 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 1955d; Mason 1958a); after this, time the frequency was no more than semiannual (MCW 1955d). 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 Mallinckrodt urinalyses were first performed by the University of Rochester under contract to AEC-NYOO up to about 1948. At one point, according to ORAU (1983b), there were some problems with the running of standards because there had been uranium plateout on a table. This was corrected. In 1948, Barnes Hospital began to do the urinalyses for Mallinckrodt. However, an AEC health official stated (AEC 1948) that while it had been his understanding that the analyses were being done at Barnes Hospital (at Washington University), 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 have been potentially contaminated (i.e., some of the uranium content may have come from the laboratory analyzing them).

Apparently Barnes Hospital resumed doing the urinalyses (AEC 1949g, MCW 1950e). However, in 1949, AEC compared the Mallinckrodt analyses against those for other sites handling similar material and concluded that the results were consistently inexplicably high (MCW 1950e), although Mallinckrodt thought the agreement was acceptable (MCW 1949j). They then sent Mallinckrodt some spiked samples and also had an independent Mallinckrodt chemist 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 to standard ones. The conclusion was that the samples were indeed reading too high at Barnes. (It is not clear if the spiked sample comparison referred to in MCW (1949j) is this same set of samples, but if so, the data can be found in MCW (1949j), along with a statement that the reliability of the Mallinckrodt sample testing is +/- 15%). 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 were of doubtful value (AEC 1950l). Still, AEC (1950i) 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 (1950q) 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. 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 1950l).

It is not clear who did the urinalyses from 1950 to 1954, although MCW (1950m) suggests that this was no longer being done at Barnes Hospital but at AEC-NYOO, presumably at HASL. Also, in September 1951 AEC-NYOO was clearly performing them, but directed AEC St. Louis area representative not to have any more routine samples sent during the last quarter of 1951 because of an "unusual work load" that its chemical laboratory had (AEC 1951c); emergency samples could still be sent, however. In 1954 AEC gave Mallinckrodt permission to perform their own urinalyses (MCW 1954e, ORAU 1983b), 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 (HASL) must have resumed performing the analyses, because a 1955 Mallinckrodt report describing its health program stated that NYOO was doing so (MCW 1955d). This report stated that NYOO was analyzing about 2500 Mallinckrodt urine samples a year and that urine samples that were taken were split, with half going to AEC-NYOO for the radiological analysis and half to Barnes Hospital for the medical analysis.

Referring to urine samples sent to the University of Rochester from any AEC site, ORAU (1983b) stated that samples were collected from workers in four-ounce glass bottles with bakelite caps and shipped to HASL. After 1949, only samples taken within one hour of the start of the weekly shift were accepted (ORAU 1983b).

The radiological analysis was apparently only for uranium content (referred to as "X in urine" or "uranium-in-urine"). However, one set of urinalysis records shows for a single individual and for periods from March to May 1956 the notation "Shoot for radium". Thus it appears that radium in urine could be analyzed as a special case. It is not clear whether the thorium (ionium) processing workers in Plant 7E had special urinalyses for thorium or not. However, this is a possibility, as suggested by Mallinckrodt's health and safety director's obtaining a copy of a Los Alamos Scientific Laboratory procedure on urinalysis for plutonium (LASL 1955) and the director's noting on his copy that he was told that urinalysis for thorium could be done by the same method as in the procedure.

ORAU (1983b) stated that all urinalyses done at the University of Rochester used the fluorometric method; the urine was dried in a platinum dish, then fluxed with either sodium fluoride or a lithium-calcium fluoride mix and counted. 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. AEC (1949l) states that Barnes Hospital (at Washington University in St. Louis) used "fluorometric (photoelectric ultraviolet)" methods in performing urinalyses for Mallinckrodt.

ORAU (1983b) states the following about samples analyzed at the University of Rochester. These samples were run in triplicate, with the results usually being with  $\pm 2$   $\mu\text{g/L}$  of one another; if this turned out not to be the case, it indicated that there had been poor fusion of the flux and the samples were re-fused and re-run, which usually corrected the discrepancy. The value recorded was the median value of the three. For insoluble uranium, it was considered that 30  $\mu\text{g/L}$  in the urine corresponded to an air concentration of 50  $\mu\text{g/m}^3$ . The analysts felt confident of readings greater than or equal to 5  $\mu\text{g/L}$ . However, if more confidence was desired for lower-level samples (e.g., for special projects), the urine was concentrated either by ion exchange or by extraction, or more aliquots were run.

The uranium fusion photofluorimetry urinalyses performed by the University of Rochester and the AEC NYOO are known similar to those performed at other AEC facilities. Based on the lack of clear information regarding a detection threshold for Mallinckrodt urinalyses, the default detection threshold for uranium urinalysis may be assumed to be 10 µg/L based on a reported sensitivity of 5 to 10 µg/L for uranium fluorimetry urinalysis in the early years, as was reported for other AEC facilities (Wilson 1958).

Because of the questions regarding the validity of the samples, the apparent variations in sample analysis methods, and even who was doing the analyses, the Mallinckrodt urinalysis data should be used with caution, at least when the data were taken by Barnes prior to about 1951. However, it appears that the errors, if any, are in the conservative (high) 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 28. 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 and with the data from these cases to produce a category-specific distribution and standard deviation for the typical daily intake, as shown in Table 28; 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 28.

Table 28 does not include intakes for workers who processed wastes containing thorium (ionium) because there was not enough urinalysis information for such workers and what there was did not always have a clear indication of work with thorium. It appears that there were few such workers: (1) AEC (1955e) 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 appears that thorium itself in urine was measured at all, rather than uranium. 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 early 1955 on for workers who processed thorium wastes should be examined on a case-by-case basis to see if any special evaluation for thorium was done; if not, then dose estimates from air sampling data may have to be made.

### **5.3.7 Information and Available Data Regarding Other Types of Bioassay**

Breath radon measurements began to be made in June 1945 (as shown by, e.g., MED 1945e and MCW 1946g), but only for workers who worked in areas where there was a potential for radium intake.

MCW (MCW 1950l) gives a list of worker types or occupational areas, along with a rating of the need for workers of each type or in each area to have their breath sampled; most of the Manufacturing (process), Stores (warehouse), and Maintenance workers were in the "Definite" category, while most of the Power Plant, Occupancy, Plant Protection (guard), Research, Laboratory, and Laundry workers were in the "Possible" category and most of the Health & Safety, Office & Administration, and Plant 4 workers had most of their people in the "Improbable" category.

The Massachusetts Institute of Technology (MIT) or the National Bureau of Standards (NBS) did the breath radon analyses for MED/AEC until 1951, when HASL obtained an ion chamber of the type needed to perform the analyses (ORAU (1983b)). Initially, samples were taken in the infirmary of the MED/AEC site because it was thought that this area was removed from the production areas; later a respirator with bottled air was used to collect samples in order to control for radon in the ambient air (ORAU 1983b). However, the first breath radon measurements were thought to be worthless by MED because the MED expert concluded that the samples were contaminated at the time they were taken (MED 1945e). As a result, MED directed Mallinckrodt to have breath radon samples taken only in a room away from the plant and only when the employee had not worked for at least 48 hours and while he was still wearing his street clothes (MED 1945e).

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 1949g; AEC 1950a; MCW 1950g). The samples were measured at the NBS (AEC 1949g) or at HASL (AEC 1950a, MCW 1955d) by an "automatically recording pulse-counting device" (AEC 1950a). If a sample was over the "tolerance level of  $1 \times 10^{-12}$  Ci/L, then a recheck (repeat sample) was made immediately (AEC 1949g). The lower limit (of detection) at HASL was 0.1 pCi/L and there was confidence in readings of greater than or equal to 0.5 pCi/L (ORAU 1983b). In 1946, it was reported that of 40 workers tested, the maximum level was right at the tolerance level of  $1 \times 10^{-11}$  Ci/L (MCW 1946g).

In early 1950 AEC apparently became concerned about the high background that seemed to be present where the samples were being taken (MCW 1950g). 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  $0.8 \times 10^{-12}$  Ci/L, which AEC judged was a high background for a breath radon sampling area (AEC 1950k). 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 1950m); if the breath radon samples were also taken there, that could explain the relatively high background radon. In early 1951, Mallinckrodt (MCW 1951g) reported the results of a further test done at the behest of AEC in which they took breath radon samples from the same four workers in the usual location (background of 0.8 pCi/L) and in a lower-background area (background of 0.2 pCi/L). Mallinckrodt admitted that although they had been told earlier by the (National) Bureau of Standards that the test area background did not matter as long as it was on the same order as the sample, AEC had turned out to be correct in its concerns about the background: the differences between samples taken in the lower-background area and the samples taken in the higher-background area differed by almost exactly the difference between the two backgrounds (MCW 1951g). Mallinckrodt apparently corrected this problem by then using the special respirator-testers provided by AEC ((MCW 1951e); they may also have moved the breath radon sampling location to a lower-background area. Note that Srivastava et al., in their study of uranium miners (Srivastava 1986), found that post-shift measurements (i.e., after breathing ambient radon in the workplace) were 2 to 4 times higher than pre-shift measurements, which confirms the confounding influence of background radon.

A baseline (start of employment) breath radon test was not administered; the routine test during operations was thought to be sufficient (MCW 1950w). In 1949, the nominal breath radon sampling frequency was quarterly (AEC 1949g), which seems to have been the typical frequency for eligible workers (ORAU 1983b). 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 1955d). It was not always possible to obtain a termination breath radon sample because some workers left without notice or because the sample had to be taken after 48 hours of nonexposure, i.e., usually on a Monday (MCW 1950w). Mallinckrodt thought that about 80% of terminating employees had termination medical examinations (MCW 1950w), but it is not clear if this was also true of the breath radon analyses for the relevant workers. Breath radon records are available in scattered form in reconstruction project files; possibly all of it is found in the large urinalysis research file mentioned in Section 5.3.6 above.

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). ORAU (1989b) quoted a report by the MIT Radioactivity Center that stated that their lower limit of detection for breath radon was 0.006 pCi/L and that this corresponded to a minimum detectable body burden of radium-226 of 0.00059  $\mu$ Ci. ORAU (1989b) also quotes the MIT report as stating that assuming that 65% of the radon generated by the body burden of radium was exhaled, 1 pCi/L of radon in the breath corresponded to approximately 0.1  $\mu$ Ci of Ra-226 in the skeleton, which ORAU (1989b) verified in its own calculation. This can be compared to the assumptions made by Srivastava et al. (Srivastava 1986), who took breath samples of uranium miners using a controlled radon intake respirator apparatus: the equilibrium percentages of the radium-226 body burden were taken to be 33% in the lungs, 39% in cortical bone, 14% in trabecular bone, and 14% in other soft tissues and the corresponding radon escape fractions were taken to be 1.0 for lungs and other soft tissues and 0.7 for bone. Srivastava et al. thus concluded that 84% of the radon produced by decay of the Ra-226 was exhaled, a figure applicable to those working in the mines for several years (i.e., to workers chronically exposed for an extended period).

ORAU (1989a) reported the results of a study of ambient radon exposures to some 184 Mallinckrodt workers. In addition to the lung doses from the ambient radon exposures, they attempted to estimate the contribution from breathing radium dust and used breath radon data and the associated skeletal radium burden as an indicator (as per ORAU (1989b)). These estimates are given in ORAU (19889a), but as with the ambient radon exposures, the subjects are listed only by their ORAU study identification numbers.

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 (if any) 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 (if any) appear to be unavailable.

### **5.3.8 Summary Information Regarding No-Bioassay-Based Inhalation, Radon, and Ingestion Annual Intakes (Tables 29A-29F, 30, and 31A-31F)**

In order to put the measured nonbioassay-based data presented in the preceding subsections of Section 5.3 into the form most useful for dose reconstruction, these data have been converted into annual intakes.



For inhalation, the daily weighted exposure levels given in Tables 19-22 were converted to annual intakes as given below. The Plant 6 results for 1948 were used for Plants 1 and 2. The results are shown in Tables 29A-29F.

$$\text{Intake (pCi/yr)} = (\text{dust concentration (dpm/m}^3) \times 1.2 \text{ m}^3/\text{hr breathed} \times 2000 \text{ hr/yr}) / (2.2 \text{ dpm/pCi})$$

For radon, no daily weighted exposure levels are available and the reported levels tabulated in Tables 23-25 apply only to radon and not its daughters. Thus assumptions had to be made to determine conservative exposure levels, occupancy factors, and daughter equilibrium levels. The conversion to Working Level Months per year (WLM/yr) is as given below. The results, including the detailed parameter values used, are shown in Table 30.

$$\text{Intake (WLM/yr)} = (\text{radon level (pCi/L)} \times \text{equilibrium factor} \times 12 \text{ months/yr}) / (100 \text{ pCi/L per WL})$$

(Note that for use in dose reconstruction, radon concentrations reported in units of Ci/L must 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 reported results are reported in this technical basis document in the original units so that the dose reconstructor can readily use an equilibrium factor different from the ones applied in Table 30, if desired.)

For ingestion, the method of NIOSH (2004) is used with the daily weighted exposure levels given in Tables 19-22 to give annual intakes, as given below. This method is expected to yield very conservative results. The Plant 6 results for 1948 were used for Plants 1 and 2. The results are shown in Tables 31A-31F.

$$\text{Intake (pCi/yr)} = (0.2)(\text{dust concentration (dpm/m}^3) \times 1.2 \text{ m}^3/\text{hr breathed} \times 2000 \text{ hr/yr}) / (2.2 \text{ dpm/pCi})$$

## 5.4 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 1949b; AEC 1951b)). ORAU (1980b) stated that there did not appear to be any circumstance that would produce an exposure of 3 rem or greater in less than several hours and they found no incident in which an acute exposure rate of greater than or equal to 3 rem/hour was produced. The tables below are an adaptation of Table I and a summary of information given in Tables II of ORAU (1980b); the first shows the total annual gamma dose by dose level and the second shows the ten highest gamma doses to workers, both from 1947 through June 1957.

Information regarding dose rates for ore and residue drums is given in Table 32 and regarding dose rates for various forms and areas in Table 33. There is little information about conditions in Plants 1 and 2 during the wartime startup; however, some dose rate measurements from 1943 and 1944 appear to have been taken, as shown in Table 33. As noted previously, film badging did not start until late 1945, when Plants 1 and 2 were in the process of largely shutting down. Doses might have been somewhat higher than in Plants 4 and 6 due to possible greater manual involvement and probably somewhat greater bodily proximity to sources, but on the other hand the quantities involved were much lower. The dose rates given in Table 33 suggest that doses were likely to have been higher in later years due probably to the greater volume of uranium processed and to the use of pitchblende

Annual gamma exposures, 1947 – June 1957 (ORAU 1980b).

Year	Workers monitored	Annual gamma exposure, R				
		0 - 1	1 - 5	5 - 10	10 - 15	>= 15
1947	253	70	131	27	18	7
1948	366	120	171	47	19	9
1949	554	370	141	41	2	0
1950	615	475	133	7	0	0
1951	694	512	171	11	0	0
1952	757	659	88	10	0	0
1953	763	619	142	2	0	0
1954	756	566	188	2	0	0
1955	871	766	105	0	0	0
1956	958	944	14	0	0	0

Ten highest gamma doses to workers, 1947 – June 1957 (ORAU 1980B).

Year	Annual dose, R			Weekly dose, R/week		
	Min	Avg	Max	Min	Avg	Max
1947	14.4	16.1	23.5	0.28	0.31	0.45
1948	14.9	17.0	20.3	0.25	0.33	0.39
1949	7.7	9.0	13.3	0.15	0.17	0.26
1950	4.5	5.4	7.1	0.09	0.11	0.14
1951	5.0	5.9	7.1	0.10	0.11	0.14
1952	5.1	5.9	6.6	0.10	0.12	0.13
1953	4.0	4.6	5.7	0.08	0.09	0.11
1954	3.9	4.4	5.1	0.08	0.09	0.10
1955	3.9	4.4	5.1	0.08	0.09	0.10
1956	1.1	1.4	1.9	0.04	0.06	0.07

ores. It should be noted that the era of pitchblende use (early 1945 on) was mostly covered by film badge monitoring, so that the doses characteristic of this work are known. Thus it is considered to be claimant-favorable to assume that the doses at Plants 1 and 2, for the same type of work, were similar to those at Plant 4 and Plant 6 around 1948.

According to MCW (1955f), 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. Although these reports do not appear to be available, Table 33 shows some area film badge monitoring results that show what conditions were and of course film badges were consistently worn in the later years. A 1955 list of Plant 6 process cells, dust collectors, and tanks, together with the then-current uses of the tanks, appears in MCW (1955g); maximum emergency nonsurvey stay times (i.e., for urgent access and not inspections) are also given. It appears that the stay times were based on external dose rates. In general, the operator stay times were half the maintenance stay times, presumably because of the need for more frequent access by the operators.

See also Sections 5.1 – 5.2 above for some additional external dose information associated with particular handling activities or operations.

#### 5.4.1 **Gamma, Beta (Electron), and Nonspecific Beta-Gamma Exposures**

After high-grade pitchblende ores began to be used, refinery workers were exposed to photons from radionuclides in equilibrium with U-238 and U-235. Ra-226, through its Pb-214 and Bi-214 daughters, contributed 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.

In 1946 the principal large-scale source of gamma radiation was said to be the drums of ore as they were stacked in the receiving warehouse (MED 1946c). 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). 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. Dose rates from wastes could run even higher than those for the ore. 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) or up to 275 mR/hr at contact (MCW 1949g). AEC (1948d) gave the gamma contact dose rate with the (Ra-containing) Feinc filtrate residue under equilibrium conditions as over 300 mR/hr; however, they stated, they had no way of knowing how close to equilibrium it was. The dose rate depended strongly on how "aged" the material was: sample pans filled with fresh K-65 read 9 mR/hour while pans held over a day read 20 mR/hr (MCW 1948j).

A study done by AEC of the dose rates from four drums of "aged" K-65 residue grouped on a pallet showed that the dose rate at 6 feet from the grouping was 28 mR/hr, of which the back two contributed 16% and the front two 86% (AEC 1947c). Furthermore, it was found that the dose rate varied approximately as the square of the distance over the range of from three to twelve feet from the center of the grouping. With lead shielding interposed, it was found that the first half-value layer (HVL) was 1/4" and the second was 3/8".

As noted in Sections 4.7 and 5.2.3, K-65 was brought back in drums from SLAPS and reprocessed starting in early 1948. In January 1949, the gamma dose to the hands of operators opening these drums was studied by placing film badges on their wrists (MCW 1949E). It was found that the gamma dose varied from 3.3 to 5.0 mR per drum opened, with an average of 4.0 mR; for the typical situation of 44 drums opened per 24-hour day, six days per week, by three operators, the total weekly exposure per operator was 352 mR. It was estimated that this could increase by up to a factor of 2 due to drums that might require more time than average to open, variations among operators in opening the drums, and in the number of drums opened per shift. Hence the maximum wrist dose was estimated to be 700 mR per week per operator. At the time, the individual whole-body gamma dose to the operators was 300-500 mR per week; it was thought that 33-67% of this dose was due to the drum opening (MCW 1949e).

Additional specific information regarding gamma doses and dose rates in the ore, refinery, and metal processing areas are shown in Tables 32 and 33: dose rates from drums and railcars are shown in Table 32 and for various plant locations and tasks in Table 33. Additional gamma-beta dose data for ore storage at the Middlesex plant during 1944-1949 is shown below (AEC 1949b, Figure 3); this should be comparable to Mallinckrodt experience because presumably the ore was being routed through Middlesex to be distributed to the processing sites. AEC (1949b) states that the Middlesex doses were about 65% gamma.

Middlesex ore storage worker dose, 1944-1949 (AEC 1949b, 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

It should be noted that operations that were particularly manual were (1) 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; (2) the “plowing” (scraping) of the centrifuges; and (3) the scraping of cake off the Feinc filter cloths (this was the pitchblende cake during the pitchblende years) and the changing of these cloths. Thus significant external dose reduction usually followed any mechanization or improvement of these processes.

Because the gamma dose arose mainly from the radium and its daughters, the gamma dose was usually 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 1949b), especially around ore drums and storage areas for the radium-bearing residue, K-65. Thus some shielding had been designed into Plant 6 and more was added in 1948 in some areas (AEC 1949b, MCW 1950e). Still, due to the high doses Mallinckrodt found it necessary in mid-1949 to establish additional restrictions and rotation requirements on warehouse workers, who moved stored pitchblende ore drums from the airport waste storage site (apparently also an overflow ore storage site); brought “sand” (residue) drums back from the airport; unloaded the incoming ore drums from railcars; weighed the ore drums coming in from the railcars and airport site; and loaded K-65 residue drums into the railcars (MCW 1949p). It was estimated, e.g., that the following were typical weekly activities: three trips for retrieving ore drums from the airport pad, three or four drum weighing sessions, one trip for retrieving residue drums, two K-65 railcar loadings, and two ore railcar unloadings (MCW 1949p). It was required that pocket chambers be used when retrieving K-65 drums from the airport pad (MCW 1949p).

The highest principal Feinc cloth operators’ dose had been found to be an average of about 465 mrep/week (total beta and gamma) in 1949 and 1950 and the second-highest dose was similar (MCW 1951g). In January 1951, a study of beta and gamma exposures associated with preparing, repairing, cleaning, and changing cloths for the Feinc, C-3, and Recovery filters (MCW 1951a) found that operators received an average of 294 mrep per day and 1470 mrep per week gamma and an average of 82 mrep per day and 408 mrep per week beta. (See Table 33 for some of the measured dose rates.) The “per day” figures were an effective daily dose since the operation was not actually performed daily. These figures were comparable to those found in a previous 1949 study, although some of the tasks the cloth operators were doing in 1949 had been given to the area operators to do (MCW 1951a).

Mallinckrodt (MCW 1950t) summarized the gamma dose data for all high-dose workers as in the table below. Although it would appear from the disparity between the two averages below that a few individuals were getting significantly higher doses than the rest, Mallinckrodt contended that the doses were fairly evenly distributed among workers in the five rotation groups and thus that all that could be accomplished using rotation had been accomplished. For comparison, group data reported by AEC (AEC 1951b) for two periods in 1948-1949 and 1950 are shown.

Comparison of gamma and beta doses, 1946-1950.

<b>MCW 1950t</b>				
	<b>Date</b>	<b>Avg of high badges, mR or mrep</b>	<b>Avg of 90th percentile badges, mR or mrep</b>	
Gamma only	1946	780	250	
	1947	860	290	
	1948	590	250	
	1949	410	170	
	1950 (1st quarter)	320	---	
Gamma plus beta	1950 (1st quarter)	700	235	
<b>AEC 1951b</b>				
	<b>Period</b>	<b>Number over 30 mrep/week</b>	<b>Number over 150 mrep/week</b>	<b>Number over 300 mrep/week</b>
Gamma only, Plant 6	11/1/48 – 1/24/49 (267)	103	47	17
	1/2/50 – 6/19/50 (314)	124	47	11
Beta only, Plant 4	11/1/48 – 1/24/49 (91)	83	35	32
	1/2/50 – 6/19/50 (89)	65	29	12

The AEC 1951b figures are weekly averages. The number in parentheses after the period is the total number of badges worn per week, on average. The beta figure for "over 300 mrep/week for 11/1/48-1/24/49 included 8 over 700 mrep/week, 5 over 1000 mrep/week, and 2 over 1500 mrep/week; the corresponding inclusions for 1/2/50-6/19/50 were 2, 1, and zero mrep/week.

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 uranium 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 radium content in any uranium product or residue.

A 1958 AEC report on uranium mills gave 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 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 1948e). AEC (1948d) gave the beta contact dose rate with the (radium-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.

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<sub>3</sub>, and 183 mrem/hr at the surface of UF<sub>4</sub>. Further, during UO<sub>3</sub> 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<sub>6</sub> production facilities (Baker 1958). This suggests that significant buildup could occur before the UO<sub>3</sub> left the Mallinckrodt facilities since the storage time might be weeks and the transport time was likely less than a few days. Eisenbud (1975) pointed out that 90% of equilibrium beta activity was restored by 90 days after vacuum casting. Eisenbud (1975) reported high dose rates, up to 1 rad/week to the body and even more to the hands, from loading of UF<sub>4</sub> into UF<sub>6</sub> reaction vessels. This too implies that if enough time had elapsed, UF<sub>4</sub> 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 to extract the uranium from uranyl nitrate, Th-234 and Pa-234m (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. MED (1942) stated that 1942 measurements indicated that the intensity was low and that no precautions needed to be taken for disposal; however, MED/AEC appears to have been more concerned about this later on. Another source of the tails was the UO<sub>2</sub>-derived shotgun sample, which could have the Th-234 and Pa-234 concentrated to 30-300 times their activity in normal uranium metal in equilibrium, depending on how long the UO<sub>2</sub> had stood between production and sampling (MED 1944m). The fourth and final ether extraction performed in processing a shotgun sample produced a liquor so concentrated in these beta emitters that it was said that the tolerance dose of beta radiation could be reached by keeping the hands above the liquor for 10 minutes per day. Besides that, the chemist handled the sample for 5-10 minutes from removal from the furnace to bottling, wearing no gloves and directly touching the containers. MED (1944m) advised changing from rubber gloves to leather gloves (to increase the dose rate reduction from a factor of 2 to a factor of 3) and using crucible tongs (to increase the distance to about 10") for conveying the evaporation dish to the heating areas.

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 1949b; Eisenbud 1975). The impurities contained Th-234 and Pa-234, which were concentrated to a significant degree in the deposits (AEC 1949b; Eisenbud 1975); this deposit residue could have "up to 1000 times the beta activity of natural uranium" (AEC 1949b). 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 1949b), 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). Mallinckrodt (MCW 1949a) observed that 25% of Plant 4 workers received over 500 mrep/week beta and 3-6 workers per week received 2000 mrep or more; AEC (1949g) also observed that the beta values (on film badges) from Plant 4 consistently ranged up to 2.7 rep/week.

Because of the high hand doses, the processing of the derbies and billets was studied in 1948 by Mallinckrodt (MCW 1948b). They gave the results to the designer of the new Plant 6E for use in redesigning the process to reduced the doses, first by eliminating exposure to large open surfaces uranium forms and second by prevent exposure to and accumulation of scale and powdered residues (in which the UX1 and UX2 were concentrated), especially in the recasting or remelt step.

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 Section 5.3.5 and in Table 27 (from the text and Table 1 of Utnage 1958b). This is mainly beta radiation.

MED did some studies to determine the shielding afforded by gloves and clothing. MED (1943c) reported that leather gloves of 1 mm thickness cut the beta dose rate by a factor of 2, while 2-mm

gloves cut the beta dose rate by over a factor of 4. MED (1944i) gave the reduction factor as 2 in a 1944 study of rubber gloves, with the source being uranium metal in equilibrium. MED (1944a) reported the results of July-September 1944 measurements of the activity inside 16 pairs of gloves; the results showed that contamination did appear to get into gloves used at the recast furnaces but not in those used for billet sawing. This implied that some of the recast dose to the hand came from contamination inside the gloves. Based on all these results, MED (1944i) gave the time limit for handling uranium metal as 4 hours per day with rubber gloves and recommended that the time be limited to 2 hours per day with other gloves.

AEC did some further glove and clothing shielding and contamination studies using an 18" x 24" sheet of uranium metal in equilibrium with Th-234 and Pa-234 (AEC 1950i), 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 shielded 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. (These figures are included in Table 27.) The Mallinckrodt glove program for contact with radioactive material was said to be sketchy and inadequate (MCW 1955d), implying that the use of gloves was not consistent.

AEC (1949g) stated the following regarding pocket meters (pocket chambers). These were typically worn by a worker two at a time for an entire work day before recharging. The readings of the two were averaged and the averaged reading was tabulated with the film badge results. The pocket meters were vibration- and leakage-tested before first use, then calibrated for 100 mR +/- 5 mR full-scale and 50 mR +/- 10 mR half-scale. Mallinckrodt suggested discontinuing the use of the pocket meters in 1949 (AEC 1949g, MCW 1949f). In MCW (1949i), they argued that the highest possible (gamma) dose rate in their plants was 300 mR/hr, that exposures of greater than 1000 mR per week were almost unknown any more, and that operations were such that extended occupancy of high-dose-rate areas was not necessary. They stated that they had not found any dose-heavy sources or operations that could not have been found by the use of film badges or surveys; also, their latest statistical calculations showed a greater than 99.9% probability of a true correlation between film badge results and pocket meter readings, but the error at the 90% limits around the regression line gave an error of +/- 38% for a dose of 300 mR per week. Thus, they concluded, using both film badges and pocket meters constituted an unnecessary double check of dose. AEC at first refused to allow them to discontinue using the pocket meters (AEC 1949g), presumably because it was the only real-time check and the only immediate post-work check of accumulated dose available, but then relented and allowed such use to be discontinued (AEC 1949h; MCW 1950e).

Detector types and measurement methods were not specified in most reports and papers. However, it is known that there were numbered, set survey points ("observation stations") at which detector measurements were always made (AEC 1949g). MCW (1946g) stated that external dose rates were measured with an "Ion-meter". AEC (1949g) stated that one Mallinckrodt health physicist preferred the Victoreen 247 gamma survey meter and the Landsverk electrometer, while the other preferred the Zeus meter (detector) for general use. 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.

AEC (1949a) gave information regarding the Rauland Zeus detector used by Mallinckrodt. The reader is referred to the reference for the details of, e.g., the window area and the accompanying table of data. However, the conclusion was that the free area of the window was only slightly greater than 50%. This information was supplied to Mallinckrodt in the context of comparing film measurements

and detector measurements, with the conclusion that the assumed effective size of a Mallinckrodt source (such as a tank or contaminated area) might be greater than had been assumed.

Counters and meters were maintained and calibrated weekly or monthly on a set schedule by Mallinckrodt technicians (MCW 1955d). Because of the lack of space and the corrosive atmosphere in the plant, there were no instrument monitors (i.e., instantaneous, continuous, or integrating monitors) in any area except for one provided by AEC on an experimental basis (MCW 1950e). Hence film badges were placed at selected locations in the process areas to serve as integrating area monitors (see Section 5.4.3.6 below).

#### **5.4.2      Neutrons**

No neutron exposure measurements are available. However, Dupree-Ellis et al. (2000) deemed neutron exposures at Mallinckrodt to be minimal. This conclusion appears to be correct based on what is known about the source material and its handling. Nevertheless, neutron production by means of the alpha-neutron reaction neutron and production by the early RaBe source used in the Shotgun Laboratory (see Section 5.2.4) were analyzed in the preparation of this technical basis document.

In the analysis of neutron production by the alpha-neutron reaction, the forms of uranium and thorium that would produce neutrons at the highest rates were identified as  $UF_4$  and  $ThF_4$ , the latter being an intermediate product in the processing of the thorium-containing waste cake to a thorium nitrate solution (see Sections 4.5 and 5.2.3). The uranium oxide forms, soda salt ( $Na_2U_2O_7$ ), and thorium nitrate were also considered, as indicated in Table 34. Note that as long as there is a reasonable amount of target material (fluorine, oxygen, or sodium) available and intimately mixed with the source material (uranium or thorium or their alpha-emitting daughters), neutron production essentially depends on the amount of the source material.

Regarding the thorium, the total amount of cake processed to obtain the thorium nitrate solution was 350 tons, or 700,000 lbs (Table 4). It is not known how much was processed at a time. However, it is conservative to assume that the processing was done in the same type of large batch-processing tank system used for processing ore (this maximizes the quantity at one time). This is also appropriate because the cake was digested and subject to extraction in the same manner as the ore and soda salt feed were. From Table 4, at one time a typical monthly processing would include about 80,000 lbs of Eldorado black oxide, 120,000 lbs of Vitro black oxide, and 60 tons of Vitro soda salt, for a total of 260,000 lbs per month or about 8700 lbs/day. Also from Table 4, K-65 ore was processed at another period at the rate of 8000-12,000 lbs/day. Thus it is appropriate to assume that a reasonable high average processing volume of feed per day was 10,000 lbs. At this rate, it would take 70 working days to process the cake.

It can be assumed, from the way the ore and other feeds were processed, that one batch was moved from the digest tank through etherization, etc., without being mixed with another batch, at least until after the ether extraction. Thus it can be concluded that no more than 1/70th of the total Th amount was present as  $ThF_4$  at any time. This is conservative because it assumes that all of the amount processed in one day was together in one tank or container at a time. It is also conservative because the processing is known to have taken up to 18 months, not just 70 working days, so the batches are likely to have been much smaller and the amount of  $ThF_4$  present at any time in a container would also have been much smaller. This is particularly likely since the  $ThF_4$  was said to have been moved to the Hot Lab (in Plant 6) in liquid form for final processing to thorium nitrate (AEC 1955c) and thus the individual transport container quantity was limited by the amount that could be transported as a liquid. Finally, it is conservative because any self-shielding or container shielding has been ignored.



Regarding uranium forms, as shown in Table 4, a fiber or steel drum container of  $\text{UO}_3$ ,  $\text{UO}_2$ , or soda salt would weigh 75 lbs and a steel drum container of  $\text{UO}_2\text{O}_8$  (ore feed) would weigh 100 lb; most of this weight would be uranium, so it may be reasonably and conservatively assumed that the entire weight is uranium. While a larger volume could be found in, e.g., a digest tank, the liquid and the thick tank wall would provide a great deal of shielding. A larger volume could be found in an array of containers, but a great deal of self-shielding would be involved and a person would likely not spend a great deal of time near an array. Thus it is likely that that dose rate from a single container (being temporarily stored, loaded, or transported) will be the typical dose source.

The following conservative assumptions were made regarding the conversion from neutron production rate in the Th container to an annual dose at the receptor point.

1. Point source geometry used to produce a nominal ambient dose rate, with the distance to the receptor point being taken from the center
2. Irradiation geometry of 75% AP and 25% ROT (from Table 18 of this technical basis document for "ionium plant operator")
3. A U-238/U-235 breakdown of 99.3% to 0.72% by weight (for the natural uranium forms); a Th-230/Th-232 breakdown of 11.6% to 88.4% (for the thorium forms)
4. Neutron energy of 1.5 MeV (1.4-1.6 MeV is the energy range of the neutrons produce by the thorium isotopes and 1.0 - 2.0 MeV is the energy range of neutrons produced by the other isotopes; also, the neutron flux-to-dose conversion factor varies slowly in this range)
5. Neutron flux-to-dose conversion factor for 1.5 MeV of  $1.3 \times 10^{-4}$  rem/hour per neutron/cm<sup>2</sup>-sec
6. 1 hour per day spent by the receptor at 1 foot from the container and 3 hours per day were spent at 3 feet, every working day for a year
7. For the purposes of considering the effect of including daughter contributions, for full equilibrium of the daughters of natural uranium or the thorium cake mix down to radon (which would not be in chemical union with the target and would likely be largely vented), the neutron emission rate due to the parent isotope would be multiplied by the following factor: 8.1 for U-238, 13.5 for U-235, 2.2 for Th-230, and 20.9 for Th-232. However, this was applied only to demonstrate the maxima, since the daughters were not likely to have built up significantly from the parent for the uranium forms and were separated before the production of the  $\text{ThF}_4$  in the thorium case

The results are shown in Table 34. Conversion was made from ambient dose equivalent ( $H^*(10)$ ) to organ dose equivalent using the factors given in Appendix B of NIOSH (2000a).

In the analysis of the RaBe source production, the source was taken to contain 100 mg of Ra-226 (Mason 1977). There is no indication as to how long the source was used, so the period of use may be taken to have started in about April 1942 and, as indicated in Section 5.2.4, to have ended in September 1944. According to Shleien (1992), Tables 7.5 and 8.4.1, a RaBe source emits neutrons of average energy 4.0 MeV at a rate of up to  $1.3 \times 10^7$  neutrons per sec per curie and the specific activity of Ra-226 is 0.0366 TBq per gram, or 0.989 curies per gram. This gives a source strength of  $1.29 \times 10^6$  neutrons per sec for the 100-mg source, resulting in whole-body dose rates of 16 mrem/hr at one foot and 1.77 mrem/hr at three feet.

Assuming that a laboratory worker spent one hour per day at one foot from the source and one hour per day at three feet from the unshielded source, the worker would receive a dose of 10.7 rem over the 29 months, or 4.44 rem per year. Note that these estimates are conservative since by the various descriptions of laboratory work, most of the time in the laboratory would have been spent in preparing the samples (e.g., by grinding or chemical additions) and the source would have been completely shielded when not in use and likely partially or completely shielded when in use. These results are shown in Table 34, along with the organ doses. Conversion was made from ambient dose equivalent ( $H^*(10)$ ) to organ dose equivalent using the factors given in Appendix B of NIOSH (2000a).

### **5.4.3 Information and Available Data Regarding Film Badges and Extremity Dosimeters**

#### **5.4.3.1 Information Regarding the Type and Composition of Film Badges Used at Mallinckrodt**

The same film badge was in use throughout Mallinckrodt uranium operations for AEC (MCW 1961a), i.e., from some time in 1945 through the end of operations in 1958. This was a two-element type of dosimeter. It is not clear whether the same type of film badge was used during the decontamination period (see Section 8.0), but it would appear so.

Mallinckrodt (MCW 1956i) described the badge as follows. The badge frame was made by the A. M. Samples Machine Company of Knoxville. The front was shaped so that a 1-mm thick cadmium shield could be inserted to cover the upper two-thirds of the film, with a similar 1-mm cadmium shield covering the back of the film. A large rectangular window covered the badge front to allow the identification number (the "health number") perforation in the cadmium shield to be unblocked. A small rectangular window in the lower part of the badge front below the cadmium shield was covered only by the identification picture sandwiched between plastic sheets; a similar window in the badge back, below the cadmium shield, was covered only by a sheet of clear celluloid. The film was a DuPont Type 552 film packet containing two dental-size films wrapped together. The more sensitive of the two films was Type 502 and the less sensitive was Type 510. Mallinckrodt (MCW 1956i) remarked that the beta and gamma radiation generally encountered at the Mallinckrodt plants had less effect on photographic film than the same dose of X-rays that were often monitored with such film badges.

Mallinckrodt (1955i) also described the badge as having a metal frame made by the A. M. Samples Company and as using DuPont Type 550 x-ray film provided by the Dick X-Ray Company. The identification picture was said to be laminated between two pieces of thermo-coated acetate, each 0.005 inches thick, with the total thickness not exceeding 0.02 inch. MCW (1950m) stated that the Mallinckrodt badge had 3.3 mm between the face of the badge and the first surface of the film; the average absorber density between the badge face and the film was given as 81 mg/cm<sup>2</sup>.

In an unpublished report the badge 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.*

According to MCW (1956f), before the badge was issued, the week number was exposed on the edges of the film with 70 kV, 10 ma X-rays for 0.33 second. Control badges were exposed to a 10-mg radium source in a platinum needle, which was the primary gamma standard and whose intensity was taken to be 8.4 mR/hr at one meter. An earlier standard, No. R-515, sent to Mallinckrodt in 1948 by an AEC consultant on behalf of AEC, had 9.98 mg of radium, with a platinum-iridium wall thickness of 0.5 mm, producing 5.4 mR/hr at one meter from the center of the capsule (AEC 1948I).

The primary beta standards were aged metallic uranium slabs about 1/16" thick. Eight-month-old uranium was regarded as "aged" enough to have the Th-234 and the Pa-234 in secular equilibrium with the U-238; the beta contribution of the Th-230 and its daughters was considered to be negligible. The beta intensity at the surface was taken to be 239 mrep/hr (see also Section 5.4.3.2 below). Other details of the calibration, such as exposure times and distances, do not appear to be available.

#### **5.4.3.2 Film Badge Technical and Processing Information**

The University of Rochester processed the Mallinckrodt film badges from at least 1 July 1947 to 1 June 1948 (Rochester 1950, MCW 1950k); Rochester presumably also processed the badges before that under contract to AEC, as suggested by MCW (MCW 1950k). Mallinckrodt processed its own film badges from 1 June 1948 to 1 January 1950 (Rochester 1950, MCW 1948g, MCW 1950k). As is indicated by the Mallinckrodt health group monthly reports (e.g., MCW 1951b) and the 1955 Mallinckrodt health program description (MCW 1955d), Mallinckrodt appears to have continued to process their own badges even after this period. As the health group monthly reports (AEC 1950m; MCW 1951f) indicate, however, Mallinckrodt often had a significant backlog in reading the film badges; Mallinckrodt (MCW 1951e) observed that doses were frequently reported a week or more after the dose was incurred and thus expedited processing was requested for badges from such workers as the burnout and Feinc operators. But it was not unknown for this problem to occur when Rochester was processing the badges: results typically took two weeks to be sent back to Mallinckrodt and on about 19 August 1946 results were almost two months later in coming back to St. Louis from Rochester because of Rochester personnel's being on duty at the Pacific Crossroads tests (MED 1946c). This was one of the reasons that Mallinckrodt took over the processing of its own film badges.

No procedures and little other film badge specification data have been found to date. See Section 5.4.3.1 for information about the film badges themselves. There is also not much information about how the film badges were processed by either Rochester or Mallinckrodt. However, MCW (1950r) stated that an AEC report (NYOO-57) was an attempt to measure the surface dose rate from uranium (presumably metal) received through the stratum corneum of the fingers, at 7 mg/cm<sup>2</sup>. According to MCW (1950r), this report gave a dose rate of 239 mrep/hr through a depth of 7 mg/cm<sup>2</sup> and 178 mrep/hr through 44 mg/cm<sup>2</sup>. Mallinckrodt had been using a value of 265 mrep/hr in their film badge measurements, but now agreed to use the NYOO report value of 239 mrep/hr. Mallinckrodt did so because the report results were based on a filter closely approximating the dead skin layer; thus this basis was more similar to Mallinckrodt's operating conditions than their old value's basis. However, as MCW (1950r) pointed out, AEC's tolerance level was based on the "field strength" of the radiation, not on the amount of radiation at any particular depth of any particular material; it was thought that any other reference level would be impossible because of the energy distribution of the betas.

There are some documents indicating problems or variations from the norm in badge readings. MED (1945I) stated that recently read films worn from 26 November through 4 December 1945 showed abnormal density combinations and that it was inconceivable that all of the density was due to radiation exposure. It was noted that a Mallinckrodt manager had admitted that the films might have been subjected to high temperatures. It was also noted that the problem could not have occurred in

Rochester (where the films were being read at the time): the Mallinckrodt films of two weeks earlier had also shown high exposures and since that time, Rochester had been very careful in handling films from Mallinckrodt.

Mallinckrodt (MCW 1948d) reported that there was considerable fluctuation in readings on badges worn in the digest and Feinc filter areas; the explanation was given that any interruption in the process that caused a holdup of material allowed the material to "age" (i.e., daughter products to build up) and thus to exhibit more gamma activity. Breakdowns of equipment, which tended to result in higher exposures to operators doing the repairs, were another reason given for the variations.

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; AEC 1950f; MCW 1950k; AEC 1950g; AEC 1950i; MCW 1950x). This issue involved the subtraction of the film density value under the beta "shield" from the value under the window. Section 7.1 of this technical basis document states the assumption to be made about this subtraction; however, the references cited may be consulted in case of any suspect beta readings corresponding to the 1949-1950 period. In connection with this issue, Mallinckrodt undertook to do an experiment to determine whether the beta reading from the open window of the film badge was due to primary (directly emitted) beta radiation from surface contamination in an area or to secondary beta (i.e., produced by scatter of the hard gammas) (MCW 1950x). A radium source was used to expose four sets of film: one pair was exposed with a 4800-gauss magnet in place and the other pair with a set of phantom magnet yokes in place. Additionally, one of each pair had a 7/16" Lucite shield in place to eliminate direct betas from the radium source. In this way, the betas were drawn off by the magnet (including any secondary betas) or were taken out by the shield, allowing for a 98% reduction by the magnet in beta radiation arriving at the appropriate films and thus the assumption of a nearly pure gamma component being measured by those films. Mallinckrodt determined that at most a reduction of 19% in the open window could be attained by aggressive cleaning of surface contamination in an area, i.e., that most beta measured by an area film badge was not direct beta. MCW (MCW 1950x) observed, however, that film badges actually worn by workers show greater window densities for equivalent shield densities than area film badges. This was attributed to workers' badges' more frequently actually "seeing" a primary beta source, e.g., during manhole access. Thus during some types of work, workers actually received beta radiation that they would not receive merely by standing in the area.

Mallinckrodt (MCW 1948k) stated that while badge readings were supposed to be accurate within 10% (apparently an AEC requirement), Mallinckrodt's standards were within 5% as checked by "New York" (presumably Rochester or NYOO). Mallinckrodt regarded the method of reporting by Rochester prior to 1 July 1947 as "inconclusive" (MCW 1950k), presumably because of the rounding off to the nearest percent of the tolerance level and possibly also because of uncertainty in the interpretation of what the tolerance was and of what zero dose might actually translate to.

Prior to readout at Mallinckrodt, badges were disassembled in a laboratory hood (MCW 1956f). A Weston photographic analyzer, Model 877, with two stabilizers, was used in reading out the films in 1949; in 1956, a Welch Densichron densitometer was being used (MCW 1956f). Due to the assumed near proportionality of film density and radiation exposure of any given type, Mallinckrodt assumed that the following relationship was valid: Net window density from beta exposure alone = Actual net window density - Net window density from gamma exposure alone (MCW 1956f).

### 5.4.3.3 Film Badge Monitoring Periods and Wearing Practices

Workers were not individually monitored for external dose prior to June 1945. Film badge records are available for the weeks ending 10 June, 24 June, and 1 July 1945 (by memorandum report, MED 1945o) and for 29 July, 5 August, 12 August, and 26 August of 1945; then there is a gap until the week ending 9 December 1945. Total (accumulated) doses for the period from 9 December 1945 to 25 March 1946 were reported by individual in a memorandum from the University of Rochester School of Medicine and Dentistry (Rochester 1950). Besides the 1945 records, records appear to be available, with some gaps, for most weeks from 1946 through 1948; 1950 through 1951; 1952; and 1954 into 1958. Furthermore, film badge records for the postoperations decontamination period (see Section 8.0) may not be available either. It is not clear why records are missing after 1945, since clearly film badges were used continuously from 1945 on. Hence it is possible that these records may be found at some later time.

ORAU (1980b) stated that all Mallinckrodt employees who were cleared to have access to production areas wore film badges at all times, with the purpose being to provide maximum assurance that all exposures were registered. Contemporary references indicate that film badges were issued as a combination security-exposure badge to all employees, except for "office females" who presumably never entered process areas (MCW 1955d, MCW 1955c, MCW 1956i). MED (1944p) describes the film badge as being numbered and being combined with a photo ID. AEC (AEC 1948c) states that for Plant 6, the badge was a "photo [ID] film badge" for cleared employees; a film badge with a red insert and the employee clock number for employees awaiting Q clearance; plastic film badges for technicians, engineers, and management, with photo film badges in a separate rack at guard shack or changehouse for when they entered the plant from the clean buildings; plastic photo badges for office employees who did not go into plant areas; film badges with a red insert bearing a large letter V and a number, for subcontractors going into Limited and/or Contaminated areas (such badges to be issued by the guards); and a plastic badge (with no film) with bearing a large letter V and a number, for subcontractors going into Controlled and/or uncontaminated areas and for business visitors to the offices (also to be issued by the guards); and ditto last for business visitors to the offices. MCW (MCW 1955c) also states that all visitors and outside contractors entering process areas were issued badges. It is not clear how early the practice of issuing film badges to visitors and subcontractors entering process areas began.

AEC (AEC 1948c) states that film badges were to be used at Plant 4 for a trial period, suggesting that that Plant 4 employees were not badged prior to early 1948; it was recommended that employees be issued film badges but that subcontractors and business visitors be issued a plastic badge (no film) with a green insert and number.

In 1955, toward the end of operations, it was realized that since an "expansion" group had moved to new quarters in the "Rock Island Building" (presumably in St. Louis), film badges had not been worn by this group during normal activities, thus leaving a gap in exposure data for these individuals (MCW 1955a). A directive was therefore issued for badges to be worn by this group, but of course the missed period was not covered in the records. Similarly, the Mallinckrodt Uranium Division employees who transferred to the Weldon Spring site startup group in 1956 were not being monitored any longer for radiation exposure with film badges; those who might still have business at the Mallinckrodt St. Louis site were to have their badges kept for them in St. Louis (MCW 1956b). Thus these individuals were likely to have intermittent badge readings associated with the St. Louis site.

Since there were no potential sources of acute external exposure, the aim was to keep chronic exposures below tolerance levels (MCW 1950e; MCW 1955d). All exposures over 50% tolerance were reported to supervisors (MCW 1955d).

From 22 April 1946 through the end of MED/AEC work in 1957 or 1958, film badges were processed on a weekly basis as part of a routine dose monitoring program. Badges for Plant 4 began to be changed only every two weeks in early September 1954 (MCW 1954d); all badges began to be changed every two weeks as of 30 January 1955, because of a shortage of health personnel to read the badges and the comparatively low doses then being recorded on the badges (MCW 1955b, MCW 1956i). Mallinckrodt (MCW 1955d; MCW 1956e) stated that (all) badges were changed every two weeks or more often when desired for information or because of expected higher dose. Film badge results were summarized quarterly and annually (MCW 1955d).

The guards were directed that if there was no replacement film badge available for a given used badge when the badges were exchanged by the guards at midnight on Sunday, they were to remove the used one anyway (MCW 1948d). The guards were to notify the safety department of the situation on Monday morning and the individual was to wear his "current" badge for the first half of the shift, until a replacement badge was provided by the safety department. It is not clear from the reference if the used badge was for the week that ended on Sunday or for the week before that, although if it was the latter, that would explain why the individual still had a current badge that he could wear.

Workers were directed to wear their badges when they went to the Airport (SLAPS) or "the Range" (MCW 1949q); the Range appeared to be a firing range (near or at the storage area) where the guards would practice shooting and where some materials were stored (e.g., AEC 1949e reports that some UO<sub>2</sub> was drawn from this storage area for use in production). Plant 6 workers were also told to wear their Plant 6 badges when they visited Plant 4, and vice versa for Plant 4 workers, and not to wear a visitors' badge (MCW 1948k).

As shown in the comparison table in Section 5.4.1, data from AEC (AEC 1951b) shows that a weekly average of 358 badges were issued to Plants 4 and 6 workers in November 1948 through January 1949 and a weekly average of 403 badges were issues in January to June 1950. From the series of Mallinckrodt health group reports (an example of one is MCW 1951c), some 2000-3600 badges were read per month in the early 1950's, corresponding to about 460-830 badges issued weekly; these included visitors' badges and probably also some area monitoring badges and some experimental, duplicate, and supplementary (double-badging) badges.

#### **5.4.3.4 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. Records found to date show weekly badge processing cycles, with the following exceptions: records that show total dose by specified time period, records from the very later period of operations, and records from the decontamination and decommissioning period. Assignment of individual annual doses was based on deep-dose exposure (Dupree-Ellis et al. 2000).

For most of the period of operations, 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. Many of the 1948-1958 records have annual totals written on them; ORAU (1980a) stated that a sampling of records showed that the summing for the 1950-1958 records was sufficiently accurate that the totals could be accepted (i.e., for epidemiological study purposes), but not the summing for 1948-1949.

Dose summaries (in memorandum form) generally 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. All employees not working at Plants 4, 6E, or 7 were included in the Plant 6 report (MCW 1956a).

Up to 1950, Mallinckrodt recycled clock numbers, i.e., reused them as employees left and new employees were hired (MCW 1950a). However, this created difficulties with keeping dose records because as Mallinckrodt recognized, dose records needed to have identification numbers that would "remain unique in perpetuity" for tracking purposes. The film badge numbering system was therefore changed as of January 1950 and clock numbers were no longer used on the badges. However, in tabulating the doses (e.g., in memorandum form), the clock numbers were used. The potential for badge confusion due to non-unique numbers prior to 1950 must be recognized.

Some codes used in the records to identify the type of job or work area (e.g., M for maintenance) are found in MCW (MCW 1956g) and similar memorandum reports or in Table 5 of this technical basis document. Some codes used in the records to denote readout problems or other items of interest (e.g., GL for Gone Through the Laundry) are found in ORAU (1980a). These are also been shown in Table 5.

Complete records and/or dose summaries may not have 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.

One record of extremity dosimeter results (as ring badge readings) has been found – see Section 5.4.3.5 below.

#### **5.4.3.5 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 1949b). The results were reported for 25 April through 30 May 1949 in AEC (1949d). Figures were said to be "the Oak Ridge results" based on a radium gamma calibration, so presumably these films were read at one of AEC's Oak Ridge sites. The beta exposure was taken to be a factor of 1.2 times the difference between the open window and the shielded reading. Such data from other sites had been found to be variable and inconclusive, probably, AEC thought, because of improper wearing of the rings and the regular badges worn at the same time; AEC had determined that the ring response depended very much on the direction and angle of the beta sources in the process areas. Individual records of the film ring readings do not appear to be available among the regular film badge records, but AEC (1949d) has a long table giving the results by worker name and identification number.

#### **5.4.3.6 Film Badges Used as Area Dosimeters**

Film badges were placed in selected locations in the process areas to serve as integrating area monitors (i.e., to register integrated dose in an area regardless of actual occupancy) (MCW 1955d; MCW 1955h). Mallinckrodt (MCW 1955h) opined that such film badges were sometimes hung in out-of-the-way places and not in the area of highest dose rate during occupancy; however, this did not appear to be demonstrated by the comparison between the dose rates measured by the film badges and those measured by a gamma survey meter (MCW 1955h). There is no information as to how often these area film badges were collected and read.

#### **5.4.4 Information and Available Data Regarding Occupational X-Ray Examinations**

MED (1944d) stated that the medical program recommended by MED was being followed by Mallinckrodt. This included a routine chest x-ray prior to employment and annually thereafter and a pelvic x-ray for those employees handling fluorides. MED (1944d) thought that the pelvic x-ray could be dispensed with and apparently this was subsequently done. Later documents also indicate that Mallinckrodt uranium processing workers were given a pre-employment physical that included a chest x-ray (MCW 1955d; Mason 1958a); they were also given an annual physical that included a chest x-ray (MCW 1955d; Mason 1958a). That these x-rays were actually given is indicated in the series of Mallinckrodt Health Office and other reports (e.g., MCW 1951b; MCW 1954e; MCW 1955d). 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. It should also be assumed that personnel working with hydrogen fluoride or in the UO<sub>2</sub>-to-UF<sub>4</sub> conversion process in 1942-1944 received an annual pelvic x-ray.

#### **5.4.5 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; a 19 August 1946 potential significant exposure to workers, probably in the removal of K-65 in the storage area, following which working space was rearranged and the pileup of residue material at the location was reduced (MED 1946c); 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 1952b).



This may have been a longstanding problem, however, since the reference in early 1944 to the loss of material in "burnout" in the reduction step apparently was to this spontaneous ignition of derbies (MED 1944o). 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 1950m).

One incident of concern to the health department was the hand loading of raw pitchblende ore on 21 February 1950, without the knowledge of the health department (MCW 1950d). Apparently there was a malfunction of part of the ore drum conveyor. Operational pressures motivated the production supervisor to have the star valve at the bottom of the ground ore hopper feeding into the secondary elevator disconnected. A three-man crew then picked up open drums off the conveyor using a chain hoist and tipped their contents onto the floor. One worker then shoveled the ore across the floor to another worker and he to the third worker, who shoveled it into the chute to the secondary elevator. One crew worked one half-hour session and a second crew worked another half-hour session, together handling 12 drums of ore. The crews wore respirators and the downdraft ventilation into the chute was working, but the workers were not otherwise protected from direct radiation or radon, and a crew of maintenance people working around the rod mill nearby were not wearing respirators. It was noted that the gamma exposure at the surface of such an ore drum was 80-100 mR/hr (MCW 1950d); in addition, Table 24 of this technical basis document shows some radon levels for open pitchblende ore drums. However, it was also noted by MCW (MCW 1950d) that health department clearance would have been granted for such an operation if the workers had worn oxygen or air line masks, if stay times were limited to 1 hour per week per worker, and if workers were taken from low-dose areas such as the Ether House or the furnace room.

## **5.5 OTHER DATA OF DOSIMETRIC INTEREST**

### **5.5.1 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 1944p). Regarding the total number of workers with potential for exposure, Fleishman-Hilliard (1967) and Mallinckrodt (1994) listed the total number of workers as 250, the former stating that this was in 1948; AEC (AEC 1948e) listed the total number as 250 at Plant 6, but 400 if Plant 4 was included; AEC (1949b) listed the number of workers at Plant 6 as 272 and the number at Plant 4 as 94; Mallinckrodt (MCW 1950w) gave the total number as 487 and added that 275-300 individuals who worked on the project for more than three months had terminated as of 1 October 1949. Mason (1958a) stated 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 (1951b) stated that in early 1951, Plant 4 employed 100 people.

AEC dust study reports in the 1950's gave the number of each classification of workers and the number on each shift (e.g., AEC 1954b); some of these AEC reports even listed the names of process and supervisory workers and their job classifications in an appendix. For Plant 6 alone, Mallinckrodt (MCW 1956a) gave the number of manufacturing personnel as 100 and the number of nonmanufacturing personnel as 550. As noted above in Section 5.4.3.3, over 2000 film badges a month were processed in the 1950's.

### **5.5.2 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.

AEC-NYOO took the number of work hours per week to be 48 (or six 8-hour days) in calculating some of their early time-weighted average airborne concentrations (AEC 1949b). Also, AEC (1951b) stated that Plants 6E and 7 operated on a six-day, three-shift schedule. However, this does not imply that individual Mallinckrodt workers worked six days a week. MCW (MCW 1949g) [1949] states that the work week is 8 hours per day, 5 days per week. Lippmann (1958) used 40 hours in reporting data regarding Harshaw workers and Harshaw (1946) described its rotation schedule used for round-the-clock operation, which involved a 40-hour week for most individual workers and a 42-hour week for some workers. Besides these references, AEC, in its dust study reports, used the actual time worked, as given above, implying a five-day week. It can thus be assumed that Mallinckrodt workers typically worked for a full 8 hours a day, 5 days a week, or 40 hours per week. When using daily weighted average dust sampling data (e.g., in Tables 12-16 and 19-22), 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), they were carried out 24 hours per day. It is not clear what other early processes ran 24 hours per day, but AEC (1951b) implies that Plants 4 and 6 did not. However, individual dust studies cite three shifts for many process workers positions, indicating that operations were in fact carried out 24 hours per day, although perhaps not on the weekends. Guardhouses were manned around the clock, with three shifts per day (MED 1944p).

### **5.5.3 Job Types, Job Histories, Work Areas, and Work, Access, and Clothing 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 listed such notes or keywords. Various AEC dust reports also list job titles and functional work types. Job titles and types discovered to date are given in Table 18. 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 may have been part of preliminary decontamination prior to the decontamination and decommissioning of buildings and plants; however, it is known that there was a decontamination group that did ordinary or process decontamination and special decontaminations as necessary (e.g., of a lab area), so when "decontamination" appears in a record it is this type of work that should be assumed.

As previously stated, to aid in classifying workers whose job titles do not appear in Table 18 and whose work descriptions do not make it clear which job title is appropriate for use, Table 5, the keyword table, which includes information from these notes and from operational information in other references (particularly MED 1946a; AEC 1949b; and AEC 1967). The two tables should be used to help determine the principal occupational activity for an individual with missing or conflicting monitoring data.

According to ORAU (ORAU 1983b), prior to 1 October 1949, there was no "concise" or in-one-place employment history for Mallinckrodt workers in the Uranium Division (i.e., doing MED/AEC work). Then because of the high doses, it was apparently thought that workers who had received more than 90% of their (unspecified) "lifetime" exposure to dust should be removed from uranium work. Consequently, a work history was reconstructed by Mallinckrodt for the period of 1942 to 1 October 1949. Mallinckrodt tried to be as accurate as possible because of the possibility of having to remove workers and apparently the workers examined the reconstructed records, because "the work history had to withstand the scrutiny of each worker" (ORAU 1983b). Four volumes of records were produced: one master list of workers, one volume with histories of those terminating prior to 1 October 1949, one for current Plant 4 workers, and one for current Plant 6 workers.

In the Mallinckrodt Uranium Division, workers in maintenance (shop personnel, skilled craftsmen, and maintenance mechanics) and in plant services (guards, porters, nurses, laundry workers, power plant personnel, hygiene and safety personnel, etc.) were not usually assigned to a particular process, but served the entire division (Hickey and Dupree 1984). An exception may be the "area mechanic" mentioned in some AEC dust sampling reports, but even then it may be that the mechanic was assigned to cover multiple areas and his exposure may not have been characteristic of only one area. However, Hickey and Dupree (1984) note that the uranium monitoring records they examined showed a reasonably uniform exposure for both the field and the shop maintenance personnel and skilled craftsmen. Hence particular area assignments may not be critically important in, e.g., formulating surrogate sets.

ORAU (1977) stated that the highly exposed workers were transferred out of uranium operations in 1950; these were presumably some or all of the 52 workers found to have 100% or more of the lifetime tolerance dose as of October 1949 (AEC 1950a). Mallinckrodt (MCW 1951b) and AEC (AEC 1950e) also stated that some 34 workers were transferred in the summer of 1950: the former states that this was from Plant 6 to Plant 1 "for health reasons" and the latter states that this was from Plants 4 and 6 on the basis of their estimated accumulated exposure to uranium dust. While Building 51 (Plant 2) was said by ORAU to have been closed about 1 January 1947 and by Mason (1977) to have been "sealed" in about 1947, when Plant 6 started up, and information in ORNL (1981) suggests that Plants 1 and 2 might have been in use for some support work until decontamination began in 1948; also, MCW (1949e) indicated that special badges would be issued to workers at Plant 1, although this may have been for intermittent work in Plants 4 and 6. Thus the Plant 1 work, if any, would presumably have been non-uranium work. Whatever the case, Mallinckrodt stated that the transfer had been considered for over a year before it occurred and that it would send a report to AEC (1950d); this report does not appear to be available. Possibly partly as a result of the study reported by AEC (1950a), Mallinckrodt used an employee rotation program from about 1950 on (Fleishman-Hilliard 1967; AEC 1950b; MCW 1955d), 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.

A 1944 MED security survey report (MED 1944p) gave 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. MED (1944l) stated that personnel in the "MED plant" were segregated as much as possible from the general (non-MED work) personnel, with the main point of contact being during the lunch hour.

From April 1949 on, the film/ID badges were color-coded to control access (MCW 1949h); for example, Plant 6 was divided into seven zones, each with its own color. "Controlled" areas were areas not expected to become contaminated, such as the offices, the power plant, the pumphouse, and the yard areas. "Limited" areas included the main processing building, the warehouse, the Scale House, the laboratories, and so forth. Mallinckrodt's 1955 formal description of its health program (MCW 1955d) gave the following information, indicating that the area control system was continued throughout the processing years although the definitions might have changed somewhat. Mallinckrodt maintained three levels of controlled areas. These were the regulated areas, which were described as 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 the clear areas, which were areas 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 stated goal of control efforts.

An internal Mallinckrodt memorandum circa April 1948 (AEC 1948c) stated that the Building 101 facilities had been "revised" (implicitly for better control of contamination) and access status in the building and yard areas was to be broken into two classifications. The first was the "clear area", consisting of all areas in which the presence of "plant products" could be completely eliminated or reduced to negligible amounts. The designated clear areas were the guard office, the locker room, the lunchroom, the Health Unit offices and laboratory, the AEC offices, the MCW offices, and the MCW laboratory offices. The second area was the "regulated area", consisting of all areas that could not be kept clear of plant products.

MED (1942) stated that employees were required to change work clothes daily, with the "uniforms" being provided by Mallinckrodt. AEC (AEC 1948c) states that in the clear areas, either street clothing or plant clothing with cover clothing was allowed, except in the lunchroom, where only street clothing was allowed; in the regulated areas, either plant clothing or street clothing with cover clothing was allowed. In 1955, the Mallinckrodt health program was said to include the following requirements regarding clothing (MCW 1955d). 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; and cover clothing was also 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) (MCW 1955d). Regulated area workers were issued two changes of clothing per day as of 1955 (MCW 1955d) and probably much earlier due to contamination control requirements involving showering (see below).

Visitors were provided with cover clothing (smock, rubbers, etc.) (MCW 1950e). However, as of at least 1950, outside contractor personnel wore their own personal work clothing, on the grounds that visitors' garb would be "too restrictive" and thus unsafe (MCW 1950e). Besides that, suitable change room facilities were not provided for outside contract personnel (MCW 1950e).

Process (manufacturing) workers were required to shower before changing into "clear" (clean) clothing; they typically took two showers a day in 1955 (MCW 1955d), but only one in the 1942-1944 time frame (MED 1942, MED undated a) and apparently only one in April 1950 (MCW 1950e). The procedure was as follows (MCW 1948c). After punching in, workers who would be changing into plant clothing would remove their street clothing in the locker room, don plant clothing in the change room (apparently the same clothing from the second half of the previous day's shift), and enter the work area. At lunchtime, workers would remove the plant clothing in the change room, shower, don street clothing, and go to the lunchroom. After lunch, they would put on a clean set of plant clothing in the

changes room and go back to work. At the end of the shift, workers would remove the plant clothing in the change room, shower, and don their street clothing in the locker room. An extra 15 minutes was allowed for the midday showering and changing and clogs were provided for traffic between the locker room, change area, and showers (MCW 1948c). The one-way door allowing traffic to pass only from the locker room to the change area was to be supervised at shift change and lunch hours (MCW 1948c). No one was allowed to leave the plant in plant clothing (without cover clothing, presumably) (MCW 1948c). By February 1949, an AEC consultant, inspecting the change room for Plant 6 process workers, termed the operation of the change room "creditable", i.e., in line with AEC directions (AEC 1949k).

Plant 6 warehouse personnel were to follow the same general procedure in their change room, as were maintenance workers who used the process area locker room. The warehouse personnel leaving Plant 6 on trips to other regulated areas (such as Plant 4, SLAPS, or "the Range"), were allowed to make the trip in plant clothing, but in a "regulated" vehicle only; these vehicles could be jeeps, dumpsters, or large trucks) (MCW 1948c). Also, warehouse personnel leaving on trips to clear areas outside Plant 6 had to shower and change as if they were leaving work and they had to use a "clear" vehicle only (MCW 1948c).

Laboratory personnel who normally wore plant clothing were to follow the general procedure for process workers, except that they used their own locker room and change room; personnel going to the laboratory offices (a clear area) from another clear area could go directly in street clothing but had to use cover clothing to go to the laboratory; and personnel going from working in a laboratory to the lab offices had to put on cover clothing over their plant clothing (MCW 1948c).

The change requirements given above for process workers also applied to maintenance personnel who used the maintenance shop locker room: they were to use the same procedure but in their own locker room (MCW 1948c). Since the maintenance men in the shop might also work in the now non-AEC Plant 1 and presumably other clean areas at the general Mallinckrodt facilities, they had to change into special blue coveralls and either street shoes or clean safety shoes when visiting those areas; similarly, any Plant 1 maintenance men going to the AEC areas to work were to follow the change procedure as for the process workers (MCW 1948c). Instrument Shop personnel going to Plant 4, however, could go in plant clothing but in a regulated vehicle only (MCW 1948c).

Mallinckrodt (MCW 1948c) stated that no one was permitted to eat in plant clothing; that no one who had been working in plant clothing was allowed to eat without previously showering; and that there was to be no eating in regulated areas. Soft drink dispensers and washing facilities were provided in the change room, but hands were supposed to be washed before drinking (MCW 1948c). According to MED (1944p), 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.

#### **5.5.4 Miscellaneous Product 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 x 40" long	MED 1946a
Bomb liner (lime, etc.)	Depth: 1"	MED 1946a
Uranium billet	4.75" OD x 18" long	MED 1949b
Uranium billet	~ 6" OD	Mason 1977
Ore barrel	3' high x 18" across	MED 1945a
U metal samples		
Glass tube	2" OD x 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" x 5" x 13"	MED 1945a

### 5.5.5 Missouri and St. Louis Area Background Levels

The table below gives some Missouri and St. Louis area background measurements, except that the Applied Nuclear Safety measurements were taken at Building Z of the Mallinckrodt site, used as a control. Note that these measurements were all taken many years after the end of operations and were made for the purpose of characterization for possible future remedial action.

Measurement	Unit	ORNL 1979		ORNL 1981		Applied Nuclear Safety 1986	Bechtel 1987
		Range	Average	Range	Average	Average	Average
Ac-227	pCi/g	Below detectable					
Ra-226	pCi/g	0.3 - 1.3	1.05 ± 0.3		1.18		
Th-232	pCi/g	0.3 - 1.3			1.15		
U-238	pCi/g	0.3 - 1.7			1.25		
Gamma background at points distant from site	uR/hr		6.0 ± 1.7	7 - 9	8		11
Beta-gamma (GM)	mrad/hr		0.02	.01 - .04	0.02		
Radon background concentration	pCi/L				1.0	0.33	0.3
Radon daughter background concentration	WL				0.01	0.002	

## 6.0 DETERMINING RADIOACTIVITY INTAKES DURING THE OPERATING YEARS

This section applies to determination of radioactivity intakes during the operating years only. These years appear to be 1942-1950 for Plants 1 and 2 (as per Item 7 of Section 6.1 below); 1942-1957 for Plant 4; 1946-1957 for Plant 6; 1950-1957 for Plant 6E; and 1942-1958 for Plant 7. However, for purposes of dose reconstruction, it is assumed that work may have continued into 1958 at any of the plants 4, 6, 6E, or 7 and thus that any decontamination and postoperations intakes and external doses at these four plants began in 1959. For intakes during the decontamination years and the postoperations years, taken to be 1951-1995 for Plants 1 and 2 and 1959-1995 for Plants 4 through 7, see Section 8.0.

Urinalysis and other individual-specific bioassay data should be used to determine the individual's intake of radioactivity, when these data are available. However, most workers will have unmonitored periods or gaps because routine urinalysis did not begin until 1948 and because there were undoubtedly some missed bioassays even after urinalysis monitoring began. The intakes over the missing or gap periods will have to be determined either by using comparable (surrogate) worker data or by the use of time-weighted daily average dust exposure data, as explained in the sections below.

### 6.1 ASSUMPTIONS AND GENERAL INSTRUCTIONS

The following assumptions should be made in determining individual radioactivity intakes when urinalysis records, Table 30 (Section 6.2), or Tables 29A-29F (Section 6.3) are used. Note that these assumptions can also be applied if Tables 19-22 or Table 16 (Section 6.4) are used to generate intakes for comparison to urinalysis records, Table 30, or Tables 29A-29F.

1. Except for acute intakes arising from incidents (which should be treated as special cases), the intakes should be considered chronic.
2. The absorption type should be selected using the guidance from the table below (ICRP 1968). To be claimant favorable, the selection of absorption type should be made so as to maximize the dose to the organ of interest. ICRP 66 default parameters related to particles are appropriate. (See Section 5.3.1 for more information.)

Isotope	Form	Absorption Type
U	U <sub>3</sub> O <sub>8</sub> , UO <sub>2</sub>	S
	UO <sub>3</sub> , UF <sub>4</sub> , U metal	M
	UO <sub>2</sub> F <sub>2</sub>	F
Th	Oxides, hydroxides	S
	Other	M
Ra	All	M
Po	Oxides, hydroxides	S
	Other	M
Pa	Oxides, hydroxides	S
	Other	M
Ac	Halides, nitrates	M
	Sulfates	F

Note that for residues, the oxide/hydroxide form is the most probable for Th (AM-7) and that the Ra was in the form of the sulfate.

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

For source materials in which uranium isotopes were predominant (general case)

By weight, natural uranium is about 99.3% U-238, .00732% U-235, and .00006% U-234 (Shleien 1992). But by activity, it is about 48.9% U-238, 48.9% U-234, and 2.26% U-235. In the absence of other information, it is not possible to tell the degree of equilibrium between the uranium isotopes and their daughters in a urine sample, hence it may be assumed conservatively 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, generally the U-238 portion can conservatively be assumed to be U-234 as well, so it can be assumed for simplicity that there are 0.98 pCi of U-234 and 0.02 pCi of U-235.

Thus under the assumption that the daughters of the original U-234 are in equilibrium with the U-234 (but of course not the subsumed U-238), there are an additional 0.49 pCi of Th-230 and 0.49 pCi of Ra-226. With the daughters of the U-235 in equilibrium with the U-235 parent, there is an additional 0.02 pCi of Pa-231.

These conservative and claimant-favorable source terms are summarized in the table below and should be used when Table 28 is used to determine intake. For simplification of the dose reconstruction process, the low-contributing isotopes may be conservatively ignored or their contributions may be folded into those of other isotopes, when appropriate for the organ type and intake mode.

For each pCi of uranium measured in urine, assume:

Isotope	Quantity, pCi
U-234	0.98
Th-230	0.49
Ra-226	0.49
U-235	0.023
Pa-231	0.023
Ac-227	0.023

For source material in which radium-226 was the predominant isotope

Sources in which radium was the predominant isotope are associated with the job titles and areas listed below. In these areas, it can be assumed that there was approximately 100 times more radium than uranium in the air on a curie basis (see Section 5.3.1). Thus the table above for uranium should still be assumed to apply, but an adjustment must be made for radium content after the uranium pCi intake has been calculated as discussed in Section 6.2 below. The table below should be used to determine which areas or job titles are appropriate for it to be assumed that Ra-226 was the predominant isotope.



	Applicable years	Notes
<b>Job titles</b>		
C-3 centrifuge operator	1946-1955	
Cloth man/operator	1946-1955	
Feinc operator	1946-1955	
K-65 sampler	1946-1955	
Warehouse man	1953-1955	Should have "K-65" or "sampler" in title
<b>Areas</b>		
Building 25-2 (Plant 2)	1944-1945	
Building K-1E (Plant 1)	1944-1945	
Feinc filter/platform/enclosure	1946-1955	
Feinc/Niagara filter/platform/enclosure	1946-1955	
Freight car	1946-1955	Drums of residue, not ore
K-65 centrifuge	1946-1955	
K-65 return oven	1946-1955	
K-65 sampling laboratory	1946-1955	
K-65/Scalehouse Sampling Room	1946-1955	
Ledoux Laboratory (Bldgs 110A, 111)	1946-1955	
Pangborn dust collector	1946-1955	Not all dust collectors
Plate-and-frame press	1946-1955	
Railcar	1946-1955	Drums of residue, not ore
Scalehouse (Bldg 114)	1946-1955	
Warehouse ore drying oven	1948-1955	
<b>Other</b>		
Gangue, gangue lead cake, GLC, pitchblende raffinate	1946-1955	Synonyms for K-65
Sodium carbonate/sodium bicarbonate leach	1949	

For source material that was processed to concentrate thorium

For those few workers who processed thorium (Plant 7E, 1955-1957) (see Sections 4.5 and 5.3.2) , it is unclear as to whether the urinalyses measured thorium or still just uranium, although apparently urinalyses were done. There may be indications on individual records. Thus the urinalysis results should be inspected on a case-by-case basis to see if any information regarding thorium measurement methods or content was provided in the record. If not, then the intake data from Table 29F should be used instead, as appropriate.

When Table 29F is used, for each total pCi of assumed intake (not pCi in the urine), assume:

			CEDE
Th-230	0.990	pCi	8.80E-05
Ra-226	0.0065	pCi	2.32E-06
Th-232	0.00004	pCi	4.43E-04

Note that this table gives the CEDE (which can be assumed to be in arbitrary units) for comparison. Clearly, except possibly for certain organs, the intake can be assumed to be wholly Th-230.

- For urinalysis samples analyzed at the University of Rochester from about 1950 to about 1954, the reported result may be interpreted as a median value for a sample run in triplicate, with an uncertainty of  $\pm 2 \mu\text{g/L}$  for the three and a minimum detectable activity of  $5 \mu\text{g/L}$ , unless notes in the record indicate more accuracy by virtue of special treatment of the sample. (See Section 5.3.6 for more information.)

5. Air samples measured gross alpha only. For breakdown into an isotope distribution, the following claimant-favorable values should be assumed when intakes from Tables 29A-29F or concentrations from Tables 19-22 are used. Again, for simplification of the dose reconstruction process, the low-contributing isotopes may be conservatively ignored or their contributions may be folded into those of other isotopes, when appropriate for the organ type and intake mode.

For source materials in which uranium isotopes were predominant (general case)

The source terms in the table below should be used when Tables 29A-29E or Tables 19-22 respectively are used to determine intake.

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

Isotope	Quantity, dpm
U-234	489
Th-230	244
Ra-226	244
U-235	11
Pa-231	11
Ac-227	11

For each pCi of inhalation intake, assume:

Isotope	Quantity, pCi
U-234	0.489
Th-230	0.244
Ra-226	0.244
U-235	0.011
Pa-231	0.011
Ac-227	0.011

For source material in which radium-226 was the predominant isotope

For sources in which radium was the predominant isotope, it can be assumed that there was approximately 100 times more radium than uranium in the air on a curie basis (see Section 5.3.1). The following should be assumed for cases in which worker titles or functions correspond to areas where K-65 residue is present (see the table of job titles and areas given in Item 3 above)

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

Isotope	Quantity, dpm
U-234	9.6
Th-230	4.8
Ra-226	985
U-235	0.2
Pa-231	0.2
Ac-227	0.3

For each pCi of inhalation intake, assume:

Isotope	Quantity, pCi
U-234	.0096
Th-230	.0048
Ra-226	.984
U-235	.00020
Pa-231	.00020
Ac-227	.00030

For source material that was processed to concentrate thorium

The following should be assumed for cases in which workers processed residue to concentrate thorium (Plant 7E, 1955-1957) (see Sections 4.5 and 5.3.2) and the dpm figures from Table 29F are used.

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

Isotope	Quantity, dpm
Th-230	993
Ra-226	6.5
Th-232	.04

For each pCi of inhalation intake, assume:

Isotope	Quantity, pCi
Th-230	.990
Ra-226	.0065
Th-232	.000040

Note that it may be possible, for a given organ, to consider Th-230 alone.

- The default detection threshold for uranium urinalysis should be assumed to be 10 µg/L, as per Section 5.3.6.
- For use in choosing job or area categories for radon intakes (Table 30), the table below should be used to determine which areas or job titles are most apt to have been associated with elevated radon exposures.

	Applicable years	Notes
<b>Job Titles</b>		
C-3 centrifuge/process operator	1946-1955	
Cloth man/operator	1946-1955	
Digest operator	1946-1955	
Extraction operator	1946-1955	
Feinc operator	1946-1955	
K-65 sampler	1946-1955	May use "GLC" or "gangué" instead of "K-65"
Warehouse man	1953-1955	Should have "K-65" or "sampler" in title
Wash filter operator	1946-1955	
<b>Areas</b>		
Building 25-2 (Plant 2)	1944-1945	
Building K-1E (Plant 1)	1944-1945	
Feinc filter/platform/enclosure	1946-1955	
Feinc/Niagara filter/platform/enclosure	1946-1955	
Freight car	1946-1955	Drums of residue, not ore
K-65 centrifuge	1946-1955	
K-65 return oven	1946-1955	
K-65 sampling laboratory	1946-1955	
K-65/Scalehouse Sampling Room	1946-1955	
Ledoux Laboratory (Bldgs 110A, 111)	1946-1955	
Ore Room	1946-1955	
Ore Room Addition	1946-1955	
Ore thaw oven	1946-1955	
Pangborn dust collector	1946-1955	Not all dust collectors
Pitchblende	1944-1955	
Plate-and-frame press	1946-1955	
Railcar	1946-1955	Drums of residue, not ore
Scalehouse (Bldg 114)	1946-1955	
Warehouse ore drying oven	1948-1955	
Wash Oliver	1948-1955	
<b>Other</b>		
Digest, digestion	1948-1955	
Gangué, gangué lead cake, GLC, pitchblende raffinate	1946-1955	Synonyms for K-65
Ore grinding	1946-1955	
Ore milling	1946-1949	
Sodium carbonate/sodium bicarbonate leach	1949	
Q-11	1946-1955	Pitchblende ore

8. The number of work hours per year is 2000, i.e., 40 hours per week, 50 weeks per year. Adjustments should be made in individual cases if more specific information is available, such as prorating for partial years or overtime. If employment information is unclear, the most conservative or claimant-favorable appropriate job title should be used.

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 28 should be used for this, depending on how many years of data are missing. However, if he is listed as having worked as an electrician and mechanic for the year, with no time breakdown for these job titles, then it should be assumed that he spent the entire year as a mechanic (the more conservative choice).

9. For Plants 1 and 2, if no plant-specific data are available, the most conservative (usually the earliest) applicable data for Plants 4 and 6 should be used (applied retroactively), as appropriate for the worker activity. (Note that a comparison of Table 10 figures to Tables 12 and 13 figures supports this assumption since the latter are daily weighted averages and the former are more likely spot maxima.)

This should be applied up to the point at which the early plants shut down, i.e., at about the end of 1946; however, in the absence of information about residual conditions, if employment or other records indicate that the worker continued to work in Plant 1 or Plant 2, operation may be assumed to have continued through the end of decontamination and decommissioning in 1950. From that point on, it should be assumed that post-decontamination conditions applied, as covered in Section 8.0.

10. The breathing rate for all workers, if an assumption is needed, should be taken to be 1.2 m<sup>3</sup>/hr (as shown in Table 6 of ICRP 66 (ICRP 1994)).
11. Because urinalysis and film badge data are given in the records for the categories "AEC" and "Ledoux" or "Ledoux Laboratory", categories have been created for them as appropriate in Tables 19-22, Table 28, etc., for comparison and potential surrogate use. However, AEC personnel presumably worked for AEC itself and at least some of the personnel working in the Ledoux Laboratory, as previously noted, were presumably employed by the Ledoux Company and rendered services by contract to Mallinckrodt.
12. Special consideration must be given to maintenance and craft workers may have worked in process areas in 1942-1947, as explained in Section 5.3.2. The figures for these specific workers for 1942-1947 in Tables 29A-29F, 30, and 31A-31F should be assumed to correspond to their work in the shops alone and the plant or step-generic figures should be assumed to correspond to their work in the process areas.. It should be assumed that these workers spent part of their time in their shops or other dedicated areas and part in process areas, as given in the table below. Note that area mechanics were assumed to be dedicated to the particular process area or plant, with their work time being mostly spent in process areas and thus their daily weighted exposures already being representative of their residence in the process areas. (Note that the reason that the fractions below have not already been applied to the tables of intakes is that this allows for easier adjustments in the fractions based on individual claimant subject information, if available; also, it allows for a theoretical upper bound to be determined as 100% of time spent in process areas.)

Fraction of time spent in process and shop areas by maintenance and craft workers, 1942-1947.

Job or occupational title	Fraction of time spent in process areas	Fraction of time spent in shop areas
Area mechanic	1.00	0.00
Carpenter	0.50	0.50
Electrician	0.50	0.50
Graphite shop worker	0.00	1.00
Instrument machinist	0.10	0.90
Instrument technician	0.60	0.40
Machinist	0.00	1.00
Mechanic/shop mechanic (not area mechanic)	0.25	0.75
Millwright	0.50	0.50
Pipefitter	0.50	0.50
Welder	0.50	0.50

Dose reconstructors should be aware of the AEC report (AEC 1950a) in which AEC sought to reconstruct the cumulative exposures of Mallinckrodt workers who had been employed between July 1942 and October 1949 (thus including the period over which exposures were unmonitored). These estimates may possibly be found listed in individual dose records as simply an accumulated dose for the pre-monitoring period of operation, although this is not certain. See Section 5.0 for more on this.

## 6.2 DETERMINING INTAKE BY USING THE SURROGATE WORKER INTAKE DATA (TABLE 28)

Table 28, the surrogate worker annual intake table for uranium inhalation based on urinalysis data, can be used to estimate intakes when data are missing or to generate doses for comparison to doses calculated from individual urinalysis and other data, as follows. Note that when intakes are estimated from bioassay data, the mode of intake is usually assumed to be inhalation, unless there is information that indicates that other modes of intake are more likely. When using bioassay data, the inhalation intake model assumes that some of the intake behaves as ingested material. In general, intakes from bioassay will be larger when an inhalation rather than an ingestion intake is assumed.

1. 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 and 18 should be used to help make the selection. The job titles and work areas should then be tabulated by plant and by time period.
2. A surrogate worker value should be selected from the table 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 an appropriate mixed or miscellaneous value should be selected, subject to the judgment of the dose reconstructor. Where there is no generic or mixed category, then the maximum values of the category(-ies) applicable to the individual should be chosen.

For example, if worker is listed in urinalysis records as working in the "Bomb Step" of 6E in 4 out of 5 urinalysis records and only "6E" in the fifth record, it can be assumed that for the purpose of covering gaps in this records series, 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.

3. 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 28 shows, usually involved higher exposures for the most exposed workers than the later periods (Periods 2 and 3).

For example, Plant 1 laboratory workers should be assigned appropriate data from the Plant 6 laboratory worker listing.

4. Data for the unmonitored years from 1942-1947 should be taken from Period 1 for Plants 4 and 6. Data from Plants 4 and 6 should also be used as appropriate for workers in Plants 1 and 2, correlating job titles and types of work.
5. The pCi of intake should be assumed to be divided by isotope as given in Section 6.1, Item 3. Depending on the organ, low-dose-contributing isotopes may be ignored.

### **6.3 DETERMINING ANNUAL INTAKES BASED ON TIME-WEIGHTED DAILY AVERAGE INHALATION EXPOSURE DATA (TABLES 29A-29E)**

Tables 29A-29E, the tables of annual intakes based on time-weighted daily average inhalation of uranium and its daughters, may be used to determine inhalation intakes on an individual basis where urinalysis and related information is unavailable or spotty (e.g., for the period 1942-1947) or to generate doses for comparison to doses calculated from individual urinalysis and other data. While respirators were frequently and possibly even routinely used in high-dust areas, this practice is not considered to have been reflected in the time-weighted averages and thus the resulting intakes will be very conservative. Also, for a worker whose work history showed job rotation, a choice of the job title giving the maximum exposure (in Tables 29A-29E), applied through the whole year, should be conservative.

The steps are as follows.

1. The job title or work area selection(s) from Table 18 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.
2. The annual intakes from Tables 29A-29E should be selected to correspond to the job title or work area, plants, and time periods. For maintenance and craft workers and for 1942-1947 only, the annual intake from their specific job title (or "maintenance" category) should be multiplied by the fraction of time in shop areas taken from the percentage table in Section 6.1, Item 11; to this should be added the generic plant or area annual intake multiplied by the fraction of time spent in the process area(s), to yield a weighted annual intake.
3. Assumptions regarding isotopic content of the radioactivity in the air should be made as given in Section 6.1, Item 5 above.

#### **6.4 DETERMINING ANNUAL THORIUM INTAKES BASED ON TIME-WEIGHTED DAILY AVERAGE INHALATION EXPOSURE DATA (TABLE 29F)**

Table 29F, the annual intake table for the thorium processing operation, can be used to determine upper-bound inhalation intakes for missing periods or to generate doses for comparison to doses calculated from individual urinalysis and other data. This table is applicable only to those workers who were involved in processing thorium (ionium) in Plant 7E during July 1955 – March 1957. These would be only those workers who have some indication in their records (e.g., urinalysis or film badge records) that they worked in Plant 7E, the Minor Elements Production Facility, MEP, “ME processing”, 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 (which they were even for workers present for the entire period of operation, as indicated by the table). The partitioning among isotopes should be done as given in Section 6.1, Item 5.

#### **6.5 DETERMINING ANNUAL RADON DAUGHTER INTAKE BY USING RADON EXPOSURE DATA (TABLE 30)**

Radon intakes should be assigned only when the lung is the organ of interest. Table 30, the table of annual radon daughter intakes based on radon measurements, should be used to determine conservative estimates of radon daughter intakes. Note that this table was based on spot measurements that were usually taken at times of representative or maximum radon emanation and not on daily weighted average exposures, which are unavailable.

1. The job title or work area selection(s) from Table 18 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.
2. The annual intake(s) from Table 30 should then be selected to correspond to the job title or work area, plants, and time periods. For maintenance and craft workers and for 1942-1947 only, the annual intake from their specific job title (or “maintenance” category) should be multiplied by the fraction of time in shop areas taken from the percentage table in Section 6.1, Item 11; to this should be added the generic plant or area annual intake multiplied by the fraction of time spent in the process area(s), to yield a weighted annual intake.

Generally speaking, only workers who spent time in Plant 6 were likely to have been exposed to elevated levels of radon and then usually only if they spent time in an area where radon might concentrate significantly, such as in the Ore Room and Ore Room Addition, the processing areas up through the production of K-65, and the residue storage areas. The table in Section 6.1, Item 6 should be used as guidance if the choice of job title or work area in Table 30 is not clear. Note that being subject to sampling for breath radon is an additional indication of potential exposure. Thus workers who have breath radon records in a particular period should be assumed to have potential exposure during that period. Finally, some workers who participated in thorium processing in Plant 7 also have a radon exposure to consider; a conservative annual intake for them is shown in Table 30. Other workers in Plants 4, 6, and 7, such as office workers and non-thorium workers, and workers in Plant 6E can generally be assumed to have relatively minimal radon exposures, as indicated in Table 30.

## **6.6 DETERMINING ANNUAL INGESTION INTAKES BASED ON TIME-WEIGHTED DAILY AVERAGE INHALATION EXPOSURE DATA (TABLES 31A-31F)**

Tables 31A-31F, the tables of annual ingestion based on time-weighted daily average inhalation of uranium and its daughters, may be used to determine ingestion intake on an individual basis where urinalysis and related information is unavailable or spotty (e.g., for the period 1942-1947) or to generate doses for comparison to doses calculated from individual urinalysis and other data. Note that these tables were generated directly from Tables 29A-29F, as explained in Section 5.3.8.

The steps are as given below.

1. The job title or work area selection(s) from Table 18 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.
2. The annual intakes from Tables 31A-31F should be selected to correspond to the job title or work area, plants, and time periods. For maintenance and craft workers and for 1942-1947 only, the annual intake from their specific job title (or "maintenance" category) should be multiplied by the fraction of time in shop areas taken from the percentage table in Section 6.1, Item 11; to this should be added the generic plant or area annual intake multiplied by the fraction of time spent in the process area(s), to yield a weighted annual intake.
3. Assumptions regarding isotopic content of the radioactivity in the air should be made as given in Section 6.1, Item 5 above.

## **6.7 SPECIAL NOTE REGARDING DETERMINING INTAKES FOR PLANTS NO LONGER UNDER MED/AEC CONTRACTS**

There do not appear to be any records of decontamination and decommissioning work and other work at Plants 1 and 2 for the period between the time they ceased operations in 1946 and the time they were released to Mallinckrodt in 1951, i.e., from about 1947 through 1950, although this work was done under an MED/AEC contract. The decontamination itself was conducted by Mallinckrodt (ORNL 1981) and further decontamination was possibly performed in 1954 and possibly 1970 (Mallinckrodt 1994), but all of this work this was likely covered by badging and urinalysis (i.e., the workers were considered to be associated with the still-operating Plants 4, 6, 6E, or 7 and so would have been covered routinely). Thus it is expected that decontamination workers have film badge and probably urinalysis records. If not, then these Plants 1 and 2 decontamination workers, should have their 1946-1950 exposures determined on the basis of decontamination worker data as given in Section 8.0 (i.e., the Section 8.0 data would serve as surrogate data).

For any workers that may have been still working in the Plants 1 and 2 buildings on non-decontamination operations, it may be assumed that radioactive operations they formerly worked on continued as previously; this would appear to be a claimant-favorable assumption. Thus the maximum figures (either surrogate data or Tables 29-31 data) for 1942-1946 for these workers can be assumed to apply from 1947-1950 as well.

For the period after decontamination and decommissioning, i.e., from 1951 on, the exposures should be determined as described in Section 8.0, using the data of Table 40 to establish a reasonable and appropriate annual exposure.



## 6.8 USE OF BREATH RADON DATA

Because so few workers were subject to breath radon sampling and because those workers who were undoubtedly also have urinalysis data, it is expected that the breath radon data will need to be used only as a check or alternative source of information in cases where the presence of radium in the bone would affect the dose to the organ of interest. In such cases, the correspondence of 1.0 pCi/L of radon in the breath to approximately 0.1 uCi of Ra-226 in the skeleton, as given in Section 5.3.7, should be used to estimate the dose. The minimum detectable level of 0.006 pCi/L cited in Section 5.3.7 should be applied to the data, as representing the best available information, corresponding to a minimum detectable body burden of Ra-226 of 0.00059  $\mu$ Ci.

While there appear to have been a few office workers who gave breath radon samples, this seems to have been done only once and probably only for comparison purposes (e.g., to check the radon background). Thus only those workers who dealt with pitchblende ore forms, the ore-to-UO<sub>3</sub> production process up through the formation and handling of the K-65 residue (gangue lead cake), and K-65 sampling and analysis (see the list in Section 6.5) should be considered candidates for consideration of breath radon data.

**NOTE: SECTION 7.0 BELOW NEEDS TO BE REVISED TO INCORPORATE THE SURROGATE FILM BADGE DATA, WHEN AVAILABLE – DON'T USE EXCEPT IN A PROVISIONAL FORM (THE CHEST X-RAY INFORMATION SHOULD BE CORRECT, HOWEVER)**

**7.0 DETERMINATION OF EXTERNAL DOSES DURING THE OPERATING YEARS**

This section applies to determination of external gamma, beta, and neutron doses during the operating years only. For external doses during the decontamination years and the postoperations years (1959-1995), see Section 8.0.

**7.1 ASSUMPTIONS AND GENERAL INSTRUCTIONS**

The following assumptions should be made in the determination of external dose.

1. Most external dosimetry monitoring records appear to be available, but where such records are missing doses must be estimated. As alternatives for dose estimation information, area monitoring data for external radiation is sparse and although much is known about the characteristics of the process material (source term), the lack of knowledge of such relevant factors as geometry make dose estimation using this data subject to a great deal of uncertainty. Thus the approach incorporating the least uncertainty is likely to be using existing dose monitoring records to create an applicable surrogate(s) set of data.
2. Mallinckrodt dose records demonstrate that a substantial proportion of employees had film results recorded as 0-50 mrep or mr. From this it can be assumed that the dose-monitoring program was sufficiently conservative that even many individuals who did not receive significant occupational exposure were also monitored. It can be further assumed that the converse is true, that individuals who were not monitored were unlikely to receive significant occupational exposure. This assumption is supported by the observation of Hickey and Dupree (1984) that Mallinckrodt health physicists and industrial hygienists presumably monitored those jobs and workers where they thought the problems were and that it can thus be inferred that infrequently monitored workers such as the general administrative staff were not considered to be at risk of significant exposures.
3. Photon doses for all workers should be assumed to be in the 30 – 250 keV energy range. This is consistent with NIOSH (2002a). It is also consistent with the fact that all but a negligible fraction of the gammas emitted by U-235, U-235, and their daughters down to radon are in this range, including the principal gamma of Ra-226 (0.186 MeV) and the principal gammas of Th-230 and Th-232.
4. For the purposes of dose reconstruction, the "beta" readings in the Mallinckrodt dose records are assumed to be equal to the shallow dose,  $H_p(0.07)$ . Beta dose should thus be assigned as shallow dose, with a claimant-favorable dose conversion factor of 1.0 for application of this shallow dose to the skin, testes, and female breast. It should be assumed that electrons are of energy greater than 15 keV.

Also, as noted earlier, AEC studied attenuation of betas by workplace clothing (AEC 1950i). Attenuation was determined for coverall cloth to be an average of 21.8% (standard deviation of 7.5%) for distances of 5-36 inches from a sheet of uranium metal in equilibrium with its two major beta-emitting progeny, Th-234 and Pa-234m. Since this replicated work source

conditions and clothing type, the results may be applied directly in dose reconstruction. Although variability in the mean attenuation appeared to be related to distance from the source, no pattern could be identified. Hence in dose reconstruction a constant value of 20% attenuation in shallow dose at cancer sites concealed under clothing should be used, i.e., a factor of 0.8 should be applied in the testes and breast cases to allow for shielding by work clothing.

5. When job assignments are known in sufficient detail from the individual work history, geometries may be applied by specific job title from Table 18, which was derived from engineering judgment and from the time-and-motion measurements made as part of the AEC dust monitoring studies. Should the job title(s) be unclear, a reasonable assignment from Table 18 should be made on the basis of applicable job or work area notations in the film badge and/or urinalysis records.

When individual information is not present in the employee information in sufficient detail to allow an assignment in Table 18, more general categories should be applied to these cases. Although the exposure geometries for the three job categories in uranium facilities listed in NIOSH (2002a) (general laborer, machinist, and supervisor) are useful when little is known about a given uranium facility, details of the Mallinckrodt facilities are understood well enough that the general categories given below should be used when Table 18 cannot be used.

#### 50% AP/50% ROT

This category corresponds to the "supervisory" category in NIOSH (2002a). Job titles to which this geometry should be applied are supervisor, foreman, mechanic, and maintenance personnel who had no specific equipment or area assignments or were assigned to multiple buildings.

#### 25% AP/75% ROT

This category corresponds to the "general laborer" category in NIOSH (2002a). Job titles to which this geometry should be applied are warehouse worker, general laborer (personnel not assigned to specific process equipment) in process plants, engineer, forklift driver, instrument technician, and others who had frequent process area access but were not assigned to specific process equipment.

#### 75% AP/25% ROT

This category corresponds to the "machinist" category in NIOSH (2002a). This geometry should generally be applied to many process workers assigned to a particular area.

#### 90% AP/10% ROT

This category should be 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. This geometry should generally be applied to process workers in the higher-dose categories.

#### 100% ROT

This category should be used to assign dose to non-process workers, i.e., workers expected to have entered process areas only incidentally if at all and who rarely if ever approached process equipment as part of their assigned duties. Job titles to which this geometry should be applied include clerk, other office workers, and

dispensary personnel. (However, some clerks involved in materials accounting had frequent access to process areas and should not be included in this category.)

Note that a survey completed at the end of operations (MCW 1959) stated that in general most of the radioactive contamination was located in floors and in walls below the six-foot level, with walls, steelwork, and metal platforming above the six-foot level usually showing only slight contamination; this suggests except for tall tank contributions, there was not much dose contribution from above. Also, the nature of the process and available floor plans indicate that there was little overhead process piping. Further, the early process involved much direct manual handling of the radioactive material. Finally, for the workers receiving the highest doses, higher-dose activities often imparted much of the dose in a short period of time while they were directly handling the material or equipment. Thus isometric-geometry exposures are included in the detailed geometries in Table 18 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.

6. The descriptions of the film badge in Section 5.4.3.2 above do not suggest calibration using a phantom, so it is likely that open-air calibrations were performed. Thus the recommendation is that Mallinckrodt recorded doses be converted using dose conversion factors for Roentgen-to- $H_T$  dose for photons from Appendix B of NIOSH (2002a). While film badges are known to overestimate doses from low-energy photons, the low-energy component does not seem to be a significant characteristic of the Mallinckrodt spectrum. Thus no modification is proposed to recorded deep doses, once converted to organ doses using the Roentgen-to- $H_T$  dose conversion factor.
7. Examination of entries for "gamma" and "beta" in the Mallinckrodt dose records shows that the beta doses were obtained by subtracting the optical density for the shielded portion of the film from that of the unshielded part. This is also shown by a series of memoranda between the AEC and Mallinckrodt (AEC 1950f, AEC 1950h, MCW 1950o) in which the method of subtracting the two quantities was discussed. For Mallinckrodt, it is assumed that the beta readings were obtained by subtracting the density under the shield from the density under the window and assuming the difference in density was due to beta radiation (MCW 1950o).
8. For the purposes of dose reconstruction, the minimum level of detection should be assumed to be 50 mrep/week, based on 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 should thus be assigned "incidental dose" for each weekly cycle worked. This should be assigned as photon dose equal to the limit of detection divided by 2 (LOD/2), or 25 mrep, for each weekly cycle worked, as given in NIOSH (2002a). This 25 mrep should be assumed to be in the form of photons of energy between 30 and 250 keV and the exposure geometry should be taken to be 100% ROT.

Note that the use of the LOD/2 method results in "slight positive bias" for monitored workers, as stated in NIOSH (2002a) and that additional claimant-favorability arises from the fact unmonitored workers were less likely to receive significant occupational dose (as per Item 2 above). True doses are thus closer to zero than are "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.

9. The lognormal distribution should generally be used to determine missed dose, as stated in NIOSH (2002a).

## **7.2 INFORMATION REGARDING THE 1950 AEC CUMULATIVE DOSE RECONSTRUCTION STUDY**

The lack of early external monitoring data for Mallinckrodt 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 at the end of the war and 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). AEC's results are not quoted here for two reasons. First, in dose reconstruction different assumptions are made than AEC made. Second, the study develops cumulative dose data, but unfortunately does not apply it to individual workers or distinct work groups, while doses applied to individual workers for dose reconstruction should rely on recorded doses for actual worker or worker groups. 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.

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, but not necessarily, be somewhat nonconservative.

## **7.3 GAMMA AND BETA DOSE**

NIOSH (2002a), the external dose reconstruction guide, states that the hierarchy of dose determination sources are personal dosimeter (the film badge worn by the individual); pocket ionization chamber; and group or co-worker dosimeter. Pocket chamber data does not appear to be available for Mallinckrodt and in fact, use of the pocket chamber (pocket meter) was discontinued in 1949, as explained in Section 5.4.1. However, such data may come to light at a later date and in that case, some calibration and other information can be found in Section 5.4.1 and the references it cites. NIOSH (2002a) does not list the area monitoring dosimeter, such as Mallinckrodt used in many areas as a secondary means of monitoring. However, such data, if available, could be used in a comparative way if none of the other data sources can be found.

Generally, for a given claim, dates of employment should be compared to the available dose monitoring information. If dose monitoring records are likely to be available, the dose reconstructor should request project personnel to search the available records and list recorded doses for the case (or request that appropriate project personnel do so). Then reconstructed dose should be assigned for each weekly cycle worked during the unmonitored period. Dose reconstructions should then be performed in accordance with the dose reconstruction project external dose procedure (ORAUT 2003a), the NIOSH external dose reconstruction guidance (NIOSH 2002a), and any other applicable project guidance.

### **7.3.1 Selecting a Surrogate Cohort and Formulating a Surrogate Data Set**

Surrogate (analogous co-worker) data, in Mallinckrodt cases, is a matter of identifying an appropriate set of workers with a similar work history. That is, in general, to form a surrogate set the dose reconstructor should identify at least several other workers with appropriate monitoring data who did the same work at the same time as the subject worker; the monitoring results for these surrogate workers should then be pooled to arrive at a statistical representation of the likely dose to the worker. A lognormal distribution should be assumed.

For the unmonitored years, identification of a surrogate set must make use of records from monitored years and of records such as contemporaneous employment rosters showing names of employees and their work groups, to identify potential candidate surrogate co-workers.

For the monitored years, many, perhaps most Mallinckrodt film badge records and urinalysis records had some indication of job title, task, or work area. Thus the formation of a surrogate set of data should be possible for all monitored years by inspection of the weekly dose reports, supplemented as necessary by inspection of the quarterly urinalysis reports. (Note that the urinalysis reports are a useful and available additional source of co-worker and job assignment information for external dose reconstruction even though the urinalysis results themselves are not relevant to external dosimetry.) Dose reconstructors must compare information available from the DOE record and the computer-aided telephone interview (CATI) to the records in order to identify workers with a similar work history.

One complication of selecting a surrogate set for the monitored years is that from some point on in the postwar years (1949?), a rotation system was used in work assignments in order to reduce individual process worker external exposure (MCW 1950t; AEC 1951b). The work done by an individual would therefore vary over the course of a year as he was rotated in and out of high-exposure areas. Thus for best results, where data for an individual known to be working at Mallinckrodt in AEC operations is lacking or is unclear, some care must be taken to identify co-workers whose assignments are most analogous to the workers. The rotation system was done principally on a crew basis, i.e., the same small subgroup of individuals were assigned to the same work at any given time, so the most appropriate individuals are those whose names appear on the known records for the individual as doing the same work at the same time and not, say, individuals doing the same work in a later period. However, if the number of same-time co-workers is deemed by the dose reconstructor to be too small to provide adequate statistics in view of the variation in the doses, the similarly assigned co-workers doing the same work in the period immediately before or after the period of interest should be included. The rotation system apparently ended when the doses went down sufficiently, probably at some time in the early 1950's. Hence from about 1952 on, the records will likely show more sustained assignment of the same work to an individual and identification of same-time coworkers would be less important.

### **7.3.2 Determining Dose During the 1945 15-Week Monitoring Period and Any Earlier Monitored Period**

This section applies to workers who are listed in the Mallinckrodt Radiation Summary (MCW undated). Data for the initial known 15-week monitoring period are given in the Mallinckrodt Radiation Summary (MCW undated). Doses during this period should be determined by extrapolation or interpolation from the total dose listed and from any other dose records from 1945 that may become available. In MCW (undated), only total doses for all weeks worked are listed, so the average weekly dose for each individual should be computed by dividing the listed totals for gamma and beta by the number of weeks worked. This average weekly gamma and beta dose should then be assumed to apply for

each week worked during the period if the worker was employed in the AEC-sponsored operations whether or not all the weeks of work were represented in the listing for that worker in MCW (undated)

For example, if MCW (undated) shows dose for a worker covering 12 of the 15 weeks but employment records show that he was employed in the uranium work for all of the 15 weeks (and was not absent from work), then the average gamma and beta doses calculated on the basis of the 12 weeks should be applied to the other 3 weeks as well.

### **7.3.3 Estimating Dose, Unmonitored Period 1942-1945**

#### **7.3.3.1 Workers With Subsequent Dose Monitoring Records**

For workers whose covered employment includes some part of the unmonitored period in 1942-1945 and who have dose results from the early monitored period (i.e., from some time in late 1945 on), the Mallinckrodt Radiation Summary (MCW undated), any other film badge records that may be available from 1945, and the film badge records from 1946 should be used to estimate the dose during the unmonitored period.

For workers listed on the radiation summary (MCW undated) or other 1945 dose tabulations who appear to have done the same or similar work during the unmonitored period as during the monitored period, the average weekly gamma and beta doses should be determined as stated in Section 7.3.2. They should then be applied to cover each week worked during the unmonitored period, if the worker appears to have done the same or similar work during the unmonitored period as during the monitored period.

For workers who are not listed on the radiation summary or other 1945 dose tabulations, the dose records for 1946 should be checked. If the work done during the unmonitored period appears to be substantially the same in function and area as during the monitored period, then the 1946 dose should be applied on a weekly average basis to estimate the dose during the unmonitored period. In situations where data for 1945-1946 is incomplete or unavailable, the dose reconstructor should move on to subsequent periods for monitoring data.

For workers who are not listed on the radiation summary or other 1945 and 1946 dose tabulations and for workers who are listed on the summary but whose work during the unmonitored period appears to differ significantly from that during the monitored period, a surrogate worker set should be identified from the radiation summary and other 1945 and 1946 dose tabulations. Appropriate gamma and beta doses should then be calculated and applied for the unmonitored period.

For any worker for whom a surrogate set cannot be identified because of lack of clarity in the records about the nature or area of his work, doses should be assigned from Table 36 (see also Section 7.3.3.2 below). When Table 36 is used, the median dose should be applied to each cycle for which dose is reconstructed during the unmonitored period.

#### **7.3.3.2 Workers Without Subsequent Dose Monitoring Records**

This section applies to workers whose work histories indicate that they worked at the AEC-sponsored uranium processing facilities during the unmonitored period (i.e., prior to the start of film badging in about mid-1945) but who had no film badge records for the monitored period. It is assumed that such workers (1) terminated prior to the beginning of dose monitoring, (2) moved to some non-AEC work at Mallinckrodt prior to the beginning of dose monitoring, or (3) performed work at the uranium facilities during the monitored period that did not meet Mallinckrodt-AEC criteria for monitoring.

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

A surrogate dose history should be formulated based on workers with similar job titles or functions and work areas during the monitored period, i.e., from 1945, 1946, or the closest subsequent period for which sufficient data exists.

#### Workers who were outside the AEC-sponsored uranium operations during the monitored period

A surrogate dose history should be formulated based on workers with similar job titles or functions and work areas during the monitored period, i.e., from 1945, 1946, or the closest subsequent period for which sufficient data exists.

#### Workers who were apparently in the AEC-sponsored operations during the monitored period

For individuals who have no identified film badge records and who had work assignments subsequent to the unmonitored period that would probably not result in significant exposure (and who were presumably not monitored for that reason), doses should be assigned as median dose from the early monitored period, as given in Table 36. This provides a claimant-favorable estimate that likely addresses any incidental dose that may have been received from 1942-1945.

For individuals who have no identified film badge records and who had work assignments subsequent to the unmonitored period that would appear to have resulted in significant exposure (e.g., they have urinalysis or breath radon records with notations typically indicating access to process areas or other employment or health records clearly indicate some process area access), doses should be assigned as per Section 7.3.2 above.

### **7.3.3.3 Notes Regarding Dose Summaries**

Monitored workers may have received up to 150 mrep in a week without the dose being recorded in a dose summary. 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 worker 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 should be based on an average ratio derived from the weeks with specific dose monitoring entries for that individual.

### **7.3.3.4 Notes Regarding the Application of Later Monitoring Data to the Unmonitored Period**

The approach of applying later monitoring data to establish doses in the unmonitored period 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". Also, the use of 1946 data (e.g., MCW (undated)) "should provide valid exposure estimates for this early period" (Dupree-Ellis et al. 1998).

Also, to what extent exposures during early "benchtop" operations differed from production-level exposures is not known. However, processes were developed on the bench and pilot plant levels and then scaled up to the production level; the production level then increased repeatedly throughout the wartime and early postwar years. Thus it is logical to conclude that the process and conditions for benchtop and pilot plant operations were similar to the production-level operations, but on a much smaller scale (including generally much smaller source quantities at a given time).



### **7.3.3.5 Notes Regarding 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 for the reasons listed below. However, dose estimates calculated as indicated in this section represent the best information at hand and are still expected to be claimant-favorable.

1. Only total doses were listed for each worker for the number of weeks monitored (n = 1-15); there was no monthly or weekly breakdown.
2. 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.
3. As noted in Section 7.3.3.1 above, how early “benchtop” operations may have resulted in doses that differ from the production level and thus the estimates in Table 36 is not known. However, the potential source would appear to have been much higher at the production level than at the benchtop or even pilot plant level and the exposure would have been more sustained over time (constant production). Pitchblende was processed only in limited quantities until Plant 6 was built to process it in bulk, shortly after the start of monitoring. So the potential gamma-emitting source would have increased markedly over what it had been in the unmonitored period.
4. As it is not possible to determine accurate production levels for the early period and for the period covered by the 15-week monitoring, no attempt has been made to scale the exposures to reflect the quantity of material processed.

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 methodology used to create Table 36 was compared with the techniques discussed in Watson et al. (1994). Although there are some differences (e.g., the equipment changed each several years, unlike the plant studied by Watson et al.), the approach described below resembles the use of a department mean or median dose as closely as possible with the available data.

### **7.3.4 Determining Dose – Monitored Period 1946 - 1958**

This section applies for workers who have monitoring data after the initial 15-week monitoring period and for whom doses must be estimated for the operating years, i.e., 1946-1958. Plants 1 and 2 were not used for AEC work after about 1946 and underwent decontamination and decommissioning (D&D) in 1948-1950, after which they were released to Mallinckrodt in 1951 for non-AEC work. Similarly, the other plants stopped being used at varying points in 1957-1958 and underwent D&D thereafter. This

section does not apply to any worker or work area after the end of operations; see Section 8.0 for dose estimation for the D&D years and the later postoperations years.

Because there is not a formal date or dates that can serve as a cutoff for the dose reconstructor to use, some judgment will have to be applied as to how much of the dose record should be counted as contributing to dose from AEC operations. This is particularly true since after the operations and D&D years, Mallinckrodt received a license from the AEC for the use of certain radioactive materials and so some workers may have been continued to be badged. Also, there may be continuing badge records for some individuals for years after operations ended at the St. Louis (Destrehan) site because these individuals transferred to or made visits to the Weldon Spring site, also run by Mallinckrodt, and had badges issued for work there.

#### **7.3.4.1 Monitored Workers**

For workers with monitoring data following the initial 15-week monitoring period (i.e., MCW undated), i.e., during the monitored period of early 1946 on, either the workers' own data or the data provided by a surrogate worker set(s) should provide sufficient information for dose estimation. Interpretation of the dose records should be made according to the applicable previous sections of this technical basis document.

When there is missing data in the monitoring records, they should be filled in accordance with the assumptions of Section 7.1, Items 7 and 8; the guidance of NIOSH (NIOSH 2002a); and the dose reconstruction project external dose reconstruction procedure (ORAUT 2003a). This is expected to consist largely of bridging small gaps by interpolation and bridging larger gaps using statistical surrogate data and/or standard missed dose estimates.

#### **7.3.4.2 Unmonitored Workers – Plants Still Operating under MED/AEC Contracts**

As stated above, most workers who received significant occupational exposure were likely to have been monitored and thus if a worker was not monitored, especially for a lengthy period of employment, this indicates that he was deemed to have little or no exposure potential. To account for the possibility of an unmonitored individual receiving incidental exposure to photons, dose should be assigned to unmonitored Mallinckrodt employees as follows.

1. An attempt should be made to find a surrogate category. The average or median value for the surrogate category should then be assigned to the worker as per Section 7.3.1.
2. If no surrogate category can be identified – i.e., if there are no monitored workers with the same job title or the job title listed in the subject's records cannot be associated with any surrogate job title – then either the Mallinckrodt subject matter expert for the dose reconstruction project should be consulted for guidance (and possibly further research) or the subject should be assigned a nominal category. Normally, the appropriate nominal category will be a low-exposure job title such as office worker.

#### **7.3.5 Unmonitored Workers – Plants No Longer Operating under MED/AEC Contracts**

As noted above, Plants 1 and 2 for the period between the time they ceased operations in early 1946 and the time they were released to Mallinckrodt in 1951, i.e., from 1946 through 1950, it can be claimant-favorably assumed for any employees still working on non-decontamination operations that operations still continued as previously. The decontamination itself was conducted by Mallinckrodt (ORNL 1981) and further decontamination was performed in 1954 and possibly in 1970 (Mallinckrodt

1994), but this was likely covered by badging (i.e., the workers would have been considered to be associated with the still-operating Plants 4, 6, 6E, or 7 and so would have been covered routinely).

Thus non-badged (unmonitored) workers not performing decontamination may have their former exposures (or those of surrogate workers doing non-decontamination work in previous years) projected through 1946-1950 as if the work continued. Unbadged decontamination workers, if any, should have their 1946-1950 exposures determined on the basis of decontamination worker surrogate data (see Section 8.0).

For the period after decontamination and decommissioning, i.e., from 1951 on, the exposures should be determined as described in Section 8.0.

### **7.3.6 Conversion to Organ Dose**

For deep dose, the conversion to organ dose for the relevant worker category should be performed using assumptions of Section 7.1 and the energy-, geometry-, and radiation-specific dose conversion factors given in NIOSH (2002a).

## **7.4 X-RAY DOSE**

### **7.4.1 Mallinckrodt-Specific Information**

Employees of Mallinckrodt (cf. Section 5.4.5) received an annual occupationally related diagnostic x-ray (MCW 1955d; Mason 1958a). Up to some time in 1944, a pelvic x-ray was also performed for employees working with fluorides (see Section 5.4.4). The annual chest x-rays and presumably the pelvic x-rays were taken at the Barnes Hospital (the Washington University School of Medicine) (AEC 1950m; MCW 1955d) and the x-ray records remained the property of the hospital (AEC 1950m). 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. An additional note regarding x-rays during the decontamination and decommissioning period is given in Section 8.1.

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.

### **7.4.2 Chest X-Rays**

Information to be used in dose reconstruction for the early years for which no specific information is available is provided in ORAUT-OTIB-0006, the dose reconstruction project technical information bulletin covering diagnostic x-ray procedures (ORAUT 2003c). ORAUT (2003c) should be referred to regarding the underlying bases, interpretation details, and a sample of a summary data table where actual beam data are known.

Doses for organs not listed in ICRP Publication 34 (ICRP 1982) but specified in the IREP code should be 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 Liver/gall bladder/spleen Remainder organs
Abdomen	Ovaries	Urinary/bladder Colon/rectum Uterus
Head and neck	Thyroid	Eye/brain

As ORAUT (2003c) notes, for any individual entrance skin exposure (ESE) or derived organ dose, an uncertainty of  $\pm 30\%$  at the one sigma 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.

### 7.4.3 Pelvic X-Rays

Guidance regarding pelvic x-ray examinations has not yet been issued by NIOSH or the dose reconstruction project. Thus consideration of this dose contribution will have to be deferred. Note that for Mallinckrodt, such contributions would be applicable to only some workers, i.e. those working with fluorides; presumably this class would consist of workers involved with the  $UO_2$ -to- $UF_4$  and the  $UF_4$ -to-derby processes, including workers who handled the hydrogen fluoride supply and storage functions. Also, such contributions would be applicable only from perhaps 1942 to 1944 at most, as indicated in Section 7.4.1.

## 7.5 NEUTRON DOSE

As indicated in Section 5.4.2, there was no neutron monitoring done at Mallinckrodt. Therefore it is not expected that there will be any neutron monitoring data or neutron dose rate measurement data found for Mallinckrodt. Thus any estimate of neutron dose will have to be calculated on the basis of source term data, as recognized by NIOSH (2002a). As explained in Section 5.4.2, the only potentially significant source of neutron exposure would have been neutrons produced by the alpha-neutron reaction in materials in which uranium and thorium were mixed with elements of low atomic number such as fluorine and oxygen. Table 34 shows the results of the dose rate calculations and also some calculated doses, together with the occupancy assumptions on which they were based. Assumptions not given in the table may be found in Section 5.4.2.

The annual doses from the uranium forms are negligible compared to the probable doses received by process and lab workers, who were the only workers likely to have received any neutron exposure at all and theirs was clearly negligible. Hence the neutron dose contribution from the uranium forms does not need to be investigated further. While this is probably the case with the thorium forms also, the thorium neutron doses should be considered for appropriate worker cases (claimants). Note that this dose is applicable only for those years or parts of years in which the thorium was processed, i.e., from after July 1955 through approximately March 1957.

Thus in assigning neutron dose, only the thorium workers need be assigned dose and the doses calculated as given in Table 34 are claimant-favorable values.

## **7.6 OTHER DOSE CONTRIBUTIONS**

### **7.6.1 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 need to be formulated on a case-by-case basis. See Section 5.4.3.5 for information about individual ring dose data and interpretation.

### **7.6.2 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.

### **7.6.3 Shallow Dose**

As stated in Section 7.1, Item 6, Mallinckrodt dose records contain "beta" values obtained by subtracting the optical density of the film behind the cadmium shield from that behind the open window. These recorded values are assumed to be equivalent to  $H_p(0.07)$ . For the purposes of dose reconstruction, shallow dose should be assigned from the film badge data using a claimant-favorable dose conversion factor of 1.0.

## **8.0 DETERMINATION OF EXPOSURES DUE TO RESIDUAL CONTAMINATION REMAINING FROM MED/AEC OPERATIONS**

As part of the process of dose reconstruction, the doses from postoperational decontamination and decommissioning activities and from postoperational work activities must be determined, insofar as they are due to residual contamination remaining after MED-AEC operations ceased. For this purpose, operations at the Mallinckrodt St. Louis main site are considered to have ended in 1957-1958 and decontamination and decommissioning (D&D) of the various buildings used for MED/AEC work to have begun in 1959 and continued through 1961; and the postoperational period to have extended from 1962-1995. Regular operations at SLAPS are considered to have ceased in 1958 and the caretaker/D&D operations period to have extended from 1959-1962.

### **8.1 DESCRIPTION OF THE DECONTAMINATION AND DEMOLITION WORK AT THE ST. LOUIS MAIN SITE, INCLUDING HEALTH AND SAFETY PRECAUTIONS**

As noted in Section 3.0, for buildings in Plants 1 and 2, decontamination had been done some years earlier. Mason 1977 states that this started in 1949; Mallinckrodt (1994) states that there were programs to do so in 1950 and 1954 and even in 1970; and ORNL (1981) mentions only the decontamination of 1948-1950. Little is known of the Plants 1 and 2 decontamination campaign because although Mason (1977) states that detailed reports of the work, including the final surveys, were prepared, these records are not available.

What is presently known is as follows. In 1946, Mallinckrodt took core samples of the subsoil under Buildings 51 and 52 in Plant 2 (MED 1946f), boring through the concrete floor, presumably at AEC's behest. This indicates that even the earliest characterization effort likely took place after the start of film badging and urinalysis; decontamination workers may have been given badges and urinalysis due to the dust and dose rate potential of the work. The decontamination that began in 1949 was performed by "Main Plant" (Plants 1 and 2) crews under directions from Mallinckrodt Uranium Division "monitors", as the health and safety specialists were called (Mason 1977). The contaminated waste material was collected and delivered to AEC, presumably in drums or boxes, while contaminated equipment was either recycled to Plant 6 or was transferred to AEC for disposal (Mason 1977). Some of the material apparently ended up buried at SLAPS. When the work was done to the satisfaction of the AEC St. Louis Area office, monitoring personnel from AEC-NYOO did a final survey of Plants 1 and 2 (Mason 1977). When AEC-NYOO was satisfied, AEC released the plants to Mallinckrodt for unrestricted use in 1951 (FUSRAP 2002; DOE 1981).

With regard to Plants 4 and 6, some preliminary work, such as some initial cleanup, was done in 1955 and in 1958-1959 (AEC 1955b; MCW 1958; MCW 1959; MCW 1961b). For example, the process equipment was thoroughly cleaned by Mallinckrodt at the time the plants went into standby, before the formal decontamination and decommissioning work began (MCW 1961b). Some initial surveys to evaluate Plants 4, 6, 6E, and 7 were then performed (AEC 1955b; MCW 1958; MCW 1959; MCW 1961b). It was determined that many buildings at the site were so contaminated that it would have been too expensive to clean them to usable levels, and they were torn down. All of the Plant 4 buildings and most of the Plant 6 buildings were torn down, but much of Plant 6E and 7 survived (Mallinckrodt 1994), amounting to about 20% of the MED/AEC plants at the site (MCW 1961b).

MCW (1961b) describes the health and safety (H&S) aspects of the decontamination and demolition (D&D) work at Plants 4, 6, 6E, and 7; this is the source of the information that follows in the rest of this section (8.1), except where another source is explicitly indicated. This work was performed by several construction and demolition companies apparently contracting directly with AEC. Mason (1977) states that one of them, or the principal one, was Arch Wrecking Company. H&S coverage was

provided by Mallinckrodt, again under contract with AEC, because AEC considered that while the D&D companies were qualified to deal with normal hazards of the work, they were not experienced in the sort of chemical and radiological hazards they would encounter at the Mallinckrodt site (MCW 1961b; Mason 1977). The Mallinckrodt H&S coverage was by experienced full-time personnel from the Destrehan (St. Louis) site and part-time personnel from the Weldon Spring site, which was also run by Mallinckrodt (MCW 1961b; Mason 1977). Oversight was provided by AEC (MCW 1961b; Mason 1977); Mason (1977) states that only AEC made the decisions regarding items that could be released for restricted or unrestricted use. The Mallinckrodt Uranium Division performed a final decontamination survey of the four remaining plants for AEC in 1960-1961 and gave a report to AEC (Mason 1997). Only part of the report of this closeout survey is available.

A physical checkup of all prospective workers on the project was provided. This included chest x-rays (PA and lateral, using full-size 14 x 17 films) and blood tests. Approximately 125 contract workers were examined. Work clothing was provided and postwork showers were required.

Film badges were issued to all persons working in or visiting the Destrehan site during all phases of equipment removal, decontamination, and demolition. These were of the standard badge type always used at Mallinckrodt: an A. M. Samples stainless steel film badge holder with open-window and cadmium filters, using DuPont Type 552 dosimeter film; the gamma standard was a platinum-encapsulated radium needle and the beta standard was an aged natural uranium block. Film badges were processed monthly, with 80 to 124 contractor badges processed each month. Film badges worn by Mallinckrodt and AEC personnel were those provided them through the Weldon Spring facility for their work at the Destrehan site in St. Louis.

Workers were also required to submit urine samples before the start of the project, at approximately six-week intervals during the project, and at the end of the project. The regular samples were taken on Friday after work and on Monday before work. Special samples were taken from those working in high dust exposure areas or in special operations such as sandblasting contaminated tanks. Urinalysis was done at Weldon Spring as a uranium-in-urine fluorometric analysis using a Jarrell-Ash fluorimeter, sodium fluoride as the fluxing agent, and a platinum dish as the sample holder. Each urine sample was analyzed in triplicate, with a 0.1 ml aliquot used each time.

AEC, the Mallinckrodt H&S people, and the D&D companies held pre-work planning discussions to determine how to do the work on the basis of the surveys. As work began in each area, further meetings and work area inspections were held to re-evaluate the approach for cleaning the particular area, based on how much contamination was revealed by equipment removal, how tenacious the contamination was, etc. Thus any of various decontamination and survey methods were used, depending on the characteristics of the area. Methods used for decontamination included mechanical "scratching" (to remove embedded particles on tar and gravel roofs); dry sandblasting; water blasting; shotblasting; steam cleaning with caustic-detergent additives; paint stripping; acid-detergent wash; immersion in solvents; burning; and sweeping, shoveling, and vacuum-cleaning.

Some particular operations performed and precautions taken were as follows.

1. In scrap removal and decontamination, areas were first inspected to verify that there was no gross radioactive material content and to plan the means of containment, such as removal to containers or sealing. Approximately 80% of the equipment was handled during the D&D work.

To steam-clean scrap, surfaces were wetted using high-pressure fog or spray, to which a caustic-detergent agent had usually been added; they were removed with hoists; and washing

with water hoses was done, with runoff retained in the localized area. Grossly contaminated items were steam-cleaned on a grating placed over a vat, with the overflow going into the sewer through a weir. Half-face respirators were used for steam cleaning.

Paint stripping was also done where necessary prior to steam cleaning, with the stripper being applied by brushing or dipping, often on the grating over the vat. Nickel-bearing steel pieces were cleaned in the open air by lowering the pieces into a vat containing acid-detergents and allowing them to soak for several hours; then a wire brush was used to loosen the scale and steam-cleaning was used to wash it away. Solvents (chlorinate hydrocarbons) were used on some items of low contamination level; this cleaning was done in the open air using one vat for cleaning and one for rinsing, with the solvent recirculating through a 5-micron Cuno filter and with the workers wearing face shields and gloves. After draining, the items were dried with forced air.

For sandblasting of relatively portable items, a large walk-in hood in Building 116 of Plant 6E was reactivated. Tarpaulins were used to extend the hood area and to enclose the hood face partially. The hood exhaust was through a high-efficiency bag filter. For any item that could not be taken to this hood, a portable canvas hood was set around the item, with ventilation provided. About 60 vessels were cleaned by dry sandblasting; the remaining several vessels (5%) that could not be cleaned to required levels had been used in the pitchblende digestion and radium extraction operations.

Insulation was burned off cable with added fuel, followed by a water rinse.

2. In building and structure decontamination, the most effective and intensive surface cleaning was done by dry or wet sandblasting. Dry sandblasting was the preferred method for removal in depth of masonry materials, paint, and encrusted surface contamination. A method called Vacu-blast, using steel shot, was also used; it provided vacuum pickup of the resulting particulates but recovery of the shot was time consuming. Full-face air-line supply masks and hoods were required, so care was taken to locate the air pump intakes upwind of the sandblasting operation or in a dust-free area. Generated dust was recovered or washed to sumps. Air changes were minimized by controlling outside openings; it was recognized that this increased interior concentrations in the short term, but it decreased exterior concentrations and, by decreasing air velocities in the area, accelerated the settling of the dust.

Water blasting was used on many roof structural parts and beams and was also used on other parts to remove loose particles before sandblasting. Scrubbing with a detergent and brush was also used. Sweeping, shoveling, and vacuum cleaning were generally done with respiratory protection, due to the dust.

3. In decontamination of concrete pads in the yard, dry sandblasting was done in a canvas-covered booth on wheels, which was moved by two workers to sit over the spot to be blasted. Ventilation in the booth was provided by a fan discharging through a large furnace cleaning bag; the materials collected in the bag were removed every time the bag was moved. The operator in the booth wore supplied-air respiratory protection and his helper outside wore a half-face mask. It was noted that the radiation levels of the particles collected by the fan and caught in the filter bag were higher than the levels of the coarser particles that remained on the surface being cleaned, so that capture of radioactivity appeared to be efficient.

Dust from process areas was considered to be contaminated even before sampling and thus masks at a minimum were required for all dust-producing and fume-producing operations, including torch



cutting. Respirators used for radiological hazards included high-efficiency mechanical dust respirators; bottled-air-supplied masks (for short-duration entries into high-concentration atmospheres and emergency use); and airline-supplied masks and hoods. Airline-supplied masks and hoods were required for sandblasting operations. The half-face dust masks were typically the MSA Dustfoe 66.

Regarding interior air sampling, samples were taken on a routine basis during the work shift, with filters being changed at the end of each daily sampling period; also, additional samples were drawn, either in the general work area or downwind, during the particular operations listed above and during other scrap cleaning. Air sampling was done with high-volume air samplers by Gelman Hurricane, Staplex Type TF1A, or the equivalent. The collection medium was Whatman #41 or HV-70 filter paper or Gelman AM-4 membrane filters. Sampling rates averaged 5 liters of air per square centimeter of filter media. Analysis for uranium was done by acid-leaching the filter, then counting an aliquot by photofluorometric analysis.

It was estimated that about 1% of the work during equipment removal, decontamination, and demolition was in areas where the airborne uranium concentration was on the order of 10-100 MPCa; for this category, full-flow air-supply masks were used. 10% of the effort was estimated to have been spent in areas where the concentration was 1 to 10 MPCa; for this category, personal half-face, dust-type masks were used. The rest of the work was done in areas of less than 1 MPCa. General area ("zone") concentrations during sandblasting were found to be higher around the local tarpaulin enclosures than around the fixed hood, but still below the (unspecified) AEC guide levels.

Regarding exterior air sampling, the generation of dust during demolition was at or near ground level; there were no discharge points to the upper atmosphere since the stacks were not being used. Dust sampling stations were established around the property line so as to have at least one always downwind of the work. The average of the uranium-in-air concentrations measured outside the buildings during demolition was  $4 \times 10^{-13}$  uCi/cc, said to be about one-tenth of the MPCa. It was observed that the gross alpha concentrations in the outside air were not much different from the uranium measurements, leading to the conclusion that radionuclides other than uranium were not present in significant quantities. The gross beta activities measured were judged to reflect the background seen at the time due to nuclear weapons testing.

The cleanup goals were surface alpha activity, 1000 dpm/100 cm<sup>2</sup> average and 5000 dpm per 100 cm<sup>2</sup> maximum spot; beta-gamma activity, 0.1 mrep/hr average and 1.0 mrep/hr maximum spot. This was achieved for the site and buildings, although the average beta-gamma level in some areas was somewhat above 0.1 mrep/hr. For alpha radiation surveys, the survey meters were calibrated in dpm per 100 cm<sup>2</sup> against normal uranium; they could be of the air ionization, proportional, or scintillation type and could detect 500-50,000 dpm per 100 cm<sup>2</sup>, depending on type. For beta-gamma activity surveys, the survey meters were calibrated in mrad/hr or mrep/hr against normal uranium; they could be of the Geiger tube, air ionization, or scintillation type, could measure 0.3 to >1.0 mrad/hr, depending on type, and had to have a minimum unshielded probe face area of 2 square inches.

For surveys of removable contamination, for both alpha and beta-gamma, two wipe passes with half of a 4" disk of Whatman paper over 100 cm<sup>2</sup> were performed. All material items exceeding 50 lbs were monitored separately. Material items weighing less than 50 lbs, except for pipes, were monitored as a lot using a 20% random sample, providing the lot was from the same plant sources; if destined for uses other than smelting, they were monitored individually. Items were monitored both inside and out, for both fixed and removable contamination. If an item could not be monitored internally, it was considered to be contaminated. If it could be, then for beta-gamma, an item was considered to be contaminated if any surface scan reading was greater than 1.0 mrep/hr or if any smear exceeded 0.3 mrep/hr; no wipe test was done if all scan readings were less than 0.3 mrep/hr.

For alpha, an item was considered to be contaminated if any surface scan reading was greater than 25000 dpm per 100 cm<sup>2</sup>, if the average of the surface scan readings was greater than 5000 dpm per 100 cm<sup>2</sup> or if any smear exceeded 2000 dpm per 100 cm<sup>2</sup>; no wipe test was done if no scan reading exceeded 2000 dpm per 100 cm<sup>2</sup>.

Because alpha probes were too large to be put inside pipes but Geiger tubes were not, the beta-gamma measurement was used as a surrogate for the alpha measurement; this was said to be because Th-234 and Pa-234, both beta emitters, reached equilibrium with uranium in approximately 250 days. However, it was recognized that nonequilibrium conditions or the presence of other beta and gamma-emitting isotopes could significantly affect the accuracy of the estimate of inferred uranium content. Pipes were not sampled as a lot. They were cleaned and unbent or unkinked, when possible, before monitoring. The presence of visible uranium deposits automatically caused a pipe to be classified as contaminated, as did the presence of bends, elbows, valves, fittings, or crushed sections. A Thyac meter on a ten-foot pole ("ten-foot probe") was used for long sections.

Final contamination measurements are given in detail in MCW (1961a) and in summary in MCW (1961b). During the final survey, the following instruments were used: for alpha, the Eberline PAC-3G gas proportional counter and the Victoreen Model 356 ionization chamber survey meter; for beta-gamma, the Victoreen Model 389C Thyac (G-M) survey meter, background about 0.1 mrep/hr. Calibrations were as given above. A spot sampling method was used for wall, ceilings, and beams, while a path scanning method was used for floors, yards, pads, and roofs. The alpha measurements for the roofs, however, were spot readings. During demolition and the final survey, it could be seen that some amount of residual contamination was buried at the site. This contamination was generally located adjacent to foundations, between joints and concrete floors, under storage pads, and between joints and structural steel members. This was judged to be fixed and not to present a problem.

Table 37 shows the experience reported on a groupwise basis in MCW (1961b), including film badge, urinalysis, and air sampling results.

## **8.2 POST-DECONTAMINATION CONDITIONS AT THE ST. LOUIS MAIN SITE**

After the decontamination of Plants 1 and 2, the plants were released to Mallinckrodt in 1951 (FUSRAP 2002; DOE 1981). No information about post-decontamination conditions there appears to have been produced until the ORNL survey of 1977 (ORNL 1981).

Following the decontamination or demolition of the buildings composing Plants 4, 6, 6E, and 7, post-decontamination use of the site with residual MED/AEC contamination began. This is considered to have started in 1962 and continued through 1995, the year when the Formerly Utilized Sites Remedial Action Project (FUSRAP) took over the site for final decontamination to modern standards. But in fact, release of the site to Mallinckrodt may have occurred plant by plant over 1961-1962, as suggested by Mallinckrodt (1994). A survey was done at the end of the decontamination period to demonstrate that the site was ready for release by AEC. This survey is documented in MCW (1961a).

No further survey of any of the plants to gauge the residual contamination appears to have been done in the post-D&D period until 1977, when a survey team from Oak Ridge National Laboratory did a detailed contamination, radiation, and radon survey of the site (ORNL 1981). A summary of the ORNL contamination findings is shown in Table 38. Also shown in Table 38 are radon concentrations reported in 1981 by ORNL (ORNL 1981) and in 1986 and 1990 by Applied Nuclear Safety (1986; 1991). These show that the post-decontamination radon levels were low compared to the levels of the operational years (Table 25).

### **8.3 GENERAL CONSIDERATIONS AND APPROACH FOR ST. LOUIS MAIN SITE DECONTAMINATION AND POST-DECONTAMINATION DOSE RECONSTRUCTION**

As noted in Section 8.0, exposures during the D&D work appear to have been completely monitored, with film badge, urinalysis, and supplementary air sampling data being available. For individual D&D workers for which personal monitoring data are unavailable, surrogate exposure data should be assembled by the dose reconstructor based on work group identity and the nature of the work performed. Data from Table 37 may be used to supplement or interpret surrogate information.

An applicable note in MCW (1961b) should be mentioned here with respect to surrogate data for the D&D period. In MCW (1961b) it was stated that Mallinckrodt experience at the Destrehan plant during the operating years was that for individuals whose daily integrated particulate air exposure was 50 mg of uranium per cubic meter of air, the after-work urine samples collected on Friday typically were in the range of 0.050-0.060 mg per liter and the before-work samples collected on Monday were in the range of 0.025-0.030 mg per liter. The D&D urine samples typically were found to be about half this level. (Note that the reference gave 50 "mg" per cubic meter of air as the daily integrated exposure, but it is likely that 50 micrograms per cubic meter was meant, since that was the standard tolerance level and would have been the logical quantity to cite.)

For the D&D years, if surrogate data are also lacking or it is doubtful that a particular individual was a D&D worker, then exposures calculated as discussed below may be used. For the post-D&D period, it is expected that there will be little or no individual monitoring data available and that the interpretation of such data might be confounded by Mallinckrodt's non-AEC work with radionuclides. Thus exposures calculated as discussed below should be used.

It should be noted regarding the post-D&D years that although some employees (remaining) at the St. Louis main site may be found to have urinalysis records extending into the late 1960's, this monitoring was apparently done for Mallinckrodt's post-AEC work with radioactive materials (e.g., its columbium-tantalum processing operations). These urinalysis records may be helpful in establishing the elimination curve of radioactivity from the body for anyone who (1) worked in the uranium processing operations up to 1958 and then worked in Mallinckrodt's non-AEC operations or (2) was involved in the D&D work and then continued to work at the site in Mallinckrodt's non-AEC work. However, these records may be misleading because they may indicate new uptakes from non-AEC sources. Also, people who worked in the decontaminated and released buildings from the release date on would likely not have been covered by film badge and urinalysis programs; in any case, persons monitored after 1961 were not monitored under the aegis of AEC. Thus bioassay or external dose information for them, if any, may not be available in dose reconstruction project files.

### **8.4 GENERAL CONSIDERATIONS AND APPROACH FOR SLAPS POST-OPERATIONS DOSE RECONSTRUCTION**

Because SLAPS did not receive wastes on a regular basis after the end of Mallinckrodt St. Louis main site operations in 1958, the "postoperations" period for SLAPS may be considered to have started at that point, i.e., in 1959. The end of this period is set at the end of 1962 because in that year control of the site was passed to a private entity by the granting of a license to the entity by AEC.

There was no decontamination of the site per se during the period 1959-1962. However, some material was removed and some new material was added, as follows. In April 1959, a railroad siding and loading facilities were installed, apparently in preparation for moving out the residues and other material (AEC 1959); the tailings from the magnesium fluoride slag processing were then sent to the Fernald site (AEC 1959). This appears to have been the only removal of residues from the site during

this period (the rest were removed after the transfer of control to the private entity.) Additionally, some of the scrap and rubble from the demolition and decontamination of the main St. Louis site facilities was buried at the west end of the site (AEC 1972; ORNL 1979) in about 1959-1960; this was the same area where contaminated metal and debris had been buried previously (presumably in 1948-1950, following the decontamination of Plants 1 and 2), and where in 1952 a large area was filled in deeply with earth (AEC 1964).

It is not clear who did the work, but it seems likely – and is assumed here -- that the burial, at least, was done by the same contractor(s) as were doing the demolition and removal work at the St. Louis main site. Thus it appears likely – and is assumed here -- that this work was at least overseen by AEC and Mallinckrodt health and safety people. Because they were done in the same time period, it is similarly assumed that the railroad construction and the tailings removal were performed with AEC and Mallinckrodt health and safety oversight and support. These assumptions are strengthened by the fact that at some point in about 1959, a building consisting of a changeroom, a shower, and office space was moved to the site (AEC 1959; AEC 1964).

No information is available as to the conditions under which the railroad facility installation and the tailings removal were done, but presumably these were typical construction and earthmoving processes such as had taken place previously at SLAPS. No information is available as to the conditions under which the 1959-1960 burial was done, but presumably it was a typical process of digging a hole(s) in the ground, depositing the debris, and pushing the removed soil back into the hole. As noted above, there was a building installed that included a changeroom, shower, and office. Thus it appears that normal contamination control procedures of the time were followed.

The workers might not have been badged, however, because the potential for exposure may have been viewed as too low; for example, during 1949, the crane and bulldozer operators at SLAPS (who were apparently working only with the residue piles and not with any aspect of the K-65 storage or removal operation) were not being badged because they averaged less than 8 hours per week on the raffinate heap work and the radiation level from the raffinate/residue heaps was believed to be low (MCW 1949g). If the workers were badged, however, this was undoubtedly done through the Weldon Spring site, as was done for the decontamination and decommissioning workers at the main St. Louis site. Thus it is not clear if the workers were badged but in any case the Weldon Spring film badge records are presently unavailable.

Before and after the burial and tailings removal work, it can be assumed that only caretaker functions were performed, that is, that periodically a guard would visit the site to check the locks and verify that entry into or disturbance of the site had been made. In addition, there were likely some inspection visits by AEC in the company of prospective purchasers of the residues. The AEC people may have been wearing their own badges, but there is no indication that the visitors did.

This technical basis document covers Mallinckrodt employees only, but an effort has been made to provide information about other workers on the Mallinckrodt St. Louis main site and SLAPS, for information and for efficiency of later evaluation of the other workers' exposure, if required. Thus the categories of exposed workers are assumed to include all those below, but they should not be assumed to be Mallinckrodt employees. Visitors are not included.

Note that in 1976 and 1978, Oak Ridge National Laboratory surveyed SLAPS for AEC years after the piles had been removed (ORNL 1979). They found that although much of the soil inside the SLAPS fence had terrestrial levels of U-238 and Ra-226, there were several places where the levels were elevated. The highest U-238 level was 260 pCi/g (normal range 0.3 – 1.7) and the range of elevated Ra-226 values was 1.4 – 78 pCi/g (normal range 0.3 – 1.3). Ac-227 was also found in the range of

0.5 – 77 pCi/g; the source was most likely the Sperry cake because of its concentration of Pa-231, a precursor of Ac-227, but the highest reading was found where the AM-7 was stored and some elevated readings were also said to be associated with a location near where the barium sulfate cake was stored.

## **8.5 CALCULATION OF DECONTAMINATION AND POST-DECONTAMINATION INTERNAL AND EXTERNAL EXPOSURES FOR THE ST. LOUIS MAIN SITE WHEN INDIVIDUAL AND SURROGATE DATA ARE LACKING**

To estimate claimant-favorable doses to workers from MED/AEC contamination alone when individual data and surrogate data from records are lacking, use was made of the results of the initial and release Mallinckrodt contamination and dose rate surveys, i.e., those performed before and after the 1959-1961 decontamination (reported in MCW 1958 and MCW 1959 for before decontamination; in MCW 1961a for after). The data taken from these references and used in the calculation of exposure is shown in summary form in Table 39; it must be stressed that this represents only a small and select subset of data from larger sets of hundreds of data points.

The RESRAD-BUILD computer code (ANL 2003) was used to calculate annual exposures from inhalation of airborne particulates and radon (and its daughters). Separate hand calculations were performed to estimate annual ingestion and external exposures.

Source terms for both types of calculations were derived from the measured data shown in Table 39. Conservative maximum averages of surface and bulk (volume) contamination were used to produce the Inhalation and radon source terms for RESRAD-BUILD and the inhalation RESRAD-BUILD results were used to produce the source term for the ingestion calculations, while the maximum (or average maximum) and typical measured dose rates from gamma and beta radiation were used in the hand calculations to estimate annual external exposures.

For RESRAD-BUILD parameters other than the source term, conservative but Mallinckrodt-suitable values were used, when they could be determined; when no specific or suitable values could be determined, conservative default values given in the RESRAD-BUILD manual (ANL 2003) or other guidance documents were used. These values should be claimant-favorable.

### **8.5.1 Assumptions Made in RESRAD-BUILD and Related Internal Exposure Calculations**

The principal assumptions made for the RESRAD-BUILD calculations are given below.

1. The inhalation and radon source terms were derived on the basis of the highest average surface and bulk contamination levels, respectively, in each plant, regardless of building or room location. Without regard to the actual correspondence of gamma dose rate, surface contamination, and bulk contamination levels in particular rooms, the room model (work area) was assumed to contain the highest measured average surface contamination concentration, the highest bulk contamination concentration, and the highest spot or average gamma and beta dose rates found anywhere in the respective plant. This is a claimant-favorable assumption since in fact there was no such location where all these indicators were simultaneously at the maximum for the plant. These sources are given in Table 39.
2. The room model was assumed to have the measured surface concentration over all wall and floor surfaces and to have the measured bulk concentration extend 6 inches into the walls and floors, which were taken to be concrete. This is reasonable because in MCW (1958) contamination in concrete was measured typically from 4 to 6 inches into the concrete (but

much less in steel) and in MCW (1958; 1959; 1961a) the overheads were generally found to be far less contaminated than the walls and floor and so would contribute negligibly to the total.

3. Source contamination was measured as gross alpha and as either total beta and total gamma separately (MCW 1958; MCW 1959) or total beta-gamma together (MCW 1961a). Because of the difficulty of determining the degree of equilibrium of the uranium with its daughters, it was assumed for the inhalation case that there was 100% equilibrium; this appears to be reasonable because of the length of time between the cessation of operations and the beginning of intrusive decontamination operations. The source terms were then determined by assuming that the alphas were being emitted by U-238, U-234, Th-230, and Ra-226 (together yielding 97.8% of the total alpha emissions -- see Section 6.1, Item 5) and by U-235, Pa-231, and Ac-227 (together yielding 2.2% of the total alpha emissions).
4. The worker was assumed to spend his entire work time (8 hours per work day) in the room, i.e., in the most contaminated area of the given plant.
5. The worker was assumed to spend 2000 hours per year in the one location. The takedown of a building may have been on the order of weeks and decontamination on the order of months; however, continuous decontamination and demolition work over the course of a 50-week year is assumed for such workers.
6. The room size was taken to be about 10' x 20' x 10' high (3 m x 6 m x 3 m). There were many process areas that were larger, but they were often partitioned and they were undoubtedly decontaminated in sections. Thus assuming a smaller room would be conservative in terms of concentrating or confining the contamination in the ventilated space.
7. One air change per hour was assumed. While only limited information is available regarding the ventilation systems at Mallinckrodt, it was clear that the process areas had forced ventilation. These were apparently not always used during significantly dusty work, as suggested by MCW (1961b), but in those cases respirators were worn by the workers and enclosures were typically used as well. The enclosures had forced ventilation (MCW 1961b). Thus it is reasonable to assume that either the normal forced ventilation was used in the general area, in which case one air change per hour is a conservative rate, or vented enclosures were used, in which case the air change rate would have been far higher, the worker would have been wearing a respirator, and the calculated exposure would represent a marked overestimate of the likely actual exposure.
8. For the decontamination years case, the resuspension factor for the transferable contamination was assumed to be  $1 \times 10^{-4}$ ; for the post-decontamination years case, it was conservatively assumed to be  $1 \times 10^{-6}$ . The latter value is based on NRC (2002) and the former is taken to be a conservative and thus claimant-favorable value for non-respirator work, as is consistent with the discussion and tables in the RESRAD-BUILD manual (ANL 2003).
9. The deposition (settling) velocity was taken to be 0.00075 m/sec, a reasonable value for particles of 5  $\mu\text{m}$ , as shown in Figure J.3 of ANL (2003).
10. The removable fraction for the decontamination years case was assumed to be 30%, based on the fact that some early decontamination was done at the end of operations (e.g., rinsing out the process vessels and vacuuming the floors). The removable fraction for the inhalation dose calculation in the post-decontamination years case was assumed to be 10%. This

should be reasonably conservative since the post-decontamination period followed an extensive decontamination. Default erosion, radon emanation, and associated values were used because they are conservative and thus claimant favorable.

11. Three types of exposure levels were used to represent the different exposure potentials of different types of workers. "High" exposure potential represents those working in the most contaminated areas, i.e., the former process areas; these would be those performing decontamination or later working substantial periods of time in the former process areas. "Moderate" exposure potential represents those accessing the less contaminated areas or infrequently accessing the former process areas; these would be those supervising the decontamination on an intermittent basis or those having only occasional need to enter the former process areas. It would also include those working in the former laboratories. "Low" exposure potential represents those who accessing the slightly contaminated or uncontaminated areas, such as the former office areas.
12. Since the inhalation and radon calculations did not depend on the position of the receptor in the room model and since the isotope proportions were taken to be the same at the beginning of the calculation, one wall of the maximally contaminated plant was modeled with the D&D sources for the surface case and similarly for the volume case; the same was done with the post-D&D sources for the surface and volume cases. The results were then ratioed to produce results for the entire wall and floor area for the various plant and exposure potential cases.
13. Because 1959-1961 data for Plants 1 and 2 was not available and because the post-D&D surface and volume data of Plants 1 and 2 were bounded by the Plants 4, 6, 6E, and/or 7 data, as shown by comparisons of the data for all the plants in ORNL (1981), it was assumed that they could be assigned the maximum post-D&D inhalation exposures for the "High" category from calculations for the other plants. Thus it was assumed that it was not necessary to create separate source terms and models for inhalation exposures for Plants 1 and 2.
14. Because 1959-1961 data for Plants 1 and 2 was not available, it was assumed to be appropriate to use the post-D&D calculated radon exposure data for the other plants. While the typical radon measurement data of Plants 1 and 2 given in ORNL (1981) were in the same range as the radon measurement data for Plants 4, 6, 6E, and/or 7 given in ORNL (1981), there was one high area reading in one building in Plant 1 and one in Plant 2 that far exceeded the other readings. Although the high reading may not be representative of the true exposure, it was assumed that the maximum calculated exposure for the year 1975 (the evaluated year closest to 1977, the year the ORNL survey was done) could be ratioed by the factor or difference seen in the ORNL (1981) data for the respective plants and the calculation. Also, due to the lack of variation in the calculated doses over time, it was assumed that the calculated 1962 post-D&D results, after ratioing, could be extrapolated back to 1959 for Plants 1 and 2 (since they had already been cleaned up and were not in D&D). Thus it was assumed that it was not necessary to create separate source terms and models for radon exposures for Plants 1 and 2.

#### **8.5.2      Results of RESRAD-BUILD Calculations and Conversion to Dosimetrically Useful Quantities**

For use in dose reconstruction, the inhalation and radon doses that were the results of computations in RESRAD-BUILD had to be converted back to activity units, in this case to pCi and WLM of intake, respectively. The RESRAD family of codes uses the dose conversion factors for inhalation given in

Eckerman et al. (1988), as also listed in the RESRAD-BUILD manual (ANL 2003). The radon conversion is also from the RESRAD-BUILD manual (ANL 2003). Since the conversion factors are applied at the end of the RESRAD-BUILD calculation, it is appropriate to reverse the conversion using the factors. The converted results are given in Table 40.

Because of RESRAD-BUILD's limitation on how many yearly printouts can be made, inhalation and radon exposures were calculated for each year for the D&D years case but only for the first few years and every five years thereafter for the post-D&D years case. This is clearly appropriate since as the output data show, the values change little from year to year. So although multiple years may be indicated in the column headings in Table 40, the figures below them are for each year and are not the sum for the indicated years.

### **8.5.3 Assumptions for and Results of Ingestion Calculations**

It was assumed that it was appropriate to use the annual inhalation intakes derived from the RESRAD-BUILD inhalation dose results in order to produce source terms for the calculation of bounding ingestion doses according to the methodology of NIOSH (2004).

1. The appropriate inhalation exposures in pCi that were calculated as in Section 8.3.2 from the RESRAD-BUILD results were converted from pCi per year to an effective air concentration in pCi/m<sup>3</sup>, assuming a breathing rate of 1.2 m<sup>3</sup>/hr and a 2000-hour work year.
2. The air concentration in pCi/m<sup>3</sup> was multiplied by 0.2 to obtain the pCi ingested per day.
3. The pCi ingested per day was multiplied by 250 work days per year to obtain the pCi ingested per year.

The results are shown in Table 40.

### **8.5.4 Assumptions for and Results of External Exposure Calculations**

For the external exposure calculations, separate calculations were performed for gamma and beta radiation. For Plants 4, 6, 6E, and 7, the high maximum average and typical average measured dose rate values in accessible areas were used for the "High" exposure potential case; moderate maximum average and typical average values for the "Moderate" case; and low maximum average and typical average values for the "Low" exposure case. These are defined as in Item 11 of Section 8.4.1 above.

1. Because exposure (dose) rates were used, the source terms did not have to be translated into activity units. However, while the pre-decontamination survey measured values were given separately as gamma and beta dose rates (MCW 1958; MCW 1959), the final release survey gave values as combined beta-gamma dose rates (MCW 1961a). These were ratioed using the pre-decontamination data in order to produce separate gamma and beta dose rates. The resulting assumed source terms are shown in Table 39.
2. In the surveys, the measurement point for betas or mixed beta-gamma radiation was usually a contact or near-contact dose rate for both walls and floors, while for gammas, it was most often a contact or near-distance dose rate for walls and a three-foot measurement for floors. However, the gamma-only measurements with a microrem-reading detector was usually taken in the middle of each survey grid block. It was thus assumed that the measured beta dose rate and the measured mixed beta-gamma dose rate represented all-beta radiation emanating from a wall surface to a receptor point at 1 cm from a wall surface; similarly, the measured



gamma dose rate was assumed to represent gamma radiation emanating from a wall surface to a receptor point at 1 meter from a wall surface.

3. A series of calculations were done to see what size of source (e.g., point, small-radius, large-radius) was most appropriate for the measured data for each type of radiation. It was found for both beta and gamma that an large-radius source was most appropriate. For the gamma case, it was assumed that the source was of infinite radius (because it was not a very large increase from, e.g., a 4-m radius while the room could be assumed to be on the order of the room used for the RESRAD-BUILD calculation, or about 3.3 x 6.7 meters for the wall lengths). For the beta case, it was assumed that the source was of essentially infinite radius, i.e., 8.5 m, the range of the most energetic beta emitted from the uranium-daughter source mix.
4. The dose rates as per Item 2 above were used to determine the areal source strength for beta and gamma separately and then the source strengths were used to calculate the dose rates at 1 foot and 1 meter for beta and at 1 cm and 1 foot for gamma. As per NIOSH direction, the respective dose rates at 1cm were then considered to be the maximum dose rates, the dose rates at 1 foot the most likely dose rates, and the dose rates at 1 meter the minimum dose rates.
5. The receptor was assumed to stay in the maximum average location for his exposure potential for two hours per work day and in the typical average location for his exposure potential for six hours per work day, for a total time of 2000 hours per year. This ignored break time, which was usually spent in areas of very low or no contamination, such as a lunchroom.
6. For Plants 1 and 2, there was not sufficient data to create the three dose potential categories and there was data for only the one time (i.e., the 1977 ORNL survey data point (ORNL 1981)). Thus there is only a single category of dose potential and the same measured numbers are used for all the post-D&D years. Because the figures were generally mixed beta-gamma and not separate gamma and beta exposure rates, except for one specific gamma measurement, the maximum value was assumed to represent gamma and beta in turn, except for that one gamma measurement. It should be recognized that the exposures calculated in this way for Plants 1 and 2 are likely to be extremely conservative.

Once the annual gamma doses had been calculated for each case from ambient measurement data, the doses had to be converted to photon doses to individual organs. Conversion factors from Appendix B of NIOSH (2002a) were used to do this. It was assumed that for gammas, half of the dose was from photons of energy between 30 and 250 keV and half from photons of energy greater than 250 keV. A geometry of 50% AP and 50% ROT was assumed, as seems reasonable from Section 5.4.3.1 above. The results are shown in Table 41.

The beta dose rate data given in Table 39 above was used to calculate electron doses to skin, breast, and testes. To account for attenuation by clothing (see Section 7.6.3), a factor of .8 was applied in the calculation of the breast and testes doses. The results are shown in Table 42.

## **8.6 CALCULATION OF DECONTAMINATION AND POST-DECONTAMINATION INTERNAL AND EXTERNAL EXPOSURES FOR SLAPS WHEN INDIVIDUAL AND SURROGATE DATA ARE LACKING**

There does not appear to be any work time or work practice information available for SLAPS for the period 1959-1962. There also does not appear to be available any external dose rate, radon, or dust concentration data available for SLAPS for this period. Thus work conditions must be inferred that are

judged to be conservative based on indications in the reference; source terms or dose rates must be inferred from the data from other periods, chosen because the known sources of those other periods are comparable to or higher than those for 1959-1962.

The exposure modes during the removal work at SLAPS are considered to be external gamma and beta radiation, radioactive dust; and radon. The radioactive sources would have been any residues dumped on the ground in or near the work area. It is not clear which residues were dumped where on the site, thus it must be assumed that the digging for burial and removal was near the worst source. (It is assumed that burial would not have been done under the piles, as that would have required moving more material and would also have involved more health hazards.)

The worst source appears to be the barium sulfate (AJ-4) wastes. (Note that the K-65 had been removed years earlier.) First, although as Table 4 indicates there was more total uranium in the AM-7 and AM-10 raffinates -- 113 and 48 tons respectively versus the 29 tons total in the leached and unleached barium sulfate residues -- the barium sulfate contained the residual radium that had not been captured in the K-65 precipitation. As Table 4 shows, this was about 1 mg per ton. The radium would contribute to both the external and radon exposures. Second, even after the removal of the wastes in the late 1960's, a beta-gamma survey showed that the area that had contained the AJ-4 residues read higher than any other area (AEC 1972), also suggesting a high radium content compared to the other two residues. Third, as Table 33 shows, the gamma dose rates were highest from the "aged" barium cake material, which would correspond to the piles found after 1958 at SLAPS. Thus the assumption is made that the calculated doses can be based on barium sulfate as the maximal residue.

### 8.6.1 Assumptions for Work Time and Worker Types

It is not clear how long the work burial and removal work took, but it does not appear to have been a continuous process since the generation of material during the St. Louis main site D&D would not have been continuous. Thus it is assumed that the work took place over a period of six months, evenly spaced out over 1959-1960. The excavation/removal workers were assumed to be present for 8 hours per day, while the Health and Safety workers and AEC representatives were assumed to be present for 4 hours per day. The guard is assumed to have been present for two hours a day (to open up the site and lock up, if necessary) during the work and for one hour per week during the remainder of the time from 1959-1962, i.e., during three and a half years. AEC representatives are assumed to have spent two hours per month (i.e., 12 two-hour visits) at the site during 1961-1962. The fractions of the work year (2000 hours) spent at the site are thus as shown below.

Fraction of the work year spent at SLAPS.

	1959	1960	1961-1962
Bulldozer/truck driver, crane operator	0.25	0.25	---
Other material workers (e.g., riggers)	0.25	0.25	---
Health & Safety worker	0.125	0.125	---
AEC	0.125	0.125	0.012
Guards	0.081	0.081	0.025

### 8.6.2 Assumptions for Radioactive Source Terms

AEC (AEC 1949m) states that the barium sulfate residue contained 0.1% uranium (by weight) and  $4 \times 10^{-9}$  grams of Ra-226 per gram of residue. Assuming that the other daughter isotopes of U-238 were in equilibrium with their parents and assuming a natural uranium mix, this gives:

Concentration of radionuclides in barium sulfate residue.

Isotope	Quantity, pCi/g
U-238	3.35E+02
Ra-226	3.96E+03
Th-230	3.35E+02
Ac-227	2.47E-02

For each pCi of inhalation or ingestion intake, assume:

Isotope	Quantity, pCi
U-238	7.24E-02
Ra-226	8.55E-01
Th-230	7.24E-02
Ac-227	5.34E-06

### 8.6.3 Assumptions for Inhalation Exposure Calculations

It is conservative to assume that the residue – which was deposited loose on the ground in piles – can be treated in calculations as though it were soil. ORNL (ORNL 1979) performed a calculation of the concentration in air due to wind alone and due to mechanical resuspension (i.e., excavation or other soil disturbances), based on measurements of the radioactive content of SLAPS soil and on measured wind speeds and directions at SLAPS. Although these results are not directly applicable since the residues had been removed by the time the measurements and the calculation were done, it appears that the assumptions made in the calculation were such that it can be scaled to the actual situation, that is, by treating the barium sulfate residue as though it resuspended in the same way as the soil when disturbed by wind or mechanical action.

Inferred values of airborne dust concentrations for barium sulfate residue piles.

Radionuclide	Reference point (ORNL ORNL 1979)			Ratios		Barium sulfate		
	Wind resuspension, pCi/m <sup>3</sup>	Mechanical resuspension, pCi/m <sup>3</sup>	Mean soil conc, pCi/g	Ratio, wind resuspension/ mean soil conc	Ratio, mech resupens/ mean soil conc	Mean residue conc, pCi/g	Wind resuspension, pCi/m <sup>3</sup>	Mech resuspension, pCi/m <sup>3</sup>
Ra-226	1.00E-08	0.03	12.6	7.94E-10	2.38E-03	3.96E+03	3.14E-06	9.42E+00
Th-230	1.00E-08	0.03	8.3	1.21E-09	3.63E-03	3.35E+02	4.05E-07	1.22E+00
Ac-227	6.00E-09	0.01	8.8	6.80E-10	1.13E-03	2.47E-02	1.68E-11	2.80E-05
U-238	4.00E-08	0.1	8.3	4.83E-09	1.21E-02	3.35E+02	1.62E-06	4.05E+00

The wind suspension values in the next-to-last column are to be applied when no work is going on (e.g., when the guard or AEC is making an inspection visit) and the mechanical resuspension values in the last column are to be applied when work is going on.

As for the St. Louis main site case, the assumption is made that the worker breathing rate is 1.2 m<sup>3</sup>/hr and that the standard work year is 2000 hours.

The results are shown in Table 43.

### 8.6.4 Assumptions for Ingestion Exposure Calculations

Although the method of NIOSH (2004) appears to be inappropriate for the SLAPS work situation because of the outdoor location, it is clear that the method will give a very conservative result and it is an approved method. Thus it will be applied as follows in this technical basis document until further guidance is provided.

1. The air concentration in pCi/m<sup>3</sup> from Section 8.6.3 was multiplied by 0.2 to obtain the pCi ingested per day.
2. The pCi ingested per day was multiplied by 250 work days per year and by the fraction of the year from Section 8.6.1 to obtain the pCi ingested per year.

The results are shown in Table 43.

### **8.6.5 Assumptions for and Results of Radon Exposure Calculations**

No radon measurements have been found for SLAPS after 1949, i.e., after the high-radium K-65 residue was removed. The content of the barium sulfate residue,  $4 \times 10^{-9}$  g per gram of residue, is equivalent to about 4000 pCi/g of residue, as given in Section 8.6.2. This can be compared to the 1.0-1.2 pCi/g of soil that ORNL (ORNL 1979; ORNL 1981) found to be the typical Missouri soil content. Clearly the concentration of Ra-226 was elevated over background levels and thus radon emanation would be greater than in typical Missouri soils.

ORNL (1979) provides some measured data by which the radon emanation rate can be related to surface soil content of radium. The maximum onsite radon concentration measured was  $1.3 \times 10^{-1}$  pCi/l of air. The average surface soil concentration of Ra-226 for the three highest radon-emanating points was found from data in Tables 3 and 13 of ORNL (1979) to be 1.3 pCi/g. This gives a ratio of 0.1 pCi/l of radon per pCi/g of Ra-226. Thus for the assumed 3960 pCi/g in the residue (see Section 8.6.2 above), there would be a radon concentration in the air of 396 pCi/l.

Although in the outdoors environment the equilibrium factor of the radon daughters is likely to be very low, the conservative assumption will be made that the ratio is .4. The occupancy factors can be taken to be as given above. Thus we can calculate the SLAPS intakes as shown below.

$$\text{Annual intake, WLM} = \text{occupancy factor} \times \text{equilibrium factor} \times .12 \text{ WLM/yr per pCi/l} \\ \times \text{radon concentration, pCi/l}$$

The results are shown in Table 43.

### **8.6.6 Assumptions for and Results of External Exposure Calculations**

The gamma dose rate of .5 mR/hr reported in MCW (MCW 1949g) for a bulldozer cab was used to calculate the exposures from the piles of barium sulfate residue. Since the piles themselves are assumed not to be disturbed, the beta dose rates are assumed to be negligible at the worker positions. Thus only the gamma radiation is assumed to contribute. Also, the bulldozer cab appeared to be appropriate because the work appeared to consist entirely of processes such as excavation, dumping from trucks, and inspection from trucks.

Once the annual gamma doses had been calculated for each worker case from the gamma dose rate, considered as ambient measurement data, the doses had to be converted to photon doses to individual organs. Conversion factors from Appendix B of NIOSH (2002a) were used to do this. It was assumed that the dose was from photons of energy between 30 and 250 keV. A geometry of 100% ROT was assumed because of the large-pile geometry.

The results are shown in Table 44.

## **8.7 USE OF DECONTAMINATION AND POST-DECONTAMINATION EXPOSURE DATA FOR ST. LOUIS MAIN SITE DOSE RECONSTRUCTION**

As stated above, where urinalysis and film badge data are available for an individual, they should be used to determine the internal and external exposure to the individual; the methodology of Sections 6.0 and 7.0 respectively should be used as guidance for this, as appropriate. Also, for the D&D years it should be assumed that a worker had an annual x-ray (see Sections 8.1 and 7.4 above for the

rationale and for guidance, respectively). It should be remembered that as noted in Section 8.1 above, some AEC and Mallinckrodt personnel film badge records for this period may be found in the Weldon Springs site set of records (and not in the Destrehan-St. Louis site set of records) because their badges were issued from Weldon Springs.

Where there is missing dose data in records, the dose reconstructor should identify surrogate worker data from records available in the dose reconstruction project, based on similarity of job title and location. Surrogate data are not provided in this TBD for this time period because of the low number of likely claimants requiring it and because records have not been located. Caution must be taken in the case of workers whose work histories show them apparently still doing work with radioactive materials after the decontamination period, since (1) such work during the post-decontamination years was not AEC-contracted work, (2) it is uncertain what work may have been done and what materials may have been used, and (3) there may be no available records covering these years.

Where appropriate surrogate data cannot be found for the decontamination years case, the data of Table 37 may be used to provide surrogate data on a group basis. A conservative and claimant-favorable value should be assumed. In particular, the default assumption should be "High" exposure, where that choice is available. Where gaps still exist, reference can then be made to the data given in Tables 40-42.

For the post-decontamination years case, where individual surrogate data cannot be found for the post-decontamination years case, as is likely, the data of Tables 40-42 should be used. The default assumption should be "High" exposure, where that choice is available.

In both cases, in dose reconstruction using Tables 40-42, the applicable years of employment for each indicated period should be determined and then the number of years should be multiplied by the annual value.

With regard to determining the exposure potential category in Tables 40-42, it should most often be possible to determine the degree of exposure of a worker by his job title, e.g., if a worker was a secretary, then the worker should be assigned to the "low" exposure potential category. In cases where it is not possible to determine the category, then the "moderate" or "high" category should be used.

## **8.8 USE OF DECONTAMINATION AND POST-DECONTAMINATION EXPOSURE DATA FOR SLAPS DOSE RECONSTRUCTION**

As stated earlier, where urinalysis and film badge data are available for an individual, they should be used to determine the internal and external exposure to the individual; the methodology of Sections 6.0 and 7.0 respectively should be used as guidance for this, as appropriate. If a worker was badged or given urinalysis during the years 1959-1961, it should be assumed that a worker had an annual x-ray (since if the SLAPS workers were involved in the decontamination and demolition operations, whether as Mallinckrodt workers or as contractor workers) this would have been the case. It should be remembered that as noted in Section 8.1 above, some AEC and Mallinckrodt personnel film badge records for this period may be found in the Weldon Springs site set of records (and not in the Destrehan-St. Louis site set of records) because their badges were issued from Weldon Springs; this may be the case as well for the D&D contractor workers.

Where there is missing dose data in records, the dose reconstructor should identify surrogate worker data from records available in the dose reconstruction project, based on similarity of job title and

location. Surrogate data are not provided in this TBD for this time period because of the low number of likely claimants requiring it and because records have not yet been located.

Where appropriate surrogate data cannot be found for the years 1959-1962, as is likely, the data of Tables 43-44 should be used to determine conservative annual intakes and external doses. In determining both intakes and external doses, the applicable years of employment for each indicated period should be determined and then the number of years should be multiplied by the annual value. For the intakes, the isotopic breakdown should be assumed to be as given in Section 8.6.2. The default assumption should be "High" exposure, where that choice is available.

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Table 1. Plants and buildings used at the St. Louis Downtown Site for MED/AEC 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	For MED/AEC work, used only from 1944-1946
1	A	General plant maintenance (for all of Mallinckrodt)	
1	P	Engineering Department (for all of Mallinckrodt)	
1	X	Locker room	
1	Z	Company headquarters; administrative offices	Administrative headquarters for MED work until Plant 6 began operating in 1946
2	38B	Personnel change house	FUSRAP (2003a) says 38B, but ORAU (Mason 1977) says 38A
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 <sub>4</sub> experiments, mechanical repairs, tank storage, other	Ore concentrates, UO <sub>3</sub> product; tanks of stored process liquids; UF <sub>4</sub> experiments performed in the "sulfur burner room"
2	51	U <sub>3</sub> O <sub>8</sub> feed preparation (nitric acid dissolution), recovery, other	
2	51A	Denitration of UNH to UO <sub>3</sub> , reduction of UO <sub>3</sub> to UO <sub>2</sub>	
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	This was a special restricted area because of the 100-mg RaBe source used in the neutron absorption testing
4	400	Production of UF <sub>4</sub> , U metal; slag handling, production control laboratory, changehouse; metals pilot plant	UF <sub>4</sub> product, U recast
4	400, 401	1 <sup>st</sup> 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	2 <sup>nd</sup> 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	Maintenance, metal storage, and UF <sub>4</sub> 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	1 <sup>st</sup> floor: lathe & forging areas; storage of slag, dolomite, KOH, NH <sub>3</sub> , 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 (air conditioning), spectrographic laboratory	
6	104	Main refinery building: ore to UO <sub>3</sub> to UO <sub>2</sub>	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	Pitchblende
6	105	Main refinery: the " Ether House"	Extraction
6	106	Nitric acid recovery	
6	106A	Nitric acid recovery	
6	107	Nitric acid recovery, tank farm pump house	

Table 1 (Continued)

Plant	Building	Process, function, or area	Notes
6	108	Shotgun sample preparation lab	Superseded by lab in Building 102? ["Old shotgun lab"]
6	109	Acid unloading station	Includes 109, 109A, 109B
6	110	Main warehouse for bagged goods, storage of pitchblende ore and ore concentrates, UO <sub>3</sub> product	Pitchblende ore, ore concentrate, UO <sub>3</sub> and UO <sub>2</sub> 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	Automotive repair	
6	111	Sample preparation and LeDoux Lab, north end; 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 (MCW and AEC offices), Health Laboratory, dispensary; maintenance shop, instrument shop, maintenance stores	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	123	Ammonia & 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 <sub>4</sub> -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 <sub>4</sub> 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 <sub>4</sub> 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	
6E	116C	Slag (recycle) building	(Magnesium fluoride) Slag handling, grinding, and packaging. 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.



Table 1 (Continued)

Plant	Building	Process, function, or area	Notes
7	700	Warehouse, safety office, electrical and carpenter shops, temporary 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 <sub>2</sub> , UF <sub>4</sub> ; packaging station area, maintenance shop, reactor area	Reactor area had UF <sub>4</sub> product hoppers, hydraulic pumps, and access platforms. There were a UO <sub>3</sub> feed station, a Hapman UO <sub>3</sub> conveyor, blenders, a UO <sub>2</sub> (?) 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 <sub>2</sub> , UO <sub>3</sub> , UF <sub>4</sub> )	Had shipping platform. See also 704.
7	707	Ammonia cracking building (manufacturing H <sub>2</sub> and N <sub>2</sub> from NH <sub>3</sub> )	See also 704.
7	708	Magnesium storage and packaging building	
7	709	HF refrigeration equipment and pump house	Contained refrigeration equipment for the GS(?) pit
7	710	NH <sub>3</sub> 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 <sub>4</sub> , 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.

The information in this table is drawn from MED 1944p; FUSRAP 2003a ; MCW 1958; MCW 1959; Mason (1977); and ORNL 1981. 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.

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

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.

Table 2. Summary chronology of operations at the Mallinckrodt St. Louis Downtown Site (SLDS) and at the St. Louis Airport Storage Site (SLAPS).

April 1942	Plant 2 was used to develop a batch process using ether to extract uranium as UO <sub>3</sub> from milled ore and then to convert the UO <sub>3</sub> to UO <sub>2</sub> . Plant 1 was used for developmental work.
October 1942	Plant 4 was converted for use in the UO <sub>2</sub> →UF <sub>4</sub> →U metal process. The ore→UO <sub>2</sub> operations continued in Plant 2, while miscellaneous activities related to R&D work continued in Plant 1.
April 1943	Production of UF <sub>4</sub> from UO <sub>2</sub> began in Plant 4.
1944	Experimental extraction of uranium using pitchblende ores began in Plant 1.
1945	At some point in 1945 or early 1946, 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→UO <sub>2</sub> production operations shifted there. Uranium operations at Plant 2 ceased in early 1946, the work (including UO <sub>3</sub> milling) apparently shifting to Plant 6. Only Plants 4 and 6 were in operation.
1946-1947	AEC acquires SLAPS in 1946 and Mallinckrodt residues begin to be sent there for storage in about 1947.
1947-1951	Decontamination of Plants 1 and 2, with unrestricted release to Mallinckrodt in 1951.
1948-1949	K-65 residue is brought back from SLAPS for reprocessing. After about 1949, no more K-65 residue is sent to SLAPS, only low-radium residues.
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 <sub>4</sub> →U metal work shifted there from Plant 4, with the UO <sub>2</sub> →UF <sub>4</sub> 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 <sub>4</sub> production work continued until perhaps 1952 at Plant 4, while the UO <sub>3</sub> -to-UO <sub>2</sub> production at Plant 6 seems to have ended completely. Instead, UO <sub>3</sub> was sent to Plant 7 to be converted in a continuous process to UF <sub>4</sub> . Some recovery and storage operations also shifted to Plant 7.
1952-1953	At some point, the continuous UO <sub>3</sub> -to-UF <sub>4</sub> process began in Plant 7, after which time Plant 6 made only UO <sub>3</sub> .
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 <sub>4</sub> to UO <sub>2</sub> and UO <sub>3</sub> 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. Processing of high-grade pitchblende ore ceased and concentrates became the principal feed material.
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 1958, all regular site operations ceased, with some Plant 7 activities continuing until July 1958. Postprocessing and shutdown-related activities continued into 1958.
1959-1962	The St. Louis site is decontaminated in 1959-1961, with unrestricted release of the site to Mallinckrodt in about 1962.
1962	AEC issues a license to a private entity, which then took over control of the SLAPS site.
1976 and 1978	Oak Ridge National Laboratory surveys the St. Louis Airport Site (SLAPS) for DOE.
1977	Oak Ridge National Laboratory surveys the St. Louis site (SLDS) for DOE.
1986, 1990	Applied Nuclear Safety does some surveys of the St. Louis site (SLDS) for DOE.
1995	FUSRAP takes over the St. Louis site (SLDS) for remediation.

Table 3. Principal changes made in sites, processes, and equipment.

Year	Plants	New method or form	Purpose(s)
1942-1943	4	Converted Plant 4	U metal production from UF <sub>4</sub> ; UF <sub>4</sub> production from UO <sub>2</sub>
1946	6	Began operation of Plant 6	Increase production, reduce all types of exposures from processing of pitchblende ores
1946-7	SLAPS	Began operation of SLAPS	Storage of pitchblende residues
1947	SLAPS	Construction of K-65 storage shed	Control external dose, radon exposures
1948	4, 6	Start of formal health program	Track and reduce exposures
1948	6	Began to use ventilated ore railcars	Reduce radon exposures
1948	6	Began reprocessing the K-65 residue	Recover residual uranium; concerns regarding corroding drums
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 <sub>2</sub> and UF <sub>4</sub> handling methods (e.g., adding hoods to the tray loading, tray dumping, milling, blending, and packing operations)	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 <sub>2</sub> handling (pneumatic unloading and conveying systems)	Reduce airborne dust levels, eliminate hand scooping
1949	6	Revised UO <sub>3</sub> handling (pneumatic unloading and conveying systems)	Reduce airborne dust levels; eliminate hand scooping
1949	6, SLAPS	Instituted limits on time spent handling ore and K-65 in railcars and at SLAPS	Control external and radon exposure to individuals
1950	4	Installed plantwide vacuum cleaning system	Enhance dust control and reduce airbornes
1950	6	Installed equipment decontamination room, respirator decontamination facility	Control contamination
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
1952-3	6	New Ledoux sampling labs with better ventilation	Lower airborne dust levels
1952-4	6	Use of pitchblende ore began to be phased out and soluble feeds were used increasingly	Use other available feeds
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?	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

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

Material	Process or operation	Content and form notes	Amount
<b>ORES AND OTHER FEEDS</b>			
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, AQ-4) and leach products (tailings concentrates)	Most of the pitchblende processed by Mallinckrodt was obtained as a concentrate from the Belgian Congo in 1944 (AEC 1967), processed at Middlesex (AEC 1951b), and shipped to St. Louis in 55-gal drums (AEC 1967).	Pitchblende ore, up to 65% (DOE 1997, MED 1949) or 70% (Dupree-Ellis et al. 2000) U <sub>3</sub> O <sub>8</sub> by weight; up to 100 mg Ra/ton (Dupree-Ellis et al. 2000); averaged 135 mg Ra/ton (AEC 1949b); 0.185 ppm equilibrium Ra for Q-11 (60%) ores (AEC 1949b); 0.1 Ci/ton (total?), up to 70% U, average U concentration >25%, about 100 mg/ton ore for 25% U (Eisenbud 1975). Tailings: 30-50% U <sub>3</sub> O <sub>8</sub> (AEC 1951b)	3400 tons U produced during wartime (through 1944?) (Eisenbud 1975); AEC (1951b) implies that Mallinckrodt was using only Congo ore, Congo ore tailings concentrates, and soda salt around 1951
Canadian pitchblende ores (Great Bear Lake, Port Hope)		Ores at perhaps 10% U (Eisenbud 1975); at 25-30% in 1951 (AEC 1951b) ores and U <sub>3</sub> O <sub>8</sub> 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 <sub>3</sub> O <sub>8</sub> (AEC 1967)	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 <sub>3</sub> O <sub>8</sub> (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).
Ore concentrates (MGX, etc.)	Special types of ore concentrates, e.g., the MGX, a magnesium uranate prepared in Africa from low-grade ore tailings (AEC 1955a)		
Sodium diuranate (soda salt)	Na <sub>2</sub> U <sub>2</sub> O <sub>7</sub> . Packed in fiber containers (MED 1945a)	Vitro converted U ores to sodium diuranate (AEC 1951b; DOE 1997); some apparently also came from Anaconda, Durango, and Fernald (AEC 1956b). Fiber containers weighed about 75 lbs each when full (MED 1945a).	

Table 4 (Continued)

Material	Process or Operation	Content and Form Notes	Amount
<b>REFINING PRODUCTS</b>			
UNH (uranium nitrate hexahydrate)	An intermediate product in the digestion-extraction process: $UO_2(NO_3) \cdot 6 H_2O$		Small quantities produced for research purposes as needed (AEC 1951b)
$UO_3$ (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 with 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). Plant 6 produced a monthly average of 21 tons in 1950 for R&D work on the continuous $UO_3$ -to- $UF_4$ production process (apart from what went into the normal $UO_3$ - $UO_2$ production process) and 146 tons in 1Q 1951 as the principal product for the new $UO_3$ -to- $UF_4$ process (AEC 1951b).
$UO_2$ (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 (MED 1946a). 2.5-gal fiber containers weighed about 75 lbs each when full (MED 1945a). There was 349 lbs on a 4-tray charge (MED 1944o).	By DOE 1942 Mallinckrodt was producing a ton a day (DOE 1996). Mallinckrodt used 32,000 lbs weekly (MED 1944o). 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 (MED 1949a). 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 Nov-Dec 1944, and 13,000 lbs/week after that (MED 1946a). The design capacity of Plant 6 was 200 tons/month, using ore @ 65% $U_3O_8$ (AEC 1951b). The monthly averages from Plant 6 were 94 tons in 1947, 246 tons in 1948, 204 tons in 1949, 207 tons in 1950 and 133 tons in 1Q 1951; large-scale production of $UO_2$ (as a separate product) ended in March 1951 (AEC 1951b). Plant 7's design capacity was 154 tons/month (i.e., could be produced if desired as a tapoff from the continuous $UO_3$ -to- $UF_4$ process) (AEC 1951b).
$UF_4$ (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 1945a) or 5-gal containers for transfer to Plant 4 or 6E or another site (AEC 1949b).	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 1944o).	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 1944o). In 1945, 8000 lbs/week was being sent to Harshaw and 20000 lbs/week to Iowa State (MED 1945a). Average monthly production in Plant 4 was 76 tons through Dec 1946, 131 tons in 1947, 147 tons in 1948, 151 tons in 1949, 169 tons in 1950, and 189 tons in 1Q 1951 (AEC 1951b). Plant 7's design capacity was 225 tons/month originally, 375 after expansion (AEC 1951b) (unclear if expansion took place).

Table 4 (Continued)

Material	Process or Operation	Content and Form Notes	Amount
U metal in derby form	Reduction with magnesium in furnace to U metal (slag + derby); slag chipped off to leave derby	In 1944-1949, there was 135-140 lbs of UF <sub>4</sub> per bomb, along with 55 lbs of liner (MED 1944o, AEC 1949g). 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 1944o).	In 1944, 7500 lbs of biscuit was produced weekly (MED 1944o). 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 shipped out every two weeks to Hanford in a carload lot of about 30,000 lbs, from a weekly production of 13,000-15,000 lbs (MED 1945a). Average monthly production in Plant 4 was 33 tons through December 1946, 84 tons in 1947, 102 tons in 1948, 100 tons in 1949, 169 tons in 1950, 189 in 1Q 1951; average monthly production in Plant 6E was 83 tons in 4Q 1950 and 162 tons in 3Q 1951; the latter was said to be AEC's entire requirement for metal at the time (AEC 1951b). Plant 6E's design capacity was 150 tons/month originally, 265 tons/month after the expansion of 3Q 1951 (AEC 1951b).
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 1956a)	In late 1955 or early 1956, this replaced the derby-billet operation, except for occasional experimental derby production in Plant 4, per AEC (1956a). But AEC (1956c) reported that in mid-1956 (all?) billet recasting was being done in 6E, using new graphite molds. A dingot weighed about 3300 lbs (AEC 1956a).	
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 1944o) 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), presumably as the metal. Manufactured by Mallinckrodt and shipped to the Chicago Area Engineer (of MED).		150 lbs shipped daily to Chicago (MED 1945a)
<b>RECYCLED AND RECOVERED MATERIALS</b>			
Organic solution of Th(NO <sub>3</sub> ) <sub>4</sub>	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 MgF <sub>2</sub> part and a C-liner part; the MgF <sub>2</sub> 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 <sub>2</sub> part.	

Table 4 (Continued)

Material	Process or Operation	Content and Form Notes	Amount
U slag (recast)	Recast slag was recovered as residue from the recast furnace.	As the uranium melted, the slag floated to the top of the crucible and beta-emitting Th-234 and Pa-234 (UX1 and UX2) sublimed and condensed on the underside of the furnace lid; recast furnace slag was thus highly concentrated in UX1-UX2 (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 1949h)		
U scrap	Miscellaneous material, including some residues, ash from incinerating the UO <sub>3</sub> 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.		
<b>RESIDUES AND OTHER WASTES</b>			
Pitchblende raffinate (AM-7)	"Airport cake"; produced as part of the pitchblende digestion process (extraction raffinate); see also Sperry cake	0.2% U (AEC 1949b); 0.15% U (AEC 1959); 29 ppm Th-232, 3.8 ppm Th-230 (11.6 isot %) (Figgins and Kirby 1962). Pitchblende residues: Th-232/Th-230 ~ 8. In AEC (1960), sampling in June 1953 showed highest sample at .0038% th and 0.14% U	33000 lbs/day (AEC 1949b); 74K tons total, 113 tons U stored through at least 1965 (AEC 1960; AEC 1964; ORNL 1979)
De-thoriated pitchblende raffinate (AM-9)	Residue after processing AM-7 for ionium (Th-230)	0.12%U (AEC 1959). Carnotite residues: Th-232/Th-230 ~ 15-20 (AEC 1949b)	
Domestic ore raffinate (AM-10)	"Airport cake"; produced as part of the non-pitchblende digestion process	Carnotite residues: Th-232/Th-230 ~ 15-20	32.5K tons total, 48 tons U stored through at least 1965 (AEC 1959, AEC 1960; ORNL 1979)
Pb-Ra precipitate (K-65, gangue lead cake)	"Lead cake"; a Ra-bearing residue produced as part of the pitchblende digestion process (resulting from addition of sulfuric acid); sent to Lake Ontario or the airport for storage	750-900 mg Ra/ton (AEC 1949b); 750 mg/ton Ra and 0.2% U (AEC 1949b); up to 300 Ra mg/ton (Eisenbud 1975)	8000-12000 lbs/day (AEC 1949b)
Ba sulfate cake (AJ-4)	Produced as part of the digestion process (resulting from addition of barium carbonate)	0.28% U (AEC 1959); 1 mg Ra/ton, 0.1% U (AEC 1949b); .1% U, 1E-9 g Ra per g U (AEC AEC 1949m)	6800 lbs/day total AJ-4 (AEC 1949b); stored: 1.5K tons total unleached (wit 22 tons U), 8.7K tons total leached (with 7 tons U) (FUSRAP undated a, AEC 1960), i.e., 10.2K tons total (with 29 tons U (AEC 1959; ORNL 1979)

Table 4 (Continued)

Sperry cake	Produced in Sperry press from aqueous tails from the ether extraction step; some later sent to Mound for processing to extract Pa; apparently a subset of AM-7	Good source of Pa-231 (2 g/20 tons); per Salutsky (1956), this was a cake @ 50% solids, 1.6 g/cm <sup>3</sup> density, 0.1-0.3 ppm Pa-231	20 tons (AEC 1959)
Vitro residues (C-6)	Sent from Vitro (?) for storage at the airport	0.33% U (AEC 1959). C-6 and V-10 were stored in a total of 2400 drums (FUSRAP undated)	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 1949b)		
U-containing sands, precipitates (V-10)	Captured from the Japanese	C-6 and V-10 were stored in a total of 2400 drums (FUSRAP undated)	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 <sub>2</sub> ) part of the slag was detached	<2% U (AEC 1959); 1.6% U (AEC 1959). 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).	7800 tons, 122 tons U (AEC 1959); 4000 tons, 49 tons U I 1964 (ORNL 1979)
Interim Residue Plant Tailings (C-701, D-701)	Resulted from scalping the U content from the Mg fluoride slag from 1955 on; 701 apparently refers to Bldg 701 (AEC 1956d)	2.1% U (AEC 1959)	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 ether extraction step; filtered and treated with lime; precipitate become airport/Sperry cake, filtrate disposed of as liquid effluent		

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 or code	Note
	2	MED hazard index number for soluble uranium material
	4	MED hazard index number for insoluble uranium material
	6	MED hazard index number for nitrous fumes
	14	MED code for Building 51
	16	MED hazard index number for hydrogen fluoride
	32	MED hazard index number for handling of metal
	38	MED code for the laboratory area in Plant 2
	51	See "Building 51" below
	52	MED code for Plant 4
	128	MED hazard index number for hydrogen fluoride gas
	162, 172, 182	Black oxide (U <sub>3</sub> O <sub>8</sub> ); could appear as "Chemical 162", etc.
	256	MED hazard index number for radium
	264, 272	Orange oxide (UO <sub>3</sub> ); could appear as "Chemical 264", etc.
	306	Brown oxide, i.e., UO <sub>2</sub> ; could appear as "Chemical 306"
	512	MED hazard index number for radon
	1024	MED hazard index number for solvents
	2048	MED hazard index number for radiation
	4-bagger	Type of dust collector
	A	In film badge records, denotes "absent"; elsewhere, denotes non-specification grade black oxide (U <sub>3</sub> O <sub>8</sub> )
6	Acid	Acid addition: in ore digestion (nitric) or Pb-Ra precipitation (sulfuric)
7	Adams	A type of polishing filter used in Plant 7
6	AEC	Atomic Energy Commission
	Airport	SLAPS, the former airport site later used for waste storage by the AEC
6	AJ-4	Barium sulfate cake produced from pitchblende ore (ore-to-UO <sub>3</sub> )
	AJ-7	Another barium cake
6	AM-7	Raffinate cake produced by treating pitchblende ore
6	AM8	Unclear what this indicates
4,6,6E,7	Area M	Area mechanic
6	Assist LO	Assisting the lead operator
6	AQ-4	Pitchblende ore
4	Ballard	Vertical turret lathe (manufactured by Ballard) used to scalp the dingot
6	Barium	Barium salt addition
	Beets(?)	See Egg
4, 6E	Billet	Final form of uranium metal, produced by recasting from derbies
6	Bird centrifuge	Solid-bowl centrifuge (manufactured by Bird) used to separate liquids and solids
	Black oxide	U <sub>3</sub> O <sub>8</sub>
4, 6	Blender	Apparently ore in Plant 6; UF <sub>4</sub> + Mg in Plants 4, 6E; slag in Plant 6E
4, 6E	BM	Bottom man
6	Boildown	A step between digestion and ether extraction
4	Bomb	Container for Mg-UF <sub>4</sub> in the metal reduction process
4, 6E	Bomb step	The UF <sub>4</sub> -to-derby process
4, 6E	Bottom	Lower (furnace or F machine)
4, 6E	Bottom man	Bottom man in the YM-5 production process -- would physically enter the bottom part of the furnace in Plant 4
4	Box	Crucible holder (external assembly)
6E	Breakout	Removal of the derbies from the bombs
	Brown	Brown oxide, i.e., UO <sub>2</sub>
	Brown monster	Apparently the Rockwell furnace(s) (UO <sub>3</sub> -to-UO <sub>2</sub> )
	Building 51	The 50 series of buildings at Plant 2 (i.e., 50, 51, 51A, 52, 52A, and 55)
	Building K	Apparently Building K1E in Plant 1
6E	Burnout, burn	Crucible burnout (heating)
	C	On film badge records, denotes no badge issued ("clean"?)
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., centrifuging, packing) related to use of the carbonate leaching process to recover uranium from Feinc filter cake (K-65); also dust collection related to this
	C-27	Derby chippings (residue)
	C-55	As "Chemical K-35", etc., denotes black oxide (U <sub>3</sub> O <sub>8</sub> ) (may be scrap)
4, 6E	Cage	Scrap holding area
4, 6E	Cage man	Handled billet and other metal scrap, degreased billets
6E	Cap	Valved top put on the Mg-UF <sub>4</sub> drum for jolting
	Cats	High-grade ore
	CB	On film badge records, denotes contaminated badge and film

Table 5 (Continued)

Plant	Keyword or code	Note
6	CEN, Cent, Cntr	Centrifuge. Also abbreviated CNF?
	Chemical	Start of some code names; was followed by letters or numbers
4	Chipping	Removal of the slag from the derbies using a manual or power hammer
	Classifier	Equipment used in the Ore Room apparently to sort ore pieces by size
---	Cleanup	Generic for area or item cleanup: see associated keyword (e.g., TA-7)
	C-liner	Dolomite slag left after the bomb is opened and the derby removed
	C-Special	Liner slag left on bomb and possible also derby (had to be chipped off)
6	Cloth	Cloth (actual or metal) used to filter solids from liquid streams
	Cl Up	Cleanup, i.e., cleanup of process area
6	CM	Cloth man?
	Cocoa	Brown oxide, i.e., UO <sub>2</sub>
4, 6	Continuous furnace, Cont furn	Furnace for processing UO <sub>3</sub> to UF <sub>4</sub> in a continuous run (in Plant 4, experimental process in Pilot Plant)
	Croppings	Chips or pieces taken off derbies, billets, and dingots
6E	Crucible, Cruc	Crucible or crucible assembly (6 should probably be 6E)
	Crusher	Probably the UO <sub>2</sub> crusher (mill)
	CS	Refinery feed material that was an impure calcium uranate
	C-Special	Magnesium fluoride slag formed on top of the derby
	CX	Calcium uranate leach product from the processing of ore tailings at African mills; sent to Mallinckrodt for laboratory research and pilot-scale recovery of the uranium
	D	Radium (the element)
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)
	D-701	Residues collected in the slag grinding area. shipped to slag recovery
6	DA	Dissociated (cracked) ammonia or Digest area
6,6E, 7	Decontamination	Generic
	Deheading	Same as Delidding
	Delidding	Removing the lid of a drum, usually of ore
4, 6E	Derby	Crude uranium metal form produced from UF <sub>4</sub>
6	Digest, DIG, Dig	Digestion process (ore dissolution by acid), digestion area, digestors
4	Dingot	"Direct ingot", an extra-large ingot produced instead of derbies and billets
	DR	???
	DX	Probably decontamination work
	E	Designates the Mallinckrodt plants in St. Louis
	Egg	1.9-kg egg-shaped piece of U metal produced for external assays
6	Ether, Ether House, EH	Ether storage, handling for U solvent extraction process
4, 6	Extra, Extra Man	Extra (floating) chemical operator for a process or area (4, 6); possibly also "extraction" (6)
6	Extraction	Extraction of uranium in the ether extraction process
	F	Generic feed material designation for types without a code name
4, 6E	Fce	Furnace (metal-making areas)
	FD	On film badge records, denotes factory-damaged film
6	FE, Fe	Feinc (FE Inc) filter (equipment or area)
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
	FF	On film badge records, denotes film fogged, torn, or open (in badge?)
6	FH	Feed hopper?
6	Filter press	Press type of filter for separating solids from liquids and leaving a dewatered cake
	Fin	Slag or magnesium burr on billet, bomb shell lid, etc. that had to be chipped off
6E	F Machine	UF <sub>4</sub> -to-derby bomb filling ("F") machine: the top is used for the UF <sub>4</sub> , Mg mixing, the bottom for filling the bomb
7	FMFL	Fluorinated MgF <sub>2</sub> liner, used as a low-hydrogen liner in dingot bombs
4, 6	FR, Furnace, Furn	Furnace Room
	Gangue, gangue lead cake	The Pb-Ra cake also known as K-65
	GL	In film badge records, denotes "gone through the laundry" in context of film condition; denotes work with gangue lead cake in context of worker area
6	GLC	Gangue lead cake, i.e., the Pb-Ra cake also known as K-65
	Green	Green salt (UF <sub>4</sub> )
6	Gulping	Vacuum-sucking UO <sub>3</sub> out of the pot it was produced in into drums
	GWT-5	Uranium metal eggs (test samples)
	GY-3	U <sub>3</sub> O <sub>8</sub> (black oxide), having a minimum assay of 97% U <sub>3</sub> O <sub>8</sub>
	H-20	???. (H <sub>2</sub> O, i.e., water?)
7	Hapmann, Hapman	Conveyor for loose material; typically discharges into a feed hopper

Table 5 (Continued)

Plant	Keyword or code	Note
6	Hex, hex liquor	Uranyl nitrate hexahydrate in an aqueous solution
6E	Hoffman	Dust collector (manufactured by Hoffman)
All	House	Generic for dedicated additive handling and storage building or area
4, 6E	Ingot	Same as billet
6	Instrument, Instru, Instr	Instrument Shop
	Ionium	Thorium-230
	Iron maiden	C-Special, while still attached to derby
4, 6E	Jolter, jolting	The jolter-filling machine in UF <sub>4</sub> -to-U metal production, also the operator; the operation
	Juice	Orange oxide, i.e., UO <sub>3</sub>
	K-35, K-82	As "Chemical K-35", etc., denotes black oxide (U <sub>3</sub> O <sub>8</sub> )
6	K-65	K-65 (Ra-Pb) residue (gangue lead cake) from the (pitchblende) ore-to-UO <sub>3</sub> process
6E	KB-2	Derby form of uranium metal
4	Label	Apparently labeling product containers
6	Laboratory, Lab, LAB	Any of several laboratories (Analytical, Shotgun, Ledoux, etc.)
6	Laundry	For both contaminated and uncontaminated clothing; Mallinckrodt had own laundry from ~ 1948 on
	LB	In film badge records, denotes film that was opened (in badge?)
	Ld	Loading (e.g., TA-7)
	LF-9	Brown oxide (UO <sub>2</sub> )
	LFD	In film badge records, denotes film lost in the darkroom (torn open)
	LFP	In film badge records, denotes film lost in plant
	LG	Lead gangue? See GLC
6	Ledoux (LeDoux) Laboratory	The raffinate and uranium assay laboratory in Plant 6
6	Liquor	Extracted liquid concentrate, usually after removal of undesirable materials as solids
	LL	Ledoux Laboratory
	LO	Lead operator
4, 6	Loading, Load, Ld	Generic: see associated process keyword, e.g., TA-7
	Location E	The Mallinckrodt St. Louis site (SLDS)
	M	Powdered magnesium metal, work in the metal-making (derby and billet) areas, or maintenance (depending on context)
6	M(+number), M-(+number)	(1) Designates tank(s) used in processing. (2) Designates a type of development work, e.g., M-1 for slag liner work, M-2 for mold improvement, and M-7 for crucible testing
	M-20	Step or tank during which barium sulfate was added
	ME	Refers to processing of AM-7 raffinate to concentrated liquid Th form (Minor Elements)
	MFG, Mfg	Manufacturing: generic for Plant 6 and Plant 4
6	MGX, MgX, MGX Process	Refinery feed material that was an impure magnesium uranate from the Belgian Congo
4	Mag Room	Magnesium [Storage] Room
1, 2	Main Plant	Plants 1 and 2
6, 6E	Maintenance, M, MNT	Maintenance, presumably process maintenance
	ME	Refers to reprocessing of raffinate to a feed concentrate
7	MFL	MgF <sub>2</sub> liner (for use in dingot bombs); loosely, also the associated slag used (recycled) in the liner
6	Mikro	Dust collector (manufactured by Mikro)
6	Mill	See Rod mill
	Mtns	Maintenance
4	Muffle	Batch electric (muffle) furnace used to reduce UO <sub>3</sub> to UO <sub>2</sub>
	Mx (note lower case)	Uranium (generic for the element?)
	MX (note upper case)	See MGX
	My	Radium; also, used to indicate a breath radon measurement (since this measurement was used to infer radium body burden)
	Mz, MZ	Radon-222
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	In the re-extraction process, the OK liquor contained the uranium and the NOK liquor contained the dross (after filtration, it became raffinate).
6	Ntns	Maintenance (Mtns)?
4	Office, OFF	Generic for office
	OH	Hydroxide (e.g., to neutralize excess HF and recover uranium)
6	OK	In the re-extraction process, the OK liquor was the uranium-containing liquid sent to the boil-down tanks
6	Oliver	Filter press (manufactured by Oliver)
	Orange, orange juice	Orange oxide, i.e., UO <sub>3</sub>

Table 5 (Continued)

Plant	Keyword or code	Note
6	Ore, Ore Room, OR	Ore processing, storage before use; also handling of residues
	OZ	Electrically fused dolomite
4, 6, 7	Pack, packing, packaging	Appears to be generic for packaging
6	Pangborn	Type of dust collector (K-65/Ledoux Sample Lab; ore grinding room; C-3)
6	Peterson	Type of filter, often in a hood; at least some was used to filter NOK liquor to produce the raffinate
	PH	Power House
6E	Pickling	Soaking derbies in acid to remove surface impurities (scale, oxides)
All	Pilot Plant, PP	Plant 4's name (for metallurgical research and developmental UF <sub>4</sub> furnace work), after metal production moved to 6E; Plants 1 & 2, around the time Plant 6 started up; a slag recovery pilot plant in 6E; or an unspecified pilot plant at 6 (must be taken from context)
	Pk	Packing (packaging) of a product form
All	PI	Plant (e.g., PI. 7 is Plant 7)
	Plant 10	The later name of the Plant 4 area (after Plant 4 was dismantled)
2	Plant 51	Building 51 operations in Plant 2
6E	PLO	Process Lead Operator?
6	Pot, Pot Room	Denitration pot room (producing UO <sub>3</sub> )
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
	Project (+ number)	Project 89 was Plants 1 and 2; 90, Plant 4 green salt operations; 91, Plant 4 derby production; 92, Plant 4 recast operations
	Q-11	Pitchblende ore, other high-grade ore
	QM-2	Orange oxide (UO <sub>3</sub> )
6	Raffinate, Raff	Residues (mainly the cakes)
6	Railcar	Railroad car used to transport ore, K-65 residue, and sometimes scrap
6	Rapping	Knocking a dust collector (usually the Pangborn) to loosen collected material for removal
4,7	Reactor	Reaction vessel/heater in which UO <sub>3</sub> is converted to UO <sub>2</sub> with cracked ammonia
4	Recast, Recast Furnace	Where derbies were recast into billets
4	Receiving & Shipping	Generic? The main Receiving & Shipping area was in Plant 6, but there may have been plant-specific areas
6	Recovery, REC	Nitric oxide recovery (6); slag recovery (7); may have indicated other types of recovery at other plants
	Regulated	Refers to radiologically controlled areas, e.g., the regulated locker room and the general locker room
	Regulus	Same as Derby
6	Reverter (riverter?)	Unclear. Appears to be a type of pump or processor used in the recycling of dust collector material
7	RMF	Recycle magnesium fluoride (from bomb liner residue)
6E	Rockwell	Rockwell furnace (UF <sub>4</sub> -Mg reduction to derby metal)
6	Rod mill	Piece of equipment used to grind ore
	Rolls	Billets
6	Rover	Extra pair of hands or swing man?
	S	As "Chemical S", denotes sodium salt (sodium diuranate, Na <sub>2</sub> U <sub>2</sub> O <sub>7</sub> ); in urinalysis records, denoted sulfate (work)
4	Salt bath	Bath in which a dingot is put to heat it
	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
SLAPS	Sand	(1) cake residue or (2) uranium-containing sands captured from the Japanese
6E	Saw	Sawing off a portion of the metal billet as a sample
6	SC-5	Uranyl nitrate hexahydrate (UNH)
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
4	Semi-works	Term for a facility within a plant, on the scale of or slightly larger than a pilot plant (specifically, the dingot operation in Plant 4)
6	Skip hoist	Hoist used to raise ore drums, dump them into raw ore bin feeding (ore) rod mill
6E	Slag	Byproduct from the Mg-UF <sub>4</sub> reduction step (mostly MgF <sub>2</sub> )
7	Slag Processing Plant	Same as Slag Separation Plant
[4]	Slag Shed	Storage of the chipped-off bits of slag?
	SLAPS, SLAPSS	Sl. Louis Airport Storage Site
6E	Slye	Dust collector (manufactured by Slye)
6	Shotgun Laboratory	Shotgun sample preparation laboratory
6	Shotgun Samp Prep	Shotgun sample preparation (lab)
6	Soda salt	Na <sub>2</sub> U <sub>2</sub> O <sub>7</sub> (sodium diuranate, a feed material); perhaps other soluble feed material

Table 5 (Continued)

Plant	Keyword or code	Note
	SP	In film badge records, denotes film spoiled in the darkroom (development) process
6	Sperry	Filter press (manufactured by Sperry); also, the cake produced (same as or subset of AM-7)
	SR	Storeroom
	SS	Stainless steel presses, i.e., the plate and frame filters
	SSP	Usually refers to stainless steel (filter) presses; may indicate Shotgun Sample Prep Lab
	ST	Uranium metal scrap
6	Storeroom	Generic; the main storeroom was in Plant 6
6	Stripper	Unclear; probably piece of equipment rather than operator name
All	T	Generic code term for uranium, including as metal (T metal), in compounds (e.g., $\text{TO}_2$ ), and as a daughter indication (e.g., TX1)
6	T-3	Typo for C-3?
4	TA-7	Green salt ( $\text{UF}_4$ )
	TA-7R	$\text{UF}_4$ produced from $\text{UO}_2$ in the experimental continuous reactor
	Talcum	$\text{UF}_4$
6	Thawhouse	Building where ore was thawed in winter before undrumming
6	Thief	Sampling device that opens at a desired depth into the material
6	THP	THP ether?
6	Thumper	Device to "thump" feed drum to dislodge material during digester loading
4, 6E	TM	Top man, Top-off man, etc., in the YM-5 production process
4, 6E	Top	Refers to the upper or top recasting furnace or the top F machine
4, 6E	Top man	Top man, Top-off man, etc., in the YM-5 production process
4, 6E, 7	Topping	Refers to the operation of adding material to ensure proper fill
	Tubealloy	Uranium metal (generic term also used roughly to indicate any uranium)
	Tumbler, tumbling area	$\text{UO}_2$ breakup (crushing) area
	U	In film badge records, denotes "unidentifiable" in context of film condition; elsewhere, usually denotes uranium
6, 7	U-CON, U-con	Uranium concentrate slurry produced in the Slag Separation (Processing) Plant (7) from reject $\text{MgF}_2$ material and sent to Plant 6 as a feed material
6	UNH	Uranyl nitrate hexahydrate ( $\text{UO}_2(\text{NO}_3)_2 \cdot 6 \text{H}_2\text{O}$ )
	Unld	Unloading (e.g., TA-7)
6E	Utility	Utility man or "floater" who filled in as needed
	UX1, UX2	Old names for Th-234 and Pa-234m respectively
	V	In film badge records, denotes "on vacation"
	V-4	A form of soda salt used as feed material
	W	In film badge records, denotes "wet from unknown reason"
All	Warehouse, WH	Generic: various warehouses were used, with the main one in Plant 6 and later in Plant 7
4	Weigh, check weigh	Generic: feed and products were weighed at various points
6E	Wilfey	Shaker table (manufactured by Wilfey) used to separate high-U slurry from low-U material
	X	Generic code term for uranium, including in compounds (e.g., $\text{XO}_2$ )
	Yard	Open areas outside buildings and guard stations; used to store drums, unload railcars; even used postoperations for decontamination
	YB-1	$\text{UO}_2$ produced from $\text{UO}_3$ in the experimental continuous reactor
	Yellow cake	The generic form of uranium ore, somewhat preprocessed
4	YM-5	Billet form of uranium metal

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	---	$3.18 \times 10^8$	---	---	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	$1.09 \times 10^{-07}$	0.00101	Concentration: Figgins and Kirby 1962
*From Shleien 1992					
Isotope	Half-life	Activity after 15 years, Ci	Percentage of original	Notes	
<b>Th-230 Chain</b>					
Th-230	77,000 years	$2.44 \times 10^1$	~100%		
Ra-226	1,600 years	$1.58 \times 10^{-1}$	0.65%	Ignoring Ra-226 decay	
Rn-222	3.82 days	$1.58 \times 10^{-1}$	0.65%	Ignoring Rn-222 decay	
Po-218	3.05 minutes	$1.58 \times 10^{-1}$	0.65%	Ignoring Po-218 decay	
Pb-214	26.8 minutes				
Bi-214	19.9 minutes				
Po-214	164 microseconds				
Pb-210	22.3 years				
Bi-210	5.01 days				
Po-210	138 days				
<b>Th-232 Chain</b>					
Th-232	$1.41 \times 10^{10}$ years	$1.01 \times 10^{-3}$	~100%		
Ra-228	5.75 years	$8.46 \times 10^{-4}$	84%	Ignoring Ra-228 decay	
Ac-228	6.13 hours	$8.46 \times 10^{-4}$	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				

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.

Area	Location or source type	Method*	Average concentration, mg U/m <sup>3</sup>	Mass median particle size, microns	GSD
Mallinckrodt UO <sub>2</sub> Production Area (Rochester 1948b)					
UO <sub>3</sub> -to-UO <sub>2</sub> conversion	<1 foot of the blow pipe	F	2.14	1.2	2.34
Tumbling	Vicinity of furnace, tumbler tray rack	F	.11-.46	1.4-1.45	2.5-3.2
		C	.64-.93		
	Further from furnace, tumbler rack	F	.069-095		
		C	.41-.53		
	Near skip hoist	F	2.8-4.2	1.5-1.9	2.45-2.6
		C	.59-.69		
	4 feet from skip hoist	F	0.75		
		C	3.5		
	Back of the skip hoist	F		2.6	2.65
Fiberpack packaging		F, C	.060-2.2	.72-3.48	2.96-3.03
Warehouse	Closed containers of UO <sub>2</sub>	F	.017-.033	1.1	2.3
General (Non-Mallinckrodt) Foundry (Sanders 1975, Table 2)					
Foundry	Depleted U	---	---	$2.8 \pm 2.7^{**}$	---
	Enriched U	---	---	$3.3 \pm 2.2^{**}$	---
	Enriched U	---	---	$2.1 \pm 2.0^{**}$	---
Machining	Depleted U, milling dry	---	---	$3.0 \pm 2.3$	---
Extruding	Depleted U	---	---	$3.2 \pm 2.7$	---

\* This refers to the sampling method. F: filter paper (with air sampling pump) . C: cascade impactor

\*\* 88% of these particles were from particles less than 7 μm.

Table 8. Uranium dust concentrations, Plants 4 and 6, in alpha dpm/m<sup>3</sup> (Mason 1958a, Tables 1, 2).

Year	Plant 4				Plant 6									
	UO <sub>2</sub> Production	UF <sub>4</sub> Production	KB-2 Production	YM-5 Production	Warehousing	Ore grinding	UO <sub>3</sub> production				UO <sub>2</sub> production		Misc	
							Feed digest	Milling	Pot room	Packaging	Load	Unload	Packaging	
1943	2,100	2,380	1,190	2,520	---	---	---	---	---	---	---	---	---	---
1944	2,100	2,380	1,190	2,520	---	---	---	---	---	---	---	---	---	---
1945	2,100	2,380	1,190	2,520	---	---	---	---	---	---	---	---	---	---
1946	2,100	2,380	1,190	2,520	210	13,300	420	12,600	7,770	1,400	5,320	3,150	11,270	---
1947	2,100	2,380	1,190	2,520	210	13,650	420	12,600	7,770	1,400	5,320	3,150	11,270	---
1948	2,100	2,380	1,190	2,520	210	13,650	420	12,600	7,770	1,400	5,320	3,150	11,270	---
1949	420	280	280	770	210	13,650	420	12,600	7,770	1,400	5,320	3,150	11,270	---
	---	---	---	---	70	350	70	0	4,200	700	1,400	700	350	---
1950	280	140	210	770	70	350	70	*	770	700	1,400	700	350	---
	---	---	---	---	28	350	70	---	350	700	700	350	350	---
1951	280	210	---	---	35	350	140	---	140	70	420	210	350	---
1952	280	210	---	---	35	210	350	---	210	140	420	210	350	---
1953	---	---	---	---	63	140	49	---	210	140	420	210	350	---
1954	---	---	---	---	21	140	42	---	140	140	**	**	**	---
1955	---	---	---	---	21	*	56	---	140	140	---	---	---	---
1956	---	---	---	---	21	---	28	---	210	280	---	---	---	---
1957	---	---	---	---	21	---	56	---	210	70	---	---	---	---

The first two Plant 4 processes were supposedly transferred to Plant 7 in 1952-3, the last two to Plant 6E in 1950-1. Compare to information for Plants 6E and Plant 7 (Table 9). Prior to 1946, the Plant 6 operations were done in Building 51 of Plant 2; all work was transferred to Weldon Spring in March 1957. Note that the figures above reflect chronologically the significant improvements in ventilation and dust control made in 1949.

\* Discontinued

\*\* Transferred to Plant 7 in October 1952

Table 9. Uranium dust concentrations, Plants 6E and 7, in alpha dpm/m<sup>3</sup> (Mason 1958a, Tables 3, 4).

Year	Plant 6E						Plant 7		
	KB-2 production			YM-5 production			All operations		
	Average	High	Source of high reading	Average	High	Source of high reading	Average	High	Source of high reading
1950	7	21	Charging	70	126	Crucible assembly	---	---	
1951	21	56	Residue	77	126	Top furnace	---	---	
1952	28	70	Residue	84	161	Burnout	35	112	UO <sub>2</sub> dumping
1953	21	84	Charging	35	49	Top furnace	28	119	Furnace operation, TA-7 packaging
1954	35	210	Residue	63	119	Bottom furnace	35	490	Sampling, cleanup
1955	112	280	Residue	42	105	Bottom furnace	21	77	UO <sub>2</sub> dumping
1956	28	112	Capping	35	42	Bottom furnace	28	56	UO <sub>2</sub> dumping
1957	28	105	Burnout	49	84	Bottom furnace	21	56	UO <sub>2</sub> dumping
1958	56	147	Breakout	84	147	Bottom furnace	35	98	TA-7 packaging

Plant 6: KB-2 is the derby form and YM-5 the billet form of uranium metal.

Plant 7: Operations were moved to Weldon Spring in 1958.

Table 10. Early air sample data, short-term sample readings in alpha dpm/m<sup>3</sup>.

Location and operation	1943		1944		1945			1946			
	Value	No. of Samples	Value	GSD	No. of Samples	Value	GSD	No. of Samples	Value	GSD	No. of Samples
Plant 1											
Bldg K, Feinc filtration						60		2			
Bldg 25, Laboratory						7		2			
Plant 2 (Bldgs 51/51A)											
Oxide being added to Tank 1A	153	1									
Pot Room, general area	301	1	742		2	511		1			
Pot Room, aisle between pots						700		1			
Pot Room, (un)loading UO <sub>3</sub>	2,000	1				2,380		1			
Pot Room, chipping, scooping cake	11,300	1									
Milling UO <sub>3</sub>			2,800	3.03	3	3,220		1			
Sifting room general area	304	2									
Sifting room, sifting	22,50	1									
UO <sub>2</sub> being weighed	70	1									
UO <sub>2</sub> unloading			15,540		2						
UO <sub>2</sub> packaging			65,800		1						
Plant 2 (Shotgun Lab, Bldg 55)											
Shotgun residue evaporation			62		2						
Shotgun residue grinding			97	1.54	4						
Plant 4											
UF <sub>4</sub> general area						49		3			
Unloading UF <sub>4</sub>			6,160		2	91		1	563	2.36	4
Milling UF <sub>4</sub>			6,062		2	74		2	630		2
Mixing/blending/jolting UF <sub>4</sub> , Mg			1,960		1				84		2
Bomb area general			5,320	1.22	3						
Bomb loading			2,100		1						
Bomb unloading			1,154	2.79	4				324		2
Biscuit chipping			4,484	1.27	3				42		1
Biscuit sealing			1,540		1						
Slag barreling			210	1.10	4						
Crucible burnout			2,100		1						
Recast furnace general area			976		2						
Recast furnace unloading			700		1						
Recast furnace brushing			980		1						
Ore milling						720	2.70	4			
Ore handling						1,230		2			
Plant 6											
Ore storage – area									246	4.08	9
Boxcar									504	4.10	3

The sampling data used to produce the table above are from MED (1943d; 1944b; 1944c; 1944d; 1944e; 1944g; 1944h; 1945d; 1946d; 1946e; MED 1945o) and MCW (1946b; 1946c; 1946d; 1946e; 1946f). The figure given in the Value column is the median, if there were three or more samples; the mean if there were two samples; and the sole value if there was one sample.



Table 11. Airborne uranium dust concentrations in Plant 4 Areas, 1948: AEC versus Mallinckrodt measured data (AEC 1949b, Table 3).

Activity	Multiple of "Preferred Level"		ug/m <sup>3</sup>		Adjusted to dpm/m <sup>3</sup>	
	AEC	Mallinckrodt	AEC	Mallinckrodt	AEC	Mallinckrodt
LF-9 Loading						
Operator A	47.7	29.7	2.39E+03	1.49E+03	3.34E+03	2.08E+03
Operator B	47.7	30.7	2.39E+03	1.54E+03	3.34E+03	2.15E+03
Furnace Tending						
Operator A	7.5	5.7	3.75E+02	2.85E+02	5.46E+02	3.99E+02
Operator B	9.1	6.1	4.55E+02	3.05E+02	6.37E+02	4.27E+02
TA-7 Unloading						
Operator A						
- Manual	186	66.8	9.30E+03	3.34E+03	1.30E+04	4.68E+03
- Semi-mechanized		16.4		8.20E+02		1.29E+03
Operator B						
- Manual	186	57.2	9.30E+03	2.86E+03	1.30E+04	4.00E+03
- Semi-mechanized		20.7		1.04E+03		1.45E+03
TA-7 Mixing & Packing						
Operator A	63	13.1	3.15E+03	6.55E+02	4.41E+03	9.17E+02
Operator B	57	24.6	2.85E+03	1.23E+03	3.99E+03	1.72E+03
Bomb Charging	51	42.4	2.55E+03	2.12E+03	3.57E+03	2.97E+03
Topping	10.4	32.4	5.20E+02	1.62E+03	7.28E+02	2.27E+03
Jolting	51	7.5	2.55E+03	3.75E+02	3.57E+03	5.25E+02
Charge Firing	13.3	13.8	6.65E+02	6.90E+02	9.31E+02	9.66E+02
Derby Unloading						
Operator A	5	9.1	2.50E+02	4.55E+02	3.50E+02	6.37E+02
Operator B	5	18.7	2.50E+02	9.35E+02	3.50E+02	1.31E+03
Chipping	26.3	11.5	1.32E+03	5.75E+02	1.84E+03	8.05E+02
Slag Handling	1.6	2.2	8.00E+01	1.10E+02	1.12E+02	1.54E+02
Top Furnace Tending						
Operator A	61	36.5	3.05E+03	1.83E+03	4.27E+03	2.56E+03
Operator B	61	23.2	3.05E+03	1.16E+03	4.27E+03	1.62E+03
Bottom Furnace Tending	73	59	3.65E+03	2.95E+03	5.11E+03	4.13E+03
Sawing	15.8	5.4	7.90E+02	2.70E+02	1.11E+03	3.78E+02
Cage Handling	2.7	52	1.35E+02	2.60E+03	1.89E+02	3.64E+03
Office	0.6	4.1	3.00E+01	2.05E+02	4.20E+01	2.87E+02
Shipping & Receiving	1.6	6.8	8.00E+01	3.40E+02	1.26E+02	4.76E+02
Mechanics	5	10.7	2.50E+02	5.35E+02	3.50E+02	7.49E+02
Carpenter	2	4.6	1.00E+02	2.30E+02	1.40E+02	3.22E+02
Porters	0.8	2.9	4.00E+01	1.45E+02	5.60E+01	2.03E+02
Guards	0.4	1.4	2.00E+01	7.00E+01	2.80E+01	9.80E+01

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

Columns 6 and 7 represent the values obtain by multiplying Columns 4 and 5 respectively by 70 dpm/m<sup>3</sup> (assuming 70 dpm/m<sup>3</sup> is equivalent to 50 ug/m<sup>3</sup>).

Table 12. Plant 4 measured daily weighted average exposure concentrations.

Occupation	Weighted average concentration, alpha dpm/m <sup>3</sup>								
	5/1956	11/1953	3/1953	6/1950	10/1949	9/1948	5/1948	AEC 1949b	AEC 1951a
Magnesium operator				35	70				
Lime blender				35	70				
Slag man				70	105	210	140		
Cage man (handler)				190		3640	189	2940	
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 <sub>4</sub> -derby?)				91	70	570			
HF operator				91	70	570			
UO <sub>3</sub> & 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)	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	

Data from the surveys of 6/50, 10/49, 9/48, and 5/48 is from AEC 1950c; 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 1956a. Other data are from the references given in the column headings.

Table 13. Plant 6 measured daily weighted average exposure concentrations.

Occupation	Weighted average concentration, alpha dpm/m <sup>3</sup>								
	May 1956	May 1954	Oct 1953	Jan 1953	Jan 1952	Aug 1950	1949	Oct-Nov 1948	May 1948
Digest area lead operator	6	60	36	62	140	84		686	280
Digest operator	7.3	37	41	52	370	77		399	490
U-Con man #1	7.3								
U-Con man #2	14								
Feinc operator	6.2	96	38	110	175	154		980	840
Barium operator			38	130	144	126			280
Feed operator	40.8	23	100	150	110	126		910	476
C-3 wash filter operator		79	32	48	120	116		497	476
C-3 adjustments operator			22	420	120			497	476
C-3 centrifuge operator		42	630	52		140		567	476
Ore Room operator			140	170	370	392	350	13,720	4970
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	364
Raffinate operator	216	11	8	170	68	154		273	364
QM-2 (Orange) packager	268	1,961	120	130	130				
Furnace operator	12	33	55	96	150	1,400		5320	24500
Furnace room sampler								3150	
Reduction area (furn room) lead oper'r	22	25	28	69	54	147		686	
LF-9 (Brown) packager						364		11270	39200
Nitric acid recovery operator	20	9.6	19	44	35	99		46	364
Pot Room operator	234	113	45	190	100	336	770	7,770	32200
Metal dissolver #1	204								
Metal dissolver #2	21								
MGX operator		29	68	52	94				
Utility operator	88	129	94	97					
Miller (Mill Room)						X	X	12,600	46200
Pilot Plant group leader	7.5	6.9	3.1			105		91	245
Pilot Plant lead operator	7.7	8.8	6.1	77	116	105		91	245
Pilot Plant technician	1,940	9.2	6	77	116	105		91	245
Production superintendent	7.7	8.8	56	25					
Experimental continuous furnace						8,540	X	X	X
Asst. production superintendent	18	21	26						
General/Asst foreman	14	18	30	50					
Foreman	17	21	29	58				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			
Shift foreman	19	25	27	81	96			161	
Cloth & Training Grp Lead Operator			23	25				2520	
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		30	245
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 <sub>2</sub> )	21	7.5	27						
Shotgun Lab analyst	24.1	10	27	23	25	239		24 (239)	
Laboratory personnel	42	2.9	30	23	21				
MCW Laboratory west section						21		30	245
MCW Laboratory east section						13		30	245
Powder sample technician	56.5					217?		448	
Metal room sampler	420								
Outside sampling man	22.5								
Sample Room supervisor	41					245		448	
Laboratory Office personnel	42	2	5.6						

Table 13 (Continued)

Occupation	Weighted average concentration, alpha dpm/m <sup>3</sup>								
	May 1956	May 1954	Oct 1953	Jan 1953	Jan 1952	Aug 1950	1949	Oct-Nov 1948	May 1948
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	
Warehouse man -- K-65 sampler			350	270	230	84		189	196
Warehouse man	5.8	10	20	38	46	84		189	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			
Health Office - personnel	8.1	11	15	14	0			7.0	14
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		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						189			
Digest & feed AM						133			
Raffinate and C-3 AM						161			
Ether & NA House AM						77			
Welders, pipefitters, etc.						98		128	
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		7.7	33
AEC Engineer		19	9.9	31	7				
MCW Office personnel	1.5	2	2.9	0.7	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 (Oct-Nov 1948) is from MCW (MCW 1949d (repeated in AEC 1949b and MCW 1950s), the second set (May 1948). The 1949 and 1950 data are from MCW (MCW 1950q) and AEC(AEC 1953); the May 1952, January 1953, and the October 1953 sets of survey data are from AEC (AEC 1954c); the May 1954 survey data are from AEC (AEC 1954d); and the May 1956 survey data are from AEC (AEC 1956b). For some occupations (mostly office types), the May 1948 concentration was the average in the work area, not a DWE, so that the level shown would be higher than what the worker actually experienced.

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

Occupation	Weighted average concentration, alpha dpm/m <sup>3</sup>					
	7/1956	3/1955	6/1954	11/1953	4/1953	10/1952
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

The 10/52, 4/53, and 2/54 sets of data are from AEC (AEC 1954d); the 6/54 survey data are from AEC (AEC 1954e); the 3/55 survey data are from AEC (1955e); and the 7/56 survey data are from AEC (AEC 1956c).

Table 15. Plant 7 measured daily weighted average exposure concentrations.

Occupation	Weighted average concentration, alpha dpm/m <sup>3</sup>						
	7/1956	3/1955	6/1954	11/1953	4-5/1953	10/1952	9/1951
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	

The 9/51 survey data are from AEC (AEC 1951a); the 10/52 survey data are from AEC (AEC 1952a); the 4-5/53 and 11/53 survey data are from AEC (AEC 1954f); the 6/54 survey data are from AEC (AEC 1954g); the 3/55 survey data are from AEC (AEC 1955d); and the 7/56 survey data are from AEC (AEC 1956d).

The 5/53 data includes the screw-pulling operation, which was nonroutine.

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

Occupation	Weighted average concentration, alpha dpm/m <sup>3</sup> , 3/1955
Ionium plant operator	0.06
Ionium plant lead operator	0.1
Overall average	0.07

Survey data are from AEC (1955e). The ionium plant was the thorium processing plant, in operation from mid-1955 through March 1957. Some bench-scale processing was done in the spring of 1955 also.

Table 17. Average and highest airborne dust concentrations in the laundry (alpha dpm/m<sup>3</sup>) (Utnage 1958b, Table 2).

Operation	Concentration	
	Average	Worst
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

"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 18. Job titles and classifications, with geometry factors.

Plant	Job title or classification	Notes	Geometry classification, %		
			AP	ROT	ISO
7	36' Level operator	Subclassification of 7 Furnace operator (rotating jobs): mainly the UO <sub>2</sub> -to-UF <sub>4</sub> reactor area	---	---	---
6E	4th saw man	Mostly same as Saw man	90	10	
6	AEC engineer	Spent time in Plants 4, 6, 6E, and 7 but office was in 6	10	90	
6	AEC Office personnel	Spent time only in AEC office in Plant 6		100	
All	Area mechanic	May have worked in all buildings, but appears that he was usually dedicated to one building or process step	50	50	
6E	Asst foreman	See Shift foreman	50	50	
7	Asst plant superintendent	May have been in charge of only Plant 7 or of the whole site	10	90	
6	Asst production superintendent	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	Worked in the U products warehouse, apparently	25	75	
6	Bag inspector	Checked dust collector bags	75	25	
6	Barium operator	Worked in the barium salt addition phase of digestion	50	25	25
6E	Billet grinder	Cleaned and finished billets after recasting and before shipping	90	10	
4, 6E	Blender	See Lime blender	50	50	
6	Boiler House operator	Presumably worked to provide steam for the boildown processes		100	
4	Bomb charger	Blended UF <sub>4</sub> , Mg; charged bomb; dumped out dust collectors	75	25	
4	Bomb makeup operator	Blended UF <sub>4</sub> , Mg; charged bomb; dumped out dust collectors	75	25	
4	Bomb makeup/deslagging (slag grinding) operator	Performed combined functions of Bomb makeup operator and Slag grinding operator	75	25	
6E	Bottom "F" machine operator	Charged bomb (using F machine): UF <sub>4</sub> -Mg mixture, Mg	75		25
4, 6E	Bottom furnace operator/man	Removed assembly from recast furnace, removed mold, put in new assembly	75	25	
6E	Breakout operator/man	Removed (broke out) derby from bomb	75	25	
6	Brown furnace operator/unloader/ packager	See UO <sub>2</sub> operator/unloader/packager	75	25	
6E	Brushing man	Same as Chipper	75	25	
6E	Burnout man	Removed broken crucible, knocking lid off	80	20	
6	C-3 adjustments operator	Cleaned wash precipitate filter press; other duties	50	25	25
6	C-3 centrifuge operator	Operated and "plowed off" Bird(?) centrifuge (digestion process)	50	25	25
6	C-3 wash filter operator	Operated and cleaned the wash precipitate filter press	50	25	25
6E	Cage grinding man	Mostly same as Saw man	90	10	
4, 6E	Cage operator/man	Cleaned and finished billets after recasting; handled scrap in cage	90	10	
6E	Cage saw man	Mostly same as Saw man	90	10	
6E	Capping man	Put the valved top on the Mg-UF <sub>4</sub> drum for jolting?	75	25	
4	Carpenter	May have worked in all buildings, not dedicated to one	25	50	25
4	Casting operator/man	Operated the billet casting furnace	75	25	
6	C. Eng	See Chemical engineer	25	75	
4	Ceramic (technician?)	Split time: ceramic lab (Ceramic Pilot Plant), Production Research Lab	50	50	
4	Charger	Same as Bomb charger	75	25	
4	Charge firing (man)	Furnace operator for bomb furnace	75	25	
6E	Chemical engineer	Worked in production aspects; had production area access	25	75	
4	Chemical technician	Did chemical analyses in Analytical Lab; possibly some assays	90	10	
4	Chemist	Did chemical analyses in Analytical Lab; possibly some assays	90	10	
4	Chief chemist	Did chemical analyses in Analytical Lab; possibly some assays	90	10	
6	Chief guard	Spent time in Plants 4, 6, 6E, and 7 but base was in Plant 6		100	
4, 6E	Chipper	Deslagged and cleaned derbies (and dingots?)	75	25	
4, 6	Cleanup man	Miscellaneous cleanup activities	50	50	
4, 6E, 7	Clerk	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	Cut and replaced filter cloth for Feinc and similar filters	50	25	25
6	Cloth & Training Group lead operator	Apparently dual position: coordinated cloth ops, headed Training Grp	10	90	
6	Clothes issue man	Issued work and protective clothing in the locker rooms		100	
6E	Crucible assembler	Assembled crucible and mold assembly in billet production process	75		25
6E	Crucible loader	Loaded the crucible assembly into the recast furnace	75		25
6,6E,7	Decontamination man	Did decontamination in all plants, on boxcars, in Plant 6 Decon Room	50	25	25
7	Decontaminator	Same as Decontamination man	50	25	25
6E	Derby chipper	Same as Chipper	75	25	
4	Derby unloader	Unloaded bomb from furnace	75	25	
6	Digest area lead operator	Worked on the digestion process (up to extraction)	50	25	25
6	Digest operator	Worked on the digestion process (up to extraction)	50	25	25



Table 18 (Continued)

Plant	Job title or classification	Notes	Geometry classification, %		
			AP	ROT	ISO
4	Dingot operator/forging	Prepared, loaded, removed dingot bomb; probably operated furnace	50	25	25
6	Dispensary (personnel)	Medical-pharmaceutical personnel; no prod area access assumed		100	
6E	Electrician	May have worked in all buildings, not dedicated to one	25	50	25
4, 6E, 7	Engineer	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	Worked in the ether house (operating tanks, valves, etc.)	50	50	
6	Experimental Continuous Furnace	Pilot Plant project for eventual plant-scale use in Plant 7	25	50	25
6	Extraction area lead operator	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	Loaded Mg, UF <sub>4</sub> into bomb and sealed it; may have blended them	75		25
6E	F machine operator	Charged bomb (using F machine): UF <sub>4</sub> -Mg mixture, Mg	75		25
6	Feed operator	Loaded black oxide and other feeds for digestion; washed out feed Niagara; may have handled other aspects of the ore-to-UO <sub>3</sub> process	50	25	25
6	Feed sampling	Sampling of feed (soda sat, MGX, etc.)	50	25	25
6	Feinc operator	Operated Feinc filter; cleaned out cake; washed out feed Niagara	50	25	25
7	Filter operator	Operated solids-removal(?) filters in Slag Separation Plant (Bldg 701)	50	50	
7	Fire Marshall	Did inspections in Plants 4, 6, 6E, and 7, but base was in Plant 6		90	10
All	Foreman	Apparently dedicated to individual plant, but may have worked in more	50	50	
4	Forge press lead operator	Operated the forge press in dingot finishing	75		25
4	Forge press manipulator	Same as Forge press operator	75		25
4	Forge press operator	Operated the forge press in dingot finishing	75		25
4	Forge press salt bath man	Operated the salt bath segment of dingot finishing	75	25	
All	Fork truck operator/driver	Same as lift truck driver; some did work at SLAPS and with railcars	25	75	
4	Furnace and saw man	Divided duties: see Furnace operator and Saw man	75	25	
4, 6E	Furnace loader	Loaded bomb or crucible assembly into furnace, depending on plant	75		25
4, 6E	Furnace operator	Operated recasting (billet) furnace	75		25
6	Furnace operator	Operated the UO <sub>3</sub> -to-UO <sub>2</sub> (Rockwell) furnace	75	25	
7	Furnace operator	Job (Plant 7) rotated 36' Level, Panel Board, and Sampler & Cleanup tasks: see individual job titles	75	10	15
4	Furnace puller	Unloaded UO <sub>2</sub> -to-UF <sub>4</sub> furnace?	75	10	15
4	Furnace tender	Tended UO <sub>2</sub> -to-UF <sub>4</sub> furnace	75		25
6E	Furnace unloader	Unloaded bombs from furnace, cleaned out residue(?)	75		25
6, 6E, 7	General foreman	UF <sub>4</sub> production (for Plant 6E); or may have spent time in all plants	50	50	
6E	Graphite shop personnel	Assumed to be doing only clean work manufacturing graphite molds		100	
7	Green packager	Packaged UF <sub>4</sub> (green salt)	75	25	
4	Grinding and lead operator	Apparently work in the dingot area	50	25	25
All	Guard	Spent time in Plants 4, 6, 6E, and 7 and SLAPS but base was in 6		75	25
6	Health Office - office personnel	Assumed to spend all time in Health Office		100	
6	Health Office - other personnel	Spent time in Plants 4, 6, 6E, and 7 but base in 6; assume no production area access		100	
6	Health Office - plant monitor	Spent time in Plants 4, 6, 6E, 7 but base in 6; production area access	50	50	
6	Health Office - health surveyor	Spent time in Plants 4, 6, 6E, 7 but base in 6; production area access	50	50	
4, 7	HF operator	Spent some time at Bird centrifuge (7), in recovery areas (7), as well as in providing HF for the hydrofluorination process (UO <sub>2</sub> -to-UF <sub>4</sub> )(4,7)	10	90	
7	Hoisting (slag) operator	Worked in the Slag Separation Plant (Bldg 701)	50		50
6	Instrument Shop machinist	Worked only in Instrument Shop; some equipment contaminated	10	90	
6	Instrument Shop technician	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	Th-230 processing (mostly operating chemical tanks and filters)	75	25	
7E	Ionium plant operator	Th-230 processing (mostly operating chemical tanks and filters)	75	25	
4, 6E	Jolter	"Jolted" (air hammer?) bomb liner, other material to compress, remove	75	25	
6	K-65 sampler	See Warehouse man: K-65 sampler	90	10	
4, 6E	KB-2 lead operator	Handled all aspects of derby (KB-2 production)	75	15	10
6	Laboratory Office personnel	Worked in the Analytical Lab (Building 102)		100	
6	Laboratory personnel	Worked in the Analytical Lab (Building 102)	90	10	
6	Laundry lead operator	Handled operations at the laundry (incl contaminated items)	10	90	
6	Laundry operator	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 (raff)	Worked in the Ledoux Lab pulverizing, prepping, assaying raffinate	90	10	

Table 18 (Continued)

Plant	Job title or classification	Notes	Geometry classification, %		
			AP	ROT	ISO
6	Ledoux Lab technician (raff)	Worked in the Ledoux Lab pulverizing, prepping, assaying raffinate	90	10	
6	Ledoux Lab technician (K-65)	Worked in the Ledoux Lab assaying K-65 residue	90	10	
6	Ledoux Lab technician (MgF <sub>2</sub> )	Worked in the Ledoux Lab assaying MgF <sub>2</sub> , incl recycle MgF <sub>2</sub>	90	10	
4	LF-9 (furnace) loader	See Furnace loader, Furnace operator for Plant 4 (UO <sub>2</sub> -to-UF <sub>4</sub> )	75	25	
6	LF-9 unloader/packager	See UO <sub>2</sub> operator/unloader/packager	75	25	
6E, 7	Lift truck driver (operator)	Drove lift truck, handling miscellaneous materials, possibly at all plants, including SLAPS	25	75	
4, 6E	Lime blender	Charge blender for derby production	50	50	
4	Magnesium operator	Handled magnesium storage and disbursal; limited exposure potential?	75	25	
7	Magnesium Room operator	Handled magnesium storage and disbursal; limited exposure potential?		100	
6E	Maintenance man	May have worked in all buildings; assume production area access	50	50	
6	Maintenance Office clerk	Worked only in Maintenance Office		100	
6	Maintenance supervisor	Spent time in Plants 4, 6, 6E and 7 but base was in 6 (same person?)	25	75	
	Manufacturing	Generic term for process/storage area work	75	25	
4, 7W	Metal fab	Metal fabrication, i.e., the derby and recast or dingot areas	50	50	
6	MCW engineer	Spent time in Plants 4, 6, 6E and 7 but base was in 6	10	90	
6	MCW Lab (personnel)	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	Spent time in Plants 4, 6, 6E, and 7, but probably only in office and construction areas		100	
6	MCW Office maintenance	Spent time in Plants 4, 6, 6E, and 7, but apparently only in office areas		100	
6	MCW Office messenger	Spent time in Plants 4, 6, 6E, and 7, but probably only in office areas		100	
6	MCW Office personnel	Spent time only in MCW offices in Plant 6 (Bldg 112?)		100	
All	Mechanic	See Area mechanic	50	50	
6	Mechanic supervisor	See Maintenance supervisor	50	50	
6	Medic	Worked in dispensary presumably, but may have gone into production areas on occasion		100	
6	Metal dissolver (#1, #2)	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	Sampled scrap and other metal for U or content?	75	25	
6	MgX operator	Processed the MgX feed material	25	50	25
4	Microscopist	Worked full-time in the Microscopy Room, probably on U specimens		100	
4, 6	Miller	Performed the UF <sub>4</sub> pulverizing (4)? Milled UO <sub>3</sub> (orange oxide)(6)	50	50	
6E	Millwright	May have worked in all buildings, not dedicated to one	25	50	25
6	Nitric acid recovery operator	Worked in the nitric acid recovery area (several buildings)	50	25	25
6	Nurse	Worked in dispensary presumably, but may have gone into production areas on occasion		100	
4, 6E	Office employees	Assume they are Plants 4 and 6E production(?) office-only personnel		100	
6	Ore Room operator	Handled ore, residue: storage, lidding, delidding, cleaning drums	70	20	10
6	Outside sampling man	Sampled dust collectors; sampled drums (incl. opening and sealing)	50	50	
7	Panel board operator	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	Pickler	Worker in area where derbies were "pickled", i.e., put into acid bath	75	25	
6	Pilot Plant engineer	Participated in experimental extraction processes and like activities	25	75	
6	Pilot Plant group leader	Participated in experimental extraction processes and like activities	75	25	
6	Pilot Plant lead operator	Participated in experimental extraction processes and like activities	75	25	
6	Pilot Plant technician	Unclear what activities this Pilot Plant was carrying on	75	25	
6	Pipefitter	May have worked in all buildings, not dedicated to one	50		50
4	Plant superintendent	May have been in charge of only Plant 4 or of the whole site	10	90	
4, 6, 6E, 7	Porter	Some porters may have worked in a janitorial capacity, entering only office areas, while others apparently served production areas; may have worked in several plants or in only one		100	
6	Pot Room operator	Worked in the denitration (UO <sub>2</sub> -to-UF <sub>4</sub> ) pot room	50	25	25
6	Powder sample technician	Assume mainly did sampling and worked with small samples	75	25	
6E	Production clerk	Kept records, did inventories; assumed to spend some time in production area		100	
6E	Production machinist	Spent all time in graphite shop machining molds and the like		100	
6	Production Office clerk	Kept records, did inventories; assumed to spend some time in production area		100	
6	Production Office secretary	Assumed spent all time in office		100	
6	Prod Research Lab personnel	Worked in the Production Research Lab	90	10	
6	Production superintendent	Spent time in Plants 6, 6E, and 7 production areas and Plant 6 offices	50	50	
7	QM-2 dumper	Loaded UO <sub>3</sub> into trays for the UO <sub>3</sub> -to-UF <sub>4</sub> conversion	75	15	10

Table 18 (Continued)

Plant	Job title or classification	Notes	Geometry classification, %		
			AP	ROT	ISO
7	QM-2 hoister	Same as QM-2 dumper	75	15	10
6	QM-2 loader	See UO <sub>3</sub> loader	75	25	
6	QM-2 (orange) packager	"Gulped" (vacuum-extracted) UO <sub>3</sub> out of the pot and into drums; weighing and making up (weight) in drums, emptying dust collectors	75	15	10
6	Raffinate operator	Handled the various residues from the filters (drummed, sampled); spent up to half time in Pot Room	75	25	
6E	Recast furnace lead operator	Operated the billet casting furnace	50		50
6	Receiving clerk	Recorded and inventoried incoming shipments of ore and U products	50	50	
7	Record clerk (A, B)	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	Operated UO <sub>2</sub> (Rockwell) furnace; assumed to load UO <sub>3</sub> , unload UO <sub>2</sub>	75	25	
6E	Reduction (area) lead operator	Operated the bomb (UF <sub>4</sub> -to-U metal) furnace	50	25	25
6E	Reduction furnace operator	Operated the bomb (UF <sub>4</sub> -to-U metal) furnace	50	25	25
4,6E	Residue man	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	Worked full-time in the Safety Office		100	
7	Safety inspector	Did inspections in Plants 4, 6, 6E, and 7 (production area access)	10	80	10
4	Salt bath man	Same as Forge press salt bath man	75	25	
7	Sampler and cleanup man	Subclassification of 7 Furnace operator (rotating jobs): sampling UF <sub>4</sub> , cleanup of furnace platforms	---	---	---
6	Sample Room supervisor	Supervisor operations in the Sample Room (probably in Bldg 111)	75	25	
4,6E	Saw operator/man	Removed billet from quench tank; ground, sawed, and weighed it	90	10	
6	Security office (personnel)	Assumed to be other than guards (e.g., clerical)		100	
6,6E	Shift foreman	Assumed to be generic, although may have covered several plants; default geometry factors at right may be used	50	50	
4	Shipping & Receiving (personnel)	Handled the receipt and shipment of U products	50	50	
6	Shotgun Lab analyst	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	Blended C-liner and other slag from Plants 4 and 6 for use in bombs	75	25	
6E	Slag building operator	Ground C-liner and other slag, sorted it via shaker tables, drummed it	75	25	
4	Slag man, slag grinding operator	Mostly the same as Chipper	75	25	
6	Soluble feed operator	Loaded soda salt ("diuranate") at appropriate point in digestion process; see also Feed operator	75		25
6	Stockroom clerk	Stockroom possibly in Bldg 112. Spent time in Receiving (Bldg 101)		100	
6	Stockroom foreman	Stockroom possibly in Bldg 112. Spent time in Receiving (Bldg 101)		100	
6	Sump recovery operator	Worked on U recovery from sump fluids	25	50	25
6E	Supervisor	Probably same as Technical supervisor	50	50	
7	TA-7 hoisting operator (hoister)	Hoisted and loaded UO <sub>2</sub> into reactor for conversion to UF <sub>4</sub> (TA-7)	25	50	25
4,7	TA-7 packager	Packaged UF <sub>4</sub> (green salt)	75	25	
4	TA-7 Pilot Plant (personnel)	Assumed to be technicians and operators producing UF <sub>4</sub> (green salt)	50	50	
4	TA-7 unloader (operator)	Unloaded UF <sub>4</sub> (green salt) from hydrofluorination reactor	50	50	
7	Tables operator	Worked in the Slag Separation Plant (701) operating shaker tables	25	75	
6E	Technical engineer	Same as Chemical engineer or (Process) Engineer	25	75	
6E	Technical superintendent	May have spent time in all the plants	25	75	
All?	Technical supervisor	Unclear what duties were; probable frequent production area access	50	50	
	Tinner	Type of metal worker	25	50	25
4	Top cleaner	Cleaned top furnace in billet (YM-5) production; not Top seat man	75	25	
6E	Top "F" machine operator	Charged bomb (using F machine); UF <sub>4</sub> -Mg mixture, Mg	75		25
6E	Top furnace operator/man	Operated recasting (billet) furnace, removed crucible parts	50		50
6E	Top-off operator/man	"Topped off" bomb with slag, bolted on lid	75	25	
4	Topper	Same as Top-off operator?	75	25	
4	Top seat man	Involved in billet production, furnace area; same as Top-off operator?	75	25	
6	Trainer	Duties not clear. Assumed to train operators, especially in filter work	10	90	
6	Trainman	Associated with /oacing/unloading of railcars; perhaps was railcar dispatcher/coordinator/inspector; associated with the warehouse	25	50	10
6	Truck operator/driver	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 <sub>2</sub> (furnace) operator	Operated the UO <sub>3</sub> -to-UO <sub>2</sub> (Rockwell) furnace	75	25	
6	UO <sub>2</sub> unloader/packager	Unloaded UO <sub>2</sub> from the Rockwell furnace, packaged it	75	25	
4	UO <sub>3</sub> & brown packer	Loaded UO <sub>2</sub> into Rockwell furnace; unclear regarding UO <sub>2</sub>	75	25	

Table 18 (Continued)

Plant	Job title or classification	Notes	Geometry classification, %		
			AP	ROT	ISO
6	UO <sub>3</sub> loader	Loader UO <sub>3</sub> onto trays and into the Rockwell furnace (may have been collateral duty of the UO <sub>2</sub> furnace operator)	75	25	
6E	Upper furnace man	Same as top furnace man	50		50
6	U-con man (#1, #2)	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	Worked in office and vacuum fusion area; did some hands-on U work	90	10	
4	Vacuum fusion technician	Worked in office and vacuum fusion area; did some hands-on U work	90	10	
4	Vertical lathe (operator)	Scalped dingot after casting and before forge-pressing	75		25
6	Warehouse foreman	Handled storage of ore and U products	25	75	
6	Warehouse man: K-65 sample	New job, 1953: sampled K-65 residue, plus typical warehouse duties	90	10	
6	Warehouse man (other)	Handled storage of ore and U products	25	75	
6	Weighmaster	Duties not clear. Assumed to perform or approve ore, K-65 weighings	25	75	
6,7	Welder	May have worked in all buildings, not dedicated to one	10	90	
6E	YM-5 lead operator	Worked on billet (YM-5) casting	80	20	

Since these classifications are mostly based on later records (after the UO<sub>3</sub>-to-UF<sub>4</sub> direct process was established at Plant 7), UO<sub>2</sub> (brown oxide, LF-9) unloading and packaging classifications and UO<sub>3</sub> (orange oxide, QM-2) milling and loading classifications have been added for Plant 6.

Table 19. Uranium dust daily weighted average exposure levels, Plant 4.

Job title	Airborne dust exposures, alpha dpm/m <sup>3</sup>								
	Oct 1942 - 1946	1947	1948 - 1949	1950	1951	1952 - 1953	1954 - 1955	1956 - 1958	1957 - 1958
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	3640	3640	3640	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 (UF <sub>4</sub> -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
UO <sub>2</sub> /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 (UF <sub>4</sub> /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

This table is derived from the data given in Table 12 and from supplementary information in the references.

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 20. 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 - 1958
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, MgF <sub>2</sub>	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/UO <sub>2</sub> 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 <sub>3</sub> 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?

This table is derived from the data given in Table 13 and from supplementary information in the references.

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.

\* Outside sampling and U-Con positions began in 1955

\*\* Pilot Plant work began in 1948.

\*\*\* Milling work ended by June 1949.

\*\*\*\* These jobs apparently ended in 1954 or were subsumed in other job titles

\*\*\*\*\* 1961 dpm/m3 in 1955, 268 in 1956-58

Table 21. Uranium dust daily weighted average exposure levels, Plant 6E.

Job Title	Airborne dust exposures, alpha dpm/m <sup>3</sup>				
	Oct 1950 - Dec 1952	1953	1954	1955	1956 -1958
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

This table is derived from the data given in Table 14 and from supplementary information in the references.

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

Job title	Airborne dust exposures, alpha dpm/m <sup>3</sup>					
	1951	1952	1953	1954	1955	1956 – 1958
<b>Plant 7</b>						
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 <sub>3</sub> -to-UF <sub>4</sub> , 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/UF <sub>4</sub> ) packager	242	28	103	68	49	24
<b>Plant 7E (thorium/ionium process)</b>						
Ionium plant operator/lead operator***	X	X	X	X	0.1	0.3

This table is derived from the data given in Table 15 and from supplementary information in the references.

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.

UO<sub>3</sub> processing operations continued until July 1958 (Mallinckrodt 1994), but most other operations stopped in 1957. Plant 7E was said to be in its startup phase when the only known measurements were taken in March 1955 (AEC 1955e); these may have been taken as part of bench-scale processing (AEC 1955c). Thus as AEC (1955e) 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 an end date of March 1957 should be taken.

\* These positions began after July 1955. Clearly, this was in the pilot plant (as implied by the information in AEC 1955c).

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

\*\*\*The ionium pilot plant work began after July 1955 and continued until March 1957 (AEC 1955c).

Table 23. Early radon data, 1945.

	% Tolerance	Ventilation condition	Reference
Bldg 40 storeroom, 1000 lbs ore and active residues	724	F	MED 1945f
Bldg 40, center of storeroom between stacks of residue drums	<15	F	MED 1945j
Bldg 40, residue storage: BZ, residue work -- floor covered with residue	<24		MED 1945g
Bldg K, center of storeroom with ore and residues	90	F	MED 1945j
Bldg K storeroom, center, 2-3 drums fresh residue and open drums of ore	25	F	MED 1945f
(Bldg K) Pilot Plant storeroom with 2000-3000 lbs of ore	50	F	MED 1945m
(Bldg K) Pilot Plant, over digestion tank during addition of ore	147	N	MED 1945m
(Bldg K) Pilot Plant, center of Pilot Plant during digestion	132	N	MED 1945m
(Bldg K) Pilot Plant, over digestion tank 15 minutes after digestion	18	N	MED 1945m
(Bldg K) Pilot Plant, N end, away from operation	216	N	MED 1945m
Bldg K, N end of room, away from operation	<15	N	MED 1945h
Bldg K, center of room	<22	N	MED 1945h
Bldg K, center of room, no operation	26	N	MED 1945j
(Bldg K) Pilot Plant, discharge end of Feinc filter during filtration	<15	N	MED 1945m
Bldg K, S end near Feinc filter, not operating	29	N	MED 1945j
Bldg K, S end of plant near Feinc filter, not operating	<15	N	MED 1945h
Bldg K, vicinity of Feinc filter, no operation	<12	W	MED 1945f
Bldg K, work desks at NE corner	12	W	MED 1945f
Bldg K, work desks, center of room	12	W	MED 1945f
Bldg K, alley outside at exhaust	<11		MED 1945f
Bldg K alley, directly under stack emitting brown fumes	<15	N	MED 1945j
Storeroom on RR siding, between 2 tiers of residue drums, 10' from each	32		MED 1945g
Plant 4, ore storage: center of room with 1800 lbs ore	211	F	MED 1945h
Plant 4(?), W end of ore room during full operation	65	F, N	MED 1945i
Plant 4, W end or ore milling area near sifter, full operation	58	F, N	MED 1945i
Plant 4, center of ore milling room near mill	113	F, N	MED 1945i
Plant 4, operator's hand when unloading ball mill, 300 lbs of ore, fan on	407	F	MED 1945f
Plant 4, near mill, 10 min after unloading, fan on	<15	FW	MED 1945f
Plant 4, opening at top of empty mill	<25		MED 1945f
Plant 4, ore milling area: no operation for 3 days	30	N	MED 1945h
Plant 4, residue storage: directly above drums of residue	763		MED 1945g
Plant 4, laboratory: center of cage	<26	N	MED 1945h
Plant 6 ore storage warehouse, SE corner	55	N	MED 1945k
Plant 6 ore storage warehouse, center of empty aisle	21	N	MED 1945k
Inside [unspecified] lab, no activity	<11		MED 1945f

\* Fan on (F), windows open (W), natural ventilation (N)

The data above was taken at various times in 1945. The tolerance level was  $1.0 \times 10^{-10}$  Ci/L of radon.

"Bldg K" was apparently Building K1E, also known as a pilot plant.



Table 24. Measured radon concentrations, 1947-1949, in units of  $1 \times 10^{-10}$  Ci/L.

	1947				1948					1949				
	No.	Min	Med/ Mean	Max	No.	Min	Med/ Mean	Max	GSD	No.	Min	Med/ Mean	Max	
<b>INDOOR AREAS</b>														
Ore Milling					11	0.03	0.39	0.81						
Ore Rm: open drums*											0.58	8.50	260	
Ore Storage					27		0.46		3.28					
Ore Storage					58	0.03	0.30	2.86						
Thawing oven, K-65														
Heat off, fan off										28		3.84		
Heat off, fan on										36		0.60		
Heat on, fan on										18		4.06		
Outside, heat on										12		1.09		
Outside, heat off										24		0.07		
Thawing oven, K-65**										4	540	622	805	
Scalehouse			0.10		21	0.00	4.05	33		44	0.03	0.45	4.4	
Scalehouse	2		.60		193	0.03	2.02	32.8		158	0.03	1.03		
Scalehouse	5	.09	.27	.84										
Scalehouse/Ore Storage/Warehouse	4	.55	.69	.92								5.00		
Scalehouse Sample Rm	46	0.0	2.40	13	6	0.22	4.10	19						
Scalehouse Sample Rm	3	.06	.09	.12	68	0.03	2.84	25						
Digest/Feed	4	.05	.23	.52	57	0	0.39	7.8						
Extraction Cells					14	0	1.08	4.1						
Centrifuge Area	2		.38		74		1.00			74	0.00	0.76	3.86	
Centrifuge Area					141	0	1.13	12		48	0	1.55	12	
Feinc/Filter/C-3/Raffinate/Cloth Storage/Niagara	4	.08	.12	.2	9		0.18		1.98					
Feinc/Filter/C-3/Raffinate/Cloth Storage/Niagara					56	0.00	0.05	9.74						
Feinc/Filter/C-3/Raffinate/Cloth Storage					186	0	12.3	894		172	0	0.75	468	
Ledoux Lab					30	0	0.08	0.4						
Recovery area (aisle betw Recovery and feed makeup)	4	.05	.16	.31										
Sump by M-19, skid of recovery cake beside sump			.26											
Maintenance Shop (aisle between shop and Feincs)	4	.04	0.11	.18										
Dispensary	3	.04	.07	.11										
<b>YARDS AND OTHER OUTDOOR AREAS</b>														
General Plant 6					35	0	0.19	2.1						
Bldg 104/Scalehouse	3	.07	0.17	.36	9		0.07		1.47					
Bldg 104 (Pilot Plant)					7	0	0.15	0.6						
Warehouse					17		0.10		2.05					
Warehouse exhaust					33	0.1	0.91	3.3						
Near warehouse, K-65 drum welding					8		0.11		2.84					
Labs, guard office					8		0.06		1.38					
Parking lot area					9		0.13		1.56					
Scalehouse intake/exhaust					3		0.12		2.06					
Scalehouse exhaust					18		0.13		3.08					
Scalehouse exhaust					1		0.93							
Scalehouse exhaust					24	0	2.2	49						
Ore storage intake/exhaust					6		0.68		2.44					
Ore storage exhaust					2		0.31		1.77					
Railcar, ore, fans on*					2	0.5	<1.00	7						
Drums outside Scalehouse					4	0.0	0.39	0.90						
K-65 drums in sun**										2	637	654	670	
<b>SLAPS</b>														
In K-65 storage shed					5		4.2		3.2					
At K-65 storage shed												19		
15 ft from K-65 shed					2	0.04	0.99	24	93					
25-30 ft, K-65 shed					2		7.8		1.6			6.6		
50 ft from K-65 shed					3		3.8		2.1			4.4		
50-120 ft, K-65 shed					13		2.1		5.0					
100 ft from K-65 shed												2.4		
150 ft from K-65 shed, at guard shack					3	0.00	0.21	1.1	14			1.4		
180-250 ft, K-65 shed					5		1.1		5.8					
200 ft from K-65 shed												0.94		

## Table 24 (Continued)

Values in this and the next table are taken from AEC (AEC 1948b; AEC 1949; AEC 1948j; AEC 1949j) and MCW (various, MCW 1950b; MCW 1948i; MCW 1948e; MCW 1948j; MCW 1948e; MCW 1951c; MCW 1949f).

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 were 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.

Control readings were taken in the Dispensary. Measurements were taken at face level whenever possible.

\* The single asterisk items are an exception to the note above. For the Ore Room case, the value in the Min column is the point at which the concentration drops below  $1 \times 10^{-10}$  Ci/L (25 minutes), the value in the Mean column is the average concentration over the elapsed time (i.e., the 25 minutes), and the value in the Max column is the value at time zero. For the railcar case, the value in the Min column is the average of readings at about 3.5 hours (stable concentration), the value in the Mean column is the point at which the concentration drops below  $1 \times 10^{-10}$  Ci/L (about 20 minutes), and the value in the Max column is the average value at time zero. More information can be found in MCW (MCW 1949m) and MCW (MCW 1948h) respectively.

\*\* The double asterisk items correspond to samples taken of the standard 30-gallon K-65 drums sitting inside sealed 55-gallon drums (to facilitate sampling) after heating in the thawing oven or being allowed to heat in the sun (MCW 1949r); these thus represent the maximum radon evolved over 2-4 hours of heating, concentrated in the larger drum head space but not actually in the breathing zone.

Table 25. Measured radon concentrations, 1950-1957, in units of  $1 \times 10^{-10}$  Ci/L.

	1950			1951			1952			1953			1954				1955			1956			1957					
	No.	Med/ Mean	GSD	No.	Med/ Mean	GSD	No.	Med/ Mean	GSD	No.	Med/ Mean	GSD	No.	Min	Med/ Mean	Max	GSD	Min	Med/ Mean	Max	No.	Med/ Mean	GSD	No.	Med/ Mean	GSD		
<b>INDOOR AREAS</b>																												
Scalehouse				35	0.09	5.9	95	0.09	6.0	66	0.01	5.0																
Scalehouse		1.02																										
Scalehouse/Ore Storage/Warehouse													74		0.01		5.4	5	0.01	1.00								
Scalehouse Sample Room																	0.09	0.24	0.50									
Digest/Feed				2	0.05	11				17	0.12	5.2	57		0.03		3.8				18	0.01	5.1	3	0.03	5.5		
Extraction Cells				33	0.36	5.9	92	0.37	5.3	59	0.28	3.8	101		0.26		5.8				33	0.01	7.0	3	0.01	8.7		
Centrifuge Area	8	0.11	2.3	35	0.06	4.8	95	0.12	5.0	55	0.05	5.6	51		0.07		6.5				7	0.01	5.2	3	0.01	1.0		
Feinc/Filter/C-3/ Raffinate/Cloth Storage/Niagara		34		34	0.18	3.7	94	0.14	4.1	60	0.10	4.8	114		0.14		6.2	<.01	0.50	1.7	41	0.07	5.8	5	0.01	6.8		
Orange Packing													1	0.12	0.12	0.12												
Pot Room													2		0.02		2.2											
Ledoux Lab										6	0.10	1.3	10		0.02		3.4											
Shotgun Lab													2		0.04		5.8											
Other Lab (Research/Con-trol/X- ray/MY)													3		0.01		1.0						2	0.04	8.0			
6E Breakout													3		0.01		1.0											
6E Recast													4		0.01		1.0											
Recovery area													1	0.11	0.11	0.11												
Decontamination Room													1	0.01	0.01	0.01												
Metal Dissolver Bldg													4		0.01		2.6											
NA House													3		0.01		16											
Ether House													2		0.02		2.7											
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		1.0											
Maintenance Shop													3		0.04		6.9											
Smoking Room													1	0.01	0.01	0.01												
Production Office													1	0.01	0.01	0.01												
Dispensary													2		0.04		6.1											
<b>YARDS AND OTHER OUTDOOR AREAS</b>																												
Ether House/ Bldg 109													1	0.01	0.01	0												
Drum storage outside Bldg 115													3		0.30		8.6											

Values in this and the next table are taken from AEC (AEC 1948b; AEC 1949; AEC 1948j; AEC 1949j) and MCW (MCW various, MCW 1950b; MCW 1948i; MCW 1948e; MCW 1948j; MCW 1948e; MCW 1951c; MCW 1949f).

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 were 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. Potential radon exposures from thorium processing.

Isotope	Maximum radon content, Ci	Average concentration, Ci/L
Rn-220	$8.46 \times 10^{-4}$	$5.37 \times 10^{-13}$
Rn-222	0.158	$1.00 \times 10^{-10}$

The maximum radon content is from Table 6, assuming a 15-year buildup.

Emanation is based on an assumption of 1% radon content outgassed to the room; this should be conservative, since most radon 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 1.75 years (July 1955-March 1957), or 3500 hours. Thus the emanation per working hour is 1% of the maximum ore content, divided by 3500 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 x 3 m x 2.5 m (about 10 ft x 10 ft x 7.5 ft), a conservatively small process area. This gives an air volume of 22,500 liters in the room and an hourly 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 27. Contamination levels and associated dose rates from work clothing.

Surface contamination measurements for various types of work clothing					
Item	Spot		Whole garment or group		Contamination notes
	Max	Average	Max	Average	
Regulated coveralls	80% had $\geq 1$ -2 in <sup>2</sup> spot >3000 cpm	Most coveralls had more than 1 spot >1 mr/hr	60% had $\geq 1$ mrep/hr over whole garment	1.5 mrep/hr; range, 0.2 to 12; 100% had avg >100 cpm per 2 in <sup>2</sup>	Apparent U spots on 70%; area was from 10 cm <sup>2</sup> to 30% of total area
Nonregulated coveralls	30% have more than 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 <sup>2</sup>	All: heavy
Shoe covers				>90% have >1,000 cpm	"Destrehan": "high"
Gloves, contaminated on the inside			47 mrep/hr	Range 23-47 mrep/hr	Beta dose rate, on contact with the inside
Shielding of beta radiation by various materials					
Item	Distance	Reduction factor	Std deviation		
Coveralls, 9-oz denim	5 inches-3 ft	.78	7.5%		
Gloves, neoprene-covered cotton		.50			3 gloves were measured

Measurements of surface contamination on clothing are from Utnage (1958b); measurements of beta shielding and exposure rates inside gloves are from AEC (AEC 1950j). Measurements were taken after wearing but before washing; gloves contaminated on the inside were taken at random from workers actually using the gloves and were not discarded gloves.

The beta reduction factor is the ratio of shielded dose rate to unshielded dose rate. The source was a sheet of uranium metal, 18" x 24", in equilibrium with UX1 and UX2.

The "smocks" appear to be cover clothing.

Table 28. Surrogate (comparable) worker inhalation intakes calculated from urinalysis data, 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)	2.51E+04	1.62	21	8.29E+04	1.87	13	2.12E+04	1.78	7
	Mostly Cloth, Raffinate, Feinc	--	--	--	5.61E+04	2.71	3	2.87E+04	1.16	3
	Mostly Digest	2.10E+04	1.70	3	4.45E+04	2.54	3	*1.98E+04	--	1
	Mostly Ether House	2.19E+04	1.64	5	3.08E+04	1.22	4	2.32E+04	1.00	3
	Mostly Packaging	--	--	--	1.28E+05	5.13	3	--	--	--
	Mostly Pot Room, Orange Oxide	--	--	--	1.80E+05	2.01	5	2.26E+04	2.32	5
		Period 12			Period 1			Period 2		
	Mostly re Room	*2.45E+05 - 4.96E+04	--	2	*4.83E+04 - 5.96E+04	--	2	*3.84E+04	--	1
Plant 6E		Period 123			Period 1			Period 23		
	Generic (mixed, miscellaneous, or unknown)	2.98E+04	1.57	12	4.79E+04	2.29	4	3.12E+04	1.55	13
	Bomb Step (UF4→Derby)	3.19E+04	1.40	3	2.30E+04	1.51	4	2.59E+04	1.94	6
	Recast (Derby→Ingot)	*2.49E+04 - 2.02E+04	--	2	4.71E+04	1.78	3	3.44E+04	1.66	4
		Period 12								
	Graphite Shop	1.56E+04	1.57	3						
Plant 4		Period 123			Period 1			Period 23		
	4 Metal (Derby, Ingot)	--	--	--	1.24E+05	2.54	11	--	--	--
	4 Pilot Plant (Dingot, Metallurgical, etc.)	*1.65E+04 - 1.04E+04	--	2	2.29E+04	2.40	3	2.92E+04	1.62	8
Plants 4 & 7		Period 123			Period 1					
	(Green Salt)	UF4 Production Work, First at 4, Then at 7	1.81E+04	1.57	8	1.18E+05	4.48	7		
Plant 7		Period 23			Period 2					
	Generic (mixed, miscellaneous, or unknown)	1.67E+04	1.50	16	2.18E+04	1.87	7			
Multi-Plant		Period 123			Period 1			Period 23		
	AEC	*7.20E+03 - 6.94E+03	--	2	1.96E+04	1.59	5	*6.01E+03 - 1.60E+04	--	2
	Decon/Cleanup	1.44E+04	1.23	3	--	--		--	--	--
	Boiler House/Power House	1.11E+04	1.22	6	1.73E+04	1.55	6	*1.23E+04	--	1
	Engineering	1.08E+04	1.40	7	3.38E+04	1.55	10	9.71E+03	1.25	10
	Instrument Shop	1.26E+04	1.30	6	2.13E+04	1.91	7	--	--	--
	Laboratories (Anal., Research, Ledoux, etc.)	1.11E+04	1.50	24	2.30E+04	2.10	22	1.17E+04	1.42	23
	Laundry	1.10E+04	1.43	6	1.73E+04	2.82	8	*9.06E+03 - 172.20E+04	--	2
	Maintenance									
		Carpenter	*9.17E+03	--	1	--	--	--	--	--
		Electrical/Electrician	1.66E+04	1.55	7	5.19E+04	1.63	7	--	--
		Insulator/Pipe Coverer	*3.25E+04	--	1	--	--	--	--	--
		Machinist/Machine Shop	*4.17E+04	--	1	--	--	--	--	--
	Mechanic/Millwright	1.75E+04	1.72	10	7.05E+04	1.79	9	2.40E+04	1.66	4
	Miscellaneous/Mixed	1.46E+04	1.45	12	3.57E+04	2.22	12	--	--	--

Table 28 (Continued)

Category	Type	Median or *Actual	GSD	No. Cases	Median or *Actual	GSD	No. Cases	Median or *Actual	GSD	No. Cases
Multi-Plant, continued	Oiler	*1.76E+04	--	1	--	--	--	--	--	--
	Painter	1.49E+04	1.42	5	1.70E+04	1.56	6	--	--	--
	Pipefitter	2.42E+04	2.00	7	2.65E+04	2.33	9	--	--	--
	Rigger	*3.24E+04 - 1.48E+04	--	2	--	--	--	--	--	--
	Tinner	*2.49E+04	--	1	*3.23E+04	--	1	--	--	--
	Welder	2.62E+04	1.54	7	3.30E+04	1.35	6	*6.63E+03 - 9.43E+03	--	2
	Office Workers	9.74E+03	1.36	23	1.98E+04	1.66	15	1.10E+04	1.81	6
	Porter/Custodian	1.12E+04	1.30	7	2.94E+04	2.45	9	8.55E+03	1.24	3
	Safety & Health, Fire	8.23E+03	1.37	3	2.06E+04	1.95	6	1.35E+04	1.87	5
	Shipping & Receiving, Warehouse, Storeroom, Fork Truck Operator	1.11E+04	1.46	22	1.52E+04	2.32	20	9.63E+03	1.20	3
	Supervision & Management (where not specified by plant)	1.95E+04	1.48	7	3.46E+04	2.88	7	--	--	--

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

The sample size was assumed to be 1.4 l; the assumed activity equivalence is .676 pCi per ug nat U (or 676 pCi/mg); the sample data were 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 pCi per mg U x 1.4 l = 946 pCi-l/mg, 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 3.45 x 10<sup>4</sup>.

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 and Type M was used. 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 29A. Annual inhalation intakes, Plants 1 and 2, April 1942-1945.

Job title	Intake, pCi/yr
Barium operator	1.96E+03
Boiler/Ether House/Nitric acid operator	5.02E+04
Centrifuge/wash filter operator	6.19E+05
Chemist (generic)	2.67E+05
Cloth operator	7.26E+05
Crafts: Carpenter/Pipefitter/Welder	1.37E+05
Digest/Extraction/Reduction operator	7.48E+05
Dispensary: Nurse/Medic/Other (personnel)	1.91E+05
Engineer (research or chemical)	5.02E+04
Feinc/Feed operator	1.07E+06
Foreman//Technical supervisor	1.76E+05
Furnace operator	2.70E+07
Guard/Chief guard	3.49E+04
Health/Safety field personnel	5.02E+04
Health/Security office personnel	1.64E+04
Instrument Shop machinist/technician	2.75E+05
<b>Laboratory (generic)</b>	4.89E+05
Laboratory office personnel	1.09E+05
Laboratory personnel (chemist, technician)	2.67E+05
Maintenance supervisor	5.46E+04
<b>Manufacturing (generic)</b>	7.26E+05
Mechanic/Area mechanic	2.06E+05
Miller (UO <sub>3</sub> QM-2)	1.37E+07
<b>Office (generic)</b>	5.46E+04
Office, administrative: Clerk/Office maintenance/Messenger/Porter/AEC	5.46E+04
Office, Production and Receiving: Bookkeeper*	3.13E+05
Office, Production and Receiving: Clerk/Secretary	1.76E+05
Ore Area/Room operator	1.50E+07
Pot Room operator	8.48E+06
Production superintendent/Asst production superintendant	2.73E+04
QM-2 (orange) loader	5.80E+06
QM-2 (orange) packager	1.53E+06
Raffinate/Sump operator	2.98E+05
Stockroom foreman/clerk	2.29E+04
Truck/forktruck operator/driver	8.18E+04
UO <sub>2</sub> /LF-9/Brown packager/unloader	4.25E+07
Warehouse foreman/assistant foreman/warehouseman/railcar handling	2.14E+05
<b>Workman (generic)</b>	7.26E+05

The bolded entries represent generic choices if the specific job title cannot be determined. The generic entries represent medians for the job titles associated with the generic process.

\* The "bookkeeper" title in early film badge records appears to indicate a production area accountability clerk, not an office worker. Thus 25% production area access is assumed.

Table 29B. Annual inhalation intakes, Plant 4, October 1942-1958.

Job title	Intake, pCi/year								
	Oct 1942 - 1946	1947	1948 - 1949	1950	1951	1952 - 1953	1954 - 1955	1956	1957- 1958
Blender/Bomb makeup	3.28E+06	3.28E+06	3.28E+06	2.29E+05	6.98E+04	6.98E+04	3.60E+04	9.27E+04	---
Bomb charger/ Charger	3.28E+06	3.28E+06	3.28E+06	2.29E+05	6.98E+04	6.98E+04	3.60E+04	9.27E+04	---
Cage operator/man	3.98E+06	3.98E+06	3.98E+06	2.07E+05	---	---	---	---	---
Carpenter/Other craft	1.53E+05	1.53E+05	1.53E+05	9.16E+04	1.64E+04	1.64E+04	2.40E+04	2.40E+04	---
Casting operator	5.56E+06	9.93E+05	1.07E+06	1.53E+05	5.24E+05	5.24E+05	1.20E+05	1.20E+04	---
Charge firing (man)	1.02E+06	9.93E+05	1.07E+06	1.53E+05	---	---	---	---	---
Chemist/technician: miscellaneous	4.36E+04	4.36E+04	4.36E+04	4.36E+04	7.64E+03	7.64E+03	1.09E+04	1.09E+04	---
Chemist/technician: vacuum fusion	---	---	---	---	---	6.44E+04	6.44E+04	6.44E+04	---
Chipper	2.06E+06	2.06E+06	9.93E+05	1.53E+05	1.53E+05	1.53E+05	1.53E+05	1.53E+05	1.53E+05
Cleanup man	2.06E+06	2.06E+06	9.93E+05	1.53E+05	1.53E+05	1.53E+05	1.53E+05	1.53E+05	1.53E+05
Dingot lead operator	1.02E+06	6.87E+05	6.11E+05	3.82E+04	2.07E+04	2.07E+04	8.95E+03	2.07E+04	---
Dingot operator	3.28E+06	3.28E+06	3.28E+06	2.29E+05	6.98E+04	6.98E+04	3.60E+04	9.27E+04	---
Derby unloader	3.82E+05	3.05E+05	1.37E+06	1.91E+05	---	---	---	---	---
Engineer/Technical supervisor	1.91E+05	1.91E+05	1.91E+05	6.11E+04	1.31E+04	1.31E+04	1.09E+04	2.51E+04	---
Foreman/Shift foreman	1.91E+05	1.91E+05	1.91E+05	6.11E+04	1.31E+04	1.31E+04	1.09E+04	2.51E+04	---
Forge press operator/manipulator	---	---	---	---	---	2.51E+04	2.51E+04	2.51E+04	---
Furnace and saw man	---	---	---	---	1.96E+04	1.96E+04	1.96E+04	1.96E+04	---
Furnace loader (UF <sub>4</sub> -derby)	3.67E+06	3.67E+06	2.44E+06	3.05E+05	---	---	---	---	---
Furnace (recast) operator	5.56E+06	9.93E+05	1.07E+06	1.53E+05	5.24E+05	5.24E+05	1.20E+05	1.20E+04	---
Furnace puller	1.02E+06	6.87E+05	6.11E+05	3.82E+04	2.07E+04	2.07E+04	8.95E+03	2.07E+04	---
Furnace tender	6.11E+05	6.11E+05	3.82E+05	7.64E+04	---	---	---	---	---
Guard/Chief guard	3.05E+04	3.05E+04	3.05E+04	3.05E+04	3.05E+04	6.33E+03	2.95E+03	7.75E+03	---
HF (fluorination) operator	6.22E+05	6.22E+05	6.22E+05	7.64E+04	---	---	---	---	---
Jolter	3.82E+06	3.82E+06	5.35E+05	7.64E+04	---	---	---	---	---
KB-2 lead operator	1.02E+06	6.87E+05	6.11E+05	3.82E+04	2.07E+04	2.07E+04	8.95E+03	2.07E+04	---
<b>KB-2/Derby production (generic for reduction operations)</b>	1.02E+06	9.93E+05	1.07E+06	1.53E+05	6.98E+04	6.98E+04	3.60E+04	9.27E+04	1.53E+05
Laboratory: ceramics/microscopy	---	---	---	---	1.96E+04	1.96E+04	1.96E+04	1.96E+04	---
Lime blender/Magnesium operator	7.64E+04	7.64E+04	7.64E+04	3.82E+04	---	---	---	---	---
<b>Manufacturing (generic)</b>	1.02E+06	9.93E+05	1.07E+06	1.53E+05	2.07E+04	2.29E+04	2.51E+04	2.40E+04	1.53E+05
Mechanic/Area mechanic	3.82E+05	3.82E+05	3.82E+05	9.16E+04	1.64E+04	1.64E+04	2.40E+04	2.40E+04	---
Miller-mixer (UF <sub>4</sub> /TA-7)	5.12E+06	5.12E+06	1.07E+06	7.64E+04	---	---	---	---	---
Office: Plant superintendent/ Clerk/Other	4.58E+04	4.58E+04	4.58E+04	4.58E+04	4.58E+04	6.33E+03	2.95E+03	7.96E+03	---
Ore miller/handler	7.86E+05	---	---	---	---	---	---	---	---
Porter	1.22E+05	1.22E+05	1.22E+05	6.11E+04	6.11E+04	6.33E+03	2.95E+03	4.36E+04	---
Residue man	---	---	---	---	---	---	3.05E+04	3.05E+04	---
Salt bath man/Vertical lathe operator	---	---	---	---	---	---	3.05E+04	3.05E+04	---
Saw operator/man	2.06E+06	2.06E+06	9.93E+05	1.53E+05	1.53E+05	1.53E+05	1.53E+05	1.53E+05	1.53E+05
Shipping & Receiving	1.37E+05	1.37E+05	1.37E+05	1.37E+05	1.64E+04	1.64E+04	2.40E+04	2.40E+04	---
Slag man/Slag grinding operator	1.53E+05	1.53E+05	2.29E+05	7.64E+04	---	---	---	---	---
TA-7 packager	7.87E+06	7.87E+06	7.87E+06	2.67E+05	---	---	---	---	---
TA-7 unloader (operator)	1.42E+07	1.42E+07	1.68E+06	2.29E+05	---	---	---	---	---
Top cleaner	5.12E+06	5.12E+06	1.07E+06	7.64E+04	---	---	---	---	---
Topper	9.16E+05	9.16E+05	2.52E+06	2.29E+05	---	---	---	---	---
Top seat man	5.56E+06	9.93E+05	1.07E+06	1.53E+05	5.24E+05	5.24E+05	1.20E+05	1.20E+04	---
<b>UF4/TA-7/green production (generic)</b>	2.80E+06	2.18E+06	8.46E+05	8.40E+04	1.85E+04	1.85E+04	1.65E+04	2.24E+04	---
UO2/LF-9 loader/packer	4.58E+06	3.67E+06	2.44E+06	3.05E+05	---	---	---	---	---
YM-5 lead operator	1.02E+06	6.87E+05	6.11E+05	3.82E+04	2.07E+04	2.07E+04	8.95E+03	2.07E+04	---
<b>YM-5/billet/dingot production (generic for recast operations)</b>	3.63E+06	9.95E+05	1.07E+06	1.53E+05	6.98E+04	4.75E+04	3.05E+04	2.07E+04	---

Although plant operations likely ended in 1957, the end year of operations is taken conservatively to be 1958 (see Section 8.0).

The bolded entries represent generic choices if the specific job title cannot be determined. The generic entries represent medians for the job titles associated with the generic process.



Table 29C. Annual inhalation intakes, Plant 6, 1946-1958.

Job title	Intake, pCi/year							
	1946 - 1948	1949	1950	1951	1952	1953	1954	1955 - 1958
AEC engineer	---	---	---	7.64E+03	3.38E+04	1.08E+04	2.07E+04	2.07E+04
Barium operator	1.96E+03	1.96E+03	1.37E+05	1.57E+05	1.42E+05	4.15E+04	---	---
C-3 centrifuge/wash filter/adjustments operator	6.19E+05	6.19E+05	1.53E+05	1.53E+05	4.58E+05	6.87E+05	8.62E+04	8.62E+04
Cleanup man/utility operator	---	---	---	1.06E+05	1.06E+05	1.03E+05	1.41E+05	9.60E+04
Cloth operator	7.26E+05	7.26E+05	2.67E+05	2.67E+05	1.00E+05	2.07E+04	1.96E+04	1.96E+04
Cloth & Training Group lead operator/trainer	2.75E+06	2.75E+06	2.52E+05	2.52E+05	2.51E+04	2.73E+04	1.96E+04	1.96E+04
Clothes issue man	1.00E+05	1.00E+05	1.00E+05	1.00E+05	1.00E+05	1.03E+04	2.07E+04	1.96E+04
Crafts: Carpenter/Pipefitter/Welder	1.37E+05	1.37E+05	1.07E+05	3.05E+04	3.05E+04	3.05E+04	3.16E+04	2.62E+04
Decontamination man/U-con man*	1.08E+05	1.08E+05	1.08E+05	1.08E+05	6.55E+04	2.07E+04	2.40E+04	1.85E+04
Cloth/Digest/Reduction operator, Outside sampling	7.48E+05	7.48E+05	2.67E+05	4.04E+05	1.00E+05	4.47E+04	6.55E+04	2.40E+04
Dispensary: Nurse/Medic/Other (personnel)	1.91E+05	1.91E+05	6.11E+04	1.08E+05	4.58E+04	6.87E+03	3.82E+03	1.42E+03
Boiler/Ether Hse/Extraction/Nitric acid rec'y operator	5.02E+04	5.02E+04	1.08E+05	5.46E+04	4.80E+04	2.07E+04	1.20E+04	3.71E+04
"Experimental Continuous Furnace": Pilot Plant project	---	9.32E+06	9.32E+06	---	---	---	---	---
Feinc/Feed/Soluble feed operator	1.07E+06	1.07E+06	1.68E+05	1.91E+05	1.64E+05	1.09E+05	1.05E+05	4.47E+04
Foreman/General foreman/Shift foreman/Technical supervisor	1.76E+05	1.76E+05	1.76E+05	1.05E+05	8.84E+04	3.27E+04	2.73E+04	2.07E+04
Furnace operator	2.70E+07	2.70E+07	1.53E+06	1.64E+05	1.05E+05	6.00E+04	3.60E+04	1.31E+04
Guard/Chief guard	3.49E+04	3.49E+04	3.49E+04	1.96E+03	2.40E+04	1.75E+04	1.53E+04	1.09E+04
Health/Security Office personnel; Engineer (MCW, chemical)	1.64E+04	1.64E+04	1.64E+04	7.64E+03	1.53E+04	1.64E+04	1.20E+04	8.84E+03
Health Office: health surveyor/plant monitor	5.02E+04	5.02E+04	5.02E+04	4.58E+04	1.53E+04	1.64E+04	1.75E+04	1.64E+04
Instrument Shop machinist/technician	2.75E+05	2.75E+05	5.56E+04	6.55E+04	4.36E+04	1.85E+04	4.80E+04	1.31E+04
Laboratory Office personnel	1.09E+05	1.09E+05	1.09E+04	6.11E+03	6.11E+03	6.11E+03	2.18E+03	4.58E+04
<b>Laboratory: chemist/technician (generic/MCW/Shotgun)</b>	4.89E+05	2.67E+05	2.62E+04	2.73E+04	2.51E+04	3.27E+04	1.09E+04	4.58E+04
Laundry operator/lead operator	---	---	---	4.91E+03	2.07E+04	1.20E+04	2.07E+04	6.76E+03
Ledoux Lab technician/asst technician - raffinate, MgF <sub>2</sub>	2.06E+05	2.06E+05	9.93E+04	4.58E+05	1.53E+05	4.25E+04	8.84E+03	2.95E+04
Ledoux Lab technician (K-65)	2.29E+06	2.29E+06	1.53E+06	2.07E+06	4.80E+05	2.95E+04	8.18E+03	2.29E+04
LF-9/brown/VO <sub>2</sub> packager/unloader	4.25E+07	4.25E+07	3.97E+05	3.82E+05	3.82E+05	---	---	---
Maintenance supervisor	5.46E+04	5.46E+04	5.46E+04	4.15E+04	4.58E+04	1.09E+04	1.42E+04	1.53E+05
<b>Maintenance (generic)</b>	2.06E+05	2.06E+05	2.95E+03	3.05E+04	3.05E+04	3.05E+04	3.16E+04	2.62E+04
<b>Manufacturing/Mfg (generic)</b>	1.07E+06	7.48E+05	2.60E+05	1.77E+05	1.42E+05	4.47E+04	3.60E+04	2.62E+04
Mechanic/Area mechanic: C-3, digest, feed, furnace, Ore Room, raffinate, Ether/Nitric Acid House	2.06E+05	2.06E+05	2.95E+03	3.05E+04	3.05E+04	3.05E+04	3.16E+04	2.62E+04
Metal dissolver (#1, #2)	---	---	---	2.23E+05	2.23E+05	2.23E+05	2.23E+05	2.23E+05
Metal room sampler	---	---	---	4.58E+05	4.58E+05	4.58E+05	4.58E+05	4.58E+05
MgX operator	1.03E+05	1.03E+05	1.03E+05	1.03E+05	5.67E+04	7.42E+04	3.16E+04	3.16E+04
Miller (UO <sub>3</sub> QM-2)	1.37E+07	1.37E+07	---	---	---	---	---	---
Office (generic)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Office, MCW: Clerk/Office maintenance/Messenger/ Porter /Expeditior	5.46E+04	5.46E+04	5.46E+04	5.24E+04	5.24E+04	2.18E+04	1.85E+04	1.64E+04
Office: MCW - Other, AEC - all AEC except Engineer	5.46E+04	5.46E+04	5.46E+04	0.00E+00	7.31E+03	3.16E+03	2.40E+03	2.40E+03
Office, Production/Receiving: Clerk/Secretary	1.76E+05	1.76E+05	5.67E+04	1.08E+05	1.85E+04	1.96E+04	2.07E+04	9.93E+03
Ore Room operator***	1.50E+07	3.82E+05	4.28E+05	4.04E+05	1.85E+05	1.53E+05	1.53E+05	---
Pilot Plant engineer	1.34E+05	1.34E+05	5.78E+04	6.33E+04	4.25E+04	3.38E+03	7.53E+03	8.18E+03
Pilot Plant lead operator/group leader	2.67E+05	2.67E+05	1.15E+05	1.27E+05	8.40E+04	6.66E+03	9.60E+03	8.40E+03
Pilot Plant technician	2.67E+05	2.67E+05	1.15E+05	1.27E+05	8.40E+04	6.55E+03	1.00E+04	2.12E+06
Pot Room operator	8.48E+06	8.40E+05	3.67E+05	1.09E+05	2.07E+05	4.91E+04	1.23E+05	2.55E+05
Powder sample technician	3.44E+06	3.44E+06	2.37E+05	2.37E+05	6.22E+04	6.22E+04	6.22E+04	6.22E+04

Table 29C (Continued)

Job title	Intake, pCi/year							
	1946 - 1948	1949	1950	1951	1952	1953	1954	1955 - 1958
Power House (generic)	5.02E+04	5.02E+04	1.08E+05	5.46E+04	4.80E+04	2.07E+04	1.20E+04	3.71E+04
Production Research Lab personnel	9.16E+04	9.16E+04	1.31E+04	3.27E+04	1.42E+04	5.46E+03	2.18E+03	4.04E+03
Production superintendent/Asst production superintendant	2.73E+04	2.73E+04	2.73E+04	2.73E+04	2.84E+04	6.11E+04	2.29E+04	1.96E+04
QM-2 (orange) loader	5.80E+06	5.80E+06	1.53E+06	4.58E+05	4.58E+05	4.58E+05	---	---
QM-2 (orange) packager	1.53E+06	1.53E+06	1.53E+06	4.58E+05	1.42E+05	1.42E+05	1.31E+05	---
Raffinate/Sump recovery operator	2.98E+05	2.98E+05	1.68E+05	8.29E+04	1.85E+05	9.27E+03	1.20E+04	2.36E+05
Sample Room supervisor	4.89E+05	4.89E+05	2.67E+05	2.67E+05	2.67E+05	4.47E+04	4.47E+04	4.47E+04
Stockroom foreman/clerk	2.29E+04	2.29E+04	2.29E+04	3.60E+04	1.64E+04	3.71E+04	1.53E+04	4.04E+03
<b>Storeroom (generic)</b>	2.29E+04	2.29E+04	2.29E+04	3.60E+04	1.64E+04	3.71E+04	1.53E+04	4.04E+03
Truck/forktruck operator/driver	8.18E+04	8.18E+04	8.18E+04	8.18E+04	6.87E+04	2.18E+04	2.07E+04	2.18E+04
<b>Warehouse (generic)</b>	2.14E+05	2.14E+05	9.16E+04	7.64E+04	4.15E+04	2.18E+04	1.09E+04	6.33E+03
Warehouse foreman/assistant foreman/warehouseman	2.14E+05	2.14E+05	9.16E+04	7.64E+04	4.15E+04	2.18E+04	1.09E+04	6.33E+03
Warehouse K-65 sampler/weighmaster	2.14E+05	2.14E+05	9.16E+04	2.51E+05	2.95E+05	3.82E+05	3.82E+05	---

Although plant operations may have ended in 1957, the end year of operations is taken conservatively to be 1958 (see Section 8.0).

The bolded entries represent generic choices if the specific job title cannot be determined. The generic entries represent medians for the job titles associated with the generic process.

Table 29D. Annual inhalation intakes, Plant 6E, 1950-1958.

Job title	Intake, pCi/year				
	Oct 1950 - Dec 1952	1953	1954	1955	1956 -1958
Area mechanic	2.51E+04	2.51E+04	2.51E+04	3.93E+04	7.96E+04
Billet grinder	3.71E+04	3.71E+04	3.71E+04	4.64E+05	7.29E+05
Blender; Lime/slag blender	9.71E+03	1.52E+04	1.42E+04	1.20E+04	6.22E+03
Bottom furnace operator	7.42E+04	3.38E+04	1.29E+05	1.17E+05	4.47E+04
Bottom/Lower "F" machine operator	2.51E+04	1.64E+04	2.62E+04	5.67E+04	3.16E+04
Breakout operator/man	2.73E+04	3.55E+04	3.05E+04	4.58E+04	2.51E+04
Brushing man	---	---	---	5.13E+04	5.13E+04
Burnout man	1.75E+05	2.84E+04	2.51E+04	3.38E+04	4.25E+04
Cage grinding/cage operator/man	6.00E+04	1.21E+05	2.18E+04	3.82E+04	3.81E+05
Cage/4th saw man	1.85E+04	8.73E+04	2.29E+04	4.15E+04	4.15E+04
Capping man	8.84E+04	5.51E+04	3.38E+04	3.49E+04	4.58E+04
Chipper/Derby chipper	2.30E+06	2.30E+06	2.30E+06	2.30E+06	2.07E+04
Crafts: Maintenance/electrician/mechanic/millwright; Graphite Shop	4.91E+04	4.31E+04	2.51E+04	3.93E+04	7.96E+04
Crucible assembler	8.84E+04	5.51E+04	3.38E+04	3.49E+04	4.58E+04
Crucible loader	3.05E+04	9.44E+04	5.35E+04	2.07E+04	6.55E+04
Decontamination operator/man	2.29E+04	2.29E+04	3.27E+04	3.71E+04	2.84E+04
Engineer/Chemical engineer/Technical engineer	2.95E+04	1.47E+04	1.64E+04	2.62E+04	6.22E+03
Extra man	4.04E+04	4.80E+04	3.60E+04	4.15E+04	5.46E+04
F (machine) charger	4.04E+04	4.80E+04	3.60E+04	4.15E+04	5.46E+04
Foreman, Assistant/General	2.18E+04	1.36E+04	2.07E+04	2.95E+04	6.66E+03
Foreman, Shift	4.91E+04	4.36E+04	2.84E+04	3.93E+04	2.95E+04
Furnace (recast) operator/unloader	7.42E+04	3.38E+04	1.29E+05	1.17E+05	4.47E+04
Furnace (recast) unloader	7.42E+04	3.38E+04	1.29E+05	1.17E+05	4.47E+04
Furnace (reduction) loader	1.64E+04	2.13E+04	2.51E+04	2.51E+04	2.51E+04
Jolter	3.05E+04	5.29E+04	5.02E+04	1.23E+05	2.62E+04
<b>KB-2/derby production (generic for reduction operations)</b>	3.05E+04	4.36E+04	3.05E+04	4.36E+04	2.62E+04
<b>Lead operator (generic)</b>	7.42E+04	3.38E+04	1.29E+05	1.17E+05	4.47E+04
Lift truck driver (operator)	3.27E+04	1.58E+04	1.85E+04	2.40E+04	8.73E+03
Office employees/Clerk; Production clerk	1.42E+04	1.69E+04	8.51E+03	1.53E+04	1.04E+04
Porter	4.91E+04	4.36E+04	2.84E+04	3.93E+04	2.95E+04
Production machinist	4.15E+05	1.47E+04	8.18E+03	1.20E+04	7.64E+03
Recast furnace/YM-5 lead operator	5.35E+04	2.18E+04	5.13E+04	3.27E+04	7.75E+04
Reduction furnace operator	1.64E+04	2.13E+04	2.51E+04	2.51E+04	2.51E+04
Reduction/KB-2 lead operator	4.91E+04	4.36E+04	2.84E+04	3.93E+04	2.95E+04
Residue man (dust collector work)	7.20E+04	1.58E+05	1.25E+05	3.27E+05	2.62E+04
Saw operator/man	3.27E+04	3.60E+04	3.71E+04	4.64E+05	1.42E+04
Slag building operator	1.20E+05	1.20E+05	1.20E+05	2.44E+05	1.96E+04
Superintendent/Supervisor	2.95E+04	1.47E+04	1.64E+04	2.62E+04	6.22E+03
Top/upper furnace operator	2.29E+04	2.29E+04	3.27E+04	3.71E+04	2.84E+04
Top/Upper/Generic "F" machine operator; Top(-ping) operator	3.05E+04	5.29E+04	5.02E+04	1.23E+05	2.62E+04
Utility operator (sump recovery; extra hand)	4.04E+04	4.80E+04	3.60E+04	4.15E+04	5.46E+04
<b>YM-5/billet production (generic for recast operations)</b>	5.35E+04	3.38E+04	3.71E+04	3.93E+04	4.47E+04

Although plant operations may have ended in 1957, the end year of operations is taken conservatively to be 1958 (see Section 8.0). The bolded entries represent generic choices if the specific job title cannot be determined. The generic entries represent medians for the job titles associated with the generic process.

Table 29E. Annual inhalation intakes, Plant 7, 1951-1958.

Job title	Intake, pCi/year					
	1951	1952	1953	1954	1955	1956 – 1958
Area mechanic	4.04E+04	1.53E+04	4.04E+04	7.64E+03	1.42E+04	1.53E+04
Clerk/Record clerk; Porter	2.40E+04	2.29E+04	1.09E+04	1.42E+04	3.49E+04	3.49E+04
Decontamination man/Decontaminator	1.76E+05	2.29E+04	1.31E+04	9.82E+03	1.85E+04	1.96E+04
Engineer	2.40E+04	2.29E+04	1.09E+04	7.64E+03	7.64E+04	3.49E+04
Filter/Tables operator*	---	---	---	---	9.82E+03	9.82E+03
Foreman, Asst	2.40E+04	2.29E+04	1.09E+04	7.64E+03	7.64E+04	3.49E+04
Foreman	3.05E+04	3.05E+04	2.40E+04	1.31E+04	1.75E+04	1.96E+04
Furnace operator	2.73E+04	3.05E+04	7.31E+04	2.51E+04	1.96E+04	1.85E+04
HF Room/Magnesium Room operator	8.73E+03	1.53E+04	9.82E+03	5.46E+03	5.46E+03	5.78E+03
Hoisting (slag) operator*	---	---	---	---	1.64E+04	1.64E+04
Lead (UF <sub>4</sub> /TA-7) operator	4.15E+04	2.29E+04	1.85E+04	9.82E+03	3.27E+04	3.27E+04
Lift truck driver (operator)	1.53E+04	1.53E+04	1.09E+04	1.53E+04	2.84E+04	4.47E+04
Panel board/36' level operator	4.15E+04	2.29E+04	1.85E+04	9.82E+03	3.27E+04	3.27E+04
Plant superintendent	2.40E+04	2.29E+04	1.09E+04	7.64E+03	7.64E+04	3.49E+04
UO <sub>2</sub> /QM-2 dumper/hoister	1.17E+05	6.11E+04	6.66E+04	4.58E+04	6.87E+04	1.22E+05
Safety clerk	1.85E+04	1.85E+04	1.85E+04	9.82E+03	1.53E+04	1.53E+04
Safety inspector/Fire marshal	3.05E+04	3.05E+04	2.40E+04	1.31E+04	1.75E+04	1.96E+04
Sampler and cleanup man	---	3.05E+04	3.12E+05	8.73E+03	8.73E+03	9.93E+03
Supervisor, Technical	3.05E+04	3.05E+04	2.40E+04	1.31E+04	1.75E+04	1.96E+04
TA-7 hoisting operator (hoister)	1.32E+05	1.53E+04	1.42E+04	1.42E+04	1.20E+04	1.85E+04
TA-7 (green/UF <sub>4</sub> ) packager	2.64E+05	3.05E+04	1.12E+05	7.42E+04	5.35E+04	2.62E+04
<b>UF<sub>4</sub>/TA-7/Green production (generic for UF<sub>4</sub> production operations)</b>	4.15E+04	2.29E+04	4.04E+04	1.42E+04	1.96E+04	1.85E+04
Utility operator	2.73E+04	3.05E+04	7.31E+04	2.51E+04	1.96E+04	1.85E+04
Welder	4.04E+04	1.53E+04	4.04E+04	7.64E+03	1.42E+04	1.53E+04

The bolded entry represents a generic choice if the specific job title cannot be determined. The generic entry represents a median for the job titles associated with the generic process.

Table 29F. Annual inhalation intakes, Plant 7E, 1955-1957.

Job title	Intake, pCi/year	
	1955	1956 - 1957
Ionium plant operator/lead operator*	1.09E+02	3.27E+02

\* The thorium/ionium (concentration) plant work began after July 1955 and continued until March 1957; thus the annual intakes here should be ratioed by the appropriate number of months worked (i.e., a maximum of 6 in 1955, 12 in 1956, and 3 in 1957). The ionium case should use the isotopic breakdown given in Section 6.1, Item 5.



Table 30 (Continued)

Worker type	Years	General areas			Ore/K-65 open areas			Enclosed work areas			Annual Intake, WLM
		Occ Factor	Equil Factor	Radon, pCi/l	Occ Factor	Equil Factor	Radon, pCi/l	Occ Factor	Equil Factor	Radon, pCi/l	
<b>Plant 7E</b>											
Plant 7E ionium (thorium) operator	1955-1957	0.50	0.40	2.0	0.50	0.50	100	---	---	---	3.0E+00
<b>SLAPS*</b>											
Bulldozer operator/crane operator (yard workers)	1946-1949	0.20	0.40	408	---	---	---	---	---	---	3.9E+00
Bulldozer operator/crane operator (yard workers)	1950-1958	0.20	0.40	2	---	---	---	---	---	---	1.9E-02
Forktruck driver (yard worker)	1946-1949	0.013	0.40	719	0.025	0.50	1160	0.025	1.00	1160	5.7E+00
Guard, full-time	1946-1949	1.00	0.40	81	---	---	---	---	---	---	3.9E+00
Guard, full-time	1950-1951	1.00	0.40	2	---	---	---	---	---	---	9.6E-02
Guard, part-time	1952-1958	0.05	0.40	2	---	---	---	---	---	---	4.8E-03
Guard, part-time	1959-1962	0.025	0.40	2	---	---	---	---	---	---	2.4E-03
Warehouse/K-65 worker (K-65)	1946-1949	---	---	---	0.10	0.50	1160	0.05	1.00	1160	1.4E+01

The intakes above should be applied only for applicable years (July 1955-March 1957 for Plant 7E) and ratioed for the appropriate year fractions. As a default, 0.096 WLM/yr should be used for process workers and 0.048 WLM/yr for all others and a whole year should be assumed. Note that the breaks in years corresponded to events that altered radon exposure, such as the processing of the K-65 from SLAPS and the cessation of sending it there.

The radon daughter equilibrium factor was taken to be 0.4 in the case of general areas far from a radon source or very open areas (this was used in all areas in ORAUT 2004); 0.5 in the case of radon-prone but relatively well-ventilated or unenclosed areas (this was used for all areas in Applied Nuclear Safety 1986 and Applied Nuclear Safety 1991); and 1.0 in the case of areas enclosed for long periods, such as railcars and the SLAPS sheds.

\* It is not always possible to identify which workers worked wholly at Plant 6 and which spent part of their time at SLAPS; in any case, the SLAPS time constituted only a fraction of the total time of an applicable Plant 6 worker. Hence workers whose job titles fall in both Plant 6 and SLAPS in a given time period should be assigned both the Plant 6 and the SLAPS intakes (i.e., the sum) as their total annual intake.

Table 31A. Annual ingestion intakes, Plants 1 and 2, 1942-1945.

Job title	Intake, pCi/yr
Barium operator	3.92E+02
Boiler/Ether House/Nitric acid operator	1.00E+04
Centrifuge/wash filter operator	1.24E+05
Chemist (generic)	5.34E+04
Cloth operator	1.45E+05
Crafts: Carpenter/Pipefitter/Welder	2.75E+04
Digest/Extraction/Reduction operator	1.50E+05
Dispensary: Nurse/Medic/Other (personnel)	3.82E+04
Engineer (research or chemical)	1.00E+04
Feinc/Feed operator	2.14E+05
Foreman/Technical supervisor	3.51E+04
Furnace operator	5.40E+06
Guard/Chief guard	6.98E+03
Health/Safety field personnel	1.00E+04
Health/Security office personnel	3.27E+03
Instrument Shop machinist/technician	5.49E+04
<b>Laboratory (generic)</b>	5.34E+04
Laboratory office personnel	2.18E+04
Laboratory personnel (chemist, technician)	5.34E+04
Maintenance supervisor	1.09E+04
<b>Manufacturing (generic)</b>	1.45E+05
Mechanic/Area mechanic	4.12E+04
Miller (UO <sub>3</sub> QM-2)	2.75E+06
<b>Office (generic)</b>	1.09E+04
Office, administrative: Clerk/Office maintenance/Messenger/Porter/AEC	1.09E+04
Office, Production and Receiving: Bookkeeper*	6.26E+04
Office, Production and Receiving: Clerk/Secretary	3.51E+04
Ore Area/Room operator	2.99E+06
Pot Room operator	1.69E+06
Production superintendent/Asst production superintendent	5.45E+03
QM-2 (orange) loader	1.16E+06
QM-2 (orange) packager	3.05E+05
Raffinate/Sump operator	5.95E+04
Stockroom foreman/clerk	4.58E+03
Truck/forktruck operator/driver	1.64E+04
UO <sub>2</sub> /LF-9/Brown packager/unloader	8.50E+06
Warehouse foreman/assistant foreman/warehouseman/railcar handling	4.27E+04
<b>Workman (generic)</b>	1.45E+05

\* The "bookkeeper" title in early film badge records appears to indicate a production area accountability clerk, not an office worker. Thus 25% production area access is assumed.

Table 31B. Annual ingestion intakes, Plant 4, October 1942-1958.

Job title	Intake, pCi/year								
	Oct 1942 - 1946	1947	1948 - 1949	1950	1951	1952 - 1953	1954 - 1955	1956	1957- 1958
Blender/Bomb makeup	6.56E+05	6.56E+05	6.56E+05	4.58E+04	1.40E+04	1.40E+04	7.19E+03	1.85E+04	---
Bomb charger/ Charger	6.56E+05	6.56E+05	6.56E+05	4.58E+04	1.40E+04	1.40E+04	7.19E+03	1.85E+04	---
Cage operator/man	7.94E+05	7.94E+05	7.94E+05	4.14E+04	---	---	---	---	---
Carpenter/Other craft	3.05E+04	3.05E+04	3.05E+04	1.83E+04	3.27E+03	3.27E+03	4.80E+03	4.80E+03	---
Casting operator	1.11E+06	1.98E+05	2.14E+05	3.05E+04	1.05E+05	1.05E+05	2.40E+04	2.40E+03	---
Charge firing (man)	2.03E+05	1.98E+05	2.14E+05	3.05E+04	---	---	---	---	---
Chemist/technician: miscellaneous	8.72E+03	8.72E+03	8.72E+03	8.72E+03	1.53E+03	1.53E+03	2.18E+03	2.18E+03	---
Chemist/technician: vacuum fusion	---	---	---	---	---	1.29E+04	1.29E+04	1.29E+04	---
Chipper	4.12E+05	4.12E+05	1.98E+05	3.05E+04	3.05E+04	3.05E+04	3.05E+04	3.05E+04	3.05E+04
Cleanup man	4.12E+05	4.12E+05	1.98E+05	3.05E+04	3.05E+04	3.05E+04	3.05E+04	3.05E+04	3.05E+04
Dingot lead operator	2.03E+05	1.37E+05	1.22E+05	7.63E+03	4.14E+03	4.14E+03	1.79E+03	4.14E+03	---
Dingot operator	6.56E+05	6.56E+05	6.56E+05	4.58E+04	1.40E+04	1.40E+04	7.19E+03	1.85E+04	---
Derby unloader	7.63E+04	6.10E+04	2.75E+05	3.82E+04	---	---	---	---	---
Engineer/Technical supervisor	3.82E+04	3.82E+04	3.82E+04	1.22E+04	2.62E+03	2.62E+03	2.18E+03	5.01E+03	---
Foreman/Shift foreman	3.82E+04	3.82E+04	3.82E+04	1.22E+04	2.62E+03	2.62E+03	2.18E+03	5.01E+03	---
Forge press operator/manipulator	---	---	---	---	---	5.01E+03	5.01E+03	5.01E+03	---
Furnace and saw man	---	---	---	---	3.92E+03	3.92E+03	3.92E+03	3.92E+03	---
Furnace loader (UF <sub>4</sub> -derby)	7.32E+05	7.32E+05	4.88E+05	6.10E+04	---	---	---	---	---
Furnace (recast) operator	1.11E+06	1.98E+05	2.14E+05	3.05E+04	1.05E+05	1.05E+05	2.40E+04	2.40E+03	---
Furnace puller	2.03E+05	1.37E+05	1.22E+05	7.63E+03	4.14E+03	4.14E+03	1.79E+03	4.14E+03	---
Furnace tender	1.22E+05	1.22E+05	7.63E+04	1.53E+04	---	---	---	---	---
Guard/Chief guard	6.10E+03	6.10E+03	6.10E+03	6.10E+03	6.10E+03	1.26E+03	5.89E+02	1.55E+03	---
HF (fluorination) operator	1.24E+05	1.24E+05	1.24E+05	1.53E+04	---	---	---	---	---
Jolter	7.63E+05	7.63E+05	1.07E+05	1.53E+04	---	---	---	---	---
KB-2 lead operator	2.03E+05	1.37E+05	1.22E+05	7.63E+03	4.14E+03	4.14E+03	1.79E+03	4.14E+03	---
<b>KB-2/Derby production (generic for reduction operations)</b>	2.03E+05	1.98E+05	2.14E+05	3.05E+04	1.40E+04	1.40E+04	7.19E+03	1.85E+04	3.05E+04
Laboratory: ceramics/microscopy	---	---	---	---	3.92E+03	3.92E+03	3.92E+03	3.92E+03	---
Lime blender/Magnesium operator	1.53E+04	1.53E+04	1.53E+04	7.63E+03	---	---	---	---	---
<b>Manufacturing (generic)</b>	2.03E+05	1.98E+05	2.14E+05	3.05E+04	4.14E+03	4.58E+03	5.01E+03	4.80E+03	3.05E+04
Mechanic/Area mechanic	7.63E+04	7.63E+04	7.63E+04	1.83E+04	3.27E+03	3.27E+03	4.80E+03	4.80E+03	---
Miller-mixer (UF <sub>4</sub> /TA-7)	1.02E+06	1.02E+06	2.14E+05	1.53E+04	---	---	---	---	---
Office: Plant superintendent/ Clerk/Other	9.16E+03	9.16E+03	9.16E+03	9.16E+03	9.16E+03	1.26E+03	5.89E+02	1.59E+03	---
Ore miller/handler	1.57E+05	---	---	---	---	---	---	---	---
Porter	2.44E+04	2.44E+04	2.44E+04	1.22E+04	1.22E+04	1.26E+03	5.89E+02	8.72E+03	---
Residue man	---	---	---	---	---	---	6.10E+03	6.10E+03	---
Salt bath man/Vertical lathe operator	---	---	---	---	---	---	6.10E+03	6.10E+03	---
Saw operator/man	4.12E+05	4.12E+05	1.98E+05	3.05E+04	3.05E+04	3.05E+04	3.05E+04	3.05E+04	3.05E+04
Shipping & Receiving	2.75E+04	2.75E+04	2.75E+04	2.75E+04	3.27E+03	3.27E+03	4.80E+03	4.80E+03	---
Slag man/Slag grinding operator	3.05E+04	3.05E+04	4.58E+04	1.53E+04	---	---	---	---	---
TA-7 packager	1.57E+06	1.57E+06	1.57E+06	5.34E+04	---	---	---	---	---
TA-7 unloader (operator)	2.83E+06	2.83E+06	3.36E+05	4.58E+04	---	---	---	---	---
Top cleaner	1.02E+06	1.02E+06	2.14E+05	1.53E+04	---	---	---	---	---
Topper	1.83E+05	1.83E+05	5.04E+05	4.58E+04	---	---	---	---	---
Top seat man	1.11E+06	1.98E+05	2.14E+05	3.05E+04	1.05E+05	1.05E+05	2.40E+04	2.40E+03	---
<b>UF4/TA-7/green production (generic)</b>	5.59E+05	4.35E+05	1.69E+05	1.68E+04	3.71E+03	3.71E+03	3.29E+03	4.47E+03	---
UO <sub>2</sub> /LF-9 loader/packer	9.16E+05	7.32E+05	4.88E+05	6.10E+04	---	---	---	---	---
YM-5 lead operator	2.03E+05	1.37E+05	1.22E+05	7.63E+03	4.14E+03	4.14E+03	1.79E+03	4.14E+03	---
<b>YM-5/billet/dingot production (generic for recast operations)</b>	7.26E+05	1.98E+05	2.14E+05	3.05E+04	1.40E+04	9.48E+03	6.10E+03	4.14E+03	---



Table 31C. Annual ingestion intakes, Plant 6, 1946-1958.

Job title	Intake, pCi/year							
	1946 - 1948	1949	1950	1951	1952	1953	1954	1955 - 1958
AEC engineer	---	---	---	1.53E+03	6.76E+03	2.16E+03	4.14E+03	4.14E+03
Barium operator	3.92E+02	3.92E+02	2.75E+04	3.14E+04	2.83E+04	8.28E+03	---	---
C-3 centrifuge/wash filter/adjustments operator	1.24E+05	1.24E+05	3.05E+04	3.05E+04	9.16E+04	1.37E+05	1.72E+04	1.72E+04
Cleanup man/utility operator	---	---	---	2.11E+04	2.11E+04	2.05E+04	2.81E+04	1.92E+04
Cloth operator	1.45E+05	1.45E+05	5.34E+04	5.34E+04	2.01E+04	4.14E+03	3.92E+03	3.92E+03
Cloth & Training Group lead operator/trainer	5.49E+05	5.49E+05	5.04E+04	5.04E+04	5.01E+03	5.45E+03	3.92E+03	3.92E+03
Clothes issue man	2.01E+04	2.01E+04	2.01E+04	2.01E+04	2.01E+04	2.05E+03	4.14E+03	3.92E+03
Crafts: Carpenter/Pipefitter/Welder	2.75E+04	2.75E+04	2.14E+04	6.10E+03	6.10E+03	6.10E+03	6.32E+03	5.23E+03
Decontamination man/U-con man*	2.16E+04	2.16E+04	2.16E+04	2.16E+04	1.31E+04	4.14E+03	4.80E+03	3.71E+03
Cloth/Digest/Reduction operator, Outside sampling	1.50E+05	1.50E+05	5.34E+04	8.07E+04	2.01E+04	8.94E+03	1.31E+04	4.80E+03
Dispensary: Nurse/Medic/Other (personnel)	3.82E+04	3.82E+04	1.22E+04	2.16E+04	9.16E+03	1.37E+03	7.63E+02	2.83E+02
Boiler/Ether Hse/Extraction/Nitric acid rec'y operator	1.00E+04	1.00E+04	2.16E+04	1.09E+04	9.59E+03	4.14E+03	2.40E+03	7.41E+03
Experimental Continuous Furnace (Pilot Plant project)	---	1.86E+06	1.86E+06	---	---	---	---	---
Feinc/Feed/Soluble feed operator	2.14E+05	2.14E+05	3.36E+04	3.82E+04	3.27E+04	2.18E+04	2.09E+04	8.94E+03
Foreman/General foreman/Shift foreman/ Technical supervisor	3.51E+04	3.51E+04	3.51E+04	2.09E+04	1.77E+04	6.54E+03	5.45E+03	4.14E+03
Furnace operator	5.40E+06	5.40E+06	3.05E+05	3.27E+04	2.09E+04	1.20E+04	7.19E+03	2.62E+03
Guard/Chief guard	6.98E+03	6.98E+03	6.98E+03	3.92E+02	4.80E+03	3.49E+03	3.05E+03	2.18E+03
Health/Security Office personnel; Engineer (MCW, chemical)	3.27E+03	3.27E+03	3.27E+03	1.53E+03	3.05E+03	3.27E+03	2.40E+03	1.77E+03
Health Office: health surveyor/plant monitor	1.00E+04	1.00E+04	1.00E+04	9.16E+03	3.05E+03	3.27E+03	3.49E+03	3.27E+03
Instrument Shop machinist/technician	5.49E+04	5.49E+04	1.11E+04	1.31E+04	8.72E+03	3.71E+03	9.59E+03	2.62E+03
Laboratory Office personnel	2.18E+04	2.18E+04	2.18E+03	1.22E+03	1.22E+03	1.22E+03	4.36E+02	9.16E+03
<b>Laboratory: chemist/technician (generic/MCW/ Shotgun)</b>	5.34E+04	5.34E+04	5.23E+03	5.45E+03	5.01E+03	6.54E+03	2.18E+03	9.16E+03
Laundry operator/lead operator	---	---	---	9.81E+02	4.14E+03	2.40E+03	4.14E+03	1.35E+03
Ledoux Lab technician/asst technician – raffinate, MgF <sub>2</sub>	4.12E+04	4.12E+04	1.98E+04	9.16E+04	3.05E+04	8.50E+03	1.77E+03	5.89E+03
Ledoux Lab technician (K-65)	4.58E+05	4.58E+05	3.05E+05	4.14E+05	9.59E+04	5.89E+03	1.64E+03	4.58E+03
LF-9/brown/VO <sub>2</sub> packager/unloader	8.50E+06	8.50E+06	7.94E+04	7.63E+04	7.63E+04	---	---	---
Maintenance supervisor	1.09E+04	1.09E+04	1.09E+04	8.28E+03	9.16E+03	2.18E+03	2.83E+03	3.05E+04
<b>Maintenance (generic)</b>	4.12E+04	4.12E+04	5.89E+02	6.10E+03	6.10E+03	6.10E+03	6.32E+03	5.23E+03
<b>Manufacturing/Mfg (generic)</b>	2.14E+05	1.50E+05	5.19E+04	3.54E+04	2.83E+04	8.94E+03	7.19E+03	5.23E+03
Mechanic/Area mechanic: C-3, digest, feed, furnace, Ore Room, raffin., Ether/Nitric Acid House	4.12E+04	4.12E+04	5.89E+02	6.10E+03	6.10E+03	6.10E+03	6.32E+03	5.23E+03
Metal dissolver (#1, #2)	---	---	---	4.45E+04	4.45E+04	4.45E+04	4.45E+04	4.45E+04
Metal room sampler	---	---	---	9.16E+04	9.16E+04	9.16E+04	9.16E+04	9.16E+04
MgX operator	2.05E+04	2.05E+04	2.05E+04	2.05E+04	1.13E+04	1.48E+04	6.32E+03	6.32E+03
Miller (UO <sub>3</sub> QM-2)	2.75E+06	2.75E+06	---	---	---	---	---	---
Office (generic)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Office, MCW: Clerk/Office maintenance/ Messenger/Porter /Expeditor	1.09E+04	1.09E+04	1.09E+04	1.05E+04	1.05E+04	4.36E+03	3.71E+03	3.27E+03
Office: MCW - Other, AEC - all AEC except Engineer	1.09E+04	1.09E+04	1.09E+04	0.00E+00	1.46E+03	6.32E+02	4.80E+02	4.80E+02
Office, Production/Receiving: Clerk/Secretary	3.51E+04	3.51E+04	1.13E+04	2.16E+04	3.71E+03	3.92E+03	4.14E+03	1.98E+03
Ore Room operator***	2.99E+06	7.63E+04	8.55E+04	8.07E+04	3.71E+04	3.05E+04	3.05E+04	---
Pilot Plant engineer	2.68E+04	2.68E+04	1.16E+04	1.26E+04	8.50E+03	6.76E+02	1.50E+03	1.64E+03
Pilot Plant lead operator/group leader	5.34E+04	5.34E+04	2.29E+04	2.53E+04	1.68E+04	1.33E+03	1.92E+03	1.68E+03
Pilot Plant technician	5.34E+04	5.34E+04	2.29E+04	2.53E+04	1.68E+04	1.31E+03	2.01E+03	4.23E+05
Pot Room operator	1.69E+06	1.68E+05	7.32E+04	2.18E+04	4.14E+04	9.81E+03	2.46E+04	5.10E+04
Powder sample technician	6.87E+05	6.87E+05	4.73E+04	4.73E+04	1.24E+04	1.24E+04	1.24E+04	1.24E+04
Power House (generic)	1.00E+04	1.00E+04	2.16E+04	1.09E+04	9.59E+03	4.14E+03	2.40E+03	7.41E+03
Production Research Lab personnel	1.83E+04	1.83E+04	2.62E+03	6.54E+03	2.83E+03	1.09E+03	4.36E+02	8.07E+02
Production superintendent/Asst production superintendent	5.45E+03	5.45E+03	5.45E+03	5.45E+03	5.67E+03	1.22E+04	4.58E+03	3.92E+03
QM-2 (orange) loader	1.16E+06	1.16E+06	3.05E+05	9.16E+04	9.16E+04	9.16E+04	---	---
QM-2 (orange) packager	3.05E+05	3.05E+05	3.05E+05	9.16E+04	2.83E+04	2.83E+04	2.62E+04	---
Raffinate/Sump recovery operator	5.95E+04	5.95E+04	3.36E+04	1.66E+04	3.71E+04	1.85E+03	2.40E+03	4.71E+04
Sample Room supervisor	9.77E+04	9.77E+04	5.34E+04	5.34E+04	5.34E+04	8.94E+03	8.94E+03	8.94E+03
Stockroom foreman/clerk	4.58E+03	4.58E+03	4.58E+03	7.19E+03	3.27E+03	7.41E+03	3.05E+03	8.07E+02

Table 31C (Continued)

Job title	Intake, pCi/year							
	1946 - 1948	1949	1950	1951	1952	1953	1954	1955 - 1958
<b>Storeroom (generic)</b>	4.58E+03	4.58E+03	4.58E+03	7.19E+03	3.27E+03	7.41E+03	3.05E+03	8.07E+02
Truck/forktruck operator/driver	1.64E+04	1.64E+04	1.64E+04	1.64E+04	1.37E+04	4.36E+03	4.14E+03	4.36E+03
<b>Warehouse (generic)</b>	4.27E+04	4.27E+04	1.83E+04	1.53E+04	8.28E+03	4.36E+03	2.18E+03	1.26E+03
Warehouse foreman/assistant foreman/ warehouseman	4.27E+04	4.27E+04	1.83E+04	1.53E+04	8.28E+03	4.36E+03	2.18E+03	1.26E+03
Warehouse K-65 sampler/weighmaster	4.27E+04	4.27E+04	1.83E+04	5.01E+04	5.89E+04	7.63E+04	7.63E+04	---

Table 31D. Annual ingestion intakes, Plant 6E, 1950-1958.

Job title	Intake, pCi/year				
	Oct 1950 - Dec 1952	1953	1954	1955	1956 -1958
Area mechanic	5.01E+03	5.01E+03	5.01E+03	7.85E+03	1.59E+04
Billet grinder	7.41E+03	7.41E+03	7.41E+03	9.27E+04	1.46E+05
Blender; Lime/slag blender	1.94E+03	3.04E+03	2.83E+03	2.40E+03	1.24E+03
Bottom furnace operator	1.48E+04	6.76E+03	2.57E+04	2.33E+04	8.94E+03
Bottom/Lower "F" machine operator	5.01E+03	3.27E+03	5.23E+03	1.13E+04	6.32E+03
Breakout operator/man	5.45E+03	7.09E+03	6.10E+03	9.16E+03	5.01E+03
Brushing man	---	---	---	1.02E+04	1.02E+04
Burnout man	3.49E+04	5.67E+03	5.01E+03	6.76E+03	8.50E+03
Cage grinding/cage operator/man	1.20E+04	2.41E+04	4.36E+03	7.63E+03	7.61E+04
Cage/4th saw man	3.71E+03	1.74E+04	4.58E+03	8.28E+03	8.28E+03
Capping man/capper	1.77E+04	1.10E+04	6.76E+03	6.98E+03	9.16E+03
Chipper/Derby chipper	4.60E+05	4.60E+05	4.60E+05	4.60E+05	4.14E+03
Crafts: Maintenance/electrician/mechanic/millwright; Graphite Shop	9.81E+03	8.61E+03	5.01E+03	7.85E+03	1.59E+04
Crucible assembler	1.77E+04	1.10E+04	6.76E+03	6.98E+03	9.16E+03
Crucible loader	6.10E+03	1.89E+04	1.07E+04	4.14E+03	1.31E+04
Decontamination operator/man	4.58E+03	4.58E+03	6.54E+03	7.41E+03	5.67E+03
Engineer/Chemical engineer/Technical engineer	5.89E+03	2.94E+03	3.27E+03	5.23E+03	1.24E+03
Extra man	8.07E+03	9.59E+03	7.19E+03	8.28E+03	1.09E+04
F (machine) charger	8.07E+03	9.59E+03	7.19E+03	8.28E+03	1.09E+04
Foreman, Assistant/General	4.36E+03	2.73E+03	4.14E+03	5.89E+03	1.33E+03
Foreman, Shift	9.81E+03	8.72E+03	5.67E+03	7.85E+03	5.89E+03
Furnace (recast) operator/unloader	1.48E+04	6.76E+03	2.57E+04	2.33E+04	8.94E+03
Furnace (recast) unloader	1.48E+04	6.76E+03	2.57E+04	2.33E+04	8.94E+03
Furnace (reduction) loader	3.27E+03	4.25E+03	5.01E+03	5.01E+03	5.01E+03
Jolter	6.10E+03	1.06E+04	1.00E+04	2.46E+04	5.23E+03
<b>KB-2/derby production (generic for reduction operations)</b>	6.10E+03	8.72E+03	6.10E+03	8.72E+03	5.23E+03
<b>Lead operator (generic)</b>	1.48E+04	6.76E+03	2.57E+04	2.33E+04	8.94E+03
Lift truck driver (operator)	6.54E+03	3.16E+03	3.71E+03	4.80E+03	1.74E+03
Office employees/Clerk; Production clerk	2.83E+03	3.38E+03	1.70E+03	3.05E+03	2.07E+03
Porter	9.81E+03	8.72E+03	5.67E+03	7.85E+03	5.89E+03
Production machinist	8.28E+04	2.94E+03	1.64E+03	2.40E+03	1.53E+03
Recast furnace/YM-5 lead operator	1.07E+04	4.36E+03	1.02E+04	6.54E+03	1.55E+04
Reduction furnace operator	3.27E+03	4.25E+03	5.01E+03	5.01E+03	5.01E+03
Reduction/KB-2 lead operator	9.81E+03	8.72E+03	5.67E+03	7.85E+03	5.89E+03
Residue man (dust collector work)	1.44E+04	3.16E+04	2.51E+04	6.54E+04	5.23E+03
Saw operator/man	6.54E+03	7.19E+03	7.41E+03	9.27E+04	2.83E+03
Slag building operator	2.40E+04	2.40E+04	2.40E+04	4.88E+04	3.92E+03
Superintendent/Supervisor	5.89E+03	2.94E+03	3.27E+03	5.23E+03	1.24E+03
Top/upper furnace operator	4.58E+03	4.58E+03	6.54E+03	7.41E+03	5.67E+03
Top/Upper/Generic "F" machine operator; Top(-ping) operator	6.10E+03	1.06E+04	1.00E+04	2.46E+04	5.23E+03
Utility operator (sump recovery; extra hand)	8.07E+03	9.59E+03	7.19E+03	8.28E+03	1.09E+04
<b>YM-5/billet production (generic for recast operations)</b>	1.07E+04	6.76E+03	7.41E+03	7.85E+03	8.94E+03

Table 31E. Annual inhalation intakes, Plant 7, 1951-1958.

Job title	Intake, pCi/year					
	1951	1952	1953	1954	1955	1956 - 1958
Area mechanic	8.07E+03	3.05E+03	8.07E+03	1.53E+03	2.83E+03	3.05E+03
Clerk/Record clerk; Porter	4.80E+03	4.58E+03	2.18E+03	2.83E+03	6.98E+03	6.98E+03
Decontamination man/Decontaminator	3.51E+04	4.58E+03	2.62E+03	1.96E+03	3.71E+03	3.92E+03
Engineer	4.80E+03	4.58E+03	2.18E+03	1.53E+03	1.53E+04	6.98E+03
Filter/Tables operator*	---	---	---	---	1.96E+03	1.96E+03
Foreman, Asst	4.80E+03	4.58E+03	2.18E+03	1.53E+03	1.53E+04	6.98E+03
Foreman	6.10E+03	6.10E+03	4.80E+03	2.62E+03	3.49E+03	3.92E+03
Furnace operator	5.45E+03	6.10E+03	1.46E+04	5.01E+03	3.92E+03	3.71E+03
HF Room/Magnesium Room operator	1.74E+03	3.05E+03	1.96E+03	1.09E+03	1.09E+03	1.16E+03
Hoisting (slag) operator*	---	---	---	---	3.27E+03	3.27E+03
Lead (UF <sub>4</sub> /TA-7) operator	8.28E+03	4.58E+03	3.71E+03	1.96E+03	6.54E+03	6.54E+03
Lift truck driver (operator)	3.05E+03	3.05E+03	2.18E+03	3.05E+03	5.67E+03	8.94E+03
Panel board/36' level operator	8.28E+03	4.58E+03	3.71E+03	1.96E+03	6.54E+03	6.54E+03
Plant superintendent	4.80E+03	4.58E+03	2.18E+03	1.53E+03	1.53E+04	6.98E+03
UO <sub>3</sub> /QM-2 dumper/hoister	2.33E+04	1.22E+04	1.33E+04	9.16E+03	1.37E+04	2.44E+04
Safety clerk	3.71E+03	3.71E+03	3.71E+03	1.96E+03	3.05E+03	3.05E+03
Safety inspector/Fire marshal	6.10E+03	6.10E+03	4.80E+03	2.62E+03	3.49E+03	3.92E+03
Sampler and cleanup man	---	6.10E+03	6.23E+04	1.74E+03	1.74E+03	1.98E+03
Supervisor, Technical	6.10E+03	6.10E+03	4.80E+03	2.62E+03	3.49E+03	3.92E+03
TA-7 hoisting operator (hoister)	2.64E+04	3.05E+03	2.83E+03	2.83E+03	2.40E+03	3.71E+03
TA-7 (green/UF <sub>4</sub> ) packager	5.28E+04	6.10E+03	2.25E+04	1.48E+04	1.07E+04	5.23E+03
<b>UF<sub>4</sub>/TA-7/Green production (generic for UF<sub>4</sub> production operations)</b>	8.28E+03	4.58E+03	8.07E+03	2.83E+03	3.92E+03	3.71E+03
Utility operator	5.45E+03	6.10E+03	1.46E+04	5.01E+03	3.92E+03	3.71E+03
Welder	8.07E+03	3.05E+03	8.07E+03	1.53E+03	2.83E+03	3.05E+03

Table 31F. Annual inhalation intakes, Plant 7E.

Job title	Intake, pCi/year		
	1954	1955	1956 - 1957
<b>Plant 7E (thorium/ionium concentration process)</b>			
Ionium plant operator/lead operator*	---	2.18E+01	6.54E+01

\* The thorium/ionium (concentration) plant work began after July 1955 and continued until March 1957; thus the annual intakes here should be ratioed by the appropriate number of months worked (i.e., a maximum of 6 in 1955, 12 in 1956, and 3 in 1957). The ionium case should use the isotopic breakdown given in Section 6.1, Item 5.

Table 32. Exposure rates from K-65 residue and Q-11 ore, in mR/hr (AEC 1949b, 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 railcar	One drum group centerline perpendicular to long side of railcar (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 railcar, over one group (A); over empty center (B)	Contact		21	11	
5 railcars in a row containing unspecified amount of K-65	Along a line perpendicular to the axis of the line of railcars, even with the center of the middle car	10	50			
		25	22			
		43	13			
		50	10.2			

The total length of a railcar was given as 57 feet.

Table 33. Measured dose rates in various work areas.

	Exposure, % tolerance	Exposure, mrep/hr or mR/hr*	Year	Reference
<b>PLANTS 1 and 2</b>				
Soda salt, near-contact: gamma; beta	20; 20	2.5; 13	1943	MED 1944f
Soda salt, 6": gamma; beta	10; 20	1.2; 13	1943	MED 1944f
Vanadium sludge, over 1 month old, 10 cm from 216 jar: gamma; beta	1.5; 20	.19; 13	1943	MED 1944f
High-grade pitchblende ore, 55-gal drum, 1000 lbs ore: 60"		3.8	1945	Rochester 1945
High-grade pitchblende ore, 55-gal drum, 1000 lbs ore: 45"		6.1	1945	Rochester 1945
High-grade pitchblende ore, 55-gal drum, 1000 lbs ore: 30"		12	1945	Rochester 1945
High-grade pitchblende ore, 55-gal drum, 1000 lbs ore: 15"		29	1945	Rochester 1945
High-grade pitchblende ore, 55-gal drum, 1000 lbs ore: 6"		66	1945	Rochester 1945
High-grade pitchblende ore, 55-gal drum, 1000 lbs ore: contact		100	1945	Rochester 1945
High-grade pitchblende ore, 15-gal drum, 443 lbs ore: 60"		2.4	1945	Rochester 1945
High-grade pitchblende ore, 15-gal drum, 443 lbs ore: 45"		3.6	1945	Rochester 1945
High-grade pitchblende ore, 15-gal drum, 443 lbs ore: 30"		7.1	1945	Rochester 1945
High-grade pitchblende ore, 15-gal drum, 443 lbs ore: contact		90	1945	Rochester 1945
Ether extraction tanks	25	3.1	1943	MED 1944f
Residue drier (beta only)	120	75	1943	MED 1944f
"SM sub 2": gamma; beta	42; 40	5.2; 25	1943	MED 1944f
"SN sub 4": gamma only	30	3.8	1943	MED 1944f
"SB sub 3": gamma; beta	35; 40	4.4; 25	1943	MED 1944f
Tank 1A cake from SN sub 2: gamma; beta	10; 120	1.2; 13	1943	MED 1944f
Tank 7 press cake, 10 days old, 10 cm from the edge: gamma; beta	20; 400	2.5; 250	1943	MED 1944f
308 [material] from Tank 7 press cake residue, 10 days old: beta only	400	250	1943	MED 1944f
Residue Chem. 4217, 2 months old, 10 cm from 2-lb bottle: gamma; beta	5; 30	.62; 10	1943	MED 1944f
Over top of Shed #1 recovery cake: gamma, beta	12; 30	1.5; 19	1943	MED 1944f
Acid press cake from tank treatment, 10" above: gamma; beta	---	6.3; 300	1944	MED 1945b
Barrel of residue after storage for 6 months, top: gamma; beta	---	6.2; 50	1944	MED 1945b
Barrel of residue after storage for 6 months, 6' from side: gamma, beta	---	6.2; 75	1944	MED 1945b
Caustic precipitate before it enters the drier, 5-6": gamma; beta	---	6.2, 450	1944	MED 1945b
Plate of residue being dried in oven, 3", beta only	---	250	1944	MED 1945b
Trays in drier, pile, in which NG & SNG residues are dried: 2 " above: gamma; beta	---	5; 50	1944	MED 1945b
Trays in the drier, along the axis about 1': gamma, beta	---	6.2, 250	1944	MED 1945b
Flat dish of residue on top of above crucible covering, 3": gamma; beta	---	0; 1000	1944	MED 1945b
Concrete crucible covering, residue cooling for 4 hours, 3" above: beta	---	400	1944	MED 1945b
Flat dish of slag dust, 3", beta only	---	0	1944	MED 1945b
Floor of Hood #6, 4", where most 4th extractions spilled: gamma; beta	50; 30	6.2; 19	1944	MED 1944m
Most contaminated part of hood floor where shotgun samples dried: gamma; beta	70; 40	8.8; 25	1944	MED 1944m
Shotgun prep lab table top with daily change of brown paper, 4": gamma; beta	---	<13; <25	1944	MED 1945b
Lip of evaporating dish with 3rd-extraction liquor, .5": gamma; beta	50; 30	6.2; 19	1944	MED 1944m
Lip of evapor'g dish w/ 4th-extraction liquor, .5" away, 2" above liquor: gamma; beta	100; 600	13; 375	1944	MED 1944m
Lip of evaporating dish with shotgun sample, .5": gamma; beta	60; 100	7.5; 62	1944	MED 1944m
Lip of evaporating dish containing shotgun sample, 7": gamma; beta	30; 20	3.8; 13	1944	MED 1944m
Lip of evaporating dish containing 5.17-g shotgun sample, 10": beta only	20	13	1944	MED 1944m
Lip of evaporating dish, cleaned, that had held shotgun sample, .5": gamma; beta	30; 20	2.5; 25	1944	MED 1944m
3.36 g shotgun sample, 3" above: gamma; beta	200; 1600	25; 1000	1944	MED 1944m
5.15 g shotgun sample in bottom of evaporating dish, 4": gamma; beta	130; ---	16; >375	1944	MED 1944m
4.31 g shotgun sample, 7": gamma; beta	100; 400	13; 250	1944	MED 1944m
5.15 g shotgun sample in bottom of evaporating dish, 7": beta only	700	440	1944	MED 1944m
5.15 g shotgun sample in bottom of evaporating dish, 11": beta only	340	215	1944	MED 1944m
5.15 g shotgun sample in dish, 11", through rubber glove: beta only	170	106	1944	MED 1944m
Surface of rubber glove above: beta only	20	13	1944	MED 1944m
Outside bottom of evaporating dish with 3.36 g sample, .5": gamma; beta	50; 140	6.2; 88	1944	MED 1944m
Bottom of cleaned evaporating dish (had held shotgun sample), 2": gamma; beta	20; 40	2.5; 25	1944	MED 1944m
Glass shipping bottle with 3.08-g shotgun sample, 1": gamma; beta	60; 100	7.5; 62	1944	MED 1944m
Shotgun package containing three bottles: gamma; beta	---	2.5; 0	1944	MED 1945b
Bottom of package with 5 shotgun samples to be shipped, 2": gamma; beta	100; 0	13; 0	1944	MED 1944m

Table 33 (Continued)

	Exposure, % tolerance	Exposure, mrep/hr or mR/hr*	Year	Reference
<b>PLANT 4</b>				
Subliming material, 6" from pail: gamma; beta	42; >400	5.2; >250	1943	MED 1944f
Insulating brick from recast furnace: beta only	>400	>250	1943	MED 1944f
Freshly cast metal: beta only	10	6.2	1943	MED 1944f
Green salt, form normally handled, 1": beta only	---	100	1944	MED 1945b
Green salt, contact with tray of green salt: beta only	---	108	1948	MCW 1948a
Green salt, exposure to any large surface (tray, open can, etc), 1': beta only	---	64	1948	MCW 1948a
Above bench on which green salt is packed, 4": gamma, beta	---	<13; <25	1944	MED 1945b
Bomb step, exposure to large surfaces of green salt, 1': beta only	---	50	1948	MCW 1948b
Bomb step, loading bomb, full bomb, 1': beta only	---	53	1948	MCW 1948b
Bomb step, unloading bomb, knockout grate, 1': beta only	---	3.6	1948	MCW 1948a
Bomb step, at edge of unloader jolter, 1': beta only	---	3	1948	MCW 1948a
Top of table where ingot is pushed out of bomb, beta only	---	100	1944	MED 1945b
Bomb step, derby transport table, 1': beta only	---	5.3	1948	MCW 1948a
Bomb step, contact with unchipped derby: beta only	---	116		MCW 1948a
Bomb step, chipping, 1' (chipper location): beta only	---	42	1948	MCW 1948a
Top of chipper's table, beta only	---	125	1944	MED 1945b
Contact with the chipper's table: beta only	---	465	1948	MCW 1948a
Ingot storage room, 4' from pile of ripe metal, beta only	---	25	1944	MED 1945b
Ingot storage and packing room, 3' from ore scrap pile in crib, beta only	---	25	1944	MED 1945b
Recasting step, cleaning crucible lids and stoppers, 1' above tray: beta only	---	3000	1948	MCW 1948B
Recasting step, cleaning crucible lids and stoppers, chest high: beta only	---	280	1948	MCW 1948a
Recasting furnace platform, 6" above, beta only	---	168	1944	MED 1945b
Recasting step, above top of furnace immediately after opening, 1': beta only	---	1450	1948	MCW 1948a
Recasting step, above top of furnace, baffle & crucible lid removed, 1': beta only	---	650	1948	MCW 1948a
Recasting step, contact with cleaned crucible lid: beta only	---	155	1948	MCW 1948a
Recasting step, chest high while cleaning top of furnace: beta only	---	135	1948	MCW 1948a
Recasting step, cleaning furnace top, edge of top cleaning hood: beta only	---	220	1948	MCW 1948a
Recasting step, inside bottom of furnace before removing rolls, 1': beta only	---	12	1948	MCW 1948a
Recasting step, inside bottom of furnace after cleaning, 1': beta only	---	16	1948	MCW 1948a
Recasting step, average for general area of bottom furnace work: beta only	---	16	1948	MCW 1948a
Recasting step, above drum of D-7, 1': beta only	---	140	1948	MCW 1948a
Recasting step, above D-7 table, 1': beta only	---	270	1948	MCW 1948a
Billets stored by desk and scale, gamma+beta		90-270	1953	MCW 1953e
Saw with no uranium billet in it, gamma+beta		100-150	1953	MCW 1953e
		300-		
Empty furnace, lid off, top center//edge//1 foot, gamma+beta		400//100//70	1953	MCW 1953e
Furnace lid and brush, center//edge, gamma+beta		1200//100	1953	MCW 1953e
Furnace bottom plate (operator foot position), gamma+beta		800	1953	MCW 1953e
Empty furnace, bottom opening, edge//1 foot, gamma+beta		300//100-250	1953	MCW 1953e
Used crucible before loading		380	1953	MCW 1953e
Sample storage room (Plant 4), beta only	---	25	1944	MED 1945b
Storage and packaging, average for general area: beta only	---	3	1948	MCW 1948a
Storage and packaging, facing table of derbies, 1' above table edge: beta only	---	21	1948	MCW 1948a
Storage and packaging, surface of cleaned derby: beta only	---	85	1948	MCW 1948a
Storage and packaging, box of rolls, 1' above: beta only	---	5	1948	MCW 1948a
Slag from reaction bomb, 4", beta only	---	250	1944	MED 1945b
Bomb step, edge of the slag barrel: beta only	---	66	1948	MCW 1948a
Pile of slag in sample aging room, 2": gamma; beta	---	<25, 200	1944	MED 1945b
Piece of slag (~30 in3), 1.5": gamma; beta	---	2.5; 100	1944	MED 1945b
<b>PLANT 6</b>				
Ore barrels, direct contact with a group	---	200	1947	AEC 1947a
Ore drum, 4" away through 2" of steel(?) shielding	---	9.5	1948	AEC 1948a
Removing lids from ore drums, hands	---	25-38	1948	AEC 1948d
Ore milling feeder tube, 3" away, gamma	---	53	1948	AEC 1948a
Ore milling hopper general vicinity, first platform	---	15	1948	AEC 1948a
Ore milling hopper, 8" away through 1/8" steel plate shielding	---	40	1948	AEC 1948a
Ore milling hopper, 3" away, first platform	---	20	1948	AEC 1948a
Ore milling hopper, 35" from revolving ore drum at first platform guardrail	---	7	1948	AEC 1948a
Ore milling gas blower, 15" from revolving ore drum	---	9.5	1948	AEC 1948a
By Tank M-2 on platform, 5 hrs after addition of 6000 lbs ore: 1 foot	100		1946	MCW 1946a

Table 33 (Continued)

	Exposure, % tolerance	Exposure, mrep/hr or mR/hr*	Year	Reference
By Tank M-2, on platform (catwalk): 6"; 18"; 36" from tank	230; 120; 90		1947	AEC 1949f
By Tank M-3 on platform while adding ore (2000 lbs in tank): 1 foot	70		1946	MCW 1946a
By Tank M-3, on platform (catwalk): 6"; 18"; 36" from tank	220; 120; 90		1947	AEC 1949f
Under Tank M-3, containing GLC: 1 foot	120		1946	MCW 1946a
By Tank M-4, on platform (catwalk): 6"; 18"; 36" from tank	80-200; 50-60; 40		1947	AEC 1949f
By Tank M-72, containing wash water: 1 foot	50		1946	MCW 1946a
By Tank M-1, on platform: about 250 gal GLC (3 days old), 1 foot	90		1946	MCW 1946a
By Tank M-1, on platform (catwalk): 6"; 18"; 36" from tank	220; 180; 90		1947	AEC 1949f
By Tank M-83: three-quarters full of GLC (2 days old), 1 foot	220		1946	MCW 1946a
By Tank M-83: 6" from tank	500		1947	AEC 1949f
At operator position between skid and Tank M-14, on platform: 1 foot	120		1946	MCW 1946a
Above skid of GLC on M-14: 1 foot	280		1946	MCW 1946a
Between Tanks M-14 and M-20, midway, on platform (catwalk)	350		1947	AEC 1949f
By Tank M-14, on platform (catwalk): 6"; 18"; 36" from tank	450; 400; 250		1947	AEC 1949f
By Tank M-19, on platform:reslurrying skid cake batch: 1 foot	120		1946	MCW 1946a
By Tank M-19, on platform: 18" from tank	300		1947	AEC 1949f
By Tank M-19, on top of tank: 1 foot	250		1946	MCW 1946a
In front of Feinc filter while filtering reslurry batch: 1 foot	210 (2)		1946	MCW 1946a
At Feinc filter GI-4/GI-9: front (walkway); side; back; top (all at 6")	400; 350; 500; 900		1947	AEC 1949f
Near Feinc filter, on platform: gamma min//avg//max		5//16//50	1948	MCW 1948E
Feinc cloth change, < 3 feet from Feinc: gamma, beta		30; 69	1951	MCW 1951a
Feinc cloth change, general vicinity: gamma, beta		12; Negligible	1951	MCW 1951a
Leach (cell) cloth change, < 3 feet: gamma, beta		16; 158	1951	MCW 1951a
Leach (cell) cloth change, general vicinity: gamma, beta		10; 40	1951	MCW 1951a
Wash (cell) cloth change, < 3 feet: gamma, beta		42; 150	1951	MCW 1951a
Wash (cell) cloth change, general vicinity: gamma, beta		17; 48	1951	MCW 1951a
Old material work in old cloth room: average gamma, beta		5; 20	1951	MCW 1951a
Carrying, laundering Feinc, Leach, & Wash cloths, old cloth room: gamma, beta		3; 25	1951	MCW 1951a
Carrying, repairing Feinc blankets, old cloth room: gamma, beta		6; 30	1951	MCW 1951a
Washing Feinc blanket with brush on floor: carrying//changing -- gamma, beta		28; 105//28; 150	1951	MCW 1951a
Changing strings, Feinc, Leach, and Wash filters in cells: typical gamma, beta		30;75	1951	MCW 1951a
Cloth storage room, gamma		0.3 - 2.0	1955	MCW 1957
Feinc filter plates (removed for cleaning, with some residue caked on them)		<1-5; <10	1950	MCW 1950b
Floor surface under Feinc platform: 1 foot	30 (8)		1946	MCW 1946a
Floor around Feinc filters: 1 foot	110 (7)		1946	MCW 1946a
Feinc filtrate residue, contact (gamma; beta)		>300; >500	1948	AEC 1948k
Operator position while filling drums of GLC: about 1 foot	110 (2)		1946	MCW 1946a
Skids of acid press cake (2-3 days old): 1 foot	200 (5)		1946	MCW 1946a
55-gal drum: 521 lbs of K-65 less than 24 hours old, side contact (gamma)	275		1949	MCW 1949g
GLC (3 days old), centered among 4 barrels; between 2 barrels	150; 120		1946	MCW 1946a
4 drums "aged" K-65, 6 feet	---	28	1947	AEC 1947c
2 drums "aged" K-65, 6 feet	---	23	1947	AEC 1947c
Sump recovery skids, all full (1 foot)	80 (5)		1946	MCW 1946a
Dempster body of Chem 6BC; Chem 6BP (1 foot)	30; 40		1946	MCW 1946a
Scalehouse sample room, sampling K-65: gamma; beta		2.0-4.0; 2.5-5.0	1955	MCW 1955n
Scalehouse sample room, carrying K-65 sample pans: gamma; beta		6.0; 12.5	1955	MCW 1955n
Sample Prep Room, pile of K-65 in hood: 1 foot	60		1946	MCW 1946a
Sample Prep Room, 3-gal bottle of K-65 at equilibrium; 3 2-qt bottles at equil (1 foot)	160; 100		1946	MCW 1946a
Sample Prep Room, operator position at Ro-Tap	50		1946	MCW 1946a
Sample Prep Room, operator position while milling GLC	130		1946	MCW 1946a
Sample Prep Room, near drying oven: 1 foot	20		1946	MCW 1946a
Laboratory sample room: center; vault	0; 80		1946	MCW 1946a
Analytical Lab, Dry Sample Prep Room, making up shotgun samples: gamma, beta	3; 1		1956	MCW 1956l
Shotgun Lab, scooping samples into vats: gamma, beta	3; 8		1956	MCW 1956l
Shotgun Lab, draining residue, 1st ether contact, max (NLO sample): gamma, beta	5; 8		1956	MCW 1956l



Table 33 (Continued)

	Exposure, % tolerance	Exposure, mrep/hr or mR/hr*	Year	Reference
Shotgun Lab, draining residue, later ether contacts, max: gamma, beta	6; 50		1956	MCW 1956l
Shotgun Lab, moving residue to hot plate, max: gamma, beta	6; 25		1956	MCW 1956l
Shotgun Lab, removing material from muffle furnace, max: gamma, beta	8; 30		1956	MCW 1956l
Shotgun Lab, removing material from mold, max: gamma, beta	8; 25		1956	MCW 1956l
Shotgun Lab, paint and place in box: gamma, beta	8; 10		1956	MCW 1956l
Shotgun Lab, counting samples: gamma, beta	2; 2		1956	MCW 1956l
Shotgun Lab, lab assay work	1.5; ND		1956	MCW 1956l
Shotgun Lab, general area work	1; ND		1956	MCW 1956l
Fork truck driver position while loading GLC(rail?)car	140		1946	MCW 1946a
UO <sub>2</sub> packing area, cylindrical boxes containing UO <sub>2</sub> , cover on, beta	4.5		1948	Rochester 1948b
UO <sub>2</sub> packing area, cylindrical boxes containing UO <sub>2</sub> , cover off, beta	22.5		1948	Rochester 1948b
UO <sub>2</sub> packing area, inside 55-gal drum half-filled with UO <sub>2</sub> , beta	27		1948	Rochester 1948b
Warehouse, on 25 cylindrical boxes containing UO <sub>2</sub> , cover on, beta	15		1948	Rochester 1948b
<b>PLANT 6E</b>				
Lid cleaner of the furnace enclosures: gamma, beta		170; 7500	1955	MCW 1955t
Crucible, large unpainted, contact: gamma, beta		5; 3000	1955	MCW 1955s
Crucible, large painted, contact: gamma, beta		4; 1000	1955	MCW 1955s
Crucible, small unpainted, contact: gamma, beta		4; 700	1955	MCW 1955s
Crucible, small painted, contact: gamma, beta		2; 560	1955	MCW 1955s
Painting used crucible: gamma, beta		1; 300	1955	MCW 1955s
Painting used crucible, body or arm: gamma, beta		2; 500	1956	MCW 1956k
Painting used crucible, hand: gamma, beta		4; 1500	1956	MCW 1956k
Assembling used crucible: gamma, beta		1; 70	1955	MCW 1955s
Assembling crucible, body at enclosure armhole: gamma, beta (mR/wk, mrep/wk)		36; 2500	1956	MCW 1956n
Assembling crucible, body: gamma, beta		2; 200	1956	MCW 1956k
Assembling crucible, arm: gamma, beta (in mR/week, mrep/week)		74; 17500	1956	MCW 1956n
Assembling crucible, arm: gamma, beta		6; 1800	1956	MCW 1956k
Assembling crucible, hand: gamma, beta (in mR/week, mrep/week)		78; 25000	1956	MCW 1956n
Assembling crucible, hand: gamma, beta		4; 1500	1956	MCW 1956k
General crucible assembly area: gamma, beta		ND; 30	1955	MCW 1955s
General crucible assembly area work: gamma, beta		0.5; 3	1956	MCW 1956k
Crucible assembly operator, wrist: gamma, beta (mR/day, mrep/day)		50; 740	1956	MCW 1956m
Adjusting crucible jack: gamma, beta		1; 25	1956	MCW 1956k
Assembled used crucible, before loading: gamma, beta		1; 20	1955	MCW 1955s
Loading high-carbon/CST, max, body: gamma, beta		1; 20	1956	MCW 1956k
Loading high-carbon/CST, max, arm: gamma, beta		2; 120	1956	MCW 1956k
Loading high-carbon/CST, max, hand: gamma, beta		6; 300	1956	MCW 1956k
Loading crucible: gamma, beta		1; 20	1955	MCW 1955s
Lining up crucible: gamma, beta		1; 48	1955	MCW 1955s
Handling crucible lid: gamma, beta		1; 300	1955	MCW 1955s
Top insulation block: gamma, beta		1; 75	1955	MCW 1955s
Fixing stuck (crucible removal) sleeve: gamma, beta		2; 400	1955	MCW 1955s
General furnace enclosure area: gamma, beta		0.5; 8	1955	MCW 1955s
General furnace enclosure area work: gamma, beta		1; 100	1956	MCW 1956k
Crucible loader (top man), wrist: gamma, beta (mR/day, mrep/day)		0; 90	1956	MCW 1956m
Cleaning furnace enclosure, body at enc armhole: gamma, beta (mR/wk, mrep/wk)		23; 196	1956	MCW 1956n
Cleaning furnace enclosure, body at enclosure armhole: gamma, beta		1; 100	1956	MCW 1956k
Cleaning furnace enclosure, arm: gamma, beta (in mR/week, mrep/week)		23; 488	1956	MCW 1956n
Cleaning furnace enclosure, arm: gamma, beta		1; 300	1956	MCW 1956k
Cleaning furnace enclosure, hand: gamma, beta (in mR/week, mrep/week)		25; 628	1956	MCW 1956n
Cleaning furnace enclosure, hand: gamma, beta		1; 240	1956	MCW 1956k
Vacuum-cleaning burners: gamma, beta		1; 120	1955	MCW 1955s
Setting crucible over to cool: gamma, beta		1; 25	1955	MCW 1955s
Unlidding crucible: gamma, beta		1; 25	1955	MCW 1955s
Removing crucible lid, body: gamma, beta		3; 215	1956	MCW 1956k
Removing crucible lid, arm: gamma, beta (in mR/week, mrep/week)		22; 506	1956	MCW 1956n
Removing crucible lid, arm: gamma, beta		4; 1600	1956	MCW 1956k
Removing crucible lid, hand: gamma, beta (in mR/week, mrep/week)		23; 685	1956	MCW 1956n
Removing crucible lid, hand: gamma, beta		8; 2400	1956	MCW 1956k
Removing crucibles and slugs from enclosure: gamma, beta		2; 400	1955	MCW 1955s

Table 33 (Continued)

	Exposure, % tolerance	Exposure, mrep/hr or mR/hr*	Year	Reference
General burnout area: gamma, beta		1; 8	1955	MCW 1955s
General burnout area work: gamma, beta		0.5; 3	1956	MCW 1956k
Gen'l burnout area work, body at encllo armhole: gamma, beta (mR/wk, mrep/wk)		22; 200	1956	MCW 1956n
Burnout operator, wrist: gamma, beta (mR/day, mrep/day)		90; 215	1956	MCW 1956m
<b>SLAPS</b> (all as "gamma; beta" except where indicated)				
At contact with aged raffinate heaps		0.5-3.3;0.3-0.8	1949	MCW 1949g
Fresh raffinate heap, 1 foot		70; 1.6	1949	MCW 1949g
Fresh raffinate heap, chest height		33; 1.3	1949	MCW 1949g
Fresh raffinate heap, on bulldozer cab pushed into heap		2.7; 1.0	1949	MCW 1949g
"C" material heap, top of pile at waist height		11.5; 1.6	1949	MCW 1949g
"C" material heap, bulldozer cab pushed into heap (ratioed by raff bulldozer result)		7.7; 0.8	1949	MCW 1949g
Aged BC (barium sulfate cake) heap, top of pile at waist height		10; 3-10	1949	MCW 1949g
Aged BC heap bulldozer cab pushed into heap (ratioed by raff bulldozer result)		8.9; 0.13	1949	MCW 1949g
Fresh BC (barium sulfate cake) heap, top of pile at waist height		35; 2.5	1949	MCW 1949g
Fresh BC heap bulldozer cab pushed into heap (ratioed by raff bulldozer result)		2.5; 0.5	1949	MCW 1949g
K-65 storage shed, 2 feet (gamma only)	17.6	2.2	1948	MCW 1950f
K-65 storage shed, 3 feet (gamma only)	12.4	1.6	1948	MCW 1950f
K-65 storage shed, 6 feet (gamma only)	9.0	1.1	1948	MCW 1950f
K-65 storage shed, 9 feet (gamma only)	7.5	0.94	1948	MCW 1950f
K-65 storage shed, 12 feet (gamma only)	6.2	0.78	1948	MCW 1950f
K-65 storage shed, 15 feet (gamma only)	4.3	0.54	1948	MCW 1950f
K-65 storage shed, 18 feet (gamma only)	3.6	0.45	1948	MCW 1950f
K-65 storage shed, 21 feet (gamma only)	2.6	0.33	1948	MCW 1950f
K-65 storage shed, 24 feet (gamma only)	1.8	0.23	1948	MCW 1950f
K-65 storage shed, 27 feet (gamma only)	1.3	0.16	1948	MCW 1950f
K-65 storage shed, 30 feet (gamma only)	0.8	0.10	1948	MCW 1950f
K-65 storage shed, 150 feet (gamma only) -- guard shack location	0.032	0.004	1948	MCW 1950f
<b>PLANT 4, measured beta dose rates analyzed for the design of Plant 6E</b>				
	<b>Meter reading, mrep/week</b>	<b>Worker film badge avg beta, mrep/wk</b>	<b>Year</b>	<b>Reference</b>
Green salt, loading and unloading	816	480	1948	MCW 1948b
Green salt, box pulling	300	415	1948	MCW 1948b
Green salt, milling	432	530	1948	MCW 1948b
Green salt, extra man	300	510	1948	MCW 1948b
Green salt, lead operator	300	360	1948	MCW 1948b
Bomb step, jolting	600	440	1948	MCW 1948b
Bomb step, charging	600	370	1948	MCW 1948b
Bomb step, topping	600	380	1948	MCW 1948b
Bomb step, furnace tender	500	380	1948	MCW 1948b
Bomb step, unloading	600	460	1948	MCW 1948b
Bomb step, chipping	1900	845	1948	MCW 1948b
Bomb step, lime mixing	---	415	1948	MCW 1948b
Bomb step, magnesium mixing	---	300	1948	MCW 1948b
Recasting, furnace tending	500	665	1948	MCW 1948b
Recasting, top furnace tending	2125	1220	1948	MCW 1948b
Recasting, bottom furnace tending	1050	800	1948	MCW 1948b
Recasting, sawing	>500	535	1948	MCW 1948b
Recasting, weighing and packing	613	580	1948	MCW 1948b
<b>PLANT 6, gamma dose rates at area film badge monitoring locations</b>				
	<b>Meter reading, mR/hr</b>	<b>Average, mR/hr</b>	<b>Year</b>	<b>Reference</b>
Digest area: upper platform	2.5	3.8	1955	MCW 1955c
Digest area: lower platform	3	5	1955	MCW 1955c
Cell: lower C-3 area (M-14, M-203); upper C-3 area (Olivers); leach area (Olivers)	2.5; 10; 3	2.6; 14.2; 3.1	1955	MCW 1955c
C-3: lower platform at M-214; upper platform	2; 2	3.8; 2.4	1955	MCW 1955c
Centrifuge area	2	3.4	1955	MCW 1955c
Feinc area: lower platform; upper platform; east area	2; 2; 4.5	3.1; 2.0; 6.5	1955	MCW 1955c
Cell: Feinc Niagara area	1.5	1.7	1955	MCW 1955c

### Table 33 (Continued).

\* The mrep/hr should be assumed for mixed beta-gamma or for beta alone; the mR/hr should be assumed for gamma only (i.e., either when stated explicitly or when it can be assumed, such as from the side of a tank or bottle). Slashes indicate multiple values. ND means not detectable.

Many figures are given in units of per cent of tolerance, defined in MCW (1949f) as "the amount of exposure that a person can receive 8 hrs/day for an indefinite period of time", presumably corresponding to 100 mR per eight-hour day for gammas and 500 mrep per eight-hour day for betas at the relevant time period. The exposure rates in mR/hr or in mrep/hr were in most cases converted from the original units of R per 8 hours. MED (1945b) gave beta exposure rate figures in "beta units", which as MED (1945c) explained, were the same as "T units", with a T unit being 0.25 "r/hr" of beta radiation. This unit was taken to be 0.25 rep in the table above.

Parentheses indicate the number of measurements, if more than one, used to form the average reported. Data from AEC 1949f were taken at waist height except where indicated.

Table 34. Neutron dose rates and doses from the alpha-neutron reaction sources and from a RaBe source.

Alpha-neutron source information and dose rates						
Form	Source	Target element(s)	Weight in container	Dose rate at 1 foot, rem/hr	Dose rate at 3 feet, rem/hr	Annual dose, rem
U <sub>3</sub> O <sub>8</sub>	U natural mix	O	100 lbs	1.29E-07	1.44E-08	4.31E-05
	U natural mix + daughters	O	100 lbs	1.10E-06	1.22E-07	3.67E-04
UO <sub>3</sub> , UO <sub>2</sub>	U natural mix	O	75 lbs	9.71E-08	1.08E-08	3.24E-05
	U natural mix + daughters	O	75 lbs	8.27E-07	9.19E-08	2.76E-04
UF <sub>4</sub>	U natural mix	F	75 lbs	6.92E-06	7.69E-07	2.31E-03
	U natural mix + daughters	F	75 lbs	5.91E-05	6.57E-06	1.97E-02
Na <sub>2</sub> U <sub>2</sub> O <sub>7</sub> (soda salt)	U natural mix	O, Na	75 lbs	2.61E-07	2.90E-08	8.70E-05
	U natural mix + daughters	O, Na	75 lbs	2.13E-06	2.37E-07	7.11E-04
ThF <sub>4</sub>	Th-230/Th232 mix	F	198 g	4.08E-04	4.53E-05	1.36E-01
	Th-230/Th-232 mix + daughters	F	198 g	8.97E-04	9.96E-05	2.99E-01
Th(NO <sub>3</sub> ) <sub>4</sub>	Th-230/Th232 mix	O	309 g	4.74E-06	5.26E-07	1.58E-03
	Th-230/Th-232 mix + daughters	O	309 g	1.04E-05	1.16E-06	3.47E-03
RaBe source information and dose rates						
RaBe	Ra-226	---	100 mg Ra	1.60E-02	1.77E-03	4.44E+00
Annual organ doses (based on ThF <sub>4</sub> for the alpha-neutron case; Ra-226 for the RaBe case)						
Organ				Alpha-neutron dose, rem	RaBe dose, rem	
Bladder				2.09E-01	5.00E+00	
Bone marrow				1.16E-01	3.37E+00	
Bone surface				1.34E-01	3.15E+00	
Breast				3.10E-01	5.08E+00	
Colon				1.34E-01	4.17E+00	
Esophagus				1.17E-01	4.02E+00	
Lung				1.62E-01	4.32E+00	
Gonads (ovaries)				1.19E-01	4.15E+00	
Gonads (testes)				3.39E-01	5.50E+00	
Liver				1.78E-01	4.54E+00	
Remainder organs				2.57E-01	4.13E+00	
Skin				9.64E-09	4.33E+00	
Stomach				2.20E-01	4.96E+00	
Thyroid				2.95E-01	5.15E+00	

Data used to calculate the alpha-neutron dose rates (except for the assumed amount of U, Th, or Ra material) is from Shleien (1992), Tables 8.4.1, 7.3, and 7.2; Salmon and Hermann (1993), Table 3; DOE (2001a), Table 6-5; Foderaro (1978); and Mlekodaj (2002). Data used to calculate the RaBe dose rates is from Shleien (1992), Tables 7.5 and 8.4.1, and Foderaro (1978). In both cases, the dose conversion factors were taken from NIOSH (2002a). The quantities listed correspond to one drum of material for the uranium forms; to one day's processing for the thorium forms (on a 70-day basis); and to the known RaBe source for the Ra form.

In the alpha-neutron case, the neutron energy was taken as 1.5 MeV because it is the approximate maximum energy for Th-232, the other isotopes also emit neutrons in the range 1.0-2.0, and the flux-to-dose conversion factor varies slowly in this range. For the annual dose, it was assumed that 1 hour/day was spent at 1 foot from the container and three hours/day spent at 3 feet, every working day for a year. In the RaBe case, the neutron energy was taken as 4.0 MeV and it was assumed that 1 hour/day was spent at 1 foot from the unshielded source and 1 hour/day spent at 3 feet, every working day for a year. (This is conservative since the source was likely to be at least partially shielded when in use and completely shielded when not in use.)

In both cases, the maximum organ dose was based on the maximum annual whole-body dose taken to be the ambient dose. For the alpha-neutron source case, an exposure geometry of 75% AP/25% ROT was assumed, as per Table 18 (for "ionium plant operator"); for the RaBe case, 90% AP/10% ROT was assumed, as per Table 18 (for "Shorgun Lab analyst").

Table 35. External gamma dose rates from processing AM-7 residue to concentrate thorium.

Isotope	Gam energy, MeV	Freq	Ci	DR@1 ft, /hr	Annual Dose, R
Th-230	0.142	0.0007	24.4	2.08E-04	6.93E-02
Th-230	0.143	0.00045	24.4	1.35E-04	4.49E-02
Th-232	0.126	0.0004	0.001	4.32E-09	1.44E-06
Ra-226	0.186	0.0328	0.158	8.26E-05	2.75E-02
Total	---	---	48.959	4.25E-04	1.42E-01
	Ratio, Ra/Th	---	3.24E-03	2.41E-01	2.41E-01
	Ratio, Ra/Total	---	3.23E-03	1.94E-01	1.94E-01

Note: Assumptions for the annual dose are as for Table 34, i.e., 1 hours per day were spent at one foot from the unshielded source and 3 hours per day at 3 ft for 250 working days.

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. Monitoring experience from the decontamination/demolition period, 1960-1961 ( MCW 1961b).

<b>General outside air concentration during decontamination and demolition</b>					
Date sampled	Airborne activity, in units of 10 <sup>-13</sup> uCi/cc		No. samples		
	Uranium	Gross alpha			
Dec 1960	4.0	6.8	16		
Jan 1961	7.4	6.5	48		
Feb 1961	1.1	1.6	104		
Mar 1961	1.4	1.7	141		
Apr 1961	2.0	6.9	115		
May 1961	2.0	4.0	97		
Jun 1961	3.3	5.6	69		
Jul 1961	1.6	2.8	48		
Aug 1961	1.9	4.1	77		
Sep 1961	2.2	2.9	83		
Oct 1961	3.8	5.0	77		
Nov 1961	12.0	6.7	21		
Weighted average	2.6	4.0	---		
<b>Operational area air concentrations, as airborne alpha activity in uCi/cc</b>					
Operation or Area	Average	High			
Cutting and removing iron structures, equipment	8.7 E-11	7.7 E-10			
Loading iron, equipment by hand and by lift	8.7 E-11	5.3 E-10			
Demolishing wood, concrete, or masonry	2.7 E-11	9.2 E-11			
Mechanically loading debris and rubble	1.8 E-11	1.1 E-10			
Removing tar and gravel roofs	2.5 E-11	1.5 E-11			
Dry-sandblasting the insides of buildings	3.6 E-10	7.4 E-10			
General area outside bldgs during inside sandblasting	2.7 E-11	9.5 E-11			
Dry-sandblasting outside surfaces	4.2 E-11	1.1 E-10			
Shoveling residues into small quarters	2.4 E-10	---			
Jackhammering Gunitite from tanks	8.2 E-10	1.8 E-09			
Outside hood during removal of Gunitite inside hood	3.4 E-12	---			
Cleaning sand, residues from inside vessel after sandblasting	6.4 E-11	---			
Steam cleaning of nonsalvageable materials	2.0 E-12	---			
Source sampling with wire brush inside pipe after solvent soaking	8.8 E-10	---			
Stack exhaust area, from dust collector-hood setup	3.3 E-11	---			
General air in building during period of inactivity	1.4 E-11	---			
<b>Concentrations of uranium in urine, in mg/L</b>					
Sample type	Average	Range			
Equipment removal phase	Pre-exposure sample	0.007	0.002 - 0.013		
	Monday before work sample	0.010	0.005 - 0.008		
	Friday after work sample	0.025	0.003 - 0.078		
Decontamination and demolition	Pre-exposure sample	0.005	0.001 - 0.014		
	Monday before work sample	0.019	0.003 - 0.058		
	Friday after work sample	0.036	0.006 - 0.271		
	Termination sample	0.017	0.006 - 0.027		
Special operations	Sandblasting	0.031	0.007 - 0.080		
	Torch-cutting stainless steel	0.032	---		
	Cutting, wrecking a rod mill	0.098	0.061 - 0.135		
	Dismantling vacuum, dust collector	0.065	---		
	Stripping wiring, metal from bldgs	0.045	0.007 - 0.158		
<b>Film badge data</b>					
User	Gamma			Beta	
	Annual average, rem	Highest quarterly reading, rem	Highest monthly reading, rem	Annual average, rem	Highest monthly reading, rem
Contractor	0.04	0.15	0.08	0.3	0.29
AEC	0.1	---	---	0.6	---
MCW	0.2	---	---	0.8	---
AEC/MCW	---	---	0.14	---	0.15
Visitor	---	---	0.05	---	---

Table 38. Summary of post-decontamination years exposure data as measured by two survey groups.

Plant	Bldg Remaining	1981	1986	1990	Source	Overall averages, 1981	
		Radon daughters, WL	Radon Yearly Avg, WLM/yr	Radon Yearly Avg, WLM/yr		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
	25-1	0.001		0.01	Radon daughters in air	<0.01 WL	0.0009-0.07 WL, avg daytime concentration
	25-2	0.0009		0.01	Gamma from Ra, U daughters	8 µR/hr	8-290 µR /yr @ 1 m above floor
	38						
	40						
2	50	0.0003					
	51	0.0005	0.02	0.01			
	51A		0.02	0.01			
	52A	0.07					
	52	0.0007-0.001		0.00			
6	100			0.02			
	101		0.10	0.01			
6E	116-1		0.00	0.04			
	116-2			0.00			
	116B			0.01			
	117-1			0.00			
	117-2			0.00			
7	700			0.00			
	704		0.03	0.00			
	705			0.00			
	706			0.00			
	708			0.01			

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

Table 39. Measured data used to produce source terms for decontamination and post-decontamination exposure calculations.

Plant	Case	Dose potential	Internal exposure		External exposure			
			Surface alpha, dpm/100 cm <sup>2</sup>	Volume alpha, pCi/g	Maximum average gamma, mR/hr	Typical average gamma, mR/hr	Maximum average beta, mrep/hr	Typical average beta, mrep/hr
4	Decon	Low	4.4E+03	1.0E+04	8.0E-02	2.4E-02	1.3E+01	7.5E+00
		Moderate	8.3E+03	4.2E+04	3.0E-01	9.0E-02	2.4E+01	1.4E+01
		High	1.7E+04	8.1E+04	2.0E+00	6.0E-01	4.7E+01	2.7E+01
6	Decon	Low	1.2E+02	1.0E+01	1.0E-01	1.2E-02	1.0E+00	1.2E-01
		Moderate	3.9E+03	7.7E+02	2.5E-01	2.9E-02	2.0E+00	2.4E-01
		High	6.0E+04	3.0E+03	3.0E+00	1.7E+00	3.9E+01	4.6E+00
6E	Decon	Low	4.0E+02	0.0E00	1.0E-01	5.0E-02	2.0E-01	4.3E-02
		Moderate	2.7E+03	3.8E+02	5.0E-01	1.0E-01	1.3E+00	2.8E-01
		High	3.5E+04	1.6E+03	1.4E+00	5.0E-01	1.2E+01	2.5E+00
7	Decon	Low	8.5E+01	0.0E+00	5.0E-02	2.0E-02	1.0E-01	1.7E-02
		Moderate	2.8E+03	1.9E+02	1.0E-01	4.0E-02	1.7E+00	2.9E-01
		High	1.2E+05	2.6E+02	2.5E-01	1.0E-01	1.8E+01	3.0E+00
1	Post-decon	---	---	---	8.7E-02	2.1E-02	8.9E+00	9.0E-01
2	Post-decon	---	---	---	2.1E-02	1.0E-02	9.7E+00	2.3E-01
6E	Post-decon	Low	1.2E+03	0.0E+00	5.4E-02	1.7E-02	5.0E-01	1.0E-01
		Moderate	3.0E+03	3.8E+02	8.1E-02	4.2E-02	7.5E-01	2.5E-01
		High	4.5E+03	1.6E+03	1.6E-01	8.3E-02	1.5E+00	5.0E-01
7	Post-decon	Low	1.0E+03	0.0E+00	8.1E-03	3.2E-03	2.5E-01	1.0E-01
		Moderate	2.8E+03	1.9E+02	1.6E-02	8.1E-03	5.0E-01	2.5E-01
		High	7.5E+03	2.6E+02	3.2E-02	1.6E-02	1.0E+00	5.0E-01

The data in this table was extracted from MCW (1958), MCW(1959), MCW (1961a), and ORNL (1981).

For the Plants 6E and 7 post-decontamination dose rates, the beta/gamma ratio was assumed to be the same as for the corresponding decontamination maximum case. For both decontamination and post-decontamination cases, the High maximum was taken as the maximum average or representative maximum for the respective plant; the High typical value was the average of the non-zero average levels, hence is conservative. Similarly, the Moderate maximum and the Low maximum were the respective middling and low averages. The Moderate and Low typical values were ratioed from the High typical values.

For the Plants 1 and 2 case, the maximum averages were derived from the highest representative measurements in each building and the maximum building in each plant was chosen to be representative of all buildings in that plant. Also for Plants 1 and 2, the measured beta-gamma dose rate was assumed to be all beta, for conservatism and in default of other information; the gamma measurements are based on true gamma-only readings taken with a different instrument than was used to measure the beta-gamma level. The beta-gamma measurements were taken at less than 1 inch (the MCW references) or at 1 cm (ORNL 1981), while the gamma measurements were generally at 3 feet (1 m).



Table 40. Annual internal exposures during the decontamination and post-decontamination periods.

Decontamination		Annual average exposure, 1959-1961							
		Plant 4	Plant 6	Plant 6E	Plant 7				
Inhalation, pCi	Low	8.39E+02	1.98E+01	6.86E+01	1.46E+01				
	Moderate	1.77E+03	6.67E+02	4.66E+02	4.82E+02				
	High	3.48E+03	1.03E+04	6.02E+03	1.97E+04				
Radon, WLM	Low	1.43E-02	3.73E-04	1.30E-03	2.76E-04				
	Moderate	2.69E-02	1.25E-02	8.76E-03	9.09E-03				
	High	5.36E-02	1.95E-01	1.14E-01	3.73E-01				
Ingestion, pCi	Low	1.75E+01	4.13E-01	1.43E+00	3.04E-01				
	Moderate	3.68E+01	1.39E+01	9.72E+00	1.00E+01				
	High	7.25E+01	2.15E+02	1.25E+02	4.11E+02				
Post-decontamination		Annual average exposure, 1962-1995 (1959-1995 for Plants 1 and 2)							
		Plant 1				Plant 2			
Inhalation, pCi		1959-1965	1966-1975	1976-1985	1986-1995	1959-1965	1966-1975	1976-1985	1986-1995
Radon, WLM		4.25E-01	4.17E-01	4.04E-01	3.92E-01	1.42E+00	1.39E+00	1.35E+00	1.31E+00
Ingestion, pCi		7.84E-01	7.87E-01	7.92E-01	7.85E-01	7.84E-01	7.87E-01	7.92E-01	7.85E-01
Post-decontamination		Plant 6E				Plant 7			
		1959-1965	1966-1975	1976-1985	1986-1995	1959-1965	1966-1975	1976-1985	1986-1995
Inhalation, pCi	Low	9.12E+00	5.72E+00	5.75E+00	5.70E+00	4.75E+00	4.77E+00	4.79E+00	4.75E+00
	Moderate	1.71E+01	1.72E+01	1.73E+01	1.72E+01	1.47E+01	1.48E+01	1.49E+01	1.48E+01
	High	3.35E+01	3.36E+01	3.37E+01	3.36E+01	3.76E+01	3.77E+01	3.79E+01	3.76E+01
Radon, WLM	Low	4.54E-03	4.45E-03	4.31E-03	4.18E-03	3.78E-03	3.71E-03	3.60E-03	3.48E-03
	Moderate	1.13E-02	1.11E-02	1.08E-02	1.04E-02	1.06E-02	1.04E-02	1.01E-02	9.75E-03
	High	1.70E-02	1.67E-02	1.62E-02	1.57E-02	2.84E-02	2.78E-02	2.70E-02	2.61E-02
Ingestion, pCi	Low	1.90E-01	1.19E-01	1.20E-01	1.19E-01	9.90E-02	9.93E-02	9.99E-02	9.90E-02
	Moderate	3.57E-01	3.58E-01	3.60E-01	3.57E-01	3.07E-01	3.08E-01	3.10E-01	3.07E-01
	High	6.97E-01	6.99E-01	7.03E-01	7.00E-01	7.83E-01	7.86E-01	7.90E-01	7.84E-01

Inhalation and radon data in this table was calculated with the RESRAD-BUILD computer code (ANL 2003), using measured data from MCW (1958; 1959; 1961a). Both surface contamination and bulk floor and wall contamination were taken into account in calculating the inhalation and radon contributions. Ingestion data were calculated using the ingestion model of OCAS (2004).

“High” exposure potential represents those working in the most contaminated areas, i.e., the former process areas; “Moderate”, those accessing less contaminated areas or infrequently accessing former process areas; and “Low”, those accessing uncontaminated areas. Plants 1 and 2 did not have enough data for these classifications to be applied.

The Plants 1 and 2 inhalation and ingestion figures were taken to be the same as the Plant 7 figures since the post-D&D contamination figures as given in ORNL (1981) for them were similar to the data for Plant 7. ORNL (1981) showed that while most radon daughter readings were similar in all of the plants, there was one significantly higher reading in both Plant 1 and Plant 2. Thus the Plants 1 and 2 readings are the Plant 7 readings multiplied by the factor of difference for the respective buildings (15 for Plant 1 and 50 for Plant 2). This should be quite conservative since the measured Plant 1 and 2 readings were maxima.

Table 41. Annual external photon organ doses, decontamination and post-decontamination periods (rem per year).

Decontamination years (1959-1961)													
Organ	Type	Plant 4			Plant 6			Plant 6E			Plant 7		
		Low	Moderate	High	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High
Bladder	Min	5.6E-02	2.1E-01	1.4E+00	4.9E-02	1.2E-01	3.0E+00	9.2E-02	2.9E-01	1.1E+00	4.0E-02	8.1E-02	2.0E-01
	Mode	1.1E-01	4.1E-01	2.7E+00	9.7E-02	2.4E-01	5.8E+00	1.8E-01	5.7E-01	2.1E+00	7.9E-02	1.6E-01	4.0E-01
	Max	2.9E-01	1.1E+00	7.2E+00	2.5E-01	6.4E-01	1.5E+01	4.7E-01	1.5E+00	5.5E+00	2.1E-01	4.2E-01	1.0E+00
Bone (red marrow)	Min	3.8E-02	1.4E-01	9.5E-01	3.4E-02	8.4E-02	2.0E+00	6.2E-02	2.0E-01	7.2E-01	2.7E-02	5.5E-02	1.4E-01
	Mode	7.4E-02	2.8E-01	1.9E+00	6.6E-02	1.6E-01	4.0E+00	1.2E-01	3.9E-01	1.4E+00	5.4E-02	1.1E-01	2.7E-01
	Max	2.0E-01	7.3E-01	4.9E+00	1.7E-01	4.3E-01	1.0E+01	3.2E-01	1.0E+00	3.7E+00	1.4E-01	2.8E-01	7.1E-01
Bone (surface)	Min	6.7E-02	2.5E-01	1.7E+00	6.0E-02	1.5E-01	3.6E+00	1.1E-01	3.5E-01	1.3E+00	4.9E-02	9.7E-02	2.4E-01
	Mode	1.3E-01	4.9E-01	3.3E+00	1.2E-01	2.9E-01	7.0E+00	2.2E-01	6.9E-01	2.5E+00	9.5E-02	1.9E-01	4.8E-01
	Max	3.5E-01	1.3E+00	8.6E+00	3.1E-01	7.7E-01	1.8E+01	5.7E-01	1.8E+00	6.6E+00	2.5E-01	5.0E-01	1.3E+00
Breast (female)	Min	5.9E-02	2.2E-01	1.5E+00	5.2E-02	1.3E-01	3.1E+00	9.7E-02	3.1E-01	1.1E+00	4.3E-02	8.5E-02	2.1E-01
	Mode	1.2E-01	4.3E-01	2.9E+00	1.0E-01	2.6E-01	6.1E+00	1.9E-01	6.1E-01	2.2E+00	8.3E-02	1.7E-01	4.2E-01
	Max	3.0E-01	1.1E+00	7.6E+00	2.7E-01	6.7E-01	1.6E+01	5.0E-01	1.6E+00	5.8E+00	2.2E-01	4.4E-01	1.1E+00
Colon	Min	5.0E-02	1.9E-01	1.3E+00	4.5E-02	1.1E-01	2.7E+00	8.3E-02	2.7E-01	9.6E-01	3.6E-02	7.3E-02	1.8E-01
	Mode	9.9E-02	3.7E-01	2.5E+00	8.7E-02	2.2E-01	5.3E+00	1.6E-01	5.2E-01	1.9E+00	7.1E-02	1.4E-01	3.6E-01
	Max	2.6E-01	9.7E-01	6.5E+00	2.3E-01	5.7E-01	1.4E+01	4.3E-01	1.4E+00	4.9E+00	1.9E-01	3.7E-01	9.4E-01
Esophagus	Min	3.9E-02	1.5E-01	9.8E-01	3.5E-02	8.7E-02	2.1E+00	6.4E-02	2.1E-01	7.5E-01	2.8E-02	5.7E-02	1.4E-01
	Mode	7.7E-02	2.9E-01	1.9E+00	6.8E-02	1.7E-01	4.1E+00	1.3E-01	4.0E-01	1.5E+00	5.5E-02	1.1E-01	2.8E-01
	Max	2.0E-01	7.5E-01	5.0E+00	1.8E-01	4.5E-01	1.1E+01	3.3E-01	1.1E+00	3.8E+00	1.5E-01	2.9E-01	7.3E-01
Eye	Min	6.0E-02	2.3E-01	1.5E+00	5.3E-02	1.3E-01	3.2E+00	9.9E-02	3.2E-01	1.1E+00	4.4E-02	8.7E-02	2.2E-01
	Mode	1.2E-01	4.4E-01	2.9E+00	1.0E-01	2.6E-01	6.3E+00	1.9E-01	6.2E-01	2.3E+00	8.5E-02	1.7E-01	4.3E-01
	Max	3.1E-01	1.2E+00	7.7E+00	2.7E-01	6.9E-01	1.7E+01	5.1E-01	1.6E+00	5.9E+00	2.2E-01	4.5E-01	1.1E+00
Gonads (ovaries)	Min	4.8E-02	1.8E-01	1.2E+00	4.2E-02	1.1E-01	2.5E+00	7.9E-02	2.5E-01	9.1E-01	3.5E-02	6.9E-02	1.7E-01
	Mode	9.4E-02	3.5E-01	2.3E+00	8.3E-02	2.1E-01	5.0E+00	1.5E-01	4.9E-01	1.8E+00	6.8E-02	1.4E-01	3.4E-01
	Max	2.5E-01	9.2E-01	6.1E+00	2.2E-01	5.4E-01	1.3E+01	4.0E-01	1.3E+00	4.7E+00	1.8E-01	3.6E-01	8.9E-01
Gonads (testes)	Min	6.3E-02	2.3E-01	1.6E+00	5.5E-02	1.4E-01	3.3E+00	1.0E-01	3.3E-01	1.2E+00	4.5E-02	9.1E-02	2.3E-01
	Mode	1.2E-01	4.6E-01	3.1E+00	1.1E-01	2.7E-01	6.5E+00	2.0E-01	6.5E-01	2.3E+00	8.9E-02	1.8E-01	4.4E-01
	Max	3.2E-01	1.2E+00	8.0E+00	2.9E-01	7.1E-01	1.7E+01	5.3E-01	1.7E+00	6.1E+00	2.3E-01	4.7E-01	1.2E+00
Liver	Min	5.2E-02	1.9E-01	1.3E+00	4.6E-02	1.1E-01	2.8E+00	8.5E-02	2.7E-01	9.9E-01	3.7E-02	7.5E-02	1.9E-01
	Mode	1.0E-01	3.8E-01	2.5E+00	9.0E-02	2.2E-01	5.4E+00	1.7E-01	5.3E-01	1.9E+00	7.3E-02	1.5E-01	3.7E-01
	Max	2.7E-01	1.0E+00	6.6E+00	2.4E-01	5.9E-01	1.4E+01	4.4E-01	1.4E+00	5.1E+00	1.9E-01	3.8E-01	9.6E-01
Lung	Min	5.1E-02	1.9E-01	1.3E+00	4.5E-02	1.1E-01	2.7E+00	8.4E-02	2.7E-01	9.7E-01	3.7E-02	7.4E-02	1.8E-01
	Mode	1.0E-01	3.8E-01	2.5E+00	8.9E-02	2.2E-01	5.3E+00	1.6E-01	5.3E-01	1.9E+00	7.2E-02	1.4E-01	3.6E-01
	Max	2.6E-01	9.8E-01	6.6E+00	2.3E-01	5.8E-01	1.4E+01	4.3E-01	1.4E+00	5.0E+00	1.9E-01	3.8E-01	9.5E-01
Remainder organs	Min	4.6E-02	1.7E-01	1.1E+00	4.1E-02	1.0E-01	2.4E+00	7.5E-02	2.4E-01	8.7E-01	3.3E-02	6.6E-02	1.7E-01
	Mode	9.0E-02	3.4E-01	2.2E+00	7.9E-02	2.0E-01	4.8E+00	1.5E-01	4.7E-01	1.7E+00	6.5E-02	1.3E-01	3.2E-01
	Max	2.4E-01	8.8E-01	5.9E+00	2.1E-01	5.2E-01	1.3E+01	3.9E-01	1.2E+00	4.5E+00	1.7E-01	3.4E-01	8.5E-01
Skin	Min	4.9E-02	1.8E-01	1.2E+00	4.3E-02	1.1E-01	2.6E+00	8.0E-02	2.6E-01	9.3E-01	3.5E-02	7.1E-02	1.8E-01
	Mode	9.6E-02	3.6E-01	2.4E+00	8.5E-02	2.1E-01	5.1E+00	1.6E-01	5.0E-01	1.8E+00	6.9E-02	1.4E-01	3.5E-01
	Max	2.5E-01	9.4E-01	6.3E+00	2.2E-01	5.6E-01	1.3E+01	4.1E-01	1.3E+00	4.8E+00	1.8E-01	3.6E-01	9.1E-01
Stomach	Min	5.7E-02	2.1E-01	1.4E+00	5.1E-02	1.3E-01	3.0E+00	9.4E-02	3.0E-01	1.1E+00	4.1E-02	8.3E-02	2.1E-01
	Mode	1.1E-01	4.2E-01	2.8E+00	9.9E-02	2.5E-01	6.0E+00	1.8E-01	5.9E-01	2.1E+00	8.1E-02	1.6E-01	4.0E-01
	Max	2.9E-01	1.1E+00	7.3E+00	2.6E-01	6.5E-01	1.6E+01	4.8E-01	1.5E+00	5.6E+00	2.1E-01	4.2E-01	1.1E+00
Thymus	Min	6.2E-02	2.3E-01	1.6E+00	5.5E-02	1.4E-01	3.3E+00	1.0E-01	3.3E-01	1.2E+00	4.5E-02	9.0E-02	2.2E-01
	Mode	1.2E-01	4.6E-01	3.0E+00	1.1E-01	2.7E-01	6.5E+00	2.0E-01	6.4E-01	2.3E+00	8.8E-02	1.8E-01	4.4E-01
	Max	3.2E-01	1.2E+00	8.0E+00	2.8E-01	7.1E-01	1.7E+01	5.2E-01	1.7E+00	6.1E+00	2.3E-01	4.6E-01	1.2E+00
Thyroid	Min	6.9E-02	2.6E-01	1.7E+00	6.1E-02	1.5E-01	3.7E+00	1.1E-01	3.7E-01	1.3E+00	5.0E-02	1.0E-01	2.5E-01
	Mode	1.4E-01	5.1E-01	3.4E+00	1.2E-01	3.0E-01	7.2E+00	2.2E-01	7.2E-01	2.6E+00	9.8E-02	2.0E-01	4.9E-01
	Max	3.6E-01	1.3E+00	8.9E+00	3.2E-01	7.9E-01	1.9E+01	5.9E-01	1.9E+00	6.8E+00	2.6E-01	5.2E-01	1.3E+00
Uterus	Min	4.8E-02	1.8E-01	1.2E+00	4.2E-02	1.1E-01	2.6E+00	7.9E-02	2.5E-01	9.1E-01	3.5E-02	6.9E-02	1.7E-01
	Mode	9.4E-02	3.5E-01	2.3E+00	8.3E-02	2.1E-01	5.0E+00	1.5E-01	4.9E-01	1.8E+00	6.8E-02	1.4E-01	3.4E-01
	Max	2.5E-01	9.2E-01	6.2E+00	2.2E-01	5.5E-01	1.3E+01	4.1E-01	1.3E+00	4.7E+00	1.8E-01	3.6E-01	8.9E-01
Whole-body dose rate	Min	7.6E-02	2.9E-01	1.9E+00	6.7E-02	1.7E-01	4.1E+00	1.3E-01	4.0E-01	1.5E+00	5.5E-02	1.1E-01	2.8E-01
	Mode	1.5E-01	5.6E-01	3.7E+00	1.3E-01	3.3E-01	7.9E+00	2.4E-01	7.8E-01	2.8E+00	1.1E-01	2.2E-01	5.4E-01
	Max	3.9E-01	1.5E+00	9.8E+00	3.5E-01	8.7E-01	2.1E+01	6.4E-01	2.1E+00	7.5E+00	2.8E-01	5.7E-01	1.4E+00
Post-decontamination years (1962-1995)													
Organ	Type	Plant 1			Plant 2			Plant 6E			Plant 7		
		Low	Moderate	High	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High
Bladder	Min	---	---	5.5E-02	---	---	1.9E-02	3.8E-02	7.6E-02	1.5E-01	6.5E-03	1.5E-02	3.0E-02
	Mode	---	---	1.1E-01	---	---	3.7E-02	7.5E-02	1.5E-01	3.0E-01	1.3E-02	2.9E-02	5.8E-02
	Max	---	---	2.8E-01	---	---	9.6E-02	2.0E-01	3.9E-01	7.8E-01	3.3E-02	7.6E-02	1.5E-01
Bone (red marrow)	Min	---	---	3.7E-02	---	---	1.3E-02	2.6E-02	5.1E-02	1.0E-01	4.4E-03	1.0E-02	2.0E-02
	Mode	---	---	7.3E-02	---	---	2.5E-02	5.1E-02	1.0E-01	2.0E-01	8.7E-03	2.0E-02	3.9E-02
	Max	---	---	1.9E-01	---	---	6.5E-02	1.3E-01	2.6E-01	5.3E-01	2.3E-02	5.2E-02	1.0E-01

Table 41 (Continued)

Post-decontamination years (1962-1995)													
Organ	Type	Plant 1			Plant 2			Plant 6E			Plant 7		
		Low	Moderate	High	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High
Bone (surface)	Min	---	---	6.6E-02	---	---	2.3E-02	4.6E-02	9.1E-02	1.8E-01	7.8E-03	1.8E-02	3.6E-02
	Mode	---	---	1.3E-01	---	---	4.4E-02	9.0E-02	1.8E-01	3.6E-01	1.5E-02	3.5E-02	7.0E-02
	Max	---	---	3.4E-01	---	---	1.2E-01	2.4E-01	4.7E-01	9.4E-01	4.0E-02	9.2E-02	1.8E-01
Breast (female)	Min	---	---	5.8E-02	---	---	2.0E-02	4.0E-02	8.0E-02	1.6E-01	6.9E-03	1.6E-02	3.1E-02
	Mode	---	---	1.1E-01	---	---	3.9E-02	7.9E-02	1.6E-01	3.1E-01	1.3E-02	3.1E-02	6.1E-02
	Max	---	---	3.0E-01	---	---	1.0E-01	2.1E-01	4.1E-01	8.2E-01	3.5E-02	8.0E-02	1.6E-01
Colon	Min	---	---	5.0E-02	---	---	1.7E-02	3.4E-02	6.8E-02	1.4E-01	5.9E-03	1.3E-02	2.7E-02
	Mode	---	---	9.7E-02	---	---	3.3E-02	6.7E-02	1.3E-01	2.7E-01	1.2E-02	2.6E-02	5.2E-02
	Max	---	---	2.6E-01	---	---	8.7E-02	1.8E-01	3.5E-01	7.0E-01	3.0E-02	6.9E-02	1.4E-01
Esophagus	Min	---	---	3.9E-02	---	---	1.3E-02	2.7E-02	5.3E-02	1.1E-01	4.6E-03	1.0E-02	2.1E-02
	Mode	---	---	7.6E-02	---	---	2.6E-02	5.2E-02	1.0E-01	2.1E-01	8.9E-03	2.0E-02	4.1E-02
	Max	---	---	2.0E-01	---	---	6.7E-02	1.4E-01	2.7E-01	5.4E-01	2.3E-02	5.3E-02	1.1E-01
Eye	Min	---	---	5.9E-02	---	---	2.0E-02	4.1E-02	8.2E-02	1.6E-01	7.0E-03	1.6E-02	3.2E-02
	Mode	---	---	1.2E-01	---	---	4.0E-02	8.1E-02	1.6E-01	3.2E-01	1.4E-02	3.1E-02	6.3E-02
	Max	---	---	3.1E-01	---	---	1.0E-01	2.1E-01	4.2E-01	8.4E-01	3.6E-02	8.2E-02	1.6E-01
Gonads (ovaries)	Min	---	---	4.7E-02	---	---	1.6E-02	3.3E-02	6.5E-02	1.3E-01	5.6E-03	1.3E-02	2.5E-02
	Mode	---	---	9.2E-02	---	---	3.1E-02	6.4E-02	1.3E-01	2.5E-01	1.1E-02	2.5E-02	5.0E-02
	Max	---	---	2.4E-01	---	---	8.2E-02	1.7E-01	3.3E-01	6.7E-01	2.9E-02	6.5E-02	1.3E-01
Gonads (testes)	Min	---	---	6.2E-02	---	---	2.1E-02	4.3E-02	8.5E-02	1.7E-01	7.3E-03	1.7E-02	3.3E-02
	Mode	---	---	1.2E-01	---	---	4.1E-02	8.4E-02	1.7E-01	3.3E-01	1.4E-02	3.3E-02	6.5E-02
	Max	---	---	3.2E-01	---	---	1.1E-01	2.2E-01	4.4E-01	8.7E-01	3.8E-02	8.5E-02	1.7E-01
Liver	Min	---	---	5.1E-02	---	---	1.7E-02	3.5E-02	7.0E-02	1.4E-01	6.0E-03	1.4E-02	2.7E-02
	Mode	---	---	1.0E-01	---	---	3.4E-02	6.9E-02	1.4E-01	2.7E-01	1.2E-02	2.7E-02	5.4E-02
	Max	---	---	2.6E-01	---	---	8.9E-02	1.8E-01	3.6E-01	7.2E-01	3.1E-02	7.1E-02	1.4E-01
Lung	Min	---	---	5.0E-02	---	---	1.7E-02	3.5E-02	6.9E-02	1.4E-01	6.0E-03	1.4E-02	2.7E-02
	Mode	---	---	9.9E-02	---	---	3.4E-02	6.8E-02	1.4E-01	2.7E-01	1.2E-02	2.7E-02	5.3E-02
	Max	---	---	2.6E-01	---	---	8.8E-02	1.8E-01	3.6E-01	7.1E-01	3.1E-02	7.0E-02	1.4E-01
Remainder organs	Min	---	---	4.5E-02	---	---	1.5E-02	3.1E-02	6.2E-02	1.2E-01	5.3E-03	1.2E-02	2.4E-02
	Mode	---	---	8.8E-02	---	---	3.0E-02	6.1E-02	1.2E-01	2.4E-01	1.0E-02	2.4E-02	4.8E-02
	Max	---	---	2.3E-01	---	---	7.9E-02	1.6E-01	3.2E-01	6.4E-01	2.7E-02	6.2E-02	1.2E-01
Skin	Min	---	---	4.8E-02	---	---	1.6E-02	3.3E-02	6.6E-02	1.3E-01	5.7E-03	1.3E-02	2.6E-02
	Mode	---	---	9.4E-02	---	---	3.2E-02	6.5E-02	1.3E-01	2.6E-01	1.1E-02	2.5E-02	5.1E-02
	Max	---	---	2.5E-01	---	---	8.4E-02	1.7E-01	3.4E-01	6.8E-01	2.9E-02	6.7E-02	1.3E-01
Stomach	Min	---	---	5.6E-02	---	---	1.9E-02	3.9E-02	7.7E-02	1.5E-01	6.7E-03	1.5E-02	3.0E-02
	Mode	---	---	1.1E-01	---	---	3.7E-02	7.6E-02	1.5E-01	3.0E-01	1.3E-02	3.0E-02	5.9E-02
	Max	---	---	2.9E-01	---	---	9.8E-02	2.0E-01	4.0E-01	7.9E-01	3.4E-02	7.8E-02	1.6E-01
Thymus	Min	---	---	6.1E-02	---	---	2.1E-02	4.2E-02	8.4E-02	1.7E-01	7.2E-03	1.6E-02	3.3E-02
	Mode	---	---	1.2E-01	---	---	4.1E-02	8.3E-02	1.6E-01	3.3E-01	1.4E-02	3.2E-02	6.4E-02
	Max	---	---	3.1E-01	---	---	1.1E-01	2.2E-01	4.3E-01	8.6E-01	3.7E-02	8.5E-02	1.7E-01
Thyroid	Min	---	---	6.8E-02	---	---	2.3E-02	4.7E-02	9.4E-02	1.9E-01	8.1E-03	1.8E-02	3.7E-02
	Mode	---	---	1.3E-01	---	---	4.6E-02	9.3E-02	1.8E-01	3.7E-01	1.6E-02	3.6E-02	7.2E-02
	Max	---	---	3.5E-01	---	---	1.2E-01	2.4E-01	4.8E-01	9.7E-01	4.2E-02	9.5E-02	1.9E-01
Uterus	Min	---	---	4.7E-02	---	---	1.6E-02	3.3E-02	6.5E-02	1.3E-01	5.6E-03	1.3E-02	2.5E-02
	Mode	---	---	9.3E-02	---	---	3.2E-02	6.4E-02	1.3E-01	2.5E-01	1.1E-02	2.5E-02	5.0E-02
	Max	---	---	2.4E-01	---	---	8.3E-02	1.7E-01	3.3E-01	6.7E-01	2.9E-02	6.5E-02	1.3E-01
Whole-body dose rate	Min	---	---	7.5E-02	---	---	2.6E-02	5.2E-02	1.0E-01	2.1E-01	8.9E-03	2.0E-02	4.0E-02
	Mode	---	---	1.5E-01	---	---	5.0E-02	1.0E-01	2.0E-01	4.0E-01	1.7E-02	3.9E-02	7.9E-02
	Max	---	---	3.9E-01	---	---	1.3E-01	2.7E-01	5.3E-01	1.1E+00	4.6E-02	1.0E-01	2.1E-01

Data in this table was calculated using measured data from MCW (1958; 1959; 1961a) as given in Table 39 above. Both maximum average and typical average dose rates at 1 meter (3 feet) were taken into account in calculating the effective gamma (photon) whole-body exposure rates; it was assumed that a worker spent two hours per day (500 hours per year) in the area of maximum dose rate and six hours per day (1500 hours per year) in the area of typical dose rate. The base gamma annual exposures are shown as the whole-body exposure rates above.

The Min, Mode, and Max values were taken to correspond to the effective dose rates at 1 m, 1 foot (30 cm), and 1 cm from the contaminated surface, as per NIOSH direction.

Organ dose conversion factors for the ambient dose equivalent (H\*(10) to H<sub>T</sub>) from NIOSH (2002a) were applied to produce the organ doses from photons. A geometry of 50% AP and 50% ROT was used and it was assumed that 100% of the exposure was due to photons in the 30-250 keV range.

"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. Plants 1 and 2 did not have enough data for these classifications to be applied.

Table 42. Annual external electron organ doses during the decontamination and post-decontamination periods (rem per year).

Decontamination years (1959-1961)													
		Plant 4			Plant 6			Plant 6E			Plant 7		
Organ	Type	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High
Skin	Min	2.0E+00	3.8E+00	7.4E+00	7.8E-02	1.6E-01	3.0E+00	1.9E-02	1.2E-01	1.1E+00	8.7E-03	1.5E-01	1.5E+00
	Mode	3.7E+00	6.8E+00	1.3E+01	1.4E-01	2.8E-01	5.5E+00	3.4E-02	2.2E-01	2.0E+00	1.6E-02	2.7E-01	2.8E+00
	Max	1.8E+01	3.3E+01	6.4E+01	6.8E-01	1.4E+00	2.6E+01	1.6E-01	1.1E+00	9.6E+00	7.6E-02	1.3E+00	1.3E+01
Breast	Min	8.0E-01	1.5E+00	2.9E+00	3.1E-02	6.1E-02	1.2E+00	7.5E-03	4.8E-02	4.3E-01	3.4E-03	5.8E-02	6.0E-01
	Mode	1.4E+00	2.7E+00	5.2E+00	5.5E-02	1.1E-01	2.2E+00	1.3E-02	8.7E-02	7.8E-01	6.2E-03	1.0E-01	1.1E+00
	Max	6.9E+00	1.3E+01	2.5E+01	2.7E-01	5.3E-01	1.0E+01	6.5E-02	4.2E-01	3.7E+00	3.0E-02	5.0E-01	5.2E+00
Testes	Min	3.9E-01	7.2E-01	1.4E+00	1.5E-02	3.0E-02	5.9E-01	3.7E-03	2.4E-02	2.1E-01	1.7E-03	2.9E-02	2.9E-01
	Mode	7.1E-01	1.3E+00	2.6E+00	2.7E-02	5.4E-02	1.1E+00	6.6E-03	4.3E-02	3.8E-01	3.0E-03	5.1E-02	5.3E-01
	Max	3.4E+00	6.3E+00	1.2E+01	1.3E-01	2.6E-01	5.1E+00	3.2E-02	2.1E-01	1.8E+00	1.5E-02	2.5E-01	2.5E+00
Post-decontamination years (1962-1995)													
		Plant 1			Plant 2			Plant 6E			Plant 7		
Organ	Type	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High
Skin	Min	5.3E-02	1.0E-01	6.7E-01	1.4E-02	2.8E-02	6.0E-01	4.6E-02	8.7E-02	1.7E-01	3.2E-02	7.2E-02	1.4E-01
	Mode	9.6E-02	1.9E-01	1.2E+00	2.5E-02	5.0E-02	1.1E+00	8.3E-02	1.6E-01	3.1E-01	5.7E-02	1.3E-01	2.6E-01
	Max	4.6E-01	9.0E-01	5.8E+00	1.2E-01	2.4E-01	5.2E+00	4.0E-01	7.5E-01	1.5E+00	2.8E-01	6.3E-01	1.3E+00
Breast	Min	2.1E-02	4.1E-02	2.6E-01	5.4E-03	1.1E-02	2.4E-01	1.8E-02	3.4E-02	6.8E-02	1.2E-02	2.8E-02	5.7E-02
	Mode	3.7E-02	7.3E-02	4.7E-01	9.8E-03	2.0E-02	4.2E-01	3.3E-02	6.1E-02	1.2E-01	2.2E-02	5.1E-02	1.0E-01
	Max	1.8E-01	3.5E-01	2.3E+00	4.7E-02	9.4E-02	2.0E+00	1.6E-01	2.9E-01	5.9E-01	1.1E-01	2.5E-01	4.9E-01
Testes	Min	1.0E-02	2.0E-02	1.3E-01	2.7E-03	5.3E-03	1.2E-01	8.9E-03	1.7E-02	3.3E-02	6.1E-03	1.4E-02	2.8E-02
	Mode	1.8E-02	3.6E-02	2.3E-01	4.8E-03	9.6E-03	2.1E-01	1.6E-02	3.0E-02	6.0E-02	1.1E-02	2.5E-02	5.0E-02
	Max	8.8E-02	1.7E-01	1.1E+00	2.3E-02	4.6E-02	1.0E+00	7.7E-02	1.4E-01	2.9E-01	5.3E-02	1.2E-01	2.4E-01

Data in this table was calculated using measured data from MCW (1958; 1959; 1961a) as given in Table 39 above. Both maximum average and typical average dose rates at about 1 cm were taken into account in calculating the effective electron (beta) base exposure rates; it was assumed that a worker spent two hours per day (500 hours per year) in the area of maximum dose rate and six hours per day (1500 hours per year) in the area of typical dose rate. The base annual exposures are shown as the skin exposures above.

The Min, Mode, and Max values were taken to correspond to the effective dose rates at 1 cm, 1 foot (30 cm), and 1 meter from the contaminated surface, as per NIOSH direction.

Organ dose conversion factors for conversion from skin dose to breast and testes doses were taken from ICRP (996); these are 0.49 for the breast and 0.24 for the testes. In addition, a factor of .8 was used to account for clothing coverage for the breast and testes doses.

“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. Plants 1 and 2 did not have enough data for these classifications to be applied.

Table 43. Annual dust inhalation, ingestion, and radon daughter intakes during the SLAPS postoperations period.

	Inhalation intakes, pCi/yr		Ingestion intakes, pCi/yr		Radon intakes, WLM/yr	
	1959-1960	1961-1962	1959-1960	1961-1962	1959-1960	1961-1962
Bulldozer/crane operators	8.81E+03	---	1.84E+02	---	4.75E+00	---
Other material workers (e.g., riggers)	8.81E+03	---	1.84E+02	---	4.75E+00	---
Health & Safety workers	4.41E+03	---	9.18E+01	---	2.38E+00	---
AEC	4.41E+03	1.49E-04	9.18E+01	3.10E-06	2.38E+00	2.28E-01
Guards	7.14E+02	1.00E-03	1.49E+01	6.46E-06	1.54E+00	1.54E+00

Table 44. Annual external gamma organ doses during the SLAPS postoperations period (rem per year).

Organ	1959-1960	1959-1960	1959-1960	1961-1962
	Bulldozer driver, rigger	Health & Safety, AEC	Guard	Guard
Bladder	1.32E-01	6.60E-02	4.28E-02	1.32E-02
Bone (red marrow)	1.30E-01	6.50E-02	4.21E-02	1.30E-02
Bone (surface)	2.14E-01	1.07E-01	6.92E-02	2.14E-02
Breast (female)	1.47E-01	7.34E-02	4.75E-02	1.47E-02
Colon	1.31E-01	6.53E-02	4.23E-02	1.31E-02
Esophagus	1.27E-01	6.33E-02	4.10E-02	1.27E-02
Eye	1.60E-01	8.00E-02	5.18E-02	1.60E-02
Gonads (ovaries)	1.33E-01	6.65E-02	4.31E-02	1.33E-02
Gonads (testes)	1.39E-01	6.96E-02	4.51E-02	1.39E-02
Liver	1.39E-01	6.95E-02	4.50E-02	1.39E-02
Lung	1.49E-01	7.44E-02	4.82E-02	1.49E-02
Remainder organs	1.34E-01	6.70E-02	4.34E-02	1.34E-02
Skin	1.52E-01	7.60E-02	4.92E-02	1.52E-02
Stomach	1.38E-01	6.89E-02	4.46E-02	1.38E-02
Thymus	1.42E-01	7.10E-02	4.60E-02	1.42E-02
Thyroid	1.84E-01	9.19E-02	5.95E-02	1.84E-02
Uterus	1.24E-01	6.21E-02	4.03E-02	1.24E-02
Measured whole-body dose rate	2.50E-01	1.25E-01	8.10E-02	2.50E-02

## APPENDIX A

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

(From AEC 1949b)

#### 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

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

where

- |                          |   |  |
|--------------------------|---|--|
| $5.2 \times 10^7$        | = | number of MeV/g in one rep   |
| $0.0043 \text{ rep/day}$ | = | daily acceptable dose rate   |
| $2.2 \times 10^6$        | = | number of dis/min per $\mu\text{Ci}$   |
| $60 \times 24$           | = | number of minutes per day  |
| $8.86$                   | = | sum of energies of alpha radiation from U-238 and U-234 in equilibrium, in MeV |

$$= 8 \times 10^{-6} \text{ } \mu\text{Ci/g}$$

2. Total  $\mu\text{Ci}$  in lungs for 4.3 mrep/day:

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

$$= 8 \times 10^{-3} \text{ } \mu\text{Ci}$$

3.  $\mu\text{Ci}$  per  $10 \text{ m}^3$  (inhaled in 8 hours) which will give  $8 \times 10^{-3} \text{ } \mu\text{Ci}$  to the lung at equilibrium (assuming exposure every day) =  $2.54 \times 10^{-4} \text{ } \mu\text{Ci}$  per  $10 \text{ m}^3$

where

- |                    |   |  |
|--------------------|---|--|
| $8 \times 10^{-3}$ | = | $\mu\text{Ci}$ in lungs at equilibrium             |
| $0.25$             | = | fraction of inhaled material deposited in the lung |
| $90$               | = | assumed biological half-life in the lungs, in days |
| $1.4$              | = | factor to convert half-life to mean life           |

4.  $\mu\text{Ci}$  per  $\text{m}^3$ :

$$= 2.54 \times 10^{-5}$$

$$= 56 \text{ dpm per } \text{m}^3$$

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

$$56 \text{ dpm} * (7 \text{ days}/6 \text{ days}) = 65 \text{ dpm}$$

$$\text{(i.e., 5-6 days per week actually, since } 56 \text{ dpm} * (7 \text{ days}/5 \text{ days}) = 78 \text{ dpm)}$$

and

$$= \mathbf{70 \text{ dpm per m}^3}$$

$$= \mathbf{50 \text{ }\mu\text{g per m}^3}$$

Note: As AEC 1949b 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/week.

## APPENDIX B

### Example Calculation of Daily Weighted Average Exposure (DWE)

Calculation for Continuous Experimental Furnace Operators (from MCW 1950s)

Operation	Minutes per event	# events, day shift	# events, night shift	Total time, day shift	Total time, night shift	Measured alpha conc, dpm/m <sup>3</sup>	Conc times total time, day shift	Conc times total time, night shift
Filling hopper	1.75	10	10	18	18	131000 (avg of 3) H 153000 L 102000	2,358,000	2,358,000
Removing bottle	3	16	15	48	45	1640 (avg of 3) H 3440 L 265	78,720	73,800
Dumping bottles into drum	3.5	3	3	10	10	181000 (avg of 2) H 236000 L 125000	1,810,000	1,810,000
Sampling the drum	1	3	3	3	3	407 (avg of 3) H 569 L 234	1,221	1,221
General air, furnace area				276	259	238 (avg of 6) H 908 L 8.5	65,688	61,642
General air, sampling area				60	60	175 (avg of 4) H 191 L 131	10,500	10,500
General air, smoking room				50	40	314 (avg of 3) H 378 L 248	15,700	12,560
General air, locker room				15	5	4.2 (avg of 5) H 6.5 L 0.7	63	21
General air, change room				15	15	68 (avg of 5) H 101 L 19	1,020	1,020
General air, lunchroom				30	40	1.27 (avg of 8) H 2.0 L 0.56	38.1	50.8
TOTAL	---	---	---	525	495	---	4,340,950	4,328,815
Average	---	---	---	505		---		

$$\text{Average alpha concentration} = \frac{4340950}{505} = 8596 \text{ dpm/m}^3$$

$$\text{Average "times tolerance" exposure} = \frac{8596}{70} = 123$$

Note: H and L denote the high and low values respectively.