Document Title:	
Characterization of Occupational Exposure to Radium and Radon Progeny During Recovery of Uranium from Phosphate Materials	Document Number: ORAUT-OTIB-0043 Revision: 00 Effective Date: 01/06/2006 Type of Document: OTIB Supersedes: None

Subject Experts: Gary R. Daer, Roger A. Gard, and Michalene Rodriguez

Document Owner
Approval: Signature on File — Approval Date: 01/06/2006
Elyse M. Thomas, Task 2 Manager

Concurrence: Signature on File — Concurrence Date: 01/05/2006
Kate Kimpan, Project Director

Approval: Signature on File — Approval Date: 01/06/2006
James W. Neton, Associate Director for Science

☒ New ☐ Total Rewrite ☐ Revision ☐ Page Change

FOR DOCUMENTS MARKED AS A TOTAL REWRITE, REVISION, OR PAGE CHANGE, REPLACE THE PRIOR REVISION AND DISCARD / DESTROY ALL COPIES OF THE PRIOR REVISION.

PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
01/06/2006	00	New document to describe characterization of occupational exposure to radium and radon progeny during recovery of uranium from phosphate materials. First approved issue. Training required: As determined by the Task Manager. Initiated by Gary R. Daer, Roger A. Gard, and Michalene Rodriguez.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

AEC	U.S. Atomic Energy Commission
ATSDR	Agency for Toxic Substances and Disease Registry
AWE	atomic weapons employer
Bq	becquerel
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FIPR	Florida Institute of Phosphate Research
ft	foot
g	gram
HPS	Health Physics Society
hr	hour
keV	kiloelectron volt, 1,000 electron volts
L	liter
m	meter
min	minute
mrad	millirad
mrem	millirem
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
NORM	naturally occurring radioactive material
pCi	picocurie
TENORM	technologically enhanced naturally occurring radioactive material
TIB	technical information bulletin
U.S.C.	United States Code
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WL	working level
WLM	working level-month
yr	year
μR	microroentgen

1.0 PURPOSE

Technical information bulletins (TIBs) 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. TIBs may be used to assist the National Institute for Occupational Safety and Health (NIOSH) in the completion of individual dose reconstructions.

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

This TIB characterizes occupational radiation exposure from the extraction of uranium during nonmonazite phosphate processing at atomic weapons employer (AWE) facilities. Exposure models and associated data have been acquired and/or extrapolated from existing published scientific research and Federal studies.

2.0 BACKGROUND

Phosphate rock extraction is the fifth largest U.S. mining industry in terms of quantity of mined material. Florida produces approximately 80% of the domestic capacity. North Carolina and Tennessee generate 10%, and Idaho, Utah, Montana, and Wyoming combine to produce the remaining 10%. The method chosen to handle the rock and ore depends on the desired final product—elemental phosphorous, gypsum, or fertilizer. The treatment type determines the innate physical, chemical, and radiological characteristics of the material including the distribution and concentration of naturally occurring radionuclides (such as uranium) within the matrix of the product or waste stream. In this manner, phosphate mining and processing effectively redistribute a significant fraction of uranium and its progeny within various phosphate products and byproducts, which results in what is commonly known as technologically enhanced naturally occurring radioactive material (TENORM). Phosphate ore from Florida typically contains the highest concentration of uranium, which is about 0.01% ^{238}U (in contrast to uranium ore, which contains up to 10% ^{238}U). In addition, phosphate ores contain concentrations of ^{232}Th consistent with those found in soil.

Phosphate ore is processed by either dry thermal or wet acid methods. The thermal approach produces elemental phosphorous using an electric arc furnace. The byproduct material is a vitrified slag containing uranium and ^{226}Ra. Concentrations of uranium and ^{226}Ra entrained in the slag range from 20 to 50 pCi/g and 4 to 40 pCi/g, respectively (Egidi 1997). The wet chemical phosphoric acid treatment process on the other hand primarily produces phosphate fertilizers whose principal byproducts are phosphogypsum and phosphoric acid scale. During wet chemical processing, there is selective separation and concentration of naturally occurring radium and uranium; nearly 80% of the ^{226}Ra is concentrated in the phosphogypsum while approximately 86% of the uranium ends up in the phosphoric acid scale (Egidi 1997). For work contracted under the auspices of the weapons program, only the wet acid treatment process was used to recover uranium from phosphate ores. Sites such as the Tennessee Valley Authority and Virginia-Carolina Chemical Company are known to typically employ the dry thermal methods for processing phosphate ores. However, under AWE contract, these sites employed wet process techniques to perform research and development efforts for extracting uranium from phosphate ores. The R & D efforts were performed using pilot plants which were conducted on a completely separate basis from the arc furnace facilities.

Typical phosphate plant operations consist of mining and beneficiation (separation of ore from sand and clay), ore drying and grinding, and acid processing. The majority of phosphate mining operations used strip mining. A typical strip mine is a trench 10 m deep and 99 m wide. The phosphate ore consists of rock and pebble embedded in a sand and clay matrix. During beneficiation, the sand and clay are separated from the phosphate rock. At the drying and grinding facility, the phosphate ore is reduced to pebbles in preparation for the acid wash. This process generates large quantities of dust and poses the highest potential for radon exposure in the phosphate industry (Birky 2005a). The phosphate is then transported to the acid facility where it is reacted with sulfuric acid to make phosphoric acid, typically to produce fertilizers. Because of the natural abundance of uranium in phosphate ore, some sites adjusted their processes to add steps to chemically precipitate uranium from phosphoric acid. For those sites that extracted uranium under a U.S. Atomic Energy Commission (AEC) contract, product packing also generated airborne particulate. Due to the nature of plant operations, workers were frequently in close contact with large amounts of ore, products, and wastes that contained TENORM and radium as well as their concomitant alpha-emitting progeny such as radon.

An inert gas, radon decays as a series of short-lived radionuclides that can attach electrostatically to aerosols. As mentioned above, plant operations generate large quantities of particulate (especially during loading, unloading, crushing, and drying activities), so there is a potential for elevated levels of airborne radionuclides in the work environment. Mitigating factors such as environmental conditions (ambient dust levels, etc.) and ventilation notwithstanding, it is likely that phosphate plant workers spent some fraction of their shifts exposed to airborne particulates that resulted in a corresponding occupational radiation exposure from inhalation of long-lived alpha-producing radionuclides as well as radon and its progeny.

Around 1950, the AEC was interested in developing methods for recovering uranium from low-concentration sources such as phosphate rock (Wilkinson 1976). In addition to its potential use as a nuclear fuel source, uranium was a key component of the early weapons production program. A review of the U.S. Department of Energy (DOE) Office of Worker Advocacy on-line facilities database revealed that there were efforts to recover uranium from phosphate byproducts at the following AWE sites: Allied Chemical and Dye Corporation, Armour Fertilizer Works, Blockson Chemical Company, Dow Chemical Company (Pittsburg, California), Gardinier Incorporated, International Minerals and Chemical Corporation, Mathieson Chemical Company, Tennessee Valley Authority, Texas City Chemicals Incorporated, Virginia-Carolina Chemical Corporation, and W.R. Grace Company, Agricultural Chemical Division. Each facility is described as having been under contract with the AEC to investigate methods to produce uranium from phosphoric acid. Resultant worker exposure to TENORM and its long- and short-lived progeny during wet chemical phosphate production activities at these plants are of particular interest.

3.0 LITERATURE REVIEW

Initial efforts for this bulletin focused on the collection of existing data that addresses the radiological hazards associated with uranium-mining activities and the recovery of uranium during phosphate production. The goal was to construct a technically defensible, claimant-favorable method for characterizing worker exposure to radon progeny during AEC uranium extraction operations. Preference was given to documents that addressed wet chemical phosphate production in Florida because the radiological characteristics of the ore, the production methods, and the techniques employed to extract the uranium determine the radiological source term and, correspondingly, establish the basis for potential occupational dose during work activities performed under AWE contracts.

Adequate quantification of radiation exposure to workers necessitates detailed characterization of the work environment as well as specific sources of external and internal radiation. In addition, data that directly support radiological characterization (source information, monitoring results, discrete process exposures, etc.) and information on models used to estimate radon and radon progeny levels were considered important criteria for the literature review. Of particular interest were studies that documented phosphate plant literature reviews, which provided links to additional sources of information. Scientific and epidemiological literature was culled from several sources: The Florida Institute of Phosphate Research (FIPR), the Health Physics Society (HPS), Federal agency technical information centers (which included national and international scientific committee documents), NIOSH data capture activities, DOE archives, and the U.S. Environmental Protection Agency (EPA) Region 8 Technical Library.

In general, the search process found that older studies of phosphate facilities were not typically useful because (1) the working level (WL) concept had not yet been developed, (2) measurement techniques were not as sensitive, and (3) most of the documents lacked detailed data on the radiological characteristics of phosphate operations. Of the information repositories evaluated, Federal sources such as EPA, the Agency for Toxic Substances and Disease Registry (ATSDR), international and national scientific committee reports, and studies published by HPS and FIPR usually provided the most data.

3.1 FEDERAL SOURCES

Over the last 30 yr, the EPA Office of Radiation Programs has published a variety of reports on various aspects of the uranium and phosphate industry. Research and investigative studies have produced a compendium of data on the potential for exposure to TENORM, specifically on uranium, thorium, radium, radon, and radon progeny. Much of the EPA effort has focused on radon flux, indoor WL measurements, and risk assessment model development. In addition, the ATSDR maintains an on-line registry that details the hazards associated with radon exposure. Of particular interest to this study are those sources that (1) document radon flux measurements from phosphogypsum piles at Florida phosphate plants (EPA 1986), (2) define radon exhalation rates for phosphate and uranium source material (EPA 1979), and (3) provide radon emanation rates from phosphate mining (ATSDR 2005).

According to Federal research, the concentrations of radium in gypsum piles and uranium mill tailings range from 12.8 to 42.8 pCi/g and 50 to 980 pCi/g, respectively (EPA 1979). Radon exhalation values can be as high as 8,070 pCi/(m^2-min) for gypsum and 72,000 pCi/(m^2-min) for uranium mill tailings (EPA 1979). While there are a few physical differences between phosphogypsum and uranium mill tailings, the primary difference in exhalation rate is due to lower ^{226}Ra concentrations in gypsum, a relationship directly related to the low abundance of uranium in phosphate ore (0.01% versus 0.1 to 10% for uranium ores). Measured radon flux (also referred to as exhalation) at selected Florida phosphate plants has only ranged from 26.4 to 2,526 pCi/(m^2-min) depending on factors such as the thickness of the source matrix, moisture, and degree of disturbance of the source material (EPA 1986).

3.2 FLORIDA INSTITUTE OF PHOSPHATE RESEARCH STUDY

The FIPR has evaluated data compiled over the past 20 yr and collected new information from phosphate mines, chemical plants, and outside contractors. The focus was on central Florida where concentrations of naturally occurring radioactive material (NORM) in the phosphate ore are higher. Personnel monitoring, exposure rates, area monitoring, environmental monitoring, and radon measurements were supplied by the phosphate and service industries. Samples were collected from the mine area, rock-handling area, phosphoric acid production area, dry production area, shipping area, and service area. The following sections summarize the results of these studies from FIPR (1998).

3.2.1 External Exposure

The external dosimetry data from past studies as well as that from recent research (FIPR 1998) indicate that the annual radiation dose from phosphate production activities is less than 100 mrem. One phosphate company provided thermoluminescent dosimeter data for 1979 to 1996 for approximately 650 employees. The exchange frequencies were monthly as well as quarterly, which provided over 31,200 data entries. The mine area, rock area, and phosphoric acid areas provided personnel with the highest external doses, but “few employees exceeded the annual dose limit to members of the general public” (FIPR 1998) (the limit was 500 mrem per any 12-month period b1992).

3.2.2 Internal Exposure

As a part of the FIPR (1998) study, air samples were collected at various locations throughout a phosphate facility’s various plants. The air sampling was performed in areas not only suspected to have elevated concentrations of ^{226}Ra, but also in additional working areas without suspected elevated levels. Samples were collected during work activities that would elevate air concentrations. The air samples were analyzed both for gross alpha and beta as well as gamma spectroscopy analysis to determine the radionuclides present and their fractional contributions. The calculated air sample results were not corrected to subtract out any fraction of particulate that is non-respirable.

The air sample results were coupled with inhalation Dose Conversion Factors (using ICRP Report No. 68) and results from time motion studies to estimate inhalation of TENORM. The inhalation component of the total effective dose equivalent was calculated for the various work activities or areas at the plant: Rock area, phosphoric acid area, dry products area, shipping area, pan-chipping turnaround activity, and reactor-cleaning turnaround activity. A series of lognormal dose curves were presented, which indicated that the shipping area posed the greatest risk for internal exposure with a range from 0 to 350 mrem/yr (Figure 3-1). The area with the next greatest potential was the rock area (Figure 3-2). Intake amounts were not specified.

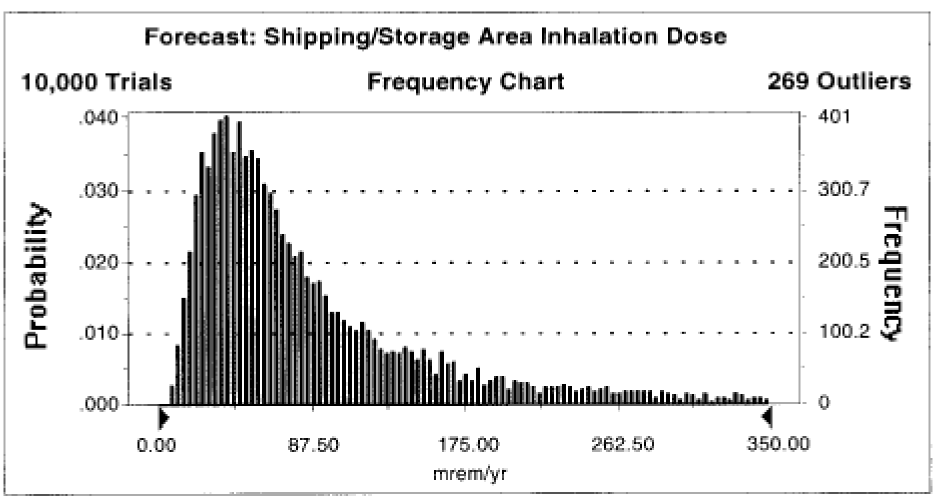

Figure 3-1. Inhalation dose for the shipping area.

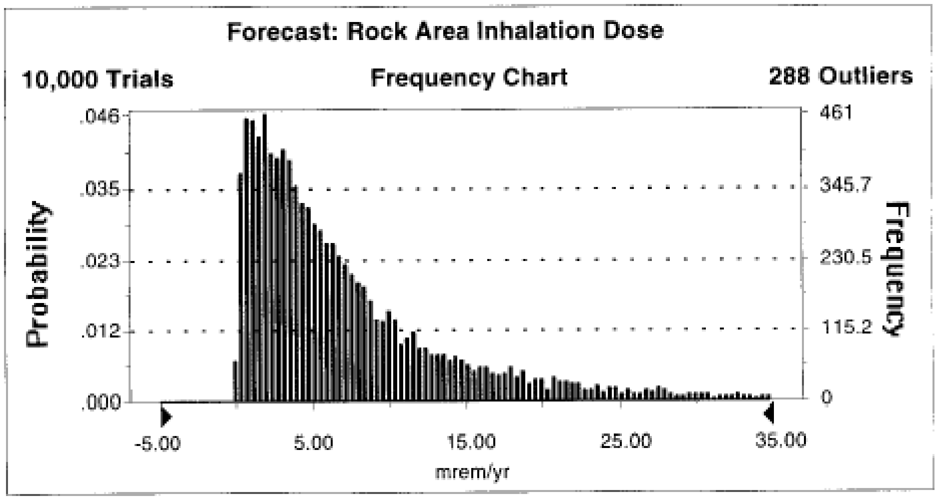

Figure 3-2. Inhalation dose for the rock area.

3.2.3 Radon Exposure

FIPR (1998) presents several sources of previously collected data as well as data from measurements collected by FIPR staff. The data from previous work is summarized as:

- A University of Florida study of radon WL exposures due to the process of wet rock loading
- Data sets of radon activity concentration measurements from 1989 to 1994, 1995 to 1996, and 1993 to 1996 indicated as being collected at a phosphate facility's chemical plant
- A data set from 1982 to 1996 indicating summary statistics of radon levels at a facility's chemical plant as well as other locations such as rock tunnels and some mining related locations
- Data sets of radon activity concentration measurements from 1996 for a facility's rock tunnels.

Several of the above studies represent normal work locations or activities that were conducted apart from uranium extraction processes conducted under AWE contracts. Due to applicability of the Defense Authorization Act, only chemical plant data is considered as being representative of radon levels that workers could have been exposed to during uranium extraction activities.

3.3 SCIENTIFIC PUBLICATIONS

Publications from the scientific community were reviewed including *Health Physics* journal articles and reports from the National Council on Radiation Protection and Measurements (NCRP) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR).

The journal articles are highly mathematically oriented and offer insight to the physical and radiological characteristics of radon and its short-lived progeny that affect airborne concentrations and thus WLs. In addition to the magnitude of a radon source and natural radioactive decay, other factors affecting WLs are loss of radon and its progeny due to ventilation, the percentage of progeny that attach themselves to airborne particulate, surface plate-out of airborne particulate with attached progeny, and to some extent gravitational settling of the progeny. While the articles were beneficial in presenting some of the fundamental concepts of radon and progeny behavior, the mathematical models found during literature review would require a series of assumptions for choosing parameter values such that use of any of the models becomes impracticable, especially when measured values are available.

Because there may be some inconsistency in values in the individual journal articles, the reports prepared by NCRP and UNSCEAR are useful in that values are presented for equilibrium fraction *F* as well as external gamma dose that are recognized by the scientific community. This analysis preferred the use of a nationally or internationally recognized value (if present) over that of any value from a single study presented in a journal article.

3.4 OTHER REVIEWS

Detailed characterization of radon and radon progeny WLs for each AWE facility requires site-specific data on the radiological conditions during wet chemical phosphoric acid uranium recovery operations. The NIOSH Project archives contain site source documents linked to a master summary spreadsheet. Source documentation contains information on personnel monitoring, cohort exposure data, area and environmental monitoring, and general site statistics.

Attachment A provides a summary of the review of the records collected for the NIOSH Project. The record survey yielded very little information of practical use for estimating site-specific occupational radon exposures. As a consequence, data and technical approaches from other existing literature were adapted to generate claimant-favorable values for occupational exposure based on conditions for workers involved with uranium extraction at a phosphate plant.

4.0 OCCUPATIONAL EXPOSURE CHARACTERIZATION

Technological enhancement of uranium during wet chemical phosphoric acid processing, as well as the subsequent radioactive decay, presents discrete radiological health concerns to phosphate plant personnel. Occupational external exposure to radium and the potential internal dose from radon and its progeny as well as respirable particulate matter containing long-lived radionuclides are of particular interest. While the most technically satisfying approach would be to address exposure concerns for each AWE facility during its specific period of uranium recovery operations, the literature review process has demonstrated that the available documentation does not provide enough detail to complete such a task in a reasonable and time-efficient approach. Therefore, this document describes the development of a single approach that covers all listed AWE phosphate facilities. The results are radon and radon progeny levels in units of WL-months (WLM).

4.1 INTERNAL AND EXTERNAL EXPOSURE CONSIDERATIONS

For the purpose of this analysis, the evaluation of occupational exposure was limited to the naturally occurring radioactive material that was technologically enhanced during the processing of phosphate ores. Analysis of additional internal and/or external exposure from uranium extract (yellow cake) has been left to the appropriate site-specific technical basis document.

During normal plant operations, activities with the potential for occupational exposure were mining and beneficiation, ore drying and grinding, the wet acid process, maintenance, work in vicinity of phosphogypsum stacks, and product packaging and handling. For the purposes of reconstructing exposures due to work under AWE contract, only the work locations and activities related to extraction of uranium from phosphate ores should be considered. As a result, mining and beneficiation, ore drying and grinding, and nonuranium product packaging and handling were not considered. The chemical plants that performed the uranium extraction using the wet acid process and the resultant waste streams in the form of the phosphogypsum stacks were considered.

4.1.1 External Exposure

The primary constituent for external exposure is ^{226}Ra because of its beta-gamma emission relative to the alpha-emitting constituents of the ^{238}U decay series. Due to chemical separation in the wet acid process, radium scale builds up at several locations in the processing equipment. The radiation levels peak in the acid-wash section, with dose rates as high as 10 mrem/hr (Lardinoye and Weterings 1982). With consideration of the nature of their duties, duration of work activities, and frequency of such work; a maximally exposed worker (operator or maintenance) could receive up to 220 mrem/yr (Lardinoye and Weterings 1982). NCRP (1993) reports exposures for a 2,000 hr/yr occupancy at phosphogypsum stacks as 70 mrem; Laiche and Scott (1991) estimated a range for that occupancy of 48 to 68 mrem. For the purposes of dose reconstruction, the above data may be represented with a lognormal distribution having a geometric mean of 70 mrem/y, a 95th percentile value of 220 mrem/y, and a geometric standard deviation of 2.00. Table 4-1 summarizes these values.

Table 4-1. Annual external exposure.

Exposure (mrem/yr)	Comments	Dose distribution	Photon energy distribution (keV)
220	Upper bound for exposures to plant workers with high occupancy in and around process equipment	Constant	50% 30–250 50% >250
70	Exposure from work located at gypsum stacks	Lognormal, GSD=2.00	50% 30–250 50% >250

a. GSD = geometric standard deviation.

4.1.2 Internal Exposure

Botezatu and Iacob (2004) conducted characterization studies in a phosphate plant for occupational exposure due to NORM. Particulate concentrations generated during operations were given as a range from 0.01 to 0.1 g/m^3. Radioactivity concentrations were given as 0.087 to 23.75 Bq/g for ^{238}U and 0.17 to 18.6 Bq/g for ^{226}Ra. The particle size measurements resulted in a percentage of respirable particles of 81% 4 μ or less.

While Botezatu and Iacob (2004) did not reveal the location of the phosphate plant, the upper range of the activity concentrations are much higher than typical ores processed in U.S. facilities. American phosphate ores contain an average of about 0.01% uranium (Roessler et al. 1979). Table 4-2 lists the activity concentrations from the Roessler et al. analysis of central Florida phosphate materials:

Table 4-2. Phosphate ^{238}U activity concentrations.

Physical form	U-238 concentration (pCi/g)	
	Average	Range
Matrix	38.5	20.2–83.4
Pebble	45.8	36.0–68.1
Rock concentrate	31.9	20.1–49.8
Clays	27.1	16.0–49.2
Tailings	4.7	1.5–10.4
5% phosphoric acid	6.3	--
10% phosphoric acid	17.1	--

30% phosphoric acid	30.0	--
Gypsum	<0.5	<0.4–<0.7

Because the average value of 45.8 pCi/g for phosphate pebble is the maximum average from Table 4-2, for conservatism, this value is used in calculating internal deposition rates. The range of 36.0-68.1 pCi/g may be approximated with a lognormal distribution with a geometric mean equal to 45.8 pCi/g, a 95th percentile value of 68.1 pCi/g, and a geometric standard deviation of 1.27.

In similar work for EPA, Guimond, Mills, and Windham (1977), found ^{232}Th activity concentrations as being 0.44 pCi/g in marketable rock (rock concentrate). According to Table 4-2 above, ^{238}U is present in 44% greater abundance in pebble product than rock concentrate. Therefore, it is reasonable to assume that ^{232}Th also exists in similar relative abundance, and an activity of 0.63 pCi/g would be expected for ^{232}Th in pebble form. Given that no range of measurement values are given for ^{232}Th, it is assumed that the abundance of thorium is also distributed lognormally with a geometric mean of 0.63 pCi/g and a geometric standard deviation of 1.27. The resulting 95th percentile value would then be 0.933 pCi/g.

Table 4-3 lists the intakes calculated using the value of 0.1 g/m^3 for dust loading, and a breathing rate of 1.2 m^3/hr. For maximizing conditions, the 95th percentile values of 68.1 pCi/g and 0.933 pCi/g are used for ^{238}U and ^{232}Th respectively. Best estimate conditions utilize the geometric mean values of 45.8 pCi/g and 0.63 pCi/g for ^{238}U and ^{232}Th respectively.

Table 4-3. Internal deposition.

Dose reconstruction approach	Distribution	Intake amount (pCi/hr)	Radionuclide
Maximizing	Constant	8.17	U-238 in equilibrium with its daughters
		1.12E-01	Th-232 in equilibrium with its daughters
Best Estimate	Lognormal GSD=1.27	5.5	U-238 in equilibrium with its daughters
		7.56E-02	Th-232 in equilibrium with its daughters

4.2 RADON EXPOSURE

Because of release of radon gas during phosphate plant operations, radon poses a high potential for occupational exposure. The literature review produced very little data about radon or WL at phosphate facilities during AWE operations. As indicated in Attachment A, Virginia-Carolina had an average daytime radon concentration between 0.6 and 0.9 pCi/L with progeny concentration measurements indicating a WL of less than 0.01. However, the measurements occurred before remediation and after the uranium extraction facility had ceased operation and been torn down. Only a concrete pad remained at the time of monitoring.

Due to the lack of data from AWE sites, this analysis used the data in FIPR (1998) to determine radon concentrations and WLs. This was possible because the factors that affect radon concentrations have changed very little over time. No significant changes in the construction of wet process acid plants had occurred since the time of AWE operations (Birky 2005b). While environmental regulations led to decreased overall emissions, the controls had little or no effect on occupational radon levels. In addition, the rate of ore processing has increased over time (Birky 2005b).

Attachment B lists the data from FIPR (1998). The data sets indicated as “Chemical Plant” refer to the building or structure that processed rock concentrate using a chemical or wet acid process (Birky 2005c). As mentioned in Section 4.1, this analysis limited consideration of occupational exposures to activities relevant to uranium extraction. Therefore, radon measurements related to rock tunnels, wet rock loading, and mining operations were not considered. Measurements from those locations have been highlighted in gray and were not included in analysis of occupational radon exposure. The data sets that gave summary radon concentrations for a span of years were given equal weight with those that gave concentrations over shorter periods. The combined measurements formed a set of 130 data points that have a geometric mean of 0.751 pCi/L and a geometric standard deviation (GSD) of 1.989. The 95th-percentile value is 2.33 pCi/L.

Table 4-4 lists WLs calculated using an equilibrium factor *F* of 0.4 (ICRP 1981; UNSCEAR 1993).

Table 4-4. Phosphate plant worker radon WL values.

DR approach	Radon concentration (pCi/L)	*F*	WL	WLM/yr	Distribution
Best estimate	0.751	0.4	0.003	0.036	Lognormal, GSD=1.989
Maximizing	2.33	0.4	0.0093	0.112	Constant

5.0 INDIVIDUAL PROGENY EQUILIBRIUM FRACTIONS AND UNATTACHED FRACTIONS

Radon daughter products primarily get trapped in the lungs; therefore the primary concern of radon daughters is lung exposure. For the purpose of the EEOICPA, radon exposures for lung cancers are expressed in units of Working Level Months. In most instances, radon exposure to organs other than the lung are negligible (> 1 mrem/year); however, there may be a small number of cases that warrant evaluation of exposure to other organs. Since the exposure unit of WLM is applicable only for lung cancer dose reconstructions, individual organ dose in rem would need to be calculated for non-lung dose reconstructions.

Inhalation rates for radon daughters would be necessary in order to determine internal doses. The equilibrium factors for each of the short-lived radon progeny and the fractions that are not attached to airborne particulate must be known for calculation of inhalation rates. Domanski (1979) calculated values for the individual equilibrium factors. To correspond with an overall equilibrium factor *F* of 0.4, the individual factors are 0.656, 0.446, and 0.259 for RaA, RaB, and RaC, respectively.

The unattached fraction is an inverse function of particle concentration with secondary dependence on particle size (NCRP 1984). As a result, unattached fractions tend to be higher for typical indoor atmospheres [8% according to Nikezic, Hack, and Yu (2002)], than in dusty conditions such as mining atmospheres where the unattached fraction is only about 1% (Birchall and James 1994).

NCRP (1984) lists the unattached fractions f_a, f_b, and f_c for RaA, RaB, and RaC, respectively, as a function of particle concentration. For a particle concentration of 1×10^4 particles/cm^3, which best represents the likely atmosphere in a phosphate facility, the resultant unattached fractions are $f_a = 0.18$, $f_b = 0.021$, and $f_c = 0.0007$.

The lung absorption half-life of Pb-214 and Bi-214 have been measured to be 10 hour and 13 hours respectively (Marsh and Birchall). Using the parameters described here and the assumed absorption half-life for Po-218 of 10 hours, the dose to various organs from radon progeny can be calculated. The dose per 2000 hour work year from the progeny associated with a 0.751 pCi/L radon gas concentration is less than 1 mrem/yr for all organs outside the respiratory tract.

The dose from the radon gas itself dissolved in the body tissues can be estimated using ICRP 32. This publication gives an equilibrium conversion factor of 3.33E-7 rem/hr per pCi/L. This conversion factor produces an annual dose to organs other than the respiratory tract of approximately 1.55 mrem per 2000 hour year for a continuous exposure to 2.33 pCi/L.

The dose to the kidney (highest exposed organ other than the respiratory tract) from radon associated with this Technical Information Bulletin is approximately 2 mrem per year. Therefore, all organs not associated with the respiratory tract will be assigned an annual radiation dose of 2 mrem to account for exposure to radon and its progeny.

REFERENCES

ATSDR (Agency for Toxic Substance and Disease Registry), 2005, *Toxicological Profile for Radon*, Section 5.5, U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, on-line database.

Birchall, A., and James, A. C., 1994, "Uncertainty Analysis of the Effective Dose per Unit Exposure from Radon Progeny and Implications for ICRP Risk-Weighting Factors," *Radiation Protection Dosimetry*, volume 53, Nos. 1–4, pp. 133–140.

Birky, B., 2005a, "Occupational, Radiological Exposures in the Phosphate Industry," electronic mail to J. Guido (Oak Ridge Associated Universities Team), July 13, Florida Institute of Phosphate Research, Bartow, Florida.

Birky, B., 2005b, "Phosphate Plant Radon Levels," electronic mail to R. Gard (Oak Ridge Associated Universities Team), September 1, Florida Institute of Phosphate Research, Bartow, Florida.

Birky, B., 2005c, "Re: Phosphate Plant Radon Levels," electronic mail to R. Gard (Oak Ridge Associated Universities Team), September 2, Florida Institute of Phosphate Research, Bartow, Florida.

Botezatu, E., and O. Iacob, 2004, "Radiation Hazard for Workers Related to NORM in Phosphate Fertilizers and Energy Production," *11th Congress of the International Radiation Protection Association*, May.

Domanski, T., 1979, "Correlation between the equilibrium factor F and the relative concentration of radon daughters in mine air", *Health Physics*, Vol. 137, 177.

Egidi, P., 1997, "Introduction to Naturally Occurring Radioactive Material," *42nd Annual Meeting of the Health Physics Society*, July.

EPA (U.S. Environmental Protection Agency), 1979, *A Preliminary Radiological Assessment of Radon Exhalation from Phosphate Gypsum Piles and Inactive Uranium Mill Tailings Piles*, EPA 520/5-79-004, Office of Radiation Programs, Washington, D.C.

EPA (U.S. Environmental Protection Agency), 1986, *Radon Flux Measurements on Gardinier and Royster Phosphogypsum Piles Near Tampa and Mulberry, Florida,* EPA 520/5-85-029, Office of Radiation Programs, Washington, D.C.

FIPR (Florida Institute of Phosphate Research), 1998, *Evaluation of Exposure to Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) in the Phosphate Industry*, Publication 05-046-155, Bartow, Florida.

Guimond, R. J., Mills, W. A., and Windham, S. T., 1977, "Radiation Exposures in the Florida Phosphate Industry," *International Radiation Protection Association Meeting #4, Paris, France*, volume 3, pp. 1049–1052.

ICRP (International Commission on Radiological Protection), 1981, *Limits for Inhalation of Radon Daughters by Workers*, Publication 32, Pergamon Press, Oxford, England.

J. W. Marsh and A. Birchall, *Determination of Lung-to-Blood Absorption Rates for Lead and Bismuth which are appropriate for Radon Progeny*, Radiation Protection Dosimetry, Vol. 83, No 4, pp 331-337 (1999)

Laiche, T. P., and Scott, L. M., 1991, “A Radiological Evaluation of Phosphogypsum,” *Health Physics*, volume 60, number 5, pp. 691–693.

Lardinoye, M. H., and K. Weterings, 1982, “Unexpected ^{226}Ra Build-up in Wet Process Phosphoric-Acid Plants,” *Health Physics*, volume 42, number 4, pp. 503–514.

NCRP (National Council on Radiation Protection and Measurements) Report No. 78, 1984, *Recommendations of the National Council on Radiation Protection and Measurements, Evaluation of Occupational and Environmental Exposures to Radon and Radon Daughters in the United States*, Bethesda, Maryland, May.

NCRP (National Council on Radiation Protection and Measurements) Report No. 118, 1993, *Recommendations of the National Council on Radiation Protection and Measurements, Radiation Protection in the Mineral Extraction Industry*, Bethesda, Maryland, November.

Nikezic, D., Haque, A. K. M. M., and Yu, K. N., 2002, “Effects of different deposition models on the calculated dose conversion factors from Rn-222 progeny.” *Journal of Environmental Radioactivity*, volume 61, number 3, pp. 305–318.

Roessler, C. E., Z. A. Smith, W. E. Bolch, and R. J. Prince, 1979, “Uranium and Radium-226 in Florida Phosphate Materials,” *Health Physics*, volume 37, September, pp. 269–277.

UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation), 1993, *Sources and Effects of Ionizing Radiation*, United Nations, New York, New York..

Wilkinson, G. E., 1976, *Uranium Recovery from Wet Process Phosphoric Acid*, Gardinier, Inc., Tampa, Florida.

ATTACHMENT A
Synopsis of Phosphate Plant Data in the NIOSH Site Research Database

Table A-1. Synopsis of phosphate plant data in the NIOSH Site Research Database

	AWE sites					
	Armour	**DOW**	**IMAC**	**Gardinier**	**Texas City**	**Virginia-Carolina**
Years of operation	1/1/51–12/31/55	1/1/47–12/31/57	1/1/51–12/31/61	1/1/52–12/31/58	1/1/52–12/31/56	1/1/52–12/31/57
Total documents[a]	2	11[b]	4	3	3	3
Contract/agreement		X	X		X	
General process & history	X	X		X	X	X
Production amount			100 tons total with a peak production of 2 to 3 tons/month; 24 tons of U_3O_8 per year[c]	60 tons of uranium concentrate per year	12 tons of U_3O_8 per year	12 tons of U_3O_8 per year
Facility dimensions		175 × 90 m (estimate)	90 × 250 ft – concrete pad		19 × 36 yd. concrete pad	10 × 10 m (concrete pad); 10 x 17 m (building)[e]
Survey report:	X	X[f]	X	X (pages 5–109 missing)		X
γ exposure rate (μR/hr)	7 inside bldg, 30 outside @ 1 m	3–7 floor surface; 1–4 overhead beam surfaces	Max. 30 @ 1 m @ pad and 100 @ 1 m adjacent to pad		120 @ 1 m[d]	22–58 @ 1 m @ pad 8–20 @ 1 m @ building 20–100 outside
β/γ dose rate (mrad/hr)	0.02	<0.01–0.06 @ overhead beams	0.1 and 0.2		0.25	0.05–0.26 @ pad 0.04–.07 @ 1 cm @ building
Samples (pCi/g)		Ra-226 0.22–1.3 (beam dust) 0.17–0.54 (debris) U-238 3.7–310 (beam dust) 0.95–1.2 (debris)		1,000 Ra-226 (floor shavings)		15–56 U-238 (residue from pad)
Soil sample results	28.3 pCi/L Ra-226				4.5-170 pCi/L Ra-226; see page 78 for location and U results	Surface (pCi/g) 14–1900 Ra-226; 6–54 U-238 Subsurface 5–360 Ra-226 2–46 U-238
Radon and radon daughter concentrations in air (pCi/L)						0.4–1.0 lunchroom 0.2–1.9 maintenance area 0.6–0.9 avg. daytime conc. Rn daughters <0.01 WL
Water sample results (pCi/L)				< guidelines		Max. 110 U-238
Background measurements:						
γ exposure rate (μR/hr)		7–11 @ 1 m				5 @ 1 m
Soil Ra-226 concentrations (pCi/g)		0.88–0.93				0.3–2.3
Soil U-238 concentrations (pCi/g)		1.0–1.1				0.1–1.1
β/γ dose rates (mrad/hr)						0.01–0.05
FUSRAP elimination report	X	X	X		X	

Total number of documents reviewed in the Site Research Database and Task 2's Data Entry Source Document Review. NOTE: Duplication of documents exists among both resource databases.

a. Includes both site locations – Walnut Creek California and Madison, Illinois
b. Information in Texas City Chemical document
c. States typical value for similar production plants in other parts of the country
d. The pilot plant at this site was disassembled in about 1960; all that remains is a concrete pad. Sometime later, a maintenance building was constructed adjacent to the pad and contains a maintenance room, tool cage, lunchroom and a small office. At the time of the survey in 1977, this building was occupied by personnel.

Survey results are for the site located in Madison, Illinois. Survey for the Walnut Creek, California location states no levels above background were detected except an inaccessible area on a fume hood.

ATTACHMENT B
Data from FIPR (1998)

Table B-1. Phosphate facility radon measurements.

	Location	Start date	End date	Result pCi/L	Comments
D	Granular 2nd floor stairs	12/3/1997	12/9/1997	1.1	
D	Reclaimer - DAP Shipping	12/2/1997	12/5/1997	1	
D	DAP #4 Granulator	12/8/1997	12/12/1997	0.5	
D	XYZ; 3rd floor workbench	12/1/1997	12/5/1997	< 0.5	
H	B Ship.; Platform over conv.	12/1/1997	12/5/1997	0.7	
M	Float Plant	12/15/1997	12/19/1997	1.6	Duplicate
M	Float Plant (Retest)	1/9/1998	1/13/1998	1.5	Duplicate
M	Rail Car Load-Out	12/4/1997	12/9/1997	1.4	
M	Pit Car #14	12/15/1997	12/19/1997	1.1	Duplicate
M	Float Plant	12/15/1997	12/19/1997	0.8	
M	Pit-Car	12/4/1997	12/19/1997	0.7	
M	Pit Car #12	12/15/1997	12/19/1997	0.7	
M	Float Plant Lab	12/4/1997	12/9/1997	< 0.5	
M	Pit-Car	12/4/1997	12/9/1997	< 0.5	
P	Phos Acid E-Train filter p. area	12/2/1997	12/5/1997	1.7	E-Perm wet
P	Phos Acid Control Room	12/3/1997	12/9/1997	1.4	Dup. with bag
P	Phos Acid Control Room	12/8/1997	12/12/1997	1.4	Dup. with bag
P	Phos Acid B filter pan area	12/3/1997	12/9/1997	0.9	
P	Phos Acid Control Room	12/9/1997	12/12/1997	< 0.5	Dup. with bag
P	Phos Acid Control Room	12/2/1997	12/5/1997	< 0.5	Dup. with bag
P	Phos Acid Control Room	12/1/1997	12/5/1997	< 0.5	Dup. with bag
R	Rock Tunnel	12/4/1997	12/9/1997	21.5	
R	Rock Tunnel	12/4/1997	12/9/1997	1.4	Duplicate
R	Rock Tunnel	12/8/1997	12/12/1997	40	
R	Rock Tunnel	12/2/1997	12/5/1997	28.8	
R	Rock Tunnel	12/9/1997	12/12/1997	15.8	
R	Rock Tunnel	12/19/1997	12/23/1997	5.8	
R	Wet rock unload; QC/Breakr.	12/2/1997	12/5/1997	2.4	

ATTACHMENT B
Data from FIPR (1998) (Continued)
Page 2 of 6

Table B-2. Annual exposure to radon progeny in wet rock loading.

Company	No.	Mean (WLM/yr)	Upper limit (WLM/yr)	Lower limit (WLM/yr)
R	2	0.0046	0.0054	0.0037
L-2	6	0.84	1.5	0.003
L-1	6	0.074	0.25	0.0017
M-N	5	0.022	0.09	0.00041
M-O	5	0.009	0.023	0.0035
K-1	2	0.14	0.2	0.082
K-2E	5	0.044	0.21	0.0024
K-2W	6	0.037	0.2	0.0017
Q	1	0.0007	0.0007	0.0007
G	12	0.059	0.35	0.0064
H	8	0.0028	0.0064	0.00052
D-2	3	0.0041	0.012	0.00018
D-1	3	0.007	0.018	0.00015
E-B	9	0.062	0.34	0.00014
E-A	5	0.017	0.036	0.004

Table B-3. Chemical plant radon readings, summary statistics 1989 to 1994.

	NE gypsum stack well	Auto shop SE fence	SW of plant	Burn area fence	Liming station ladder	Environmental monitoring well	Gypsum stack flux test	Cooling pond hand rail
Mean	2.43	2.89	0.35	1.89	1.9	2.6	6.52	2.08
Standard error	0.45	0.65	0.08	0.48	0.49	0.74	1.01	0.63
Median	0.75	2.12	0.18	0.4	0.54	0.75	4.41	0.91
Mode	0	0	0	0	0	0	0	0
Standard deviation	4.3	4.87	0.47	5.23	5.04	7.43	4.95	5.18
Sample variance	18.45	23.73	0.22	27.39	25.36	55.26	24.52	26.85
Kurtosis	9.1	20.14	12.03	29.97	40.15	32.12	0.68	19.41
Skewness	2.94	4.16	3.1	5.04	6.05	5.35	1.36	4.48
Range	21.74	30.6	2.38	40.87	40.84	56.76	15.82	27.61
Minimum	0	0	0	0	0	0	2.07	0
Maximum	21.74	30.6	2.38	40.87	40.84	56.76	17.89	27.61
Count	90	56	31	118	105	101	24	68
CL 95%	0.89	1.28	0.16	0.94	0.96	1.45	1.98	1.23

Table B-4. Radon measurements summary, 1995 to 1996.

Area	Mean (pCi/L)
NE gypsum stack monitoring well	9.51
Auto shop	2.99
Environmental monitoring well	5.11
Cooling pond hand rail	3.02
Burn area fence	1.66

ATTACHMENT B
Data from FIPR (1998) (Continued)

Table B-5. Radon readings in rock tunnels, 1996.

Start	End	μR/hr	pCi/L	Area	Location
1/5/1996	2/6/1996	6	8.6	Tunnel	Middle
1/5/1996	2/6/1996	6	7.284	Tunnel	North
1/5/1996	2/6/1996	6	6.938	Tunnel	South lower
1/5/1996	2/6/1996	6	10.121	Tunnel	South upper
2/6/1996	3/13/1996	10	7.094	Tunnel	Middle
2/6/1996	3/13/1996	7	8.669	Tunnel	North
2/6/1996	3/13/1996	10	4.819	Tunnel	South lower
2/6/1996	3/13/1996	7	10.479	Tunnel	South upper
3/13/1996	4/19/1996	10	5.295	Tunnel	Middle
3/13/1996	4/19/1996	7	28.137	Tunnel	North
3/13/1996	4/19/1996	10	4.228	Tunnel	South lower
3/13/1996	4/19/1996	7	5.157	Tunnel	South upper
4/19/1996	5/14/1996	16	6.272	Tunnel	Middle
4/19/1996	5/14/1996	9	16.626	Tunnel	North
4/19/1996	5/14/1996	14	3.441	Tunnel	South lower
4/19/1996	5/14/1996	10	4.621	Tunnel	South upper
5/14/1996	6/18/1996	16	3.349	Tunnel	Middle
5/14/1996	6/18/1996	9	5.574	Tunnel	North
5/14/1996	6/18/1996	14	1.38	Tunnel	South lower
5/14/1996	6/18/1996	10	2.135	Tunnel	South upper
6/18/1996	7/17/1996	16	9.144	Tunnel	Middle
6/18/1996	7/17/1996	9	7.572	Tunnel	North
6/18/1996	7/17/1996	14	0.785	Tunnel	South lower
6/18/1996	7/17/1996	10	1.563	Tunnel	South upper
7/17/1996	8/8/1996	16	3.295	Tunnel	Middle
7/17/1996	8/8/1996	9	7.031	Tunnel	North
7/17/1996	8/8/1996	14	0.985	Tunnel	South lower
7/17/1996	8/8/1996	10	2.562	Tunnel	South upper
8/8/1996	9/23/1996	10	3.399	Tunnel	Middle
8/8/1996	9/23/1996	5	59.599	Tunnel	North
8/8/1996	9/23/1996	10	1.63	Tunnel	South lower
8/8/1996	9/23/1996	10	2.007	Tunnel	South upper
9/23/1996	10/15/1996	8	61.33	Tunnel	South upper
9/23/1996	10/15/1996	10	4.355	Tunnel	South upper
9/23/1996	10/15/1996	12	0.964	Tunnel	South upper
9/23/1996	10/15/1996	10	1.937	Tunnel	South upper

ATTACHMENT B
Data from FIPR (1998) (Continued)
Page 4 of 6

Table B-6. Radon readings in rock tunnels using e-perms, 1996.

Start	End	µR/hr	pCi/L	Chute #
1/10/1996	2/20/1996	50	9.621	1
1/10/1996	2/20/1996	50	8.723	1
1/10/1996	2/20/1996	50	11.229	10
1/10/1996	2/20/1996	50	16.025	10
1/10/1996	2/20/1996	50	4.535	20
1/10/1996	2/20/1996	50	6.54	20
2/20/1996	3/8/1996	30	11.41	1
2/20/1996	3/8/1996	30	8.496	1
2/20/1996	3/8/1996	40	10.633	10
2/20/1996	3/8/1996	40	10.908	10
2/20/1996	3/8/1996	50	4.174	20
2/20/1996	3/8/1996	50	5.584	20
3/8/1996	4/3/1996	40	9.701	1
3/8/1996	4/3/1996	40	7.056	1
3/8/1996	4/3/1996	35	15.259	10
3/8/1996	4/3/1996	35	24.598	10
3/8/1996	4/3/1996	50	9.287	20
3/8/1996	4/3/1996	50	11.199	20
4/3/1996	5/6/1996	35	9.227	1
4/3/1996	5/6/1996	35	5.051	1
4/3/1996	5/6/1996	35	14.144	10
4/3/1996	5/6/1996	35	17.244	10
4/3/1996	5/6/1996	40	9.999	20
4/3/1996	5/6/1996	40	18.015	20
5/6/1996	6/17/1996	35	14.591	1
5/6/1996	6/17/1996	35	5.458	1
5/6/1996	6/17/1996	35	21.567	10
5/6/1996	6/17/1996	35	30.285	10
5/6/1996	6/17/1996	40	5.083	20
5/6/1996	6/17/1996	40	16.273	20
6/17/1996	7/31/1996	40	28.164	1
6/17/1996	7/31/1996	40	8.853	1
6/17/1996	7/31/1996	40	20.975	10
6/17/1996	7/31/1996	40	63.616	10
6/17/1996	7/31/1996	40	8.59	20
6/17/1996	7/31/1996	40	9.434	20
7/31/1996	8/27/1996	35	15.978	1
7/31/1996	8/27/1996	35	8.39	1
7/31/1996	8/27/1996	35	29.499	10
7/31/1996	8/27/1996	35	22.962	10
7/31/1996	8/27/1996	40	6.741	20
7/31/1996	8/27/1996	40	6.983	20
8/27/1996	9/13/1996	35	14.949	1
8/27/1996	9/13/1996	35	14.686	1
8/27/1996	9/13/1996	35	17.147	10
8/27/1996	9/13/1996	35	33.107	10
8/27/1996	9/13/1996	40	8.839	20
8/27/1996	9/13/1996	40	31.428	20
9/13/1996	10/8/1996	35	20.242	1
9/13/1996	10/8/1996	35	10.033	1
9/13/1996	10/8/1996	35	42.713	10
9/13/1996	10/8/1996	35	74.706	10
9/13/1996	10/8/1996	40	71.348	20
9/13/1996	10/8/1996	40	79.54	20

ATTACHMENT B
Data from FIPR (1998) (Continued)
Page 5 of 6

Table B-7. Terradex radon measurements, summary statistics 1982 to 1996 .

Area	Mean (pCi/L)
DAP#1 Control Room	0.2
MAP-DAP E. Wall Control Room	0.23
Area-40 5th Floor	0.27
Auto Shop	0.27
DAP#1 Storage	0.27
Area-50 Lunch Room	0.28
Area-40 Storage	0.3
DAP#1 Shipping Control Room	0.3
Met Tower Upper Level (30 ft)	0.3
MAP-DAP Shipping Office	0.34
Pilot Plant	0.4
H.P. Lab	0.43
Area-10 Control Rooms S.C.B.A.	0.52
DAP Storage W. of Conveyor	0.52
Hall	0.53
Main Office	0.58
Safety Receptionist Window	0.59
Area-20	0.61
Ball Mill Electric Room	0.61
GSTP	0.61
Phos-Acid	0.64
MAP-DAP Control Room E. Wall	0.67
MAP Storage N.E. Corner	0.71
Met Tower Lower Level (3 ft)	0.71
Area-40 Control Room	0.72
Ball Mill Cont. Room S. Wall	0.78
Dragline Inside Cab	0.86
Dozer Inside Cab	1.2
Environmental Lab	1.4
Background	1.88
Phosphate Council	3.2
Wet Rock Lower Level	6.62
Wet Rock Lower Level	8.6
Wet Rock S. Entrance	0.98
Wet Rock Behind Refrigerator	1.1
West Rock Tunnel Chute 30	5.76
West Rock Tunnel Chute 25	8.95
West Rock Tunnel Chute 20	10.24
East Rock Tunnel Chute 25	10.94
East Rock Tunnel Chute 30	11.11
West Rock Tunnel Chute 15	11.89
West Rock Tunnel Chute 1	12.51
West Rock Tunnel Chute 5	13.07
West Rock Tunnel Chute 10	14.87
East Rock Tunnel Chute 20	18.24
East Rock Tunnel Chute 10	19.56
West Rock Tunnel Chute 33	19.96
East Rock Tunnel Chute 1	23.8
East Rock Tunnel Chute 15	25.97
East Rock Tunnel Chute 5	26.07
West Rock Tunnel Chute 27	32.91
West Rock Tunnel Chute 16	40.23
West Rock Tunnel Chute 21	43.75
West Rock Tunnel Chute 8	47.56

ATTACHMENT B
Data from FIPR (1998) (Continued)

Page 6 of 6

Table B-8. Chemical plant track-etch radon results, 1993 to 1996.

Start	End	Area	pCi/L
01/22/93	07/22/93	Administrative Assistant Trailer	1
		Electric Shop	0.7
		Environmental Tech Office	1
		Filter Pan Level Offices	0.6
		Main Office Bldg	0.2
		Office	0.3
		Office	0.6
		Office	0.3
		Phos-acid Control Room	0.9
07/22/93	01/24/93	Administrative Assistant Trailer	1.5
		Electric Shop	0.8
		Employee's Residence	1.2
		Environmental Tech Office	1.8
		Filter Pan Level Offices	0.7
		Main Office Bldg	1
		Office	0.4
		Office	0.8
		Phos-acid Control Room	0.7
01/24/94	07/21/94	Administrative Assistant Trailer	0.9
		Electric Shop	0.5
		Environmental Tech Office	1.2
		Filter Pan Level Offices	0.6
		Lab Bldg (main Office Bldg)	0.8
		Phos-acid Control Room	0.6
		Residence	0.5
		Trailer	0.5
		Trailer	0.7
07/21/94	01/31/94	Electric Shop	0.3
		Environmental Tech Office	1.2
		Filter Pan Level Offices	0.3
		Instrument Shop	0.8
		Lab Bldg (main Office Bldg)	1.1
		Phos-acid Control Room	0.6
		Safety Office	0.7

Start	End	Area	pCi/L
01/31/95	07/21/95	Ball Mill Control Room	0.3
		DAP Maintenance Lunchroom	0.3
		Electric Shop	0.5
		Employee's Residence	2.1
		Filter Pan Level Offices	0.4
		Instrument Shop	0.6
		Lab Bldg (main Office Bldg)	1
		Phos-acid Control Room	0.9
		Rock Tunnel	5.8
		Safety Office	0.6
		Services	0.6
		Sulfuric Control Room	0.7
		Sulfuric Maintenance Office	1.2
07/21/95	01/22/95	Ball Mill Control Room	0.4
		DAP Maintenance Lunchroom	0.3
		Electric Shop	0.5
		Filter Pan Level Offices	0.5
		Instrument Shop	0.6
		Lab Bldg (main Office Bldg)	0.9
		Phos-acid Control Room	0.6
		Rock Tunnel	5.2
		Safety Office	0.5
		Services	0.5
		Sulfuric Control Room	0.6
		Sulfuric Maintenance Office	2.9
01/17/96	07/17/96	Ball Mill Control Room	1
		DAP Maintenance Lunchroom	0.4
		Electric Shop	0.6
		Filter Pan Level Offices	0.7
		Instrument Shop	0.8
		Main Office	1.4
		Phos-acid Control Room	1
		Safety Office	0.7
		Services	0.8
		Sulfuric Control Room	0.7
		Sulfuric Maintenance Office	1.4