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**OCCUPATIONAL EXPOSURES OF
WORKERS TO CHEMICALS AND
RADIATION DURING
URANIUM PROCESSING AT THE
LINDE CERAMICS PLANT
1943-1949**

**John L. S. Hickey
Douglas Crawford-Brown
William G. Tankersley**

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1943-1949**

by

John L. S. Hickey, P.E., C.I.H., Ph.D.
Occupational Health Studies Group
University of North Carolina at Chapel Hill

Douglas Crawford-Brown, Ph.D.
Department of Environmental Sciences and Engineering
University of North Carolina at Chapel Hill

and

William G. Tankersley
Center for Epidemiologic Research
Oak Ridge Associated Universities

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ABSTRACT

Chemical and radiation exposure profiles were constructed from processing and employment records for workers at the Linde Air Products Company Ceramics Plant in Tonawanda, New York, during 1943-1949. Several types of radiation monitoring data were also available for a portion of the period studied.

Nine substances were designated as chemical hazards, and a potential exposure code was assigned for each substance to each of 25 job subgroups. Results from individual film badge dosimeters, uranium urinalyses, and alpha radiation monitoring data were used to construct estimated ranges of external penetrating exposures and internal (lung) doses for each job title at the facility. Job titles were then grouped into semiquantitative exposure categories.

The report describes the source data, the methods used in developing these exposure profiles, and their uses and limitations in epidemiologic analyses.

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EXECUTIVE SUMMARY

This report presents a profile of estimated occupational exposures to radiation and to chemical hazards sustained by employees involved in uranium-ore and nickel processing at the Linde Air Products Company Ceramics Plant during the period 1943-1949. This plant was located in Tonawanda, New York, and was operated by the Carbide and Carbon Chemicals Company (later Union Carbide Corporation).

The chemical exposure profiles were constructed from plant processing and job records, using chemical use and work location as surrogates for exposure measurements. Some airborne dust sampling records and other direct exposure assessments were available as aids to judgment. The radiation exposure profiles were based chiefly on several types of radiation monitoring data available for a portion of the period studied.

Nine substances were selected as designated chemical exposure hazards. Jobs were classified into 25 subgroups on the basis of similarity of location and/or activity. An estimated exposure level (code 0, 1, or 2) was assigned for each of the nine substances to each of the 25 job subgroups: code 0 indicates minimal opportunity for exposure; code 1 indicates occasional exposure; code 2 indicates routine exposure. Four profiles were developed for various time periods because of changes in chemicals and processes used over time. Results from individual film badge dosimeters, from uranium urinalyses, and from alpha-radiation monitoring data were used to construct estimated ranges of external penetrating radiation exposures and of internal (lung) doses for each job title at the facility. Job titles were then assigned to semiquantitative exposure categories representing useful and distinctive exposure level groups. Categories for external exposure were designated with

the symbols ">," indicating average film badge results greater than the minimum detectable level, and "<," indicating average film badge results less than or equal to the minimum detectable level. Categories for internal exposure were based on average yearly lung dose equivalents: category A includes jobs with exposure that should lead to less than 1 rem per year; category B includes jobs with exposure that should lead to 1-10 rems per year; category C includes jobs with exposure that should lead to greater than 10 rems per year to the lung.

The report describes the source data and the methods used in developing these exposure profiles and their limitations for use in epidemiologic analyses.

1. INTRODUCTION

The purpose of this report is to present methodology for estimating chemical and radiation exposures sustained by workers processing uranium-bearing compounds and nickel, during the years 1943-1949, at the Linde Air Products Company Ceramics Plant in Tonawanda, New York.

The report describes the development of exposure profiles and provides estimates on ordinal scales of workers' potentials for exposure to a variety of chemicals, to external penetrating ionizing radiation, and to internally deposited uranium over various time periods for each occupational title appearing in the workers' job histories.

Section 2 of the report summarizes the overall methodology used in arriving at exposure estimates by job. Section 3 summarizes plant operations during the period studied. Section 4 identifies all major materials used and produced, lists the chemical and radiological hazards evaluated, and describes the rationale for their selection. Section 5 describes the compilation and grouping of job titles into groups with similar exposure potential, using as a basis the titles actually appearing on individual job histories. Section 6 explains the ordinal exposure classification systems and the rationale for assigning exposure levels and presents the exposure levels by job title groups. Section 7 discusses the limitations of the data available, methodologies used, assumptions made, and the final conclusions.

2. METHODOLOGY

CHEMICAL ASSESSMENT

Exposure profiles were developed as follows.

Initially, plant records were analyzed to identify all materials used and produced during the period 1943 to 1949. These materials were screened on the basis of chemical toxicity, availability for exposure to workers, quantity of use, and other criteria. Subsequently, nine candidate chemicals were designated as potential hazards. The specific worksites where these chemicals were present were identified from plant records.

In parallel, all job titles, including abbreviations and spelling variations, appearing in individual job histories were coded to a base list of the accepted or standardized job titles. Using original job descriptions and detailed process information, these titles were associated with specific worksites within the plant, and thus with potential exposures to specific chemicals.

Most of the jobs could be classed as having "routine exposure" or "minimal exposure" to individual chemicals. Because some jobs (such as maintenance and utility jobs) entailed occasional exposure to some chemicals, a middle category of "moderate or occasional exposure" was included, resulting in three ordinal exposure categories.

Estimates were developed for exposure potential and are presented as ordinal exposure levels in a matrix of job titles vs. chemicals (Tables 4-7). The raw, process, product, and by-product materials present in the plant varied with time; so classification of specific chemical exposure for specific job titles also varied over time. One matrix is presented for each of four time periods.

Where explicit information about processes, dates, or exposures was not available, inferences and judgments were made from whatever facts were available. For example, interviews with former employees revealed differences of recollection on which processes were resumed after the plant closed in 1946 and reopened in 1947. The bulk of information pointed to resumption only of conversion of uranium dioxide (UO_2) to uranium tetrafluoride (UF_4). Specific dates were not provided but were inferred from records of urine analyses which showed preemployment samples being taken in November 1947 and termination samples in July 1949. In like manner, it was inferred that the pilot plant operation converting uranium hexafluoride (UF_6) to uranium trioxide (UO_3) operated from 1943 to 1946, since UF_6 is listed as a hazard on work histories for those years. Toxicity and health-effects information from other sources^{1,2} was also used as an aid in designating chemical hazards.

RADIATION ASSESSMENT

The radiation hazards at the Linde facility were both external and internal. Uranium (U) ore, pitchblende, and vanadium (V) processing tails were used as raw materials that provided alpha radiation from the U decay chain and gamma radiation predominantly from the radium (Ra) generated during decay. In addition to the detailed descriptive information available on production materials, processes, and to a lesser extent on quantities of materials employed, a substantial amount of radiation monitoring data were also available. The bulk of the available radiological data, however, is restricted to measurements performed during the years 1947 and 1948, with the exception of some radon (Rn) air concentration measurements taken in earlier years. The relative radiological hazards associated with the various jobs, however, did not appear to change appreciably, a characteristic common at U-processing

facilities during the early years. This relative lack of change is also reflected in the chemical hazards assessment based on the study of processes and in the consistent volumes of radioactive materials present (i.e., U compounds).

After examining all of the available data, four general measurements were found to contain useful information:

1. air-monitoring results [alpha disintegrations per minute/m³ (α dpm/m³) or mg U/m³]
2. surface contamination (α dpm/100 cm²)
3. urinalysis results (mg U/l urine)
4. film badge results (mrem per week)

In general, these data were used in one of two ways. The personal monitoring data were first sorted by job title, and then analyzed. In some cases, data for obviously similar job titles were grouped together when it seemed accurate to do so. Area and surface monitoring data were linked to job titles through work areas and job duties, using the same process and production records used for the chemical assessment.

Separately, these data provided an approximation of the relative exposures associated with different job titles. Due to the presence of several radionuclides and several forms of monitoring data, however, it was necessary to assign numerical annual dose boundaries to several exposure-level categories and then fit the exposure data analyses into the categories.

Only in this manner, with the necessary caveats acknowledged, could the data be fully utilized. While this method is justified heuristically, it is not believed to be sufficiently precise or accurate to allow for the development of risk factors expressed in units of risk per unit dose equivalent.³ The exposure-level categories should, however, prove to be

defined sufficiently to test for differences in risk groups of individuals determined to differ in the mean dose equivalents to the primary organs of interest, taken here to be the lungs and whole body tissues.

All data used in developing this report came from Linde Ceramics Plant operations reports and other company records maintained for the U.S. Department of Energy (DOE) at Oak Ridge Associated Universities (ORAU). Information included detailed plant process, chemical use, plant organization, job description, and radiation monitoring data, as well as transcripts of extensive interviews with former plant personnel employed during the time period studied.

3. PLANT OPERATIONS

During the period 1943 to mid-1949, the Linde Air Products Company operated its Ceramics Plant at Tonawanda, N.Y., under contract with the Manhattan Engineer District. Several activities were performed at the plant:

Carnotite ores from Colorado and African pitchblende ores were processed from 1943 to 1947 to extract uranium oxide (U_3O_8). For a limited time, processing tails from V mining were also used. The U_3O_8 process, called Step I, was relatively complex, involving extremely large quantities of a number of materials in addition to the primary ores. For about one year in 1943-1944, the U_3O_8 product was processed further in the same building to yield UO_2 . This second process was called Step II. In a separate building, UO_2 from the Ceramics Plant and other sources was converted to UF_4 from 1943 to 1946 and again from late 1947 through mid-1949. This process was called Step III.

Laboratory and pilot plant studies were conducted during 1943 to develop methods for processing pitchblende, and similar small-scale studies were conducted around 1944-1946 to develop a method for converting UF_6 to UO_3 . No specific dates of operation were available for these latter two activities although extensive information is given on their chemical use and production.

From October 1944 to February 1946, metallic nickel (Ni) was processed with nitric acid (HNO_3) to produce a Ni salt, which was processed further to produce pure Ni powder.

Table A-1 in the Appendix lists the raw, process, by-product, waste, and final product materials used at the plant for each process. Figure 1 shows the approximate dates of operation for each process. The following is a brief description of plant processes:

FIGURE 1. SUMMARY OF PLANT OPERATIONS BY DATE

Process	Time of Operation						
	1943	1944	1945	1946	1947	1948	1949
<u>STEP I: Ore to U₃O₈</u> Colorado Ores (6/14/43-11/43; 1/45-12/45; 7/46)	XXXXXX		XXXXXXXXXXXXXX	X			
<u>Pitchblendes</u> (12/43-12/44; 1/46-6/46)	X	XXXXXXXXXXXXXX		XXXXXX			
<u>STEP II: U₃O₈ to UO₂</u> (4/27/43-3/8/44)	XXXXXXXXXX	XXX					
<u>STEP III: UO₂ to UF₄</u> (7/25/43-6/26/46; 11/47-7/49)	XXXXXX	XXXXXXXXXXXXXX	XXXXXXXXXXXXXX	XXXXXXXXXX		XXXXXXXXXXXXXX	XXXXXXXXXX
<u>LAB. & PILOT PLANT</u> <u>Pitchblende</u>	?000000	0000?					
<u>LAB. & PILOT PLANT</u> <u>UF₆ to UO₃</u>	?00	000000000000	000000000000	0000?			
<u>NICKEL PROCESSING</u>		XXX	XXXXXXXXXXXXXX	XX			

XXX = Known operating dates: 000 = Inferred operating dates: ? = Unknown start or end date

Step I. Ore was received by rail in burlap or paper bags and was unloaded and dumped by hand onto a conveyor or directly into a ball mill (wet-grind) where it was pulverized. The resulting slurry was treated with sulfuric acid (H_2SO_4) and sodium carbonate or soda ash (Na_2CO_3) and filtered. The filter cake containing the majority of the Ra present in the ore was taken to waste storage by truck. The liquid was treated for removal of V or molybdenum (Colorado ores) or lead and Ra (pitchblendes) and was further treated with H_2SO_4 , sodium hydroxide (NaOH), and ammonium sulfate [$(NH_4)_2SO_4$]. Uranium was finally precipitated as the ammonium salt and calcined at $1050^\circ C$ to produce U_3O_8 , which was packed in drums for shipping or further processing at the Ceramics Plant.

Step II. U_3O_8 from Step I was digested with HNO_3 to precipitate uranyl nitrate [$UO_2(NO_3)_2$], which was filtered, washed with ether to extract impurities, and heated to $475^\circ C$ to produce UO_3 . The UO_3 was heated to $700^\circ C$ in a hydrogen-gas (H_2) atmosphere to produce UO_2 , which was packaged for shipping or further processing at this plant.

Step III. UO_2 was hand-troweled onto trays, placed in ovens, and converted to UF_4 by heating to $540^\circ C$ in an atmosphere of hydrogen fluoride gas (HF) produced from anhydrous hydrofluoric acid. The trays containing the product were hand-loaded onto carts, unloaded into a vented hood, pulverized, blended, and packaged for shipping.

Pitchblende process development. Laboratory studies were carried out during an unspecified time period to develop modifications to processes used in Step I which were necessary for processing pitchblende.

Conversion of UF_6 to UO_3 : Pilot studies were carried out using a large number of chemicals in small quantities for short periods of time (exact dates not available). The process primarily studied was conversion of UF_6 to U_3O_8

by heat, and oxidation of U_3O_8 to UO_3 with HNO_3 . About 50 pounds of UO_3 were prepared during these studies.

Nickel processing. Metallic Ni slugs (small ingots) were oxidized with HNO_3 , filtered, and heated to $1200^{\circ}C$ to produce a nickel oxide (NiO). This was pulverized, mixed with ammonium chloride (NH_4Cl), and heated to form a porous mass of the oxide, which was reduced to powdered nickel by exposure to H_2 . The powder was pulverized and packaged. Step II of U processing was discontinued in March 1944 and the equipment converted to Ni processing. It is not known whether both NiO and powdered Ni or only NiO were produced in quantity at this plant.

4. DETERMINATION OF OCCUPATIONAL EXPOSURE HAZARDS

CHEMICAL HAZARDS

Criteria for Designating Hazards

Several criteria were used to select materials to be designated as occupational exposure hazards:

1. Relative quantity of the material used or produced. While a number of other materials were also involved in the processes at the Ceramics Plant, those selected as potential hazards were routinely present in very large quantities (up to tons/month). These materials were considered to be available for exposure to personnel in the work areas where the materials were processed.
2. Relative chemical toxicity (acute and chronic) of the material from inhalation exposure. Hazard to eyes and skin from contact was also considered to an extent. Radiation hazards from the U compounds were considered separately. Safety hazards, as from combustion of H₂ and ether, and heat stress were not considered.
3. Opportunity for worker exposure; that is, presence of the material in a hazardous form (e.g., wet or dry, powdered or solid).
4. Indication on contemporary plant personnel records or in processing instructions that the material was considered an exposure hazard.
5. Air-monitoring information indicating substantial quantities of the material were present.
6. Biological monitoring data indicating substantial body burdens of the material in employees.

7. Indications in process descriptions that efforts were made to control and monitor worker exposure to the material.
8. Judgment of the authors of this report.
9. Practical limitation on number of materials that could be studied for health effects.
10. Interviews in 1981-83 of former employees to obtain recollections of workplace conditions and other information.

Discussion of Considerations

We decided that a maximum of ten chemicals would be designated as occupational exposure hazards. With this in mind, we summarily eliminated several candidate chemicals from consideration. These were reagent chemicals used in the quality control laboratory and chemicals used briefly on a laboratory scale to develop the process for converting UF_6 to UO_3 . These were eliminated because the reagents listed are common to analytical laboratories and the process chemicals were used in gram to kilogram amounts.

We included those chemicals designated as "hazards" in employee records and other chemicals mentioned in the operating instructions as requiring extraordinary precautions to avoid exposure. These delimitations narrowed the candidate list to 15 chemicals, from which we selected 9 as hazards and 6 as alternates.

Selection of Hazards and Rationale

The following materials were designated as hazards or alternative candidates.

Hazards:

uranium-bearing compounds, U dusts

nitric acid and nitrous vapors; HNO_3 , NO_x

hydrofluoric acid, HF

uranium hexafluoride, UF_6

sulfuric acid, H_2SO_4

lead sulfate, PbSO_4

chlorine gas, Cl_2

silica, SiO_2

nickel-bearing substances, Ni

Alternates:

sodium carbonate, Na_2CO_3

manganese dioxide, MnO_2

ammonium sulfate, $(\text{NH}_4)_2\text{SO}_4$

ether

vanadium salts, V

sodium hydroxide, NaOH

Figure 2 shows the usage of these chemicals by process and time period. The rationale for the selection of the candidates and alternates is discussed for each material in the following paragraphs.

Uranium-bearing dust. Uranium-bearing compounds (soluble and insoluble) were listed as a hazard on personnel records; U is known to be chemically toxic; ore was used and U compounds produced in multi-ton quantities; urine samples of employees were analyzed routinely for U; the threshold limit value (TLV) for soluble and insoluble U compounds is 0.2 mg/m^3 ; operating instructions prescribed use of respirators in the ore dumping area of Step I; dry uranium-bearing material was handled by hand; dust was controlled at several locations by ventilation (Steps I, II, III); interviews with former employees indicated that some areas where uranium-bearing solids were handled were "very dusty"; safety instructions specified showers and change of clothes before departing work; U dust in air was monitored routinely.

Nitric acid. HNO_3 fumes are highly toxic when inhaled; the TLV for HNO_3 is 5 mg/m^3 ; HNO_3 was used in multi-ton quantities (Step II and Ni oxidation); it was listed as a hazard on personnel records; safety instructions specified the use of gas masks and oxygen breathing apparatus for protection against HNO_3 and against nitric oxide gas (NO), which evolves during the reaction of U_3O_8 with HNO_3 (Step II); NO was also produced during denitration (Step II); its TLV is 30 mg/m^3 ; interviews with former employees indicated a "reddish" gas was evolved in Step II, indicating that more toxic nitrogen oxides (such as NO_2) may also have been formed.

Hydrofluoric acid. HF is highly irritating to the skin and mucous membranes as an acid vapor or as HF gas; it was listed as a hazard on personnel records; the TLV for HF is 2.5 mg/m^3 in either form; anhydrous HF (99.3%) was used in ton quantities (Step III); plant safety instructions focused on eye and skin burn hazards and on inhalation hazard; employees were routinely monitored for fluoride (F) in urine; process descriptions indicated control equipment existed to prevent employee exposure to HF liquid or vapors.

Uranium hexafluoride. UF_6 is toxic due to both its U and F content; it was listed as a hazard on personnel records; it was used on a laboratory and pilot-plant scale for an unknown period of time before Spring 1946; approximately 50 pounds of UF_6 was processed; personnel were routinely monitored for U and F in urine.

Sulfuric acid. H_2SO_4 is known to be toxic when inhaled; its TLV is 1 mg/m^3 ; it was used in multi-ton quantities (Step I) in concentrated form (66° baume, 35.9N); safety instructions focused on eye and skin hazards, not inhalation; acid digest tanks were provided with fume exhaust stacks (Step I).

Lead sulfate. $PbSO_4$ is toxic due to its Pb content; its TLV is 0.15 mg/m^3 as Pb; it was used in multi-ton quantities and handled in dry form by hand (Step I); safety instructions specified the use of respirators by employees handling dry $PbSO_4$.

Chlorine gas. Cl_2 evolved when sodium chlorate was used in the lead-vanadium recovery process (Step I); Cl_2 is highly toxic; its TLV is 3 mg/m^3 ; safety instructions warned that "large amounts" of Cl_2 were liberated, that the area should be well ventilated, and that the operator should wear a gas mask during the operation.

Silica, vanadium: SiO_2 and V salts are known to be toxic; they were present in dry form, capable of becoming airborne during unloading and dumping of the ore; they were not mentioned specifically as hazards, although dust control measures were applied at the ore-receiving point; V was present at a maximum of 2.5 percent of any ore; SiO_2 content varied from 15 to over 50 percent of ores received. SiO_2 should be considered a hazard and V an alternative candidate (Step I) if the list of substances investigated is expanded.

Nickel. Ni in ingot form was processed in multi-ton quantities with HNO_3 to produce Ni salts, which were processed further to produce Ni powder; Ni is toxic and is reported in several studies to be carcinogenic in certain forms; its TLV is 0.1 mg/m^3 .

Sodium carbonate. Na_2CO_3 is not particularly toxic, but its dust can be a respiratory and skin irritant; safety instructions specified use of respirators by employees handling bagged Na_2CO_3 ; interviews indicate that the material made employees "itch all over"; Na_2CO_3 was used in powdered form in multi-ton quantities and was dispensed by hand (Steps I and III).

Manganese dioxide. MnO_2 is moderately toxic due to its Mn content; its TLV is 5 mg/m^3 (ceiling); it was used in powder form in multi-ton lots (Step I); safety instructions specified that employees wear respirators when handling MnO_2 .

Ammonium sulfate. $(\text{NH}_4)_2\text{SO}_4$ is not particularly toxic; it has no assigned TLV; it was used in multi-ton quantities (Step I); safety instructions specified that employees wear respirators while handling $(\text{NH}_4)_2\text{SO}_4$; during calcination there was sufficient $(\text{NH}_4)_2\text{SO}_4$ dust generated to warrant capture and reuse.

Ether. Ether is an anesthetic; its TLV is $1,200 \text{ mg/m}^3$; ether (generally diethyl ether) was used in an enclosed system and was thought to present no hazard unless leaks occurred; ventilation systems were prescribed.

Sodium hydroxide. NaOH is extremely caustic; its TLV is 2 mg/m^3 (ceiling); it was generally handled in liquid form as a 50% concentrate in multi-ton quantities (Step I); safety instructions specified that operators use skin and eye protection; flake caustic was kept on hand for emergency use; no particular inhalation hazard was indicated on records.

Several other chemicals were used or produced in varying quantities (see Table A-1). None were mentioned as hazards in contemporary process descriptions or safety instructions or were listed as hazards on personnel records.

RADIOLOGICAL HAZARDS

The radiological hazards at the Linde Ceramics Plant were chiefly alpha radiation from U compounds (with a Rn-daughter component) and gamma radiation from Ra and other daughters produced through decay. Routes or means of exposure were inhalation, ingestion, and direct radiation, with primary concern focused on inhalation and direct radiation. The following discussion details the various considerations given to the radiological hazards available to the plant personnel and the rationale for using the monitoring data for development of dose estimates.

Airborne Materials

Workers at the Linde facility were exposed primarily to two airborne radionuclides and/or radionuclide chains. The first was U dust in its various chemical forms, resulting from the U-processing operations in effect at the time. The second was the chain of radionuclides beginning with Rn-222.⁴ It is toward this second radionuclide chain that the initial discussion is directed. Dose assessment for U dust will follow.

The Ra present in U ore gives rise, through decay, to a daughter atom of Rn. Radon is an inert gas which is not of chief radiological concern.⁵ Instead, the radiological significance lies in the radioactive daughters of Rn, concentrations of which are usually given in units of working levels (WLs).⁶ Unfortunately, the data at the Linde facility are restricted to measurements of

the Rn alone, a practice typical of that time. It is possible, however, to estimate the WL concentration of Rn daughters from the Rn concentration if assumptions are made concerning the state of equilibrium and degree of attachment of the positively charged daughters.⁷ The state of equilibrium is assumed to be the controlling factor, with values in industrial settings typically varying between 25% and 75% depending on the rate of ventilation.⁸ A value of 50% was used in this study, with the true value for the Linde facility probably within a factor of two of the value used. In this case, 200 pCi per liter of Rn-222 would correspond to 1 WL.⁶

Estimation of the annual lung dose equivalent delivered from exposure to an air concentration of 1 WL depends on several factors, specific to either the work place or the exposed individual. Those of most importance are the state of attachment of the radionuclide to aerosols, the aerosol diameter, and the breathing rate and tidal volume of the worker. Conversion factors from working level months (WLMs, one WLM defined as exposure to 1 WL for 170 hours) to rems (to the basal cells of the bronchial epithelium) range from about 1 to 10 rems per WLM⁹ using a quality factor of 10. We have chosen to employ a value of 5 rems per WLM. As a result, annual exposure to an atmosphere containing 200 pCi per liter of Rn-222 would result in 60 rems during that year.

Radon measurements were performed primarily at the Linde Ceramics Plant proving laboratory in or around 1944. This choice of sampling location was due primarily to the fact that, at the time, this laboratory was the chief site of the Ra present in the ore. The Ra was then removed from the ore and stored. Values for Rn concentration were reported in unpublished memoranda as research notes, obtained by us from original Linde documents. These documents indicated that the Rn concentration in the proving laboratory probably averaged in the region of 25-50 pCi per liter, extending to above 200 pCi per liter at some

work locations near the digesting tanks and storage areas. A value of 50 pCi per liter would yield approximately 15 rems per year to the lungs. As a result, workers routinely in the ore storage and sampling areas, or near the box cars, digesting tanks, and Sperry press should be considered as having significant potential for exposure to Rn progeny. These findings suggest that Rn concentrations in the Ceramics Plant, in general, would be uniformly high in poorly ventilated areas. Unfortunately, there are no reported data for many of the job locations, although it seems safe to assume that the bulk of the exposures occurred in the areas detailed above.

Dose assessment for airborne U dust is, to some extent, more difficult than for the Rn daughters due to the differing solubilities of U compounds in lung fluids, leading to differing biological removal halftimes.¹⁰ On the other hand, the U atoms themselves are monitored, negating the need for any assumptions concerning the degree of equilibrium or state of attachment. Due to the effects of particle size on deposition in the pulmonary region of the lung,¹¹ it is necessary to have some information concerning the effective activity median aerodynamic diameter (AMAD) of the respirable U. Studies at other U-processing facilities indicate that the effective AMAD typically is in the range of 1-2 microns,¹² with a geometric standard deviation (GSD) of about 1.5. Fortunately, while pulmonary deposition changes rapidly for monodispersed aerosols in this size range, deposition is only slightly affected when the GSD is about 1.5 and when breathing patterns are those associated with light activity.¹³

Since the ICRP-30¹⁴ values for converting from air concentrations to annual lung dose equivalents employ an AMAD of 1 micron, these values were used in the this study. For a more detailed explanation of the methodology and results underlying the ICRP documents, refer to a series of reports published by the

Metabolism and Dosimetry Group of Oak Ridge National Laboratory (ORNL).^{15,16} Since insoluble U displays a biological halftime on the order of 120 days in the lung,^{17,18,19} this value was employed here. For other solubility classes (D and W), the halftimes suggested by the ICRP were employed.²⁰ Solubility classes for the compounds of U at the Linde facility were determined from recently published studies on lung clearance.¹⁷ A review of the process manual for the Ceramics Plant revealed that the primary dusts in Steps I, II, and III and in the conversion of K-25 gas (UF₆) were as displayed in Table 1.

As in the case of Rn measurements, reports of U air concentrations were contained in unpublished memoranda from the Linde facility. These data were, to a large extent, summarized by the Linde health physics staff, which reported average daily air concentrations for specific job titles in exposed groups of workers.

TABLE 1. PRIMARY AIRBORNE URANIUM EXPOSURES TO WORKERS
IN FOUR MAIN OPERATIONS

Process	Primary Dusts	Solubility Class ^a	Lung Halftime (days)
STEP I	U ₃ O ₈	Y	120
STEP II	U ₃ O ₈ and UO ₂	Y	120
STEP III	UO ₂ and UF ₄	Y	120
UF ₆ to UO ₃	UO ₃	W	50

(All other materials assumed Class Y)

^aSolubility classes D, Y, W distinguish compounds according to their residence times in the pulmonary region of the lung.

Surface Contamination

In general, it is not possible to determine internal doses from measures of surface contamination. Various authors have, however, shown that U contamination on work surfaces is associated with both air concentrations and levels of U in urine.^{21,22} The conversion factors for relating one quantity to another depend on the industrial conditions prevailing and the spatial relationships between dust production, dust movement, work station locations, and the locations where measurements were taken. As a result, such conversion factors probably should not be transferred from one facility to another. Since these factors are unknown for the Linde facility, no attempt was made to relate surface contamination to quantitative estimates of annual lung dose equivalents. Instead, the measurements were used to determine areas of the plant in which surface contamination indicated probable significant levels of airborne U.

As in the case of the other monitoring results, the data on surface contamination were contained in unpublished memoranda from Linde, now maintained for DOE by ORAU. These measurements of contamination, reported in units of α dpm/100 cm², resulted primarily from decontamination efforts at the facility. As a result, they were viewed as upper estimates of contamination following several years of buildup. They contained, in all likelihood, contributions from both U dust and from the plateout of Rn daughters attached to aerosols, although the short radiological halftimes associated with the latter alpha emitters (typically less than one hour) lowered the chances of their contributing significantly.

Internal Contamination

Uranium deposited in the lung is removed to the gastrointestinal tract and