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# EVALUATION OF EXPOSURE TO TECHNOLOGICALLY ENHANCED NATURALLY OCCURRING RADIOACTIVE MATERIALS (TENORM) IN THE PHOSPHATE INDUSTRY

*Prepared by*
Applied Environmental Consulting, Inc.
*with*
Environmental Radiation Group
*and*
Polk County Public Health Unit

*under a grant sponsored by*

FIPR
Florida Institute of Phosphate Research

July 1998

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FIPR is located in Polk County, in the heart of the central Florida phosphate district. The Institute seeks to serve as an information center on phosphate-related topics and welcomes information requests made in person, or by mail, email, or telephone.




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# EVALUATION OF EXPOSURE TO TECHNOLOGICALLY ENHANCED NATURALLY OCCURRING RADIOACTIVE MATERIALS (TENORM) IN THE PHOSPHATE INDUSTRY

FINAL REPORT

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## DISCLAIMER

## PERSPECTIVE

Gordon D. Nifong, Environmental Services Research Director

Several years ago the Florida Institute of Phosphate Research (FIPR) published an Agency Strategic Plan for the years 1998–2003. This described the agency's mission that must be accomplished, and described strategic research and planning efforts to be followed to meet that mission. Six research priorities and four program priorities were adopted by the Institute in order to identify the directions the agency should move toward in accomplishing its mandate. Within the Environmental area, the field of Public Health was identified as one of the six research priorities. A part of the public health objective was to define the magnitude of occupational exposures to hazardous materials within the industry, specifically to "Continue studies to determine if there are significant occupational-related risks to the health or safety of persons employed within the phosphate industry." This study was designed to determine if there were significant exposures to ionizing radiation among industry and support employees, and, if so, to recommend procedures to minimize those exposures.

Over the past twenty or so years, several studies have been made of radiation exposures to employees in the phosphate industry, primarily by personnel from the University of Florida and the Florida Department of Health. Generally those studies found very few employee exposures in excess of 500 millirem (mrem) whole body per year, which at that time was the allowable limit for members of the general public. Many phosphate industry workers are trained in radiation safety, and are monitored, and hence are considered radiation workers. For them an occupational limit of 5,000 mrem per year applies. However, many other workers are not trained in radiation safety, and hence they are considered members of the general public in terms of exposure limits. Moreover, within the past few years the state Department of Health has reduced the annual exposure limit for the public to 100 mrem. This new limit applies to radionuclides whose concentrations have been increased by human activities, and not to background radiation. With the new limit, and with changes in industry practices and materials over the years, it was not clear as to the current status of exposures or of compliance. Hence this study was performed.

The goals of the project were (1) to collect new data as needed and interpret that and existing data on radiological exposure in the Florida phosphate industry and associated service industries, and (2) to make recommendations as necessary to minimize radiological exposures in the industry.

The primary goal of any radiation control program is to maintain exposures at a level of "As low as reasonably achievable," the ALARA concept. Results of this study indicate that average exposures in the phosphate industry are to levels that are much less than the 100 mrem/year limit, and very few employees are exposed in excess of the limit. Only in shipping and handling of dry product were average exposures found in excess of 100 mrem/year. Recommendations are made in the report for lowering these exposures. In no case were average exposures to radiation workers found to exceed 5,000 mrem/year.

## ABSTRACT

The overall objective of this investigation was to provide information to the state of Florida regarding the radiation exposures to workers in the phosphate industry due to technologically enhanced naturally occurring radioactive materials (TENORM) and to provide recommended methods for reducing those exposures. This objective was met by collecting existing radiological data specific to Florida and the phosphate industry, and generating new data from sampling activities. The sampling effort involved phosphate mines, chemical plants, and outside contractors. External exposures were monitored using scintillation (micro-R) meters, ion chambers, lithium fluoride thermoluminescent dosimeters, and aluminum oxide dosimeters in conjunction with time and motion studies. Internal routes of exposure (mainly inhalation) were studied using air sampling, gross alpha and beta counting, and deposition sample analysis. The mean annual total effective dose equivalent (TEDE) to a phosphate industry worker was computed using Latin Hypercube sampling on measured parameters for each of five generalized areas. The areas and results (TEDE average, 99$^{th}$ percentile) in mrem, and rounded to the nearest whole number, are: mining area (12, 20), rock handling area (30, 60), phosphoric acid production area (34, 45), dry products (granular) area (38, 55), shipping area (112, 350), and contracted service worker (8, 11).

**ACKNOWLEDGMENTS**

A project with the scope of this investigation could not have been accomplished without the assistance of people other than those listed on the title page of this document. It was never the type of research project that could have been conducted in a “closed” laboratory where experiments were designed, built, run and analyzed. This project was destined to impact a wide variety of industries, agencies, workers, and the public. For that reason the history, the plan development, the data gathering, and to some extent the conclusions reflect the effort of a much wider range of people.

Since the early 1990s the State of Florida set out to adopt more specific standards for the individual that handles NARM (Naturally Occurring and Accelerator Produced Radioactive Materials), and more specifically: TENORM (Technologically Enhanced Naturally Occurring Radioactive Materials). The principal regulatory agency is the Radioactive Materials Section in the Office of Radiation Protection of the Department of Health and Rehabilitative Services (HRS). During the period of this investigation this agency was reorganized as the Bureau of Radiation Control within the newly created Florida Department of Health (DOH). A key individual given the major responsibility to interface with the many activities in NORM development in the USA and the industrial community of the State of Florida that could be subject to the proposed regulations, standards and licensing is Mr. Walter Cofer, the Radioactive Materials Section’s Special Projects Coordinator.

A major industry of interest is the phosphate industry. The Florida Institute of Phosphate Research (FIPR) is a severance tax-funded unit established in 1978 by the Florida Legislature. Dr. Paul Clifford’s recent Director’s Message outlined part of FIPR’s mission as “to develop the technology and knowledge needed to resolve the environmental issues of the phosphate industry.” That mission includes many diverse investigations. Dr. Gordon Nifong recently wrote about the Environmental Services Program stating FIPR’s intent “to initiate, sponsor, and evaluate studies that will have importance to public health and environmental quality in the phosphate mining and processing . . . ” Clearly, the health of the workers falls within both mission statements. Because raw phosphate ore contains higher levels of the uranium decay series than overlaying geological strata, one health concern of FIPR and the industry is that of potential exposure to radiation emissions from the radioactivity. Thus, there is the interest in NORM research and the determination of baseline data that would be a foundation for rational decisions on future NORM regulations for the State of Florida and potentially elsewhere.

Mr. Cofer presented the need for a current study of the workers’ exposures to radiation in the phosphate industry to FIPR. Dr. Nifong responded by obtaining approval for a request for proposal (RFP) on the subject. That RFP was received by a number of consultants and organizations including Mr. Bernhardt Warren of Applied Environmental Consulting, Inc. (AEC) and the Polk County Health Unit (PCHU) where Mr. Wesley Nall

was the prime contact. The RFP was skillfully written in that it allowed innovation beyond the narrow interpretation that it was a call for an update and expansion of a study by Radiation Control Services, Orlando Radiation Laboratory headed by Mr. Harlan Keaton in the 1970s and published in 1982. Mr. Warren contacted Dr. Emmett Bolch, who is approved to conduct unique consulting outside of the University of Florida under the registered name "Environmental Radiation Group."

Before drafting a proposal, Mr. Warren and Dr. Bolch had an intense discussion with Mr. Cofer on the needs of the state for a complete and comprehensive basis document. Ideas were conceived and goals were developed during that discussion. The scope of the proposal was expanded to achieve the conceived goals of the state and the industry's interest in protecting the health of its workers. A recent doctoral graduate in the field of health physics, Dr. Brian Birky, was asked to join the team as a major investigator. His credentials and availability for the field work and data interpretation were ideal for the type of investigation proposed. Another crucial participant was recruited, Mr. Thabet Tolaymat, a candidate for the master's degree in environmental engineering with a strong interest in radioactive wastes and hazardous waste.

One major concern of the Warren/Bolch/Birky/Tolaymat team was access to facilities and data. Could a set of private consultants gain access to all the necessary industry sites to obtain the necessary data? There could be some natural resistance since final determinations of this study could have a profound effect on certain aspects of the industry.

Parallel to the preparation of the AEC proposal to FIPR, the PCHU was also preparing a proposal that more closely paralleled an update of the Keaton study. Wesley Nall's PCHU proposal focused on measurements. A county health agency would have much more legal access to the various industry components.

Dr. Nifong should be credited for the suggestion that both the AEC and the PCHU approaches were valuable and that funding either, but not both, would not produce the type of investigation most valuable to the state and the industry. Dr. Nifong suggested that the two groups should talk and see if there were mutual benefits to each group and the study as a whole. Conversations between the two groups immediately reached the state of a mutual proposal with PCHU mostly involved with measurements and the AEC team providing broader research, investigations, data management, and interpretations.

The combined AEC/PCHU proposal was the one that was funded by FIPR. The team at PCHU also included Mr. Tom McNally and Mr. Robert Ammons, who carried a heavy responsibility for field and laboratory measurements. They are also due special thanks. It was important to have a representative of the Florida Phosphate Council endorse the proposal at the FIPR Board meeting where the project was approved. Still, there were some questions about how the industry would respond to the access question. The following paragraphs are

an acknowledgment of the extreme cooperation, encouragement, participation and access given by the major phosphate industries and the service companies to this project.

Dr. Bolch publicly thanked the industry for their assistance at a progress presentation at FIPR about halfway through the investigation. He stated that the total “dollar value” of the project greatly exceeds the contract budget because of the large number of person-hours contributed by the industry through such tasks as (1) locating and providing historical dosimetry data, (2) providing access, escorts, assistance, etc. to the project team members making measurements, (3) assisting the project team in planning and conducting investigations during “turnaround” events, (4) providing management backing and worker incentive training in support of the dosimetry badging efforts of this investigation, (5) sending representatives to the progress presentations to provide valuable feedback and critique of the project team’s efforts and preliminary findings, and (6) cooperating in providing answers to a multitude of questions on the industry’s processes, techniques, management, timing, and other items critical to the time and motion studies. Dr. Nifong also expressed his thanks at that meeting and even suggested that it would be informative to put an approximate dollar value on the industry efforts in conjunction with this investigation. This was considered, but not accomplished. However, this section does provide a listing of the companies and some of their representatives who should be given credit and a sincere “thank you” for their valuable assistance and input to this project. In any acknowledgment list there is always the potential to omit someone or some company that should have been included, but maybe after a round of review everyone can be included. The other problem of a list of acknowledgments is a real or implied order of importance or effort. To avoid any such implications, the following are listed in alphabetical order both by company or agency and by individuals within the organization.

The project team wishes to express its deep appreciation for assistance in many aspects of this investigation to the following:

| | |
|---|---|
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| | |
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| U.S. Geological Survey, Tampa | Mr. Ronald Miller |

The staff of the Florida Institute of Phosphate Research took part in many of the progress report meetings and contributed thoughts, critiques, etc. Thanks should go to a most helpful and always courteous group:

Dr. Paul Clifford, Dr. Gordon Nifong, Mr. Jon Harris, Ms. Mary Ellen Murphy, Ms. Lisa Jap-Tjong

A resource person with a long history in this area that often shared his thoughts and expertise was Dr. Charles E. Roessler. He contributed beyond his compensation and we express thanks for his input.

Lastly, there are the dozens of unnamed workers who helped in small and large ways, but most importantly wore the dosimeters as requested and returned them to the project. Their cooperation made a significant impact on the findings.

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## EXECUTIVE SUMMARY

The overall objective of this investigation was to provide information to the state of Florida regarding the radiation exposures to workers in the phosphate industry due to technologically enhanced naturally occurring radioactive materials (TENORM) and to provide recommended methods for reducing those exposures. This objective was met by collecting existing radiological data specific to central Florida and the phosphate industry, and generating new data from sampling activities. This study also uses a new computer analysis technique that calculates doses as distributions rather than point estimates. This provides a measure of uncertainty as described by statistical descriptors. Lack of uncertainty accounting has been a shortcoming of past studies.

The sampling effort involved phosphate mines, chemical plants, and outside contractors. External exposures were monitored using scintillation (micro-R) meters, ion chambers, lithium fluoride thermoluminescent dosimeters, and aluminum oxide dosimeters in conjunction with time and motion studies. Internal routes of exposure (mainly inhalation) were studied using air sampling, gross alpha and beta counting, and deposition sample analysis. The mean annual total effective dose equivalent (TEDE) to a phosphate industry worker was computed using Latin Hypercube sampling (a random sampling method) on measured parameters for each of six generalized areas.

The sampled areas were: mine area, rock handling area, phosphoric acid production area, dry products (granular) production area, shipping area, and service area. Mine area workers were monitored in all phases of site operations including: pit gun operation within the pit cars, washing area, and flotation area. The next area monitored was the rock handling area at the chemical plant site which included: rock receiving by rail or truck, wet grinding, sizing, storage, and cleaning of spillage by bobcat and shovel. The phosphoric acid production area involved the attack tank (reactor) area, all aspects of filtration (routine operation, cloth patching, cloth change-out), gypsum stack maintenance, and clarification. The dry products area included all aspects of monoammonium phosphate (MAP), diammonium phosphate (DAP), granular triple superphosphate (GTSP), and animal feeds production, drying, and sizing. The shipping area involved movement of dry products from production to storage, and out to market by payloader operators and laborers. The service sector included: pan maintenance, valve work, pump work, and rubber-lined pipe and vessel maintenance. Special turnaround activities monitored were attack tank cleaning (agitator removal and hydroblasting), removal of associated flash coolers and condensers, filter pan disassembly and reassembly, and filter pan chipping and cleaning.

The TEDE equation used in the generation of dose distributions and sensitivity analyses contained 30 parameters (variables) that were each described as statistical distributions. For example, a typical statistical distribution for a parameter may have been lognormal or normal, and the computer selected a value from that distribution (and the

numerous other parameters) to generate a calculated dose. The dose for each area was the result of 10,000 separate calculations of the dose by computer selection of random values from each of the distributions. The final result for each area was a dose distribution, displayed numerically and graphically, in units of mrem per year. The final calculated TEDEs for each area based on measured parameters are displayed below.

| TEDE Statistics by Area (mrem per year) | | | |
|---|---|---|---|
| | **Mean** | **Standard Error** | **99th Percentile (2.60 σ)** |
| **Mine** | 12.1 | 0.03 | 20 |
| **Rock** | 29.9 | 0.10 | 60 |
| **Phosphoric Acid Prod.** | 34.3 | 0.03 | 45 |
| **Dry Product Production** | 38.3 | 0.06 | 55 |
| **Shipping and Storage** | 111.6 | 0.91 | 350 |
| **Routine Service** | 8.5 | 1.10 | 11 |

Other special turnaround activities based on monitored activities typical for the industry and frequency of such jobs, as reported by the service supervisors, yield doses as shown in the following table.

| TEDE Statistics by Task (mrem per year) | | | |
|---|---|---|---|
| **Task** | **Mean** | **Standard Error** | **99th Percentile (2.60 σ)** |
| **Filter Assembly** | 31.6 | 0.18 | 80 |
| **Pan Chipping/Cleaning** | 22.4 | 0.14 | 60 |
| **Attack Tank Cleaning** | 73.4 | 0.61 | 250 |

Use of this uncertainty analysis technique also gives insight into effects of each parameter on the variability of the final dose. That is, of particular interest is to find which parameters tend to increase the spread of the distribution to higher dose levels. Different parameters were more important in different areas. The value of this analysis is that it becomes clear that workers in areas of airborne dust or mist should wear a basic NIOSH/MSHA-approved respirator (with a proper fit). In general, the best allocation of resources (time and money) to reduce radiation doses is for training in the proper use of respirators and encouraging their use. This is particularly important in the shipping and dry products areas, for filter cloth change-outs, dry pan chipping of gypsum scale, and attack tank hydroblasting.

Excessive radon levels were limited to the rock tunnels; however working level measurements in the tunnels were consistently low (<0.95 mWL) indicating that the air is replaced frequently enough to prevent large equilibrium fractions of radon daughters. Also, rock tunnels are low occupancy areas, visited rarely by laborers responsible for shoveling spills, and maintenance workers responsible for repairing conveyors. It is sufficient to recommend that rock tunnels be ventilated prior to entry so that all of the air is replaced, and that the ventilation remain 'on' during the period of work.

In conclusion, most workers employed by the phosphate companies receive training commensurate with the level of radiation hazard they encounter. Those workers are subject to the occupational exposure limit of 5,000 mrem/yr TEDE. The finding of this study is that it is extremely unlikely that this limit would be approached or exceeded. Engineering controls and the use of respirators should be considered part of the ALARA commitment.

Service industry workers are often not trained in radiation safety, and are consequently subject to public dose limits. This study found that service industry workers working on phosphate company sites, and more often at remote service company locations, receive doses far below the 100 mrem/yr TEDE limit for a member of the public. The only exception to this finding is workers involved in attack tank cleaning. The most significant component of the TEDE for those individuals is the inhalation dose. It is recommended that a more targeted study be conducted to reduce uncertainties in that dose component, so that appropriate actions may be taken.

# INTRODUCTION

## OBJECTIVE

The overall objective of this investigation is to provide sufficient meaningful information to the state of Florida regarding the estimated exposures to workers in the phosphate industry due to technologically enhanced naturally occurring radioactive materials (TENORM) and to provide recommended methods for reducing radiation doses to levels that are as low as reasonably achievable (ALARA).

## PROJECT DESCRIPTION

### Source and Magnitude of the Problem

The Florida phosphate industry employs many workers at mining and chemical plant sites as well as in the service sector who are not trained as radiation workers. Those workers not specifically trained in the health effects of exposure to ionizing radiation are considered members of the general public. The state of Florida has implemented reduced limits of allowable exposure to ionizing radiation for members of the public. These limits are compatible with the revised federal limits in 10CFR Part 20 as promulgated by the Nuclear Regulatory Commission (NRC), and the recommendations of the Conference of Radiation Control Program Directors, Inc. (CRCPD). Specifically, the previous individual limit of 500 mrem[1] per year attributable to an industrial practice was decreased in 1994 to 100 mrem per year as a "total effective dose equivalent" (TEDE). The TEDE is a combination of all sources of radiation exposure; i.e., all external and internal irradiation. As a result of the new limits, practices yielding exposures formerly as much as five times below the regulatory limit may now exceed the new limit. With these regulatory changes, it is now appropriate to evaluate some industrial and service activities that have received little attention in regard to radiation exposures. Also, previously suspected exposure problem areas must be more closely scrutinized. Workers who have received training in radiation safety that is commensurate with the hazards in the workplace are considered radiation workers, and are allowed 5,000 mrem (5 rem) annual dose equivalent to the whole body from all sources. The higher dose is allowed due to the nature of the workforce (all adults) and the accepted benefit of employment in exchange for the cost (as a possible increase in the risk of health detriment) of additional incurred dose.

Presently, there are multiple chemical plants and one service company which are licensed by the state of Florida, Department of Health (DOH) Bureau of Radiation Control, for the possession of TENORM. The CRCPD defines TENORM as "naturally occurring

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[1]The corresponding unit in the international system is the millisievert (mSv), which is equivalent to 100 mrem.

radionuclides whose concentrations are increased by or as a result of past or present human practices. TENORM does not include background radiation or the natural radioactivity of rocks or soils." Hence, it is the TENORM generated as an unintended byproduct of the wet phosphoric acid process, rather than NORM, that is regulated. With the newly established limits described above, it is the responsibility of all radioactive materials licensees to demonstrate their compliance with these limits. This study provides documentation necessary to evaluate compliance across the industry as a whole. The study concentrates on the central Florida phosphate region, which processes ore with higher concentrations of NORM than the northern region. This approach applies the available resources to the limiting case, that is, the region with higher potential radiation doses.

**Specific Project Goals**

1. Collect and interpret existing radiological data specific to the Florida phosphate industry. The result is a database organized by activities (e.g., mining, chemical, pan repair, etc.) and their individual practices, with statistical values (arithmetic or geometric means, medians, confidence intervals, etc.) reported when data are sufficient.

2. Produce outlines and diagrams of activities and processes necessary to interpret the results of Goal 1. The extraction, transfer, and technological enhancement of TENORM in phosphate industry practices is explained when pertinent to this study. Exposure pathways are delineated.

3. Make recommendations as necessary concerning each phosphate-related activity in Florida that is affected by TENORM regulations. Some processes impart little risk to the public and do not require procedural modifications. In other cases, lack of, or inadequacies in existing data sets were supplemented by this study, and follow-up assessments may be necessary.

4. Evaluate the critical activity and process-specific parameters and pathways. That is, existing data deficiencies are corrected by field measurements, and the new data are used with existing models. The model results are current dose estimates for practices most likely to put workers (as members of the public) at risk.

**Impact of This Study**

Compilation of existing data and the addition of new data provides industry personnel and researchers with a common database for assessing potential hazards and evaluating practices. This project team analyzed the data for the purposes described herein, but it is recognized that this data set will be useful to others for their own analyses. Data interpretation is enhanced by the process diagrams, which will also be useful to judge the appropriateness of the use of these data when processes are modified in the future. The full impact of this study will be realized when the final recommendations are made regarding which procedures should be modified, and which parameters of more important modeled processes would most effectively benefit from the application of resources to reduce doses.

### Benefit to the State of Florida

This study benefits the people of the state of Florida by providing a state-of-the-art analysis of TENORM in a major Florida industry which can be used as a template for studies of other TENORM-related industries to design acceptable practices and to improve radiation safety. Such improvements should envision a goal of not only regulatory compliance, but also the attainment of doses to the general public that are ALARA. This in-depth analysis is also beneficial to state personnel who draft regulations impacting these industries.

### Methodology

Standard statistical methods are used to characterize data sets assembled in electronic spreadsheets. Parameter uncertainty analyses are performed using Monte Carlo (Latin Hypercube) simulations. Tabulated data sets with statistical descriptors from the Introduction and Results sections are interpreted using industry and process-specific outlines and diagrams generated in the corresponding subsections of the Introduction section. Exposure scenarios and pathway models developed in the Methodology section yield dose estimates which are compared and evaluated against standards. Those dose estimates include a measure of uncertainty found in the Results section.

## LITERATURE REVIEW

### Collection of Existing TENORM Data Specific to Florida

The initial effort was collection and interpretation of TENORM exposure data already in existence, but scattered or obscure. These data were found in sources such as environmental impact statements, symposia on NORM and TENR (Technologically Enhanced Natural Radioactivity), U.S. Environmental Protection Agency (EPA) reports, and other scientific publications. Emphasis was placed on Florida and the phosphate industry, but included other industries and parts of North America. Data collection was conducted using electronic literature searches, telephone correspondence, and limited on-site interviews. The database was assembled in Microsoft Excel, which can be easily queried and annotated. Standard statistical values were generated and reported as appropriate.

The most thorough analyses to date were published twenty, seventeen, and twelve years ago, respectively. A 1977 University of Florida (UF) study was a detailed survey of radiation exposure to workers in the Florida phosphate industry. The research was supported by the Florida Phosphate Council (FPC). The study was published as a masters' thesis

(Prince, 1977), a report to the FPC (Roessler and Prince, 1978), and a journal article (Roessler et al., 1979). The impetus for this research was the description by M. Lardinoye of elevated radiation levels exhibited by filter pans. There was a subsequent publication regarding $^{226}Ra$ build-up during the wet acid process (Lardinoye et al., 1982). Another significant study was a detailed survey conducted by the DHRS Office of Radiation Control's Environmental Section (Keaton, 1987).

**EPA Research**

In 1976, the EPA published a document that estimated the radiation exposure of phosphate industry personnel. External gamma exposures were measured using thermoluminescent dosimeters (TLDs) and pressurized ionization chambers (PICs). High-volume air samplers collected airborne particulates on paper filters. These filters were analyzed to determine concentrations of airborne radionuclides, which were subsequently used to compute the total dose. The study concluded that "the direct gamma exposures were below the recommended guideline of 0.5 rem per year for individual members of the general population" (Windham, 1976). The estimate of lung exposure was also "below the current guidelines for radiation workers, and in most cases are below the 1.5 rem per year guidance for an individual member of the general population" (Windham, 1976).

That study was followed by a similar study by the EPA in 1977. This study addressed only the Idaho phosphate industry. The results are not directly comparable to the Florida industry, because the Idaho industry used the thermal process no longer used in Florida. The study reported an estimated annual dose equivalent of 79 mrem. The net annual gamma exposures ranged from "42 mrem in general plant areas to 182 mrem per work year on the slag pile" (EPA, 1977). $^{222}Rn$ concentration was also measured. On the average these readings ranged from "0.17 to 1.4 pCi/l[2] . . . but 11 pCi/l was measured in the control room of the Condenser and Fluid Bed Building" (EPA, 1977).

In 1978 the EPA published a radiological survey of Idaho phosphate ore processing plants. The estimated work year dose equivalents, where work year was defined as 2,000 hours, are summarized in Table 1. The surveys were conducted using a gamma scintillation rate meter. An estimated background gamma exposure rate of 9 mR/hr has been subtracted from the gross value to obtain the net result.

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[2]The corresponding unit to the curie (Ci) in the international system is the becquerel (Bq), such that one Bq is equivalent to 27.03 picocuries (pCi).

**Table 1. Work Year Dose Equivalent (EPA, 1978)**

| Location Description | Work Year Dose Equivalent (mrem/yr.) |
|---|---|
| Condensate Pipe | 222 |
| Scrubber Water | 182 |
| Phosphoric Acid Tank | 42 |
| Directly Over Filter | 122 |
| Ore Pile - High Grade | 152 |

The reported dose equivalents are probably overestimated. A more precise dose estimate could be obtained by dividing the time spent in each work location and using that particular exposure rate; however, the study failed to include such information. Furthermore, these estimates are based on free air measurements. The study estimated that the dose to "internal body organs varies from 0.5 to about 0.7 of the free air measurement due to the shielding effect of the body" (EPA, 1978). The ambient radon concentration ranged between "0.14 pCi/l near a dryer of the No. 100 ammonium phosphate plant to a high of 1.9 pCi/l outside the control room of the phosphoric acid plant" (EPA, 1978).

In 1978, the CRCPD, U.S. Department of Health, Education and Welfare, and the EPA formed a task force to look at natural radioactivity contamination problems. The task force examined the radioactivity concentration for the fertilizer products and phosphogypsum byproduct of several wet-process type facilities in Florida (Table 2). The task force also looked at direct gamma dose equivalents for the workers in the phosphoric acid or elemental phosphorus plants, which were estimated to range from 30 to 300 mrem per year.

**Table 2. Natural Radioactivity Concentrations (pCi/1)**

| Material | $^{226}$Ra | $^{238}$U | $^{230}$Th |
|---|---|---|---|
| NSP | 21.3 | 20.1 | 18.0 |
| DAP | 5.6 | 63 | 65 |
| Conc. Super Phosphate | 21 | 56 | 48 |
| MAP | 5 | 55 | 50 |
| Phosphoric Acid | 1 | 25.3 | 28.3 |
| Gypsum | 33 | 6 | 13 |

**The UF Study**

The movement and concentration of TENORM is important information required to ascertain the working areas where exposures should be monitored. The UF study gathered data concerning TENORM dynamics, exposure rates, worker occupancies, and radiation doses.

Much of the $^{226}Ra$ in mined material (41.1 pCi/g) is discarded with gypsum (32.2 pCi/g). Very little is retained in phosphoric acid, but is concentrated as the acid is concentrated; 5% (0.1 pCi/g) → 15% (0.2 pCi/g) → 30% (0.4 pCi/g). Radium is concentrated and precipitated in filtrate tank scale (384.8 pCi/g) and sediment (84.1 pCi/g). The primary products made at chemical plant sites are phosphoric acid, monoammonium phosphate (MAP), diammonium phosphate (DAP), and granular triple superphosphate (GTSP). A waste byproduct of phosphoric acid production is gypsum (mainly calcium sulfate). Ammonium phosphates (MAP and DAP) retain moderate amounts of $^{226}Ra$ (4.1 pCi/g), and GTSP retains a high level (20 pCi/g), although less than gypsum. Note: the gypsum concentration (32.2 pCi/g) is similar to the original mined matrix (37.6 pCi/g). $^{238}U$ is more concentrated in products; i.e., GTSP (26 pCi/g) and DAP (25.3 pCi/g) than input materials consisting of total rock (14.4 pCi/g) or pebble (22.5 pCi/g). Very little $^{238}U$ goes with gypsum (0.5 pCi/g); moderate amounts precipitate in acid reactor scale (11.4 pCi/g); and a large amount is retained in phosphoric acid; e.g., 40% phosphoric acid (20.7 pCi/g).

A companion publication in the journal *Health Physics* indicated that $^{238}U$ and $^{226}Ra$ are essentially in radioactive equilibrium in the phosphate ore matrix. Each nuclide averaged "38 pCi/g in Central Florida matrix and less than one quarter as high, 8 pCi/g, in north Florida matrix" (Roessler, 1979). Furthermore that study showed that following beneficiation the concentrations of $^{238}U$ and $^{226}Ra$ in the rock product, waste clays and sand tailings were approximately 100-300%, 100%, and 10-25%, respectively of those in the matrix. That study also observed that while $^{226}Ra$ appears in the gypsum, which is a byproduct, $^{238}U$ follows the phosphoric acid, which leads to a significant level of $^{238}U$ in the ammoniated fertilizers. On the other hand, TSP (triple super phosphate) has elevated levels of both $^{238}U$ and $^{226}Ra$. TSP is manufactured by adding phosphoric acid, which has elevated levels of $^{238}U$, with phosphate rock, which has elevated levels of both $^{238}U$ and $^{226}Ra$. As a result, the final product, TSP, will have high levels of both $^{238}U$ and $^{226}Ra$.

The study concluded that the estimated annual radiation doses to personnel from external gamma radiation "were less than the occupational Maximum Permissible Dose Equivalent (MPD) of 5 rem/year in all occupied areas studied." The highest gamma radiation levels were associated with residues in phosphoric acid production. The gamma levels ranged between "100 to 1000 mR/hr (corresponding to 4 to 40% of MPD under continuous 40-hr/wk exposure)." The industry's time-weighted average values were well below the standard. The UF study was conducted prior to the concept of effective dose equivalent (EDE). The EDE allows summing of doses from different radiation types and energies, as well as components from radioactivity taken into the body and irradiation from sources external to the body. Since this procedure was not available, the doses were considered independently. It is interesting to note that the UF study found that "time-weighted annual doses were less that 25% of the occupational guideline. However, exposures during maintenance operations may need to be evaluated on a case-by-case basis." Rock loading tunnels were observed to have the greatest potential for airborne radon progeny exposure. However, the calculated cumulative time-weighted annual exposures in 15% of the tunnels "exceeded 25% of the maximum permissible concentration; thus indicating an airborne radioactivity area" (Roessler, 1978).

## The DOE/ORNL Study

In 1980, the U.S. Department of Energy (DOE), in conjunction with Oak Ridge National Laboratory (ORNL), published an assessment of the phosphate industry. The report showed that the annual gamma radiation dose to the phosphate industry worker is 1.5 times the background level (Ryan and Cotter, 1980). The report gave an average gamma exposure level of less than 30 μR/hr ± 70% (Ryan and Cotter, 1980). The associated work force dose commitments for the 1977 work force data were estimated at 400 person-rem ± 70% (Ryan, 80). The report attributed the error to the uncertainties in the average gamma radiation exposure level and in the average number of full-time employees. The report also indicated that the method of multiplying average exposure or dose by the average number of employees is "inaccurate if a large fraction of new employees is exposed at a level that deviates significantly from the calculated average exposure" (Ryan and Cotter, 1980). The report also concluded that annual lung dose may be from two times background lung dose, as compared to the work force lung dose estimated with the International Commission on Radiological Protection (ICRP) Task Group II lung model, to four times the annual background lung dose, as compared to the lung dose estimated with the EPA lung model (Ryan and Cotter, 1980). Ryan made the final conclusion "though some of the radiological impacts are known and understood, further work is required to detail these impacts" (Ryan and Cotter, 1980). Ryan also recommended establishing long-term sampling programs in phosphate facilities and in their environs to measure radiation exposures to phosphate industry workers and the transport of radionuclides via airborne and waterborne effluents, respectively (Ryan and Cotter, 1980).

## The UNC Study

The most extensive study of the long-term health effects of the phosphate industry was an epidemiological study of mortality and work experience in the Florida phosphate industry, funded by the FPC and conducted by the University of North Carolina (UNC) in 1984. The most important conclusion was that the phosphate industry workers experienced small mortality excess of lung cancer and emphysema in comparison with the U.S. mortality rates. Florida has a higher background mortality rate of lung cancer for unknown reasons. “Florida has a sizable retirement population and the state's relatively high lung cancer rate, may in some unexplained way, be related to its atypical demographic structure" (Checkoway, 1985). However the elevations in lung cancer mortality for the phosphate industry workers disappear when compared with Florida's high background cancer mortality rate.

The second phase of the study examined if any of ten exposure agents (i.e., alpha radiation, gamma radiation, etc.) are associated with lung cancer. The authors concluded, "there was no evidence that any of the 10 exposure agents considered was associated with either lung cancer or emphysema" (Harvey, 1984). These results led the investigators to a final conclusion: "While lung cancer appeared to have clustered among long-term workers in plant-wide service and skilled crafts jobs, there is no indication that exposures indigenous to the phosphate industry were the causative factors" (Harvey, 1984).

Although this study was important, it had some limitations. The study was restricted to mortality; therefore, an evaluation of non-fatal health effects was precluded. There were no direct measurements of occupational exposures. Length of employment in jobs categorized according to work areas and agents was substituted for exposure level. This method is imprecise because it relies extensively on human judgement rather than quantified, reproducible measurements. The absence of valid information on cigarette smoking, which is the principal non-occupational determinant of lung cancer, prevents determining whether the results of the study were confounded by the smoking habits of the workers. Finally, close examination of the data reveals some obvious mistakes in recording the data (i.e., for a certain area in the plant there was a minimum reading, a maximum reading, and a mean with a sample size of only one).

**The Keaton Study**

The Keaton study dealt primarily with filtration system maintenance in wet-process phosphoric acid plants. At least some of the data were collected six years prior to publication (Keaton, 1987). Excellent recommendations were made that would greatly curtail exposure to subcontractor personnel working at offsite support facilities. It is not known how many of these recommendations have been implemented. The study showed that ten of the thirteen workers double-badged with TLDs were likely to exceed the 500 mrem per year public dose limit and two others were very close to it. Application of the 100 mrem per year limit results in all thirteen of those workers significantly exceeding the standard. Also, twenty-two of the twenty-six air samples surpassed the 2E-12 µCi/ml limit for insoluble $^{226}$Ra atmospheric concentration in unrestricted areas in force at the time of the study.

**NCRP Report No. 118**

In a recent report, the National Council on Radiation Protection and Measurements (NCRP) recommends performing periodic external gamma radiation surveys near acid filters and filtrate receiving tanks to verify that acceptable conditions are being maintained (NCRP, 1993b). The council further recommends evaluating individual assignments or special tasks involving close contact with residues in attack tank filters, piping, and filtrate receiving tanks by considering gamma exposure rates and anticipated occupancy time to estimate cumulative exposure and determine whether personnel monitoring or regular surveys and monitoring are indicated. As for radon progeny, it is recommended that tunnels and other occupied spaces of limited ventilation be evaluated on a case-by-case basis. The NCRP also recommended performing additional radon progeny surveys in such locations.

**Literature Data Summary**

Table 3 shows the $^{226}Ra$ and $^{238}U$ concentrations (pCi/g) in different input, byproduct, and product materials of phosphoric acid and ammoniated phosphates production. These measurements were collected from separate publications as indicated by footnote.

**Table 3. $^{238}U$ and $^{226}Ra$ Concentrations in Phosphate Production**

| Area | $^{238}U$ (pCi/g) | $^{226}Ra$ (pCi/g) |
|---|---|---|
| Ore matrix | 38[c] | 38[c] |
| Clays | 44[a] | 45[a] 26[c] 45[b] |
| Sand tailings | 5.3[a] | 5[c] 7.5[a] |
| Rock concentrate | 32[c] | 37[c] 42[d] |
| Rock pebble | 41[c] 32-41[d] | 42[c] 37-42[d] |
| Sodium fluosilicate | | 0.28[d] |
| Gypsum | <1[c] 0.5-6[d] | 26-33[d] |
| NSP | | 21.3[b] 25[d] |
| TSP | 57[c] | 20[c] 21[b] |
| MAP | 70[c] | 5[b] 4[c] 5[d] |
| DAP | 70[c] | 5.6[b] 4[c] |
| Phosphoric Acid | 30[c] 30-43[d] | <1[c] 0.4-0.7[d] |

[a] Guimond and Windham, 1975
[b] Guimond, 1978
[c] Roessler, 1979
[d] Owen and Hyder, 1980

The $^{226}Ra$ and $^{238}U$ concentrations are superimposed on the phosphate rock processing flow chart (Figure 1).

Additional summary tables of published data can be found in Appendix A under the Literature Data subheading. That section contains:

- Keaton study data
- UF analysis of U-238 (pCi/g) in central Florida phosphate material
- UF data for annual accumulated exposure to radon progeny

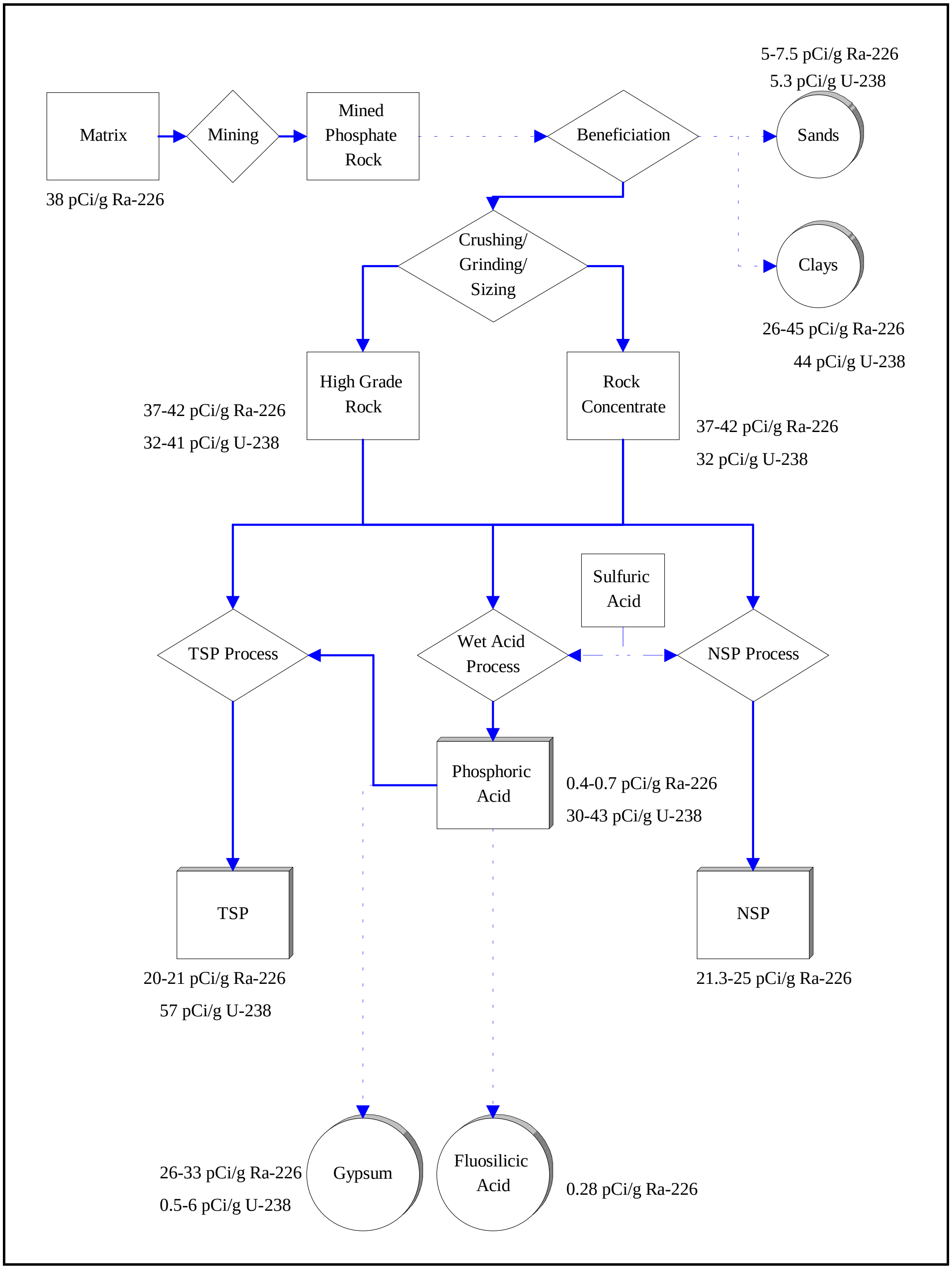



**Figure 1.** $^{226}$**Ra and** $^{238}$**U Concentrations Prior to Ammoniation**

## SAMPLING RECOMMENDATIONS FROM LITERATURE REVIEW

### External Dose Assessment

External gamma measurements are advised for areas near acid filters and filtrate receiving tanks. Also, individuals near attack tanks, including residues and associated piping, could receive excessive exposures. This is more likely for those involved in cleaning and maintenance, so exposure rates and occupancy are important. Measurements should be taken at one meter and at contact. The instrument usually used to take exposure rate measurements is the micro-R meter. It should be calibrated to extended sources with a broad energy spectrum; not to point sources with monoenergetic emissions or limited spectra.

Equipment taken out of service from phosphoric acid plants will contain scales with $^{226}$Ra concentrations ranging from 10s of pCi/g to around 100,000 pCi/g. This mainly impacts on-site maintenance personnel, transportation workers, and service industry personnel. Internal components are removed from the shielding effect of the system, and drying removes the shielding effect of liquid. Cleaning may require close proximity work for long durations, and may create airborne radioactive dusts or mists. Routine cleaning and repair should be documented for frequency, duration of task, and dynamics. The highest radium concentrations are expected immediately below the filter in the filter pans. Uncleaned pans were found measuring as much as 12 mR/hr (12,000 μR/hr) at contact.

If potash is added to fertilizer for potassium, this is a TENORM problem due to $^{40}$K even though it is not part of the mining and processing. The activity of natural potassium is 853 pCi/g due entirely to $^{40}$K. Fertilizer with 12% K is about 100 pCi/g due to $^{40}$K (having an energetic beta and gamma).

### Inhalation Dose Assessment

Airborne long-lived alpha other than short-lived radon progeny should be sampled in dusty areas; i.e., drying, grinding, storage, loading/unloading, shipping, and front-end of TSP production and fertilizer areas. Epidemiological data suggest elevated lung cancer risk in workers in shipping and drying jobs, where radiation and dust exposures were assumed to be highest. The UNC study reported long-lived alpha average concentrations of less than 0.1 pCi/m$^3$ in mine site operations to 146 pCi/m$^3$ in rock transport loading operations.

Radon progeny working-level (WL) measurements should be taken in the rock tunnels. Measurements are needed for different conditions of ventilation encountered during a shift (on/off). Occupancy is important as well as the materials handling rate. The sampling position within the tunnel and atmospheric conditions affect progeny levels. There is wide variation between different tunnels.

## REVIEW OF INDUSTRY DATA

Summaries of data supplied by the phosphate and service industries are provided in the following section as well as Appendix A under the Industry Data subheading. That section contains raw and summarized data as follows:

- external monitoring summary statistics (1981)
- ranked external exposure data for phosphoric acid production
- area monitoring results (1993 - 1996)
- radon measurements (1989 - 1994)
- radon summary statistics (1995 - 1996)
- radon in rock tunnels (1996) using E-perms
- radon in rock tunnels (1996) summary statistics
- radon track etch (Teradex) summary statistics (1982 - 1996)
- radon track etch (Teradex) in chemical plant summary statistics (1993 - 1996)

### External Radiation Exposure

**Personnel Monitoring.** One phosphate company supplied extensive personnel monitoring data spanning the years from 1979 to 1996. This company maintained about 650 badged employees. The project team assembled and analyzed two data sets, consisting of monthly and quarterly processed dosimeters. The monthly data set contained more than 31,200 data entries, and the quarterly set for the two most recent years contained 85 data entries. Statistical analyses indicated trends that were used to direct site surveys. Personnel in phosphoric acid production tended to have higher external doses than acid clean up workers, and utility operators. Working stations in the phosphoric acid production area were situated such that radium was removed along the station "train," and corresponding badge results were in agreement with radiochemical dynamics.

Older TLD data (1980s) indicated expected higher exposures for phosphoric acid production and fertilizer storage and shipping. All maintenance categories had exposures greater than background, including: phosphoric acid maintenance, fertilizer manufacturing, heavy equipment, and maintenance personnel who sometimes covered the entire plant.

A second phosphate chemical company supplied personnel monitoring results shown in tabular form (Table 4). Note that this company employs about the same size workforce as the previously considered company.

The table shows that 0.56% are already greater than 100 mrem, the suspect badges would have to be demonstrated, and some of the 14.4% workers in the 10-99 mrem range may have TEDE considerations. However, if all badged employees have radiation safety training commensurate with the potential hazard, they are subject to, and well within, the 5,000 mrem/yr occupational limit.

**Table 4. Employee Annual TLD Summary 1990 - 1995**

| Average Percentages of Employees in Indicated Dose Categories | | | | | | |
|---|---|---|---|---|---|---|
| **Year** | **<10 mrem** | **10-99 mrem** | **100-249 mrem** | **250-499 mrem** | **>449 mrem** | **N** |
| 1990 | 86 | 13.89 | 0.17 | 0 | 0 | 583 |
| 1991 | 81 | 18.12 | 0.82 | 0 | 0 | 607 |
| 1992 | 87 | 13.4 | 0 | 0 | 0 | 664 |
| 1993 | 93 | 7.34 | 0 | 0 | 0 | 586 |
| 1994 | 85 | 14.76 | 0.4 | 0 | 0.13* | 759 |
| 1995 | 80 | 17.34 | 1.96 | 0.52* | 0.13* | 762 |
| **mean** | | | | | | |
| - | 85 | 14.14 | 0.56 | - | - | - |
| sum = 99.87% + suspect | | | | | | |

* suspect badges (delete)

A service company supplied seven years of data as shown in Table 5 that follows.

**Table 5. Service Company External Exposure Data**

| **Year** | **<10 mrem** | **10-99 mrem** | **100-249 mrem** | **>249 mrem** | **N** |
|---|---|---|---|---|---|
| 1995 | 30 (85.7%) | 4 (11.4%) | 1 (2.9%) | 0 | 35 |
| 1994 | 20 (87 %) | 3 (13 %) | 0 | 0 | 23 |
| 1993 | 19 (95 %) | 1 (5 %) | 0 | 0 | 20 |
| 1992 | 16 (94.1 %) | 1 (5.9 %) | 0 | 0 | 17 |
| 1991 | 9 (100 %) | 0 | 0 | 0 | 9 |
| 1990 | 13 (100 %) | 0 | 0 | 0 | 13 |
| 1989 | 15 (100 %) | 0 | 0 | 0 | 15 |
| sum = 7 | 122 (92.4 %) | 9 (6.8 %) | 1 (0.8 %) | 0 | |

For the last two years, 11-13% of badged workers were in the 10-99 mrem range; i.e., potential for TEDE considerations. Only one has ever exceeded 100 mrem external exposure. For 1994 and 1995 the deep exposures were 109, 35, 16, 34, 60, 16, 11 and 17; yielding a mean of 37.25 mrem. Note that two workers accounted for two of those doses each (four of the eight total). There were some high skin doses in the sampling period; specifically, 513 mrem to a worker in 1993 and 299 mrem to a worker in 1995.

**Environmental TLD Data.** One phosphate producer provided environmental monitoring data for three sites displayed in Table 6.

**Table 6. Phosphoric Acid Environmental TLD (1992-1996)**

| TLD Location | Exposure Rate (μR/hr) | Average (μR/hr) |
|---|---|---|
| Wet-Acid Production | 72-247 | 154 |
| Between Settlers | 77-100 | 94 |
| Handrail Near Settler | 17-57 | 38 |
| By Carbon Columns | 52-144 | 89 |

Note: the sample number per year is always 72.

The second site monitoring locations were the filter interior, pan interiors, pan exteriors, and the pan sanding area. These locations tended to exceed 50 μR/hr, and reached as high as 349 μR/hr during the 1994-1996 monitoring period. are high; middle pan exterior is slightly high; rest room west of center pan, control room under microwave, rock tunnel below conveyor on pole and bottom of tunnel are consistently low.

At the third site, the interior and exterior exposure rates for filter pans almost always exceeded 50 μR/hr, as did the area office (average of 72 μR/hr in 1996). The highest recorded level was 358 μR/hr exterior to a filter pan. The rock storage silo and rail car rock unloading building sometimes exceeded 50 μR/hr. Other high occupancy areas, such as the supervisor's office, control room, and lunch room were always at site background levels.

The final company reported net (control corrected) ambient dose equivalent (mrem) for one quarter of 1996, but the dose was actually incurred during filter replacements (6 workers). Ambient doses recorded in the working vicinity of 6 filters were: 4.8, 4.1, 7.6, 5.6, 4.9, and 5.6 mrem.

**Survey Data.** Exposure rate measurements were used as a screening method to locate areas for potential monitoring using fixed TLD badges. The readings were assigned arbitrary labels of "low" (up to 25 μR/hr), "medium or moderate" (25-50 μR/hr), or "high" ( >50 μR/hr). Survey data from most companies was concerned mainly with filter cloths and trucks that haul them.  Filter cloths during handling and hauling were surveyed as noted from a company's procedures guide:  "Radium residues from filter pans or equipment that exceeds 250 µR/hr will be contained and transported to the chemical waste dump on the gypsum stack."  Also, for vehicles transporting radium residue-contaminated materials and used filter cloths; if exposure rates are greater than twice background, wash the truck bed and drain into cooling pond.

Monthly surveys were conducted at one company for three sites during 1995 and 1996, and provided the results that follow.

- Site 1 phosphoric acid: Highest areas include seal tanks and associated piping, laboratory sinks, and filter pan areas (including worker locations - floors, railing).  Other phosphoric acid locations; e.g., the control room, had low exposure rates.  Maintenance and fabrication areas also had low exposure rates.  Standard laboratory swipes to detect removable surface contamination were taken, and almost always resulted in less than the minimum detectible activity (MDA).   Alpha activity was usually zero cpm; but is found in the control room sink, filter pan area gratings and ladder, pad under control room, control room counter top, and lab entry floor of control room.

- Site 2 phosphoric acid:  The control room sink was consistently high.  The filter pan area was moderate throughout.  The filter cloth dumpster gave exposure rates from 1 to 2 mR/hr at one foot.

- Site 3 phosphoric acid:  Maintenance areas were low, and other working areas were moderate.  The filter pan areas and one of the filtrate receivers were high.  Again, a laboratory sink was high.  Maintenance area surveys for 1995 and 1996 included the outside area: center of floor, first vise table, second vise table, sink, and rigid threader.  Also, the lunch room was surveyed: entrance floor, south table, middle table, north table, refrigerator, and microwave.  All locations were always $\leq$22 µR/hr, and no detectable alpha-emitters except the first vise table on 12/20/95 was 48 µR/hr and 4,000 alpha cpm (GM gave 1,400 cpm).

  The remaining phosphoric acid area surveys for 1995 and 1996 included swipes that were almost always less than the MDA (MDA not given).  Alpha emitters are sometimes detected at minimal levels in the supervisor's office, filter pan areas, ground floor seal tanks, laboratory sink, filtrate receiver, laboratory counter top, ground floor pad under pan, and laboratory floor. Micro-R meter surveys were conducted around seal tanks (borderline high), filtrate receiver, filter pan area, and counter top and sinks in the laboratory which all sometimes exhibit high rates.

**Airborne Radioactivity**

Radon levels can be measured directly or via radon progeny concentrations and reported in pCi per liter of air. The E-Perm is a common device used for radon measurements. The E-Perm contains a charged electret (an electrostatically-charged disk of Teflon) which collects ions formed in the chamber by radiation emitted from radon and radon decay products. When the device is exposed, radon diffuses into the chamber through filtered openings. Ions which are generated continuously by the decay of radon and radon decay products are drawn to the surface of the electret and reduce its surface voltage. The amount of voltage reduction is related directly to the average radon concentration and the duration of the exposure period.

One company supplied radon measurements taken from 1989 through 1996. The locations that exceeded 4 pCi/l are listed in Table 7, although the levels were extremely variable. All of these locations were low or negligible occupancy areas. The full set of statistics for five monitored locations for 1995 through 1996 are given in Table 8. Note that 22-44 readings were taken for each site over that time period.

**Table 7. E-Perm Radon (1989 -1996)**

| Area | Location | Maximum (pCi/l) |
|---|---|---|
| 1989-94 auto shop | S.E. fence | 30.61 |
| 1989-94 burn area | fence | 40.87 |
| 1989-94 cooling pond | hand rail | 27.61 |
| 1989-94 environmental | monitor well | 56.76 |
| 1989-94 gypsum stack | flux test | 17.89 |
| 1989-94 liming station | ladder | 40.84 |
| 1989-94 NE gypsum stack | well | 21.74 |
| 1995 plant | NE gypsum stack | 78.72 |
| 1995 plant | monitor well | 14.81 |
| 1995 plant | cooling pond | 27.98 |
| 1996 plant | NE gypsum stack | 24.20 |
| 1996 plant | burn area | 21.22 |

**Table 8. Radon Summary in pCi/l (1995 through 1996)**

| Statistics | Auto Shop | Burn Area | Cooling Pond | Monitor Well | Gypsum Stack |
|---|---|---|---|---|---|
| Mean | 2.99 | 1.66 | 3.02 | 5.11 | 9.51 |
| Std. Err. | 0.34 | 0.50 | 1.22 | 1.89 | 2.73 |
| Median | 2.72 | 1.07 | 1.68 | 2.59 | 1.25 |
| Mode | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Std. Dev. | 1.59 | 3.34 | 5.70 | 12.51 | 18.14 |
| Smp. Var. | 2.51 | 11.13 | 32.52 | 156.39 | 329.01 |
| Kurtosis | 6.03 | 28.73 | 19.81 | 38.77 | 7.03 |
| Skewness | 1.85 | 5.05 | 4.36 | 6.07 | 2.64 |
| Min. | 0.37 | 0.00 | 0.00 | 0.00 | 0.00 |
| Max. | 8.40 | 21.22 | 27.98 | 83.82 | 78.72 |
| Count | 22 | 44 | 22 | 44 | 44 |
| CL (95%) | 0.66 | 0.99 | 2.38 | 3.70 | 5.36 |

Another method used to measure radon is by track etching. Several types of glasses and some organic polymers can be used for this purpose. When a charged particle encounters the surface of the glass, radiation damage is left along its path. The paths are made visible for counting when the glass is treated chemically or electrochemically. The trade name for one such device is Terradex, and that device was used by one company to monitor rock tunnels as shown in Table 9. The same company also tested another site using the same technology and found levels surpassing 4 pCi/l only in the rock tunnels. Those tunnels were 5.8 pCi/l (7/21/95), and 5.2 pCi/l (1/22/96).

Finally, another company placed personal air samplers on maintenance personnel involved in filter cloth replacement during a 1996 event. This was done to estimate the internal dose received from intake of airborne radioactive particulates. Fifteen individuals were monitored during the process, and ten of those worked on a table filter at any one time. The replacement took about two hours and delivered a calculated dose of 1.5 mrem per individual. Note that the filters were covered with a wet (saturated) layer of gypsum.

**Table 9. Rock Tunnel Radon (pCi/l)**

| Statistics | Chute 1 | Chute 10 | Chute 20 |
|---|---|---|---|
| Mean | 11.70 | 26.48 | 17.42 |
| Std. Err. | 1.34 | 4.20 | 5.21 |
| Median | 9.66 | 21.27 | 9.06 |
| Mode | 0.00 | 0.00 | 0.00 |
| Std. Dev. | 5.69 | 17.81 | 22.12 |
| Smp. Var. | 32.38 | 317.19 | 489.15 |
| Kurtosis | 3.09 | 2.74 | 4.64 |
| Skewness | 1.60 | 1.76 | 2.35 |
| Min. | 5.05 | 10.63 | 4.17 |
| Max. | 28.16 | 74.71 | 79.54 |
| Count | 18 | 18 | 18 |
| CL (95%) | 2.63 | 8.23 | 10.22 |

## PROCESSES OF CONCERN

The processes of concern identified using the gathered data are as follows:

- mining: fugitive rock particle dust; external beta/gamma, radon
- beneficiation: fugitive rock dust; external beta/gamma, slime pond waste stream
- wet (phos) acid: fugitive dust from hammermills; external beta/gamma; gypsum in water, ponds and piles; filters
- GTSP: fugitive dust from grinding; external beta/gamma; scrubber water
- granulation/drying: (DAP process): fugitive dust, external beta/gamma
- dissolution/slurrying: external beta/gamma
- bulk blending (mixed fertilizer): no dust, external beta/gamma

- shipping areas: fugitive dust and external beta/gamma

These processes are examined in detail in the subsections that follow. The various industries provided documents and descriptions that were assembled into outlines and diagrams by the project staff to provide an understandable description of each process in a standard format for comparison. Descriptions contain TENORM radionuclides of interest, their mobility in the process, concentration or dilution mechanisms, and concurrent chemical and mechanical processes. Information gained in literature and industry information review, and the early data collection phase of this study were used to determine which processes were relevant. That is, literature data revealed typical plant areas that have elevated exposure rates, the types of employees who tend to work in those areas and areas of airborne radioactivity, and the types of equipment (in use, in repair, scrap) that accumulate radioactive deposits. Time and motion studies documented workers' activities in relation to critical processes. Radiological surveys provided Florida industry-specific data during early reconnaissance period, which supported the choices of processes to diagram. The basic process descriptions were taken from an EPA report (EPA, 1977a), and modified or enhanced as needed.

**Mine Area**

**Mining.** The process recovers phosphate rock ore (matrix) from subsurface deposits of phosphate rock. Refer to Figure 2 for an overview of the mine area processes, and Figure 3 for a more simplified block flow representation. Mining methods employed are of the open-pit type in most (estimated greater than 95 percent) of the operations. The mined rock is deposited by draglines into an excavated sump, fragmented hydraulically by streams from high-pressure jets operated from pit cars, and conveyed as a slurry to the beneficiation plant (washer and flotation plant). The open-pit type of mining process is characterized by the enormous quantities of overburden removed and by the large quantities of water used to transport the fragmented rock to the beneficiation plant. Principal essential equipment consists of large, specially-constructed, electrically-powered draglines, and large centrifugal pumps.

The matrix plus the overburden constitute the input materials to the process. The phosphate rock matrix is nodular fluoroapatite [$CaF_2 \bullet 3Ca_3(PO_4)_2$] together with blue clay and silica sand. The blue clay and silica sand are the useless constituents known as gangue. Per metric ton of marketable rock-plus-concentrates, typical quantities are 4 to 6 metric tons of overburden removed and 3 to 4 metric tons of phosphate rock matrix recovered. The matrix is intermixed with NORM radionuclides of the uranium, actinium, and thorium series each in generally secular equilibrium; i.e, for each member of a series, the same activity concentration (in pCi/g) should exist.

Four to six tons of overburden are removed per marketable ton of rock-plus-concentrates. This is temporarily placed in piles, and ultimately deposited in mined areas. Atmospheric emissions of fugitive particle rock dust from dragline operation during dry periods is surmised. No quantitative information is available.

**Beneficiation.** The process separates and recovers the high-grade portion of phosphate rock from the phosphate rock matrix (phosphate rock plus gangue) received from mining. The beneficiation process usually includes the following steps and equipment.

- Wet crushing and grinding in hammermills.

- Wet size separation in log-washers, vibrating-screens, hydrocyclones, and Evans hydrosizers.

- Draining on dewatering screens.

- Drying in rotary dryers.

If the matrix is received as a water slurry (majority of cases), the beneficiation process usually includes the following steps and equipment:

- Washing: separation of clay from the matrix using water and vibrating screens. Phosphate pebbles (>1 mm diameter) are recovered for sale. Uses wet grinding and sizing in equipment as outlined above. Log washers are inclined tubs with two shafts (with nickel alloy paddles attached) that turn in opposite directions; used to break up mud and clay balls in the "wet rock" and to remove the slime coating on the rock particles by allowing the fine clay to carry into an overflow water stream. Desliming hydrocyclones are cone-shaped vessels, commonly called "cyclones," that remove the minus 150-mesh material from the log washer and spiral classifier overflows; also returns any plus 150 material to the classifiers; cyclones operate on the principle of centrifugal force; feed is pumped into the cyclone such that the larger and heavier particle are thrown outward and downwards to discharge through the apex; the lighter, smaller particles (slimes and clays) carry to an overflow and are removed to the retention pond. Spiral classifiers are inclined tubs 38-ft. long and 8-ft. wide with a helical screw (spiral) running the length of the tubs. The wet rock from the log washers and the underflow from the cyclones are fed to the classifiers. The function of the classifiers is to remove any material less than 150-mesh (slimes and clay) and also to de-water the rock to ease in handling and transfer.

- Two-step froth-flotation process used to separate finer particles of phosphate from sand (see Figure 2). Flotation agents and conditioning additives are used in both stages of froth flotation steps. They usually are amines and tall oil (common reagents are fuel oil, soap skimmings, and fatty acids). When coated with these substances, the phosphate particles become lighter than their companion sands and can then be easily separated. Product is dried to approximately 1% residual moisture.

- Draining on dewatering screens.

- Drying in rotary dryers typically used to reduce moisture content of rock from about 10% to 3%.

The product of the beneficiation process, usually consisting of several size ranges, may be marketed or in integrated operations may be forwarded to phosphoric acid production or GTSP production. Three to 4 metric tons of mined matrix in Florida (as 30 to 40% slurry) are processed per metric ton of marketable rock concentrates.

All process steps are conducted at atmospheric pressure and ambient temperatures. Average $P_2O_5$ content of composite marketable phosphate rock products from Florida is 32.2%. Usual size ranges of the three fractions of concentrates produced in Florida:

- 14-mesh to 18 mm (land pebble)

- 35-mesh to 14-mesh

- 150-mesh to 35-mesh

**Waste Streams.** Based on one metric ton of composite marketable phosphate rock products:

- Sands: About 1 metric ton in Florida. These are 14- to 150-mesh size and are used for filling mined-out areas and for dike construction.

- Slimes/Clays: About 1 metric ton (dry-basis), consisting of micron-size clay particles suspended in a slurry of about 5% concentration. Approximately 80% of water is reclaimed from slurry in settling ponds. Residual, thickened slurry containing about 20% solids is indefinitely ponded and requires up to 15 years to settle.

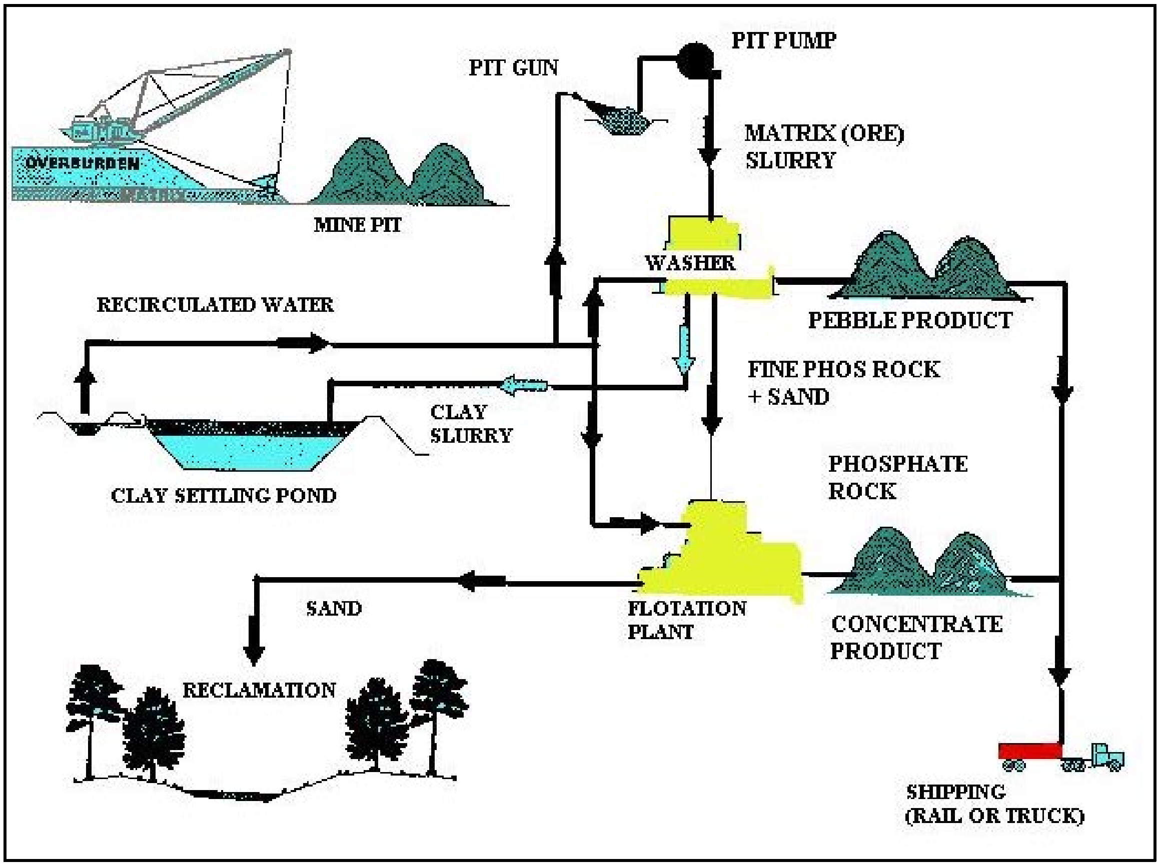



**Figure 2. Mine Area Processes**

- Particulate atmospheric emissions from rotary dryers were studied by the EPA (Partridge et al., 1978).

**Rock Area**

Rock delivered from the mines seldom has the desired particle size distribution. For obvious economic reasons, mining operations avoid crushing and grinding beyond the "liberation size." This is the size where the ore is broken down into its valuable constituents, and the less valuable (or useless) gangue. This subdivision may be necessary prior to beneficiation. Some natural deposits contain phosphates in small size aggregates in their natural state. Such small-size deposits occur in northern Florida and North Carolina in the United States and in Tunisia and Morocco.

In its modern form, wet grinding was developed early in 1973 at Agrico Chemical Company's South Pierce plant. Higher fuel prices made it clear that it was illogical to utilize fuel to dry rock which almost immediately was to be "wetted" in the attack tank. Also, the development of vacuum cooling of the reactor, in place of dilution acid coolers, provided a substantial amount of water evaporation from the reactor. This volume of water could then

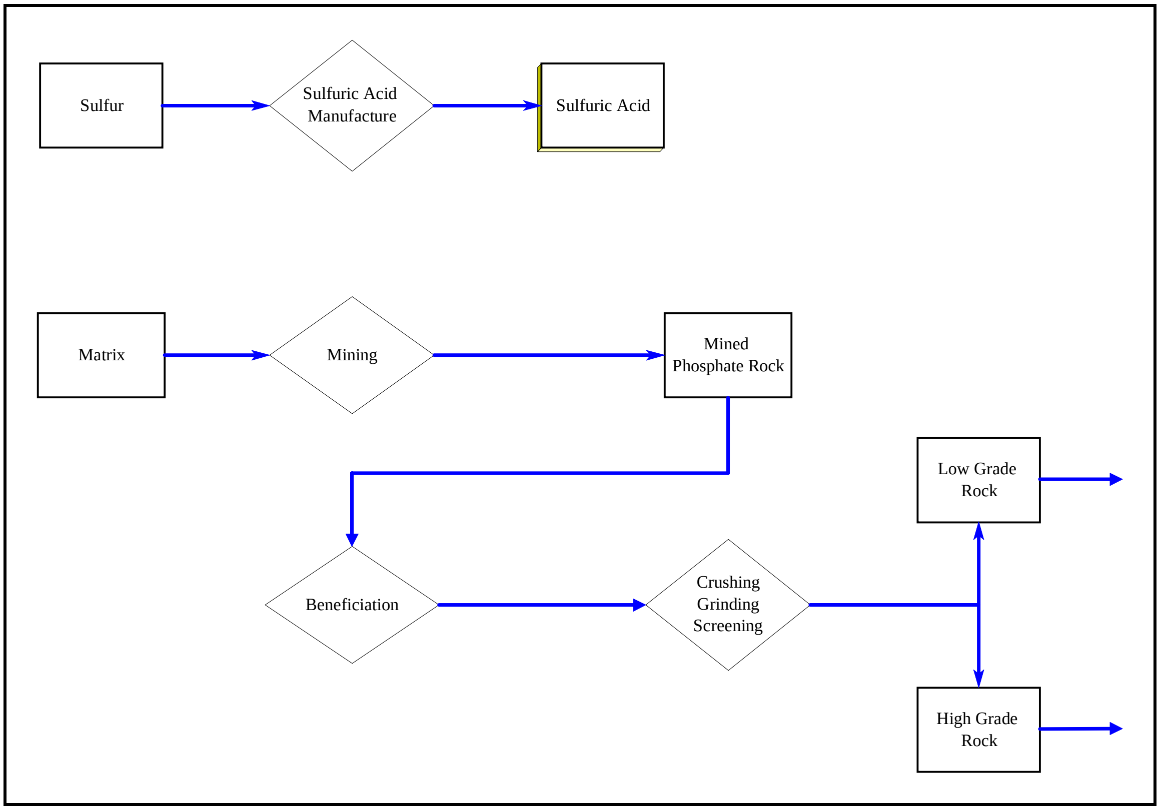



**Figure 3. Block Flow Diagram of Mining and Sulfuric Processes**

be used for rock grinding with a net reactor/ filter water balance approaching that of plants using graphite heat exchangers to remove the heat of dilution of sulfuric acid.

The great advantage of wet grinding is, of course, the elimination of fuel consumption for rock drying. Another benefit claimed for the process is elimination of dust and pollution control equipment; a reduction of 1000 lb/day of particulate matter emission for rock grinding operations.

The problems associated with wet grinding are many and include:

- Reduced $P_2O_5$ reactor strength, requiring in many cases the expansion of evaporator facilities and increased evaporation steam consumption.
- Increase in the unavailable water-soluble $P_2O_5$ which continuously accumulates in the gypsum storage areas.

Pumps and classification devices (screens, hydrocyclones) require for their operation more dilute slurries. Reported percent solids by weight in wet grinding installations varies between 62 and 70%.

**Crushing/Grinding/Screening.** The process reduces the size of lumps of mined phosphate rock matrix to the size requirement of various downstream processes. Refer to Figure 4 for details. The process is generally operated wet. Process steps usually include the following equipment:

- Ball or rod mills. In their simplest form, ball mills consist of a hollow double conical, cylindrical, or cylindroconical shell set with its axis in a horizontal or near horizontal position. The rotating shells (16.5 ft. in diameter and 17 ft. long) are no more than half full with "balls," which are generally spheres (two inch diameter steel balls), but can be cylinders or cubes as well. Material to be ground is fed through a hollow trunnion at one end and leaves the mill through another hollow trunnion at the other end. As the mill is rotated, the charge of balls is raised along the shell up to a certain height, from where they tumble by rolling (cascade) over the other balls or are projected through the air to strike the toe of the charge (cataract). Experience has shown that the best mill performance is obtained when cataracting balls strike the toe of the displaced charge and not the shell. Coarse material tends to accumulate at the toe of the charge, and the impact of the cataracting balls is a very important part of the total grinding mechanism. The inside surfaces of the mill are usually lined with an abrasion and/or corrosion-resistant material such as manganese steel, Hi-hard, or thick rubber pads. Mills lined with rubber operate quieter and can be fully acid-proofed to allow for operation on low-pH water. Inside liners are usually designed with small projections to increase the effective friction between the charge and the liner and permit operation of the mill at lower rotational speeds. Rod mills are similar to ball mills in details of construction and operating principles, except for the requirements that the mill body must be of cylindrical shape and the length-to-diameter ratio should be 1.4:2.5 to prevent rod entanglement. In addition, current manufacturing limitations place a limit of 6.8 m or 20 ft on the maximum rod length. Maximum current diameters of rod mills would be, based on the foregoing limitations, 6.8 x 4.8 m or 20 x 14 ft. Rod mills are rotating mills lined with chrome-moly steel and charged to 35-40% of their volume with e.g., 19 ft. long, 2.5 in. diameter rods. The rolling mass of rods preferentially grinds the coarser material in the feed end and with the finer particles crushed toward the discharge end.

- Shaking screens or cyclonic sizers (hydroclone). Screen analysis is a method for determining particle size distribution of phosphate rock materials; a multi-deck shaker and screens of reducing mesh size are used; calculations are made after shaking for percent material of the various mesh sizes. Hydrocyclones are cone shaped vessels that remove the oversize material and returns it to the ball mills and removes the product size ground rock to the slurry storage tanks; cyclones operate under the principle of centrifugal force;

feed is pumped into the cyclone such that the larger and heavier particles (oversize) are thrown outward and downward to discharge through the apex; the lighter, small particles (ground rock product) overflow to the slurry storage tank. Both screens and hydrocyclones are normally installed at a higher elevation than the mill feed and to provide gravity return of oversize material. Screens normally require a larger floor space than hydrocyclones and are often hard to fit in existing installation. Spiral classifiers are inclined tubs 38-ft. long and 8-ft. wide with a helical screw (spiral) running the length of the tubs. The wet rock from the log washers and the underflow from the cyclones are fed to the classifiers. The function of the classifiers is to remove any material less than 150-mesh (slimes and clay) and also to de-water the rock to ease in handling and transfer.

- Direct-fired rotary dryer

Product of the process if high grade is either marketed or forwarded to GTSP production. On-size slurry is piped to phosphoric acid production. The rock fineness has to be sufficient to allow total recovery of the $P_2O_5$ by acid attack and avoid coating. Large well-agitated tanks accept coarser rock for treatment. Some manufacturers just screen their rock through 0.5 or 1 mm and grind only the oversize; but, most of the time, particle size distribution is about 30-40% over 125 µm. The main pathway of concern is inhalation of airborne radionuclide-bearing particulates during milling, sizing, and cleaning up spillage.

**Phosphoric Acid Area**

**Sulfuric Acid Manufacture.** This process produces sulfuric acid ($H_2SO_4$) from sulfur, air, and water by oxidation of the sulfur in air followed by absorption of sulfur trioxide ($SO_3$) into wet sulfuric acid ($H_2SO_4$). Refer to Figures 2, 3, and 5. The $H_2SO_4$ produced goes to:

- Sales
- Normal superphosphate processing
- The wet-acid process
- Ammonium sulfate formation
- Ammonium phosphate or nitric phosphate processing
- Ammoniation/granulation/drying

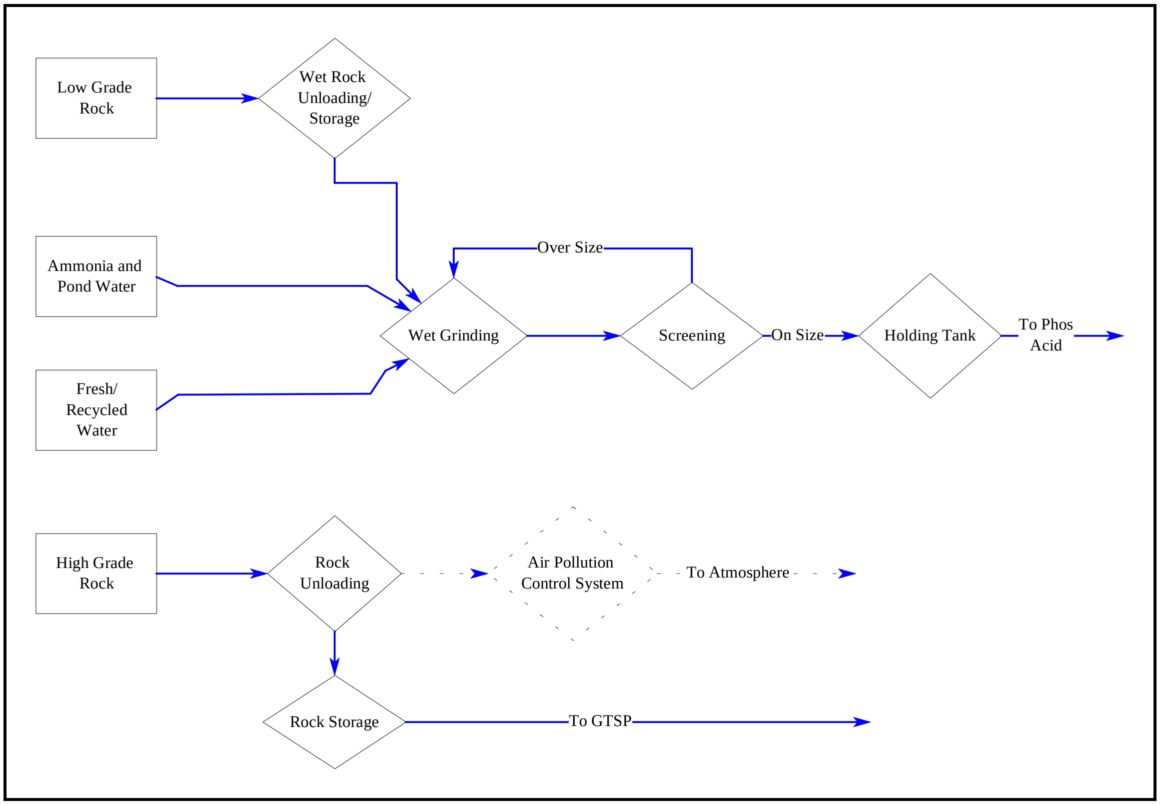



**Figure 4. Block Flow Diagram of Rock Handling Processes**

Molten sulfur from the Frasch mining process (or from hydrocarbons using the Claus process) is filtered and then burned in dry, compressed air. The resulting combustion gases containing 12% sulfur dioxide ($SO_2$) are cooled, mixed with more air, and fed to a four-stage catalyst converter. As the gas passes through the first catalyst bed, some of the $SO_2$ is converted to $SO_3$ in an exothermic reaction. The gas is then cooled and passed through the second catalyst bed where more $SO_2$ is converted to $SO_3$. The gas is then cooled and may be passed through an absorber countercurrent to 98+% $H_2SO_4$. Most of the $SO_3$ is absorbed into $H_2SO_4$. The unabsorbed gas goes to the third catalyst bed where most of the remaining $SO_2$ is converted to $SO_3$. The gas is then cooled, goes to the fourth catalyst bed, is re-cooled, and then passes through another absorber where $SO_3$ is absorbed into 98+% $H_2SO_4$. A sulfur-burning sulfuric acid production unit will produce, for each ton of 98% $H_2SO_4$, a total of about 1.15-1.50 tons of high-pressure steam. This high-pressure steam is generally put through a turbine to produce electrical or mechanical energy and released as low-pressure steam for phosphoric acid concentration by evaporation. The energy recovered during the steam reduction operation is either used partially to drive the blower in the sulfuric acid unit or completely to generate electric power (in the latter case the blower is electrically driven). Sulfuric acid manufacture is not of radiological concern, but is included to provide a complete picture of the phosphoric acid manufacturing process.

**Wet Acid Process.** The wet acid process produces ortho-phosphoric acid ($H_3PO_4$) by digesting phosphate rock or phosphate rock concentrates from beneficiation and rock handling with sulfuric acid from sulfuric acid and cogeneration: $CaF_2 \bullet 3Ca_3(PO_4)_2 + 10H_2SO_4 + 20H_2O \rightarrow 6H_3PO_4 + 10CaSO_4 \bullet 2H_2O + 2HF$. The phosphoric acid produced may be clarified to market grade, transferred to GTSP production, or ammoniated to produce MAP and DAP or animal feeds. See Figure 5 for an overview and Figure 6 for detail. At least two variations of the basic process embodying the above reaction are commercial: the hemihydrate process and the dihydrate process. The latter is the one considered here. The process includes the following essential steps and major equipment:

- Reaction (digestion or dissolution) of the ground phosphate rock with sulfuric acid and recycle phosphoric acid in reinforced concrete, brick-lined, closed reaction (attack) tanks with large agitated compartments. The violent generation of heat accompanied by vapor release creates intense turbulence where the sulfuric acid encounters the more dilute phosphoric acid. However, more effective agitation (both flow and microdispersion) is necessary to complete a perfect distribution of the $H_2SO_4$ within the reacting slurry volume so bladed impellers are installed. Another important factor has to be considered for both a high recovery of $P_2O_5$ from the rock and good crystallization; the sulfuric acid has to be fed into a medium where a certain sulfuric acid concentration limit already exists. To ease the sulfuric acid dispersion, it is generally mixed first before being introduced into the slurry with recycle acid, a diluted phosphoric acid of about 16-19% $P_2O_5$ concentration, recycled from the filtration and cake wash sectors. Recycle acid, also called return acid, is the liquid phase resulting from washing filter cake with process water. Thus the recycle acid contains the process water plus the amount of product acid that was retained within the filter cake before washing. The mixture of diluted $H_3PO_4$ and 98% $H_2SO_4$ reaches boiling point and releases some of the dilution heat in the form of vapor, which is evacuated from the reactor with other gaseous effluents. In order to maintain the proper slurry temperature a flash cooler (Figure 7; after Becker, 1989) is connected to one of the compartments.

- The flash cooler cools attack slurry and maintains temperature control inside the attack tank. Attack slurry enters the flash chamber which is operated under vacuum. The low pressure causes water to boil off and the temperature of the slurry to decrease. The vacuum flash cooler is simply a gas-liquid separator subjected to a vacuum. Of course, there has to be a vacuum/source and a means to condense the flashed vapors. Because the cooling system is under vacuum and the traditional wet-process reactors are essentially at atmospheric pressure, it is necessary to keep the cooling chamber at an elevation sufficient to seal the vacuum by two barometric legs submerged in the reaction tank. The hot feed slurry is pumped up to the flash drum and the

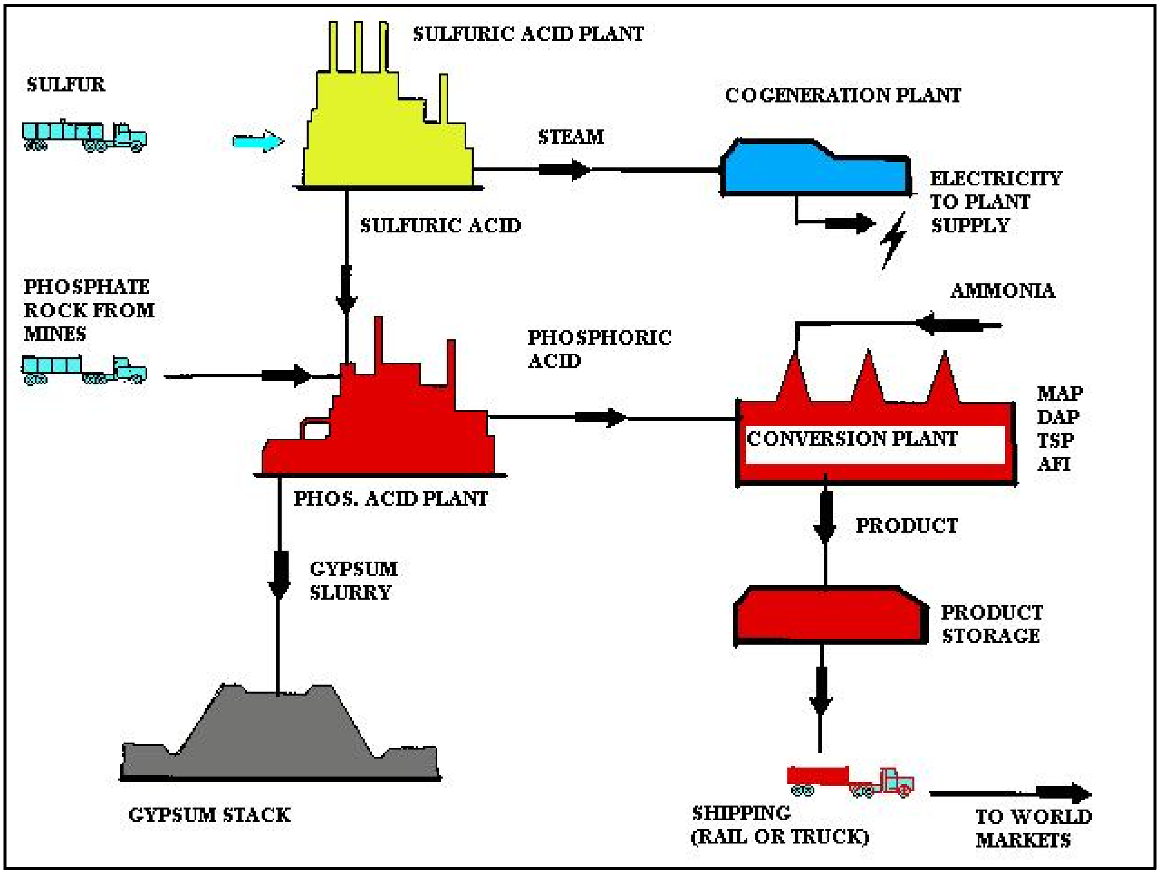



**Figure 5. Phosphate Chemical Plant Materials Flow**

cooled discharge slurry flows down the second barometric seal leg back into the reaction tank. In general, the whole system is made of rubber-lined steel, with an acid brick lining for the sections of the flash drum in direct contact with the slurry. This was found to be necessary because the erosive nature of the slurry tended to wear out the rubber lining.

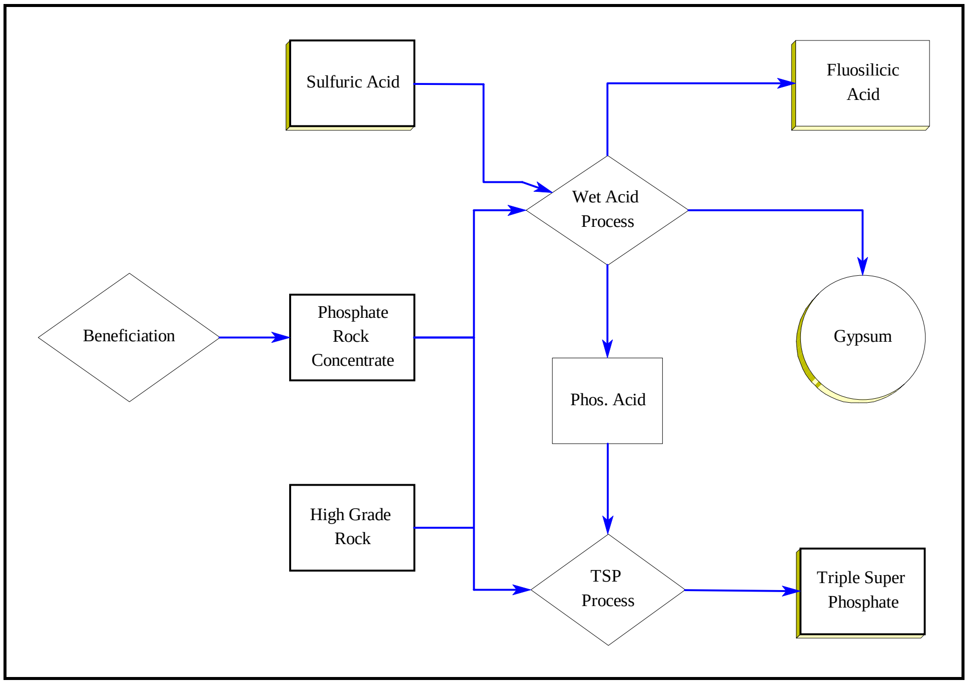



**Figure 6. Block Flow Diagram of Phosphoric Acid and TSP Production**

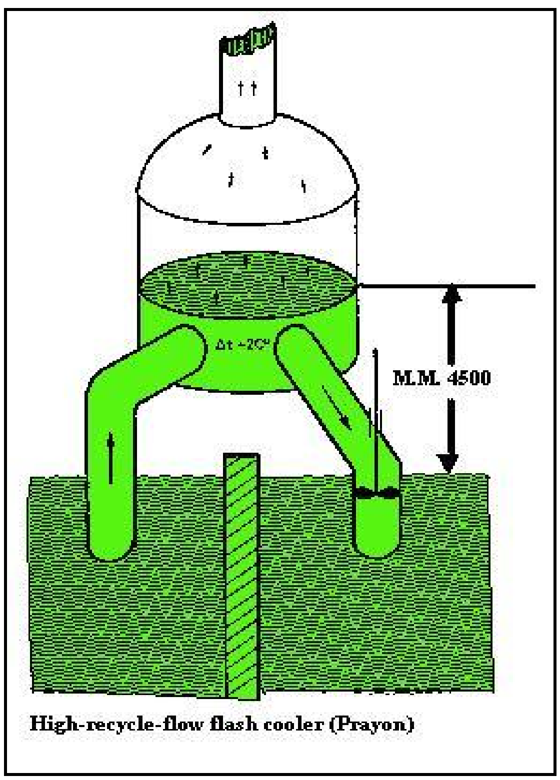



**Figure 7. High-Recycle-Flow Prayon Flash Cooler**

- Filtration of the resulting slurry on a specially designed, continuous, tilting-pan (bird) or table (auger) filter to remove gypsum crystals. This is achieved by loading the acid/crystal slurry onto a filter cloth, and then applying a vacuum to the underside. The atmospheric pressure forces the acid through the cloth-retained "crystal cake" to the vacuum side of the cloth, from where it is evacuated. The cake is a porous media crossed by capillary channels. Tilting filters consist of a number of trapezoidal filter cells or pans in circular alignment, each equipped with its own cloth and connected by flexible hose (Prayon) or by a rotating joint (Eimco) to a central vacuum distribution box, all of which rotates. According to the position of a cell as it rotates, the central distributor connects it to the corresponding vacuum and acid evacuation pipes. After having been connected successively to the product acid piping sector and the two wash acids and tail water wash sectors, the vacuum is released and the cell is mechanically tilted, upside down, to remove the gypsum cake by gravity and to wash the filter cloth, still upside down, with a high-pressure water spray. This spray has a mechanical and a dissolving action. Sometimes warm water is used as the spray, or sometimes pond water at a low pH (about 1.5).

  The rotating table filter (Figure 8) manufactured by UCEGO works like a traveling belt filter, with a continuous cake. Instead of an endless belt, there is a large rotating disk. Along the outside circumference there is an endless rubber belt forming a rim. Along the inner circumference there is a metal wall. The disk is made of a series of individual troughs bolted together and covered with perforated stainless steel plates to support the cloth. The bottom of the troughs are sloped and connected individually to a central vacuum distribution valve, similar to those working with tilting pan filters. The advantage of the table filter over tilting pan filters is that it can be operated at a higher speed of revolution. The difficulty with this type of filter lies in the cake removal, since the disk is rigid. The endless rubber belt on the outside edge of the filter has to be deflected for that purpose, and this is achieved by a series of staggered pulleys. At the point at which the belt is deflected, the cake is scraped off the cloth by means of a rotating screw conveyor. The cloth cleaning is completed by a high-flow and high-pressure water spray system.

  Filtrate is the filtered phosphoric acid (gypsum removed) from the Bird or table filters. #1 filtrate is 27-28% phosphoric acid, and is the initial acid to come through the filter (product acid). #2 filtrate is 15-18% phosphoric acid, made as a result of washing the gypsum with 8% phosphoric acid (l$^{st}$ wash). #2 filtrate is recycled back to the attack tank. #3 filtrate is 8% phosphoric acid, made as a result of washing the gypsum with pond water (2$^{nd}$ wash). #3 filtrate is used as the first wash. Gypsum cake (calcium sulfate dihydrate) is

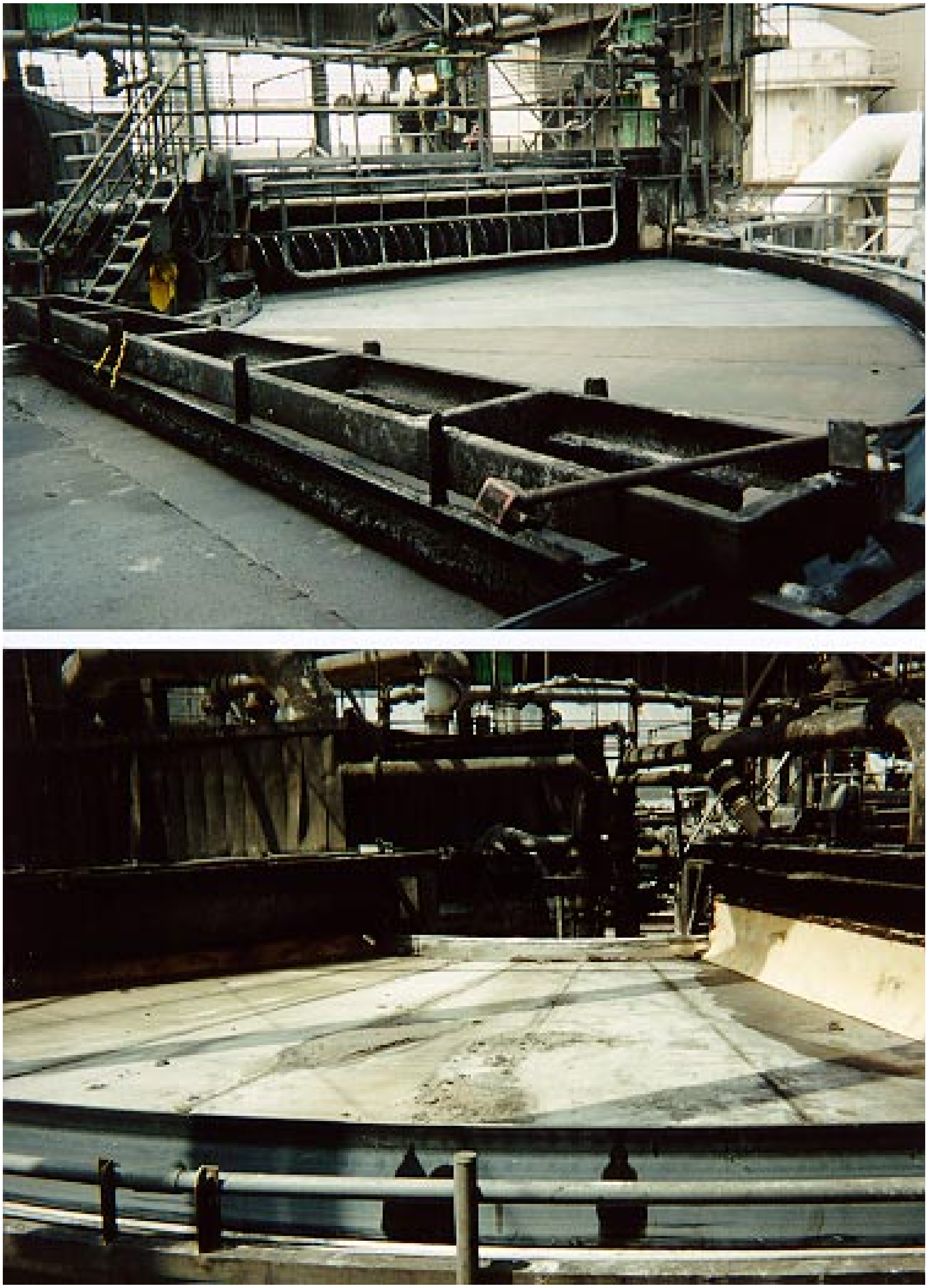


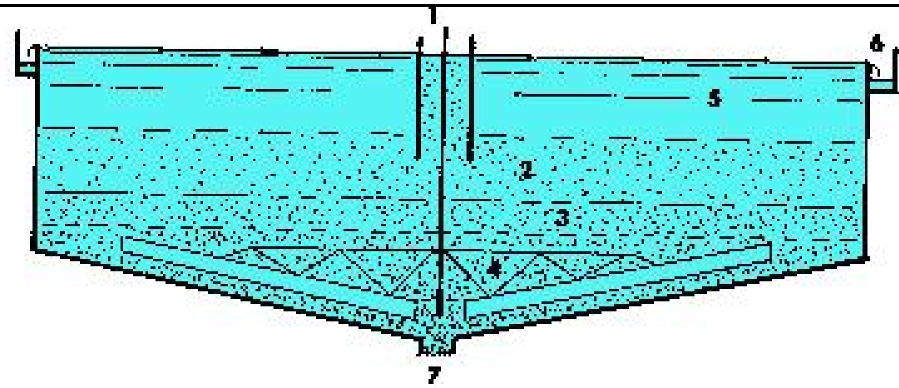
**Figure 8. Table Filters Partially Disassembled**

the waste material left behind on the filter pans after attack slurry is filtered. Gypsum is dumped from the filter pans and transferred to the gypsum stack. Almost all phosphoric acid plants in the U.S. are required to contain and store byproduct gypsum in these gigantic stacks covering hundreds of hectares and in Florida reaching 30 and even 90 m in height. Gypsum is slurried in "gypsum water" and pumped to the disposal stack, where it is partially dewatered by gravity and the drained water is recycled for further slurrying of gypsum. In most plants this gypsum storage area also serves the function of cooling the water recycled through the phosphoric acid plant barometric condensers. Over a period of time these stacks accumulate basically a large part of the soluble $P_2O_5$ losses and can reach concentrations higher than 2% $P_2O_5$. Normally, for the purpose of recovery, this gypsum water is used as the most dilute wash on the filter. In addition to recovery, the use of pond water for filter wash, is also used to keep the entire system in water balance.

Filter cloth plugging is a phenomenon common to all phosphoric acid producers, regardless of the phosphate rock and the type of filter cloth utilized. The only variable is the rate at which the filter cloth will plug. For a long time, the problem was misunderstood because the general thinking was that the plugging was due to calcium sulfate. It was accepted as long as it was not too severe. However, with certain Florida phosphates, for example, having high iron and aluminum contents, plugging is frequent enough to become a severe economic problem. When the frequency of filter cloth change becomes less than 2 weeks, the economic impact due to downtime, maintenance labor, and material costs will have a sizable effect on production costs. Viewed under a microscope, the crystals that embed themselves into the cloth resemble diamonds. These crystals belong to a complex salt composed of $SO_4$, $SiF_6$, and Ca, called chukhrovite. Filter cloths deteriorate because of this plugging, mechanical wear, and thermal deterioration. In tilting pan filters, the cloth is washed with a high-pressure water spray having both mechanical and dissolving cleaning action. But the spray washing time is very short compared to the filtration time. Filter cloth life may be between 3,000 and 4,000 hr (average 3,500 hr). Rotary table filters, because of the gypsum-removing scrolls, have a shorter cloth life of about 700 hr. Tilting pan filter frames currently last at least 10 years and can be repaired for even longer duration.

- Phosphoric acid, as used in most fertilizers, is generally produced by the dihydrate process. The acid produced in this process is normally at a concentration of 27-30% $P_2O_5$. In most cases the acid must be concentrated to a higher level for it to be acceptable as the phosphate feed material for the end fertilizer product. Depending on the fertilizer to be produced, phosphoric acid is usually concentrated to 40-55% $P_2O_5$. Concentration of clear phosphoric acid to marketable strength occurs in vacuum evaporators. The amount of water to be evaporated from phosphoric acid in most plants is generally higher than can be removed conveniently by a single evaporator. Therefore, multiple evaporators are normally installed. The evaporator is a rubber-lined steel vessel that removes water from phosphoric acid to increase its concentration. The acid is circulated through the evaporator and heated with steam through a heat exchanger. The water boils off in a flash chamber that is under vacuum, and is removed by a barometric condenser. The heat exchanger is a vessel containing shell and tube compartments. In the evaporators, acid flows through the tubes and low pressure stream through the shell. Steam transfers heat to the acid through the tube walls. Hot scrub water is a solution containing about 5% sulfuric acid ($H_2SO_4$) made by mixing 93-98% sulfuric acid with pond water. The solution is heated in the evaporators and used to wash lines, pumps, and other vessels in the complex. The primary problem in concentrating phosphoric acid is due to scaling of the heat transfer surfaces. The scale, consisting primarily of calcium sulfate and metallic silica fluorides, is difficult to remove. As the equipment is normally fabricated from rubber-lined steel and graphite, the materials of construction are somewhat fragile and do not allow vigorous descaling.

- Acid clarification is achieved using multiple settling tanks (Figure 9; after Becker, 1989) arranged in a "tank farm." Sludge removal from the acid by settling involves acid quality splitting. Settling can clear one part of the acid only by concentrating sludges in another part. For the purpose of the fertilizer industry or for the current phosphoric acid market, only a sludge-removing clarification is used, so that most of the impurities stay with the acid. The wet-process phosphoric acid impurities can be classified into the following three categories: (1) process impurities, (2) common impurities originating from the phosphate ore, and (3) trace elements originating from the phosphate ore. Sludge is the generic name for a large number of compounds that unavoidably appear as settled solids or deposits when wet-process phosphoric acid is stored. In the absence of proper design and precautionary operating procedures, such sedimentation results in the undesirable plugging of tank outlet nozzles, connected piping (Figure 10), and in-line equipment such as pumps and instrumentation. In the 30% $P_2O_5$ (acid), sludge consists mainly of calcium sulfate and alkaline silicofluorides. But in concentrated acid more compounds precipitate, including complex phosphates. Merchant-grade acid requires a very low solids content, and diammonium phosphate production also requires relatively pure acid. The amount of iron and aluminum in the acid gives a preliminary burden to the producer. Triple superphosphate (TSP) or monoammonium phosphate production does not require sludge separation from the acid. When the total acid production is to be processed for such products, only agitated storage




**Traditional Settling Tank. 1=feed, 2=feed zone, 3=transition zone, 4=compression zone, 5=clear solution, 6=overflow, 7=underflow.**

**Figure 9. Settling Tank Used for Acid Clarification**

**Figure 10. Pipe Removed to Clean Out Sludge**

tanks are required to maintain the solids suspended in the liquid. TSP production is consequently still the most common sludge acid consumer. However, most of the current phosphoric acid plants are built to sell merchant grade acid as a large part of their production.

- Recovery (optional) of the fluorine values of the input rock as $H_2SiF_6$ in off-gas scrubbing equipment.

The process embodies many recycle flows and equipment not mentioned in the above over-simplified summary. Usually, there is much more sodium than potassium in phosphate rock and $Na_2SiF_6$ is the dominant precipitating fluoride compound during the reaction and filtration stage of phosphoric acid production. Every acid producer is familiar with the large, white, scaling plates of $Na_2SiF_6$ which occur along reactor walls (Figure 11), agitator shafts (Figure 12), and especially in the 30% product acid pipes, which have to be washed about once a week. As part of this study, such scaled impeller shafts were inspected using micro-R meters and found not to emit photons above background levels; i.e., this scale does not seem to incorporate any substitute radionuclides. Of particular interest is the concentration of radium in the filtration system, the retention of uranium in the phosphoric acid, and the concentration of the little radium that remains in the acid as the acid is concentrated. Recycle acid flow is usually measured by magnetic flow meters. Nevertheless, flow is not a sufficient control mechanism for the recycle acid; specific gravity also has to be measured in order to indicate the amount of $P_2O_5$ and water recycled to the reactor. Specific gravity can be measured by gauging instruments or by differential pressure measurements in the pump feed tank of the return acid. The nuclear density gauges typically use a $^{137}Cs$ source. The study team noted the positions of installed fixed gauges to avoid any potential conflicts with TENORM measurements.

**Waste Streams.**

- Particulates of phosphate rock discharged to atmosphere from hammermills.

- Gypsum: (contains ~0.5% F). This is discharged, along with spent process water, into ponds or onto waste piles (Figure 13; after Becker, 1989).

- Fluorine: Fluorine values are discharged in form of $CaF_2$, along with $Ca(OH)_2$, slurried in water.

**Figure 11. Scale Build-up in a Phosphoric Acid Attack Tank**

**Figure 12. Scale Build-up Around Agitator Impeller**

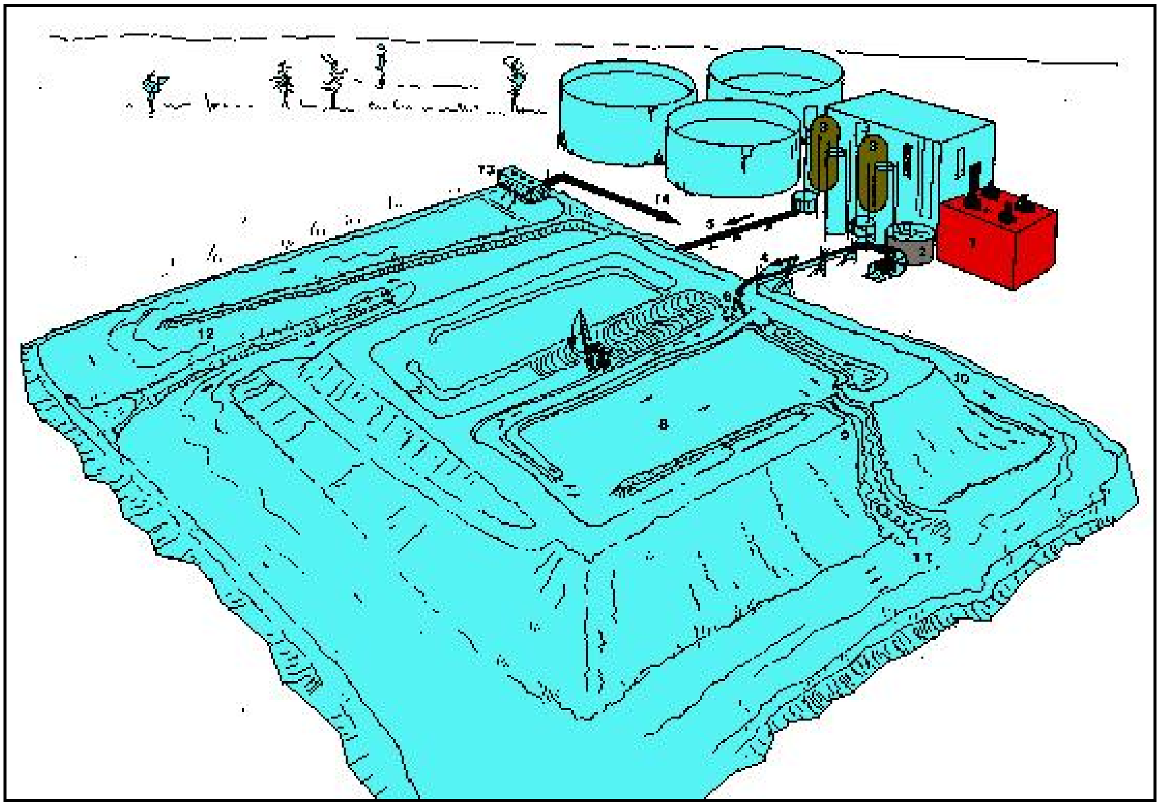


**Figure 13. Gypsum Stack and Associated Chemical Plant**

- Alkaline fluosilicates, $Na_2SiF_6$, $K_2SiF_6$, have a tendency to cause pipe scaling. The part of the phosphoric acid plant most sensitive to scaling is the filter. The acid, when it comes into the vacuum piping system, is subject to sudden cooling because of the vacuum and its subsequent flash-cooling effect. The product acid pipe system builds up most of the scaling. The wash acid pipes are usually safe from that phenomenon unless greater amounts of potassium are found in the rock or arise from other sources. This filter pipe scaling is such that periodic washing is carried out. Most plants shut down once a week, some only every 10 days; others prefer to wash a couple of hours every day. The choice of the periodic washing cycle depends on the dissolution speed of the scale, the amount of scale, and the dimensions of the pipes.

**Dry Products Area NSP Process**

The process converts marketable-grade phosphate rock or phosphate rock concentrates into normal superphosphate (NSP) by reaction with sulfuric acid: $CaF_2 \bullet 3Ca_3(PO_4)_2 + 7H_2SO_4 + 3H_2O \rightarrow 3CaH_4\,(PO_4)_2 \bullet H_2O + 2HF + 7CaSO_4$. The normal superphosphate produced is then either marketed for direct end use as fertilizer or used in making blended fertilizer. The process includes the following sequential steps and equipment:

- Dry grinding jaw crusher, ball-mills or Raymond® mills.
- Mixing ground rock with sulfuric acid and water in cone mixers and pug-mills.
- "Denning," or reaction of the acid-rock paste in specially constructed "dens" or reaction chambers.
- Slicing the "denned" product into transportable lumps.
- Curing the lump product in storage piles.
- Grinding the cured product in tube mills.

**Waste Streams.** Particulate atmospheric emissions of ~200-mesh phosphate rock from grinding equipment is surmised. No quantifying information is available. The quantity is estimated at <1 kg per metric ton of normal superphosphate produced. Effluent scrubber water (containing both HF and $H_2SiF_6$) is run into the beds of limestone to precipitate $CaF_2$. The latter is considered here to be solid waste.

**Dry Products Area GTSP Process**

The process produces triple superphosphate (TSP) by reacting high grade phosphate rock with phosphoric acid: $CaF_2 \bullet 3Ca_3(PO_4)_2 + 14H_3PO_4 \rightarrow + 10CaH_4(PO_4)_2 + 2HF$. The conversion represented by the above reaction is conducted commercially by either of two processes. One uses a process almost identical with that for the production of normal superphosphate. The other employs a combined acidification-granulation technique (see Figure 14). The latter process is described here. GTSP is made by reacting finely ground (85%, -200 mesh) nominal 75 BPL[3] phosphate rock with phosphoric acid in a reaction and granulation circuit. Normal production is about 50 tons per hour. The ground rock is moved pneumatically from the rock area dust unloading facility or the dust silo, to the rock feed bin. “Dust” is high grade, dry, finely ground phosphate rock. From the bin the rock flows into a weight scale. It is then fed into a mixing cone of the #1 reactor where it is combined with 40% phosphoric acid. The mixing cone is a conical-shaped vessel that has 42% acid entering tangentially and 75 BPL ground rock entering the center; thus allowing the rock to be

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[3]Bone Phosphate of Lime - refers to the relative percent phosphate in the rock; i.e., 76 BPL refers to a relatively high grade of rock; BPL $\div 2.185 = P_2O_5$ or BPL x $0.458 = P_2O_5$.

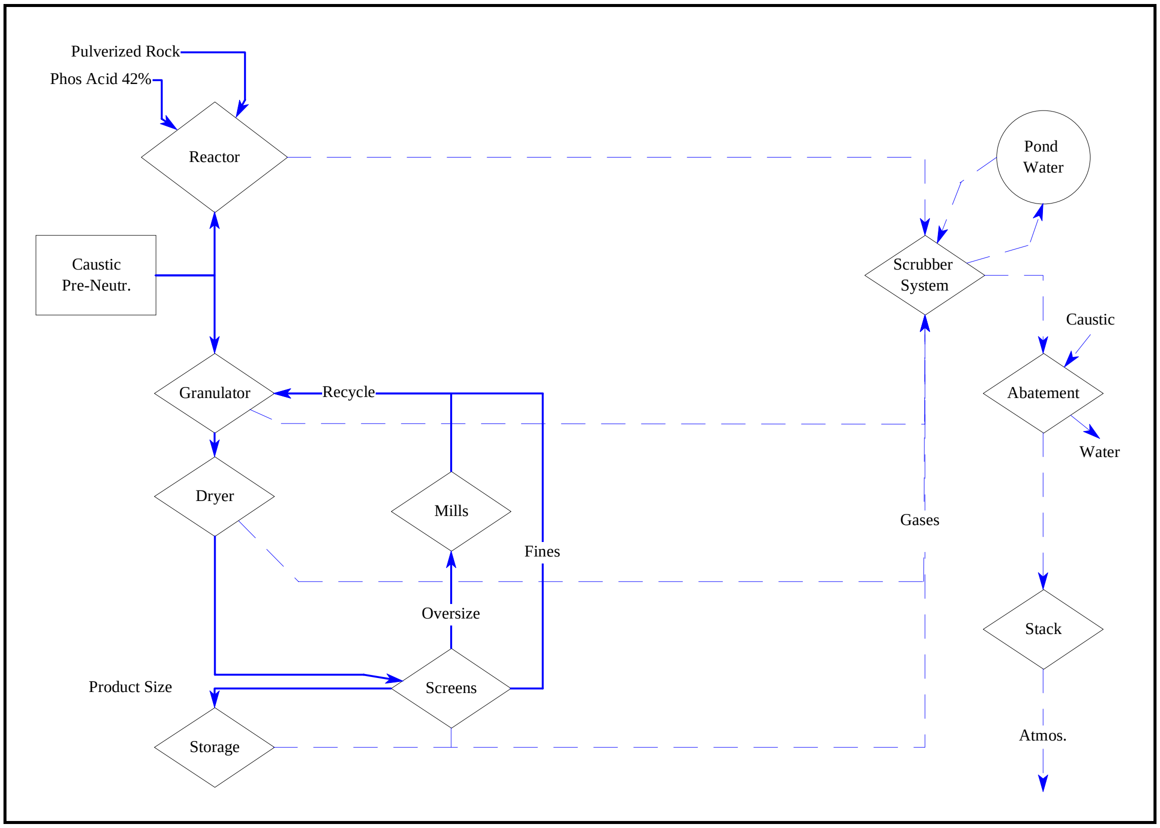


**Figure 14. Block Flow Diagram of GTSP Production**

thoroughly wetted before entering the reactor, for a more complete reaction. This solution is mixed vigorously and overflows to the #2 reactor. Retention time in the #2 reactor enables the chemical reaction to proceed further toward completion. The slurry from the #2 reactor is pumped to the granulator. The granulator is a rotating drum where slurry is sprayed onto, and coats, a recycling bed of dry material. The rolling action causes the particles to stay separate and become rounded. Recycle material consists of (1) undersize product, (2) ground oversize product, (3) product size granules, and (4) other dry product that has been reclaimed from process equipment. The recycle material serves as nuclei to which the slurry sticks to and coats. The triple superphosphate particles recycle through the system until they are coated with enough slurry layers to become round, hard, product size granules.

The material leaves the granulator in a damp mass (approximately 5% free moisture) and falls down a chute into a rotary dryer. Here a co-current flow of hot air evaporates the moisture and heats the granules to approximately 210-215°F. The phosphoric acid and phosphate rock reaction is essentially completed in the dryer. From the dryer, the dried GTSP is elevated to the screening equipment to be sized. Oversized particles flow into chain mills where they are crushed. They then drop onto a recycle conveyor where they are combined with undersize material or fines from the screens. The recycle conveyor transfers this material to the recycle or granulator feed elevator and then back to the granulator. On size material goes to the product bin. Part of it may be used to supplement the recycle system.

The overflow from the product bin is transferred by an elevator and conveyors to storage. It is then reclaimed by the shipping facility for shipment by truck or rail. GTSP production is of radiological significance because phosphoric acid, which contains uranium and lesser amounts of radium as concentrated according to the acid strength, is reacted with high-grade rock which contains full complements of both uranium and radium. External exposure as well as inhalation of fugitive dust are of concern. The process employs the following steps and equipment:

- Pulverizing the phosphate rock in ball mills.
- Pre-heating the phosphoric acid.
- Reacting the rock with acid in a revolving cylindrical reactor; the acid is injected into the burden of recycled fines and input fine rock. Steam is also injected. Granulation occurs in the reaction cylinder.
- Cooling the reactor product in a rotary cooler.
- Curing the cooled product in storage pile.

Usually no attempt is made to beneficially recover the fluorine values evolved as gases from the reactor.

**Waste Streams.**

- Particulates of phosphate rock to atmosphere from grinding equipment are surmised.
- 0.5 to 1.5 $m^3$ of scrubber water per metric ton of triple superphosphate. This flow is discharged into a limestone bed, where an estimated 10 to 12 kg of fluorine per metric ton of triple superphosphate is precipitated as $CaF_2$.

**Production of Ammonium Phosphates and Animal Feed Ingredients**

The processes in this group combine phosphoric acid and in some cases nitric or sulfuric acid with ammonia or with phosphate rock and ammonia to produce different ammonium phosphates (MAP, DAP) and nitric phosphate. These materials are used in blending mixed fertilizers. Refer to Figure 15 for DAP production. MAP and DAP are radiologically similar and carry the radionuclide contaminants of the input phosphoric acid. Creation of fugitive dust during granulation and drying is of concern for the inhalation pathway.

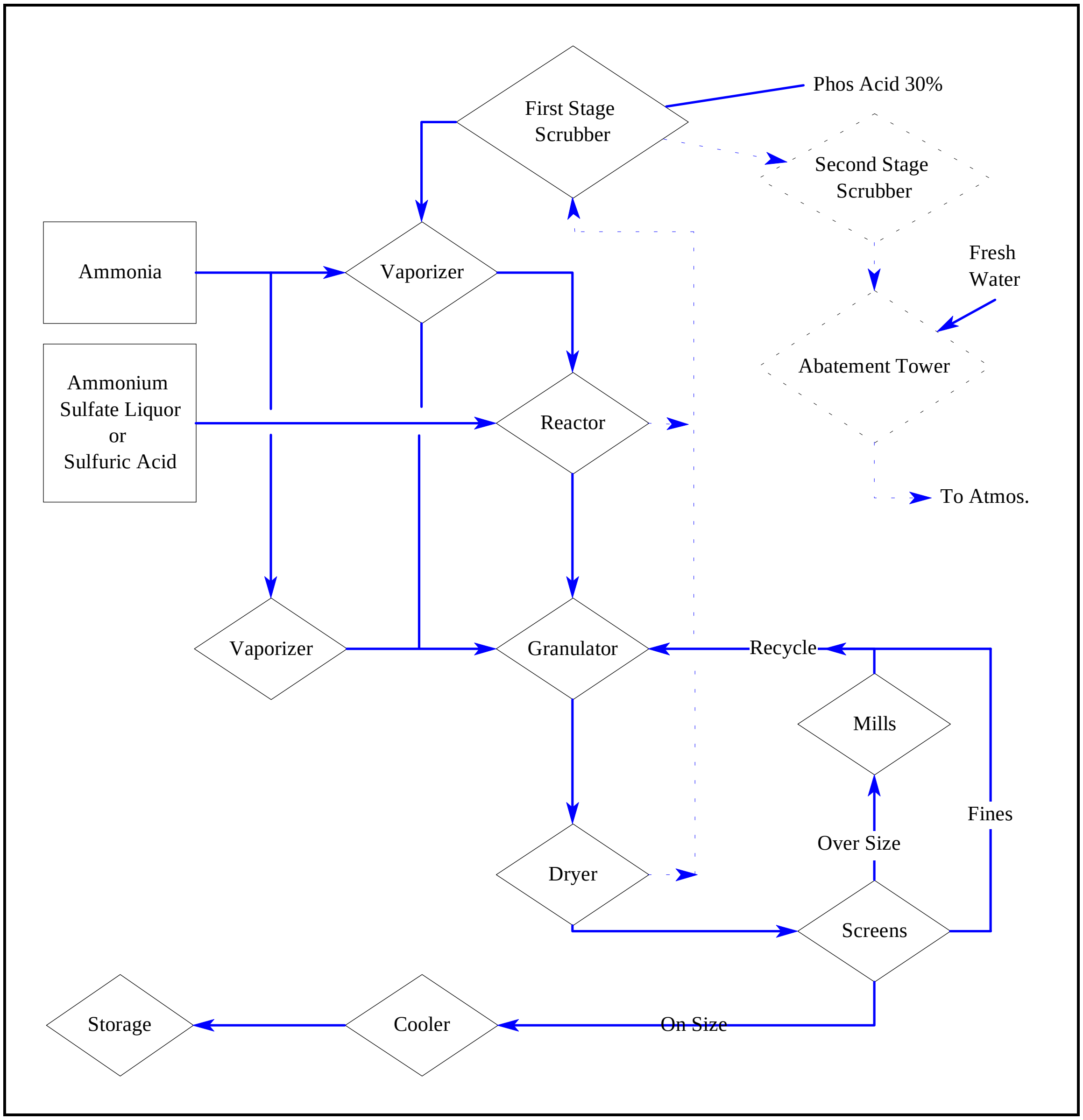


**Figure 15. Block Flow Diagram of DAP Production**

**Neutralization/Granulation/Drying.** This process reacts anhydrous ammonia with phosphoric acid or with phosphoric and sulfuric (or nitric) acid to obtain a slurry product. The slurry is then granulated and dried. The neutralization reaction can be started in a preneutralizer tank and finished in a rotary drum granulator where ammonia is injected into the slurry bed. Another arrangement is to allow the neutralization reaction to go to completion in a series of tanks before feeding the product slurry to a plunger. A third arrangement is to feed phosphoric acid onto a bed of recycled product fines in a rotary drum granulator and to inject ammonia under the bed of fines. In this third arrangement neutralization and granulation occur in the same piece of equipment. Heat of ammoniation evaporates water in all of these arrangements. Product from the rotary drum or plunger granulator is fed to a dryer and then to screens. Fines are recycled to the granulator, oversize is fed to a crusher and either recycled to the screens or to the granulator, and onsize material is conveyed to storage.

**Waste Streams.** Scrubbers are used to decrease ammonia emissions from the ammoniation tank and/or granulator. Incoming phosphoric acid can be used as the scrubbing fluid.

**Digestion/Granulation/Drying.** This process dissolves phosphate rock in nitric acid (or nitric acid plus sulfuric acid and/or phosphoric acid), neutralizes the resulting slurry with anhydrous ammonia, granulates, and dries the product. Normally, rock acidulation is carried out in two or three vessels, followed by up to twelve tanks for ammoniation. The ammoniated slurry is granulated in equipment such as pug mills, rotary drums, and the spherodizer. A rotary dryer is used to dry the slurry product. Screening separates the granules into undersize fines which are returned to the granulator, oversize material which is crushed and either recycled to the granulator or the screens, and onsize material which is conveyed to storage.

**Waste Streams.** Scrubbers are used to decrease ammonia emissions from the ammoniation tanks and/or granulator. Incoming nitric acid can be used as the scrubbing fluid. Effluent scrubber water, containing HF and $H_2SiF_6$ is run into beds of limestone to precipitate $CaF_2$. The latter is considered to be solid waste.

**Animal Feeds Production.** The animal feeds segment of the dry products area meets the market demand for low fluorine, phosphate-based animal feed supplements. Production of up to 2,000 TPD of calcium phosphate and ammonium phosphate products is possible. Also, since the fluorine is removed directly from the phosphoric acid, a valuable purified acid is produced; i.e., merchant grade 54% phosphoric acid that has been defluorinated. Merchant grade differs from run-of-pile (ROP) phosphoric acid by the low solids content due to an aging process and use of settlers and centrifuges in the clarification area. The feeds facility consists of silica unloading, storage and slurry makeup; acid defluorination/evaporation system; limestone unloading, storage and transfer system; processing plant; calcium and ammonium phosphate storage and reclaim; and shipping facilities for bulk shipping by rail and truck and a bagging system.

The first step of the production process is to defluorinate the acid. This is accomplished by recycling the acid (which is charged with ferrosilicon, commonly called "silica") through the evaporators. The fluorine is driven off with the water vapor. Water is added to the process to maintain a 54-56% $P_2O_5$ concentration. After a batch of acid reaches 0.18% F, the acid is pumped to the defluorination storage tank. The silica slurry makeup is also a batch procedure. Silica and water are mixed and controlled at 25 % (±1%) solids. The slurry is then added to the acid in one of the batch tanks. The feeds plant is also a granulation facility. In the production of ammoniated phosphate products, anhydrous ammonia is introduced into the defluorinated phosphoric acid in the reactor (additional ammonia is also added in the granulator in the production of product with higher nitrogen content). In the granulation step, the reactor slurry is pumped to the granulator and is sprayed on the dry recycle material. The product is then dried, screened and crushed. The fines and crushed oversize are used as the recycle. In the production of calcium phosphate, a pugmill is used instead of a granulator, with limestone being added to the phosphoric acid. A pugmill is a troughed vessel 18 ft long, 6 ft wide and almost 4 ft deep. Two inward turning, counter rotating shafts with paddles, uniformly mixes limestone, defluorinated phosphoric acid and recycle material. The mixing causes a reaction which forms small granules. The remaining recycle system is the same as with the ammonium phosphate production. Product-sized material from the screens are transferred to the product silos (e.g., calcium phosphate) or to bulk storage (e.g., ammonium phosphate). It is then reclaimed to the shipping facility for shipment by rail or truck in bulk or bagged form.

**Shipping and Storage Area**

The shipping and storage area as defined in this study consists primarily of dry product storage warehouses, conveyor systems, truck loading platforms and chutes, rail loading, and other physical paths used to move product from production areas to storage and on to market. As shown in Figure 16, MAP, DAP, GTSP, and animal feed ingredients are conveyed to large storage areas where a common practice is coating with oil to reduce dust emissions. Dry product is moved out using a combination of cab-operated automatic reclaimers and payloaders with a series of conveyors, hoppers, lumpbreakers, screens, splitters, and loading bins. Tailgas scrubbers are used as the final gas-cleaning stage of a gas stream before it discharges into the atmosphere. Pond water is sprayed into the gas stream in a packed section of the vessel which provides intimate contact between the gas and water and removes particulates and polluting gases. A dry packed section is then provided to remove any entrained moisture. The exhaust is moved by fans to stacks and released to the atmosphere. Shipping activities require close contact with piles of product several stories in height (approximately a very large conical volume source of radiation), and inhalation of fugitive-dust-bearing radioactive materials (in some cases so dusty that visibility is poor).

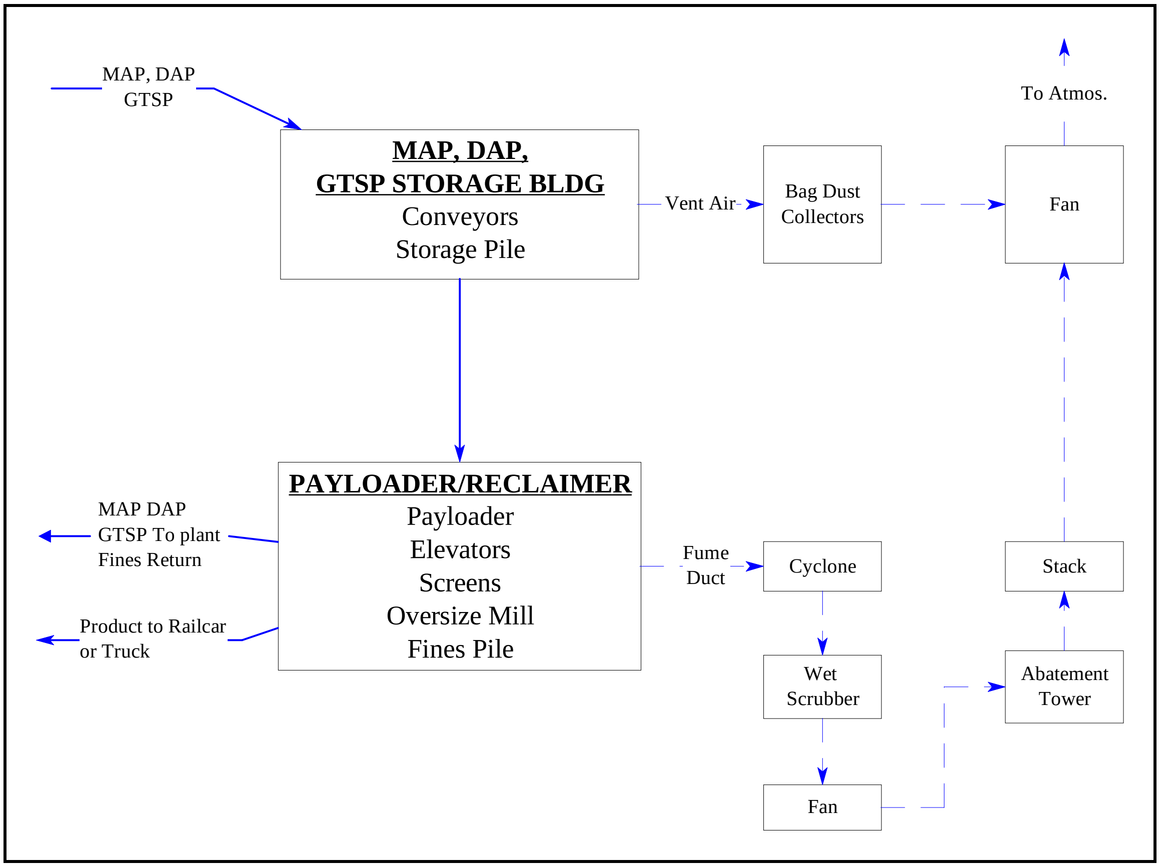


**Figure 16. Block Flow Diagram of Dry Product Shipping and Storage**

# METHODOLOGY

The sampling design was developed to obtain data from multiple locations and their subareas, with approximately equal representation in terms of numbers of participating personnel. Figure 17 displays the sampling strategy. The monitored personnel do not include administrators, and sulfuric acid manufacture personnel. The subareas occupied by the phosphate industry subpopulations of interest were arbitrarily constructed by the study team based on physical commonalities among the various sites. Note that there is some limited migration, indicated by arrows, of personnel between the subareas due to small differences in assigned duties and shift rotations between sites.

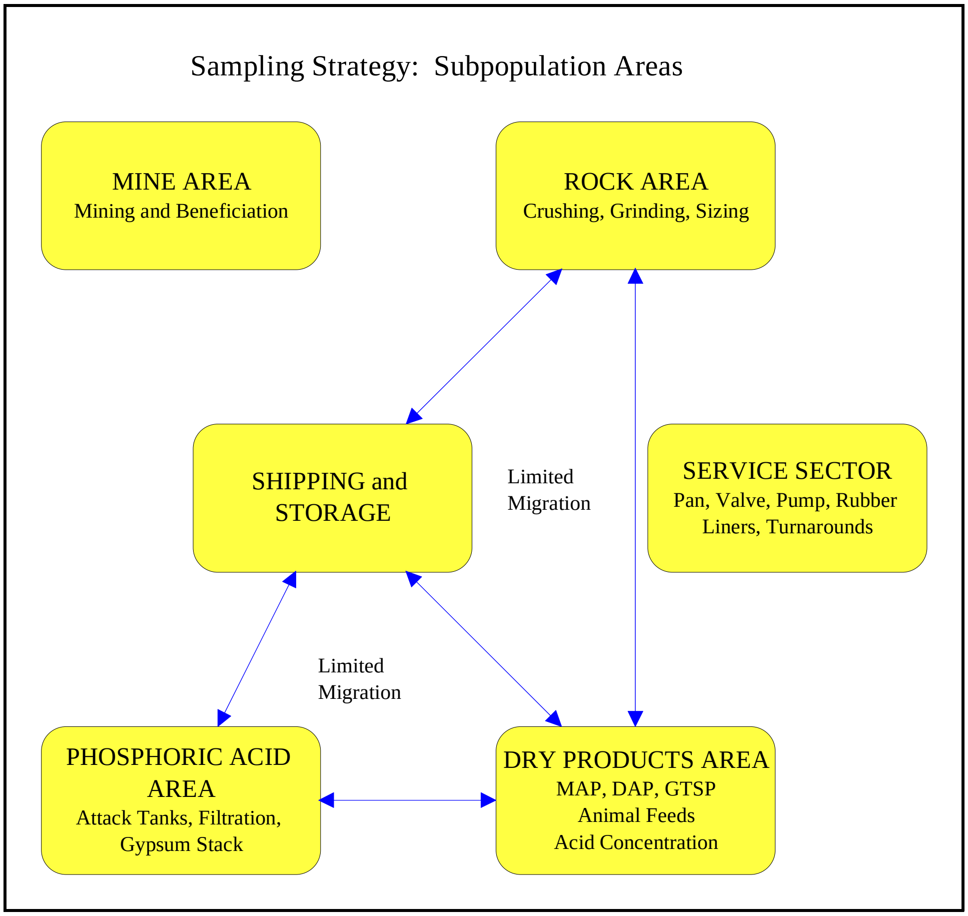


**Figure 17. Sampled Areas for Each Site**

The study as a whole (Figure 18) is made up of multiple sites such that all of Figure 17 comprises one of the satellites connected to the service company hub which represents the only source of common industry workers among the competing companies.

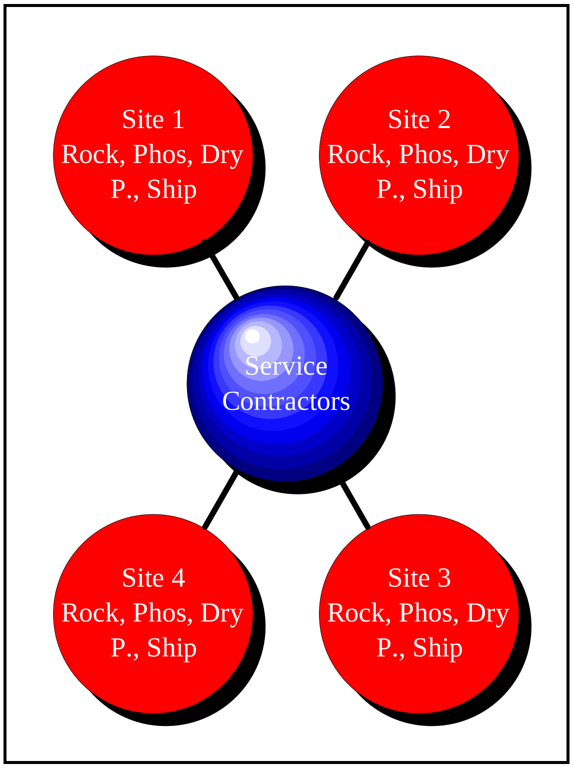


**Figure 18. Multiple Site Approach**

Note that the sample sizes can be viewed in several ways. First, there is the entire sampled population consisting of over 100 industry workers. Second, there are about 30 monitored workers per site depending upon availability and consistency of participation; i.e., individuals were checked to see that they actually wore the assigned badges to flag suspect data, and some badges were lost by the workers. Third, and most important, the workers assigned to the same areas for different sites were pooled to yield the sampled population for the industry for the mine, rock, phosphoric acid, dry products, service, and shipping subareas to yield about 30 workers for each subarea.

## WORKER TIME, MOTION, AND POSITION INFORMATION

An accounting of time integrals, motions, and positions relative to contaminated objects for workers performing specific jobs was made. Some information was derived from existing data described in the Introduction section, but more often, on-site interviews were conducted with workers, inspectors, and others who perform or observe the procedures. In some cases, it was necessary to obtain more precise information from field observations in order to estimate radiation doses to various workers. This was done with on-site measurement of time, motion and distances for quantification and dose assessments.

## Introduction

The time/motion concept originated as an industrial practice conducted to improve efficiencies of procedures and workers. For the purposes of this study, efficiency is replaced in emphasis by behavior and spatial orientation of workers in the TENORM environment. Through time and motion studies, specific common tasks can be identified with quantifiable exposure results. The more those tasks can be standardized, the more reliable the quantitative measurements become.

## Time/Motion Methodology

Working with the radiation safety officer (RSO) from each plant, the project team identified the study population; i.e., the job classifications likely to involve TENORM contact. Although specific job titles are inconsistent between plants, job assignments are common in the industry and similarly linked to individuals by necessity. A representative sample (about one-quarter to one-third) of each identified job classification was orally interviewed by one project team member using a standardized questionnaire (attached as an addendum in Appendix B). Individuals under the same job classification were interviewed in replicate fashion, because duties and techniques to accomplish them can vary from person to person.

Certain duties identified in the interview process were further investigated with time/motion observations in the working environment. In this study, assessments were conducted for filter cloth change-outs, attack tank hydroblasting, filter pan air hammering, gypsum filtration overhaul, and a variety of turnaround activities. Observations were usually made at a distance to avoid interference. However, at times it was necessary to mingle with the workers to take direct exposure rate measurements and collect air samples that were time-limited to a certain task. Movements of workers and descriptions of their activities were timed and recorded on a hand-held cassette recorder, and later transcribed to paper. Simple diagrams were drawn as needed, and a limited number of photographs were allowed.

## DATA COLLECTION

Data were collected to assess radiation doses from external and internal pathways (refer to Figure 19). The methods used to obtain measurements and perform calculations resulting in extrapolated annual doses are explained in the subsections that follow.

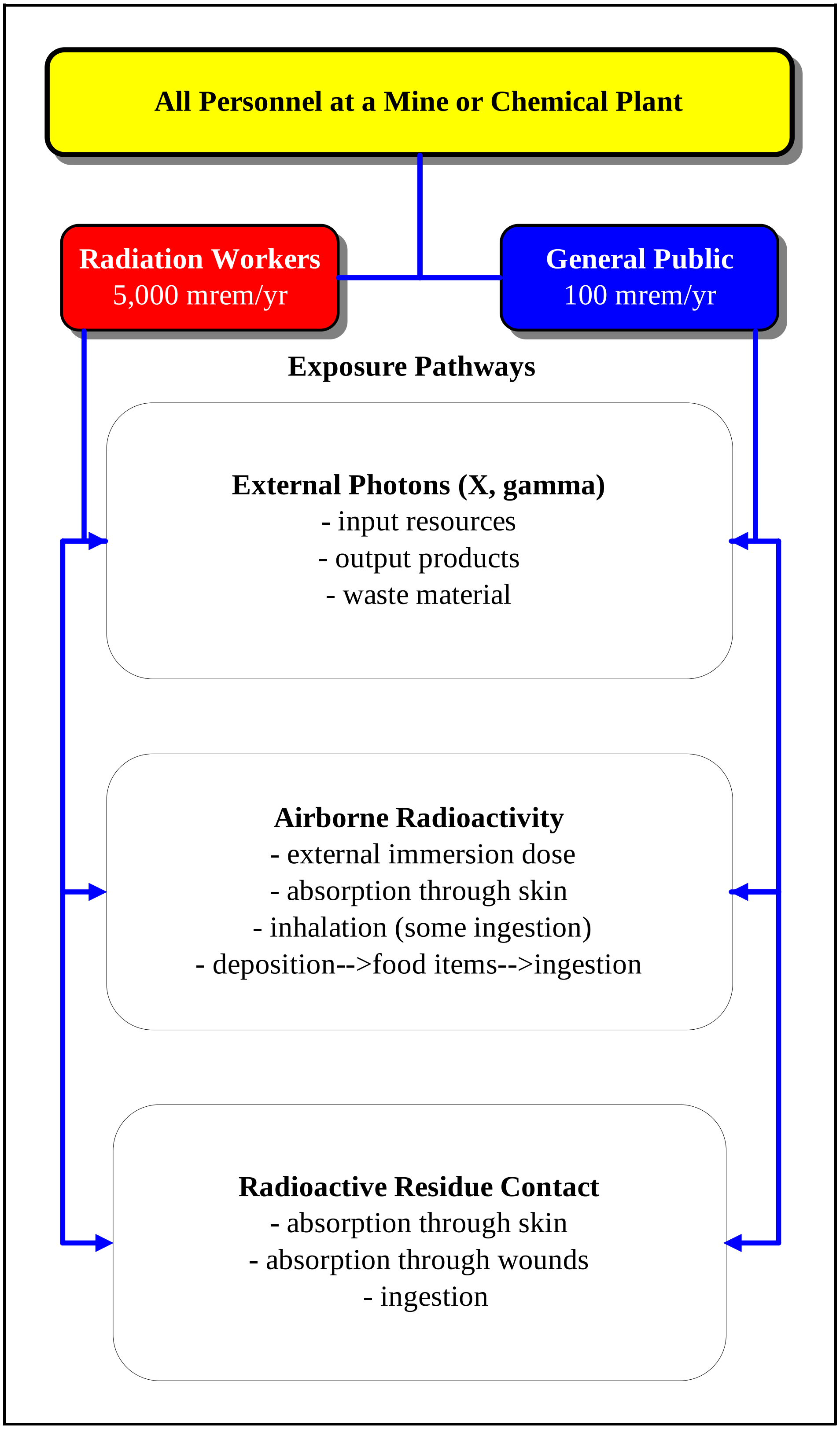


**Figure 19. Dose Assessment Pathways**

**External Dosimetry**

Radiation absorbed by the body from external sources may be encountered *directly* from the radiation source (a quantity of radioactive material), or more often *indirectly* due to attenuation and scatter (deflection with loss of energy) between the source and receptor (the worker).

**Sources.** Source material is any input, product, or waste material that contains TENORM radionuclides of the $^{238}U$, $^{232}Th$, or $^{235}U$ series. These sources include mined matrix, post-beneficiation processed rock, slurry in pipes, attack tank slurry, phosphoric acid of various percentages and radionuclide activity concentrations, TSP, MAP, DAP, animal feed ingredients, gypsum, and other wastes. The source emissions are alpha particles (of negligible concern as an external hazard), beta particles, gamma rays, and X-rays at a wide spectrum of abundances and energies. For example, Figure 20 illustrates the diversity and relative importance of uranium series gamma emissions.

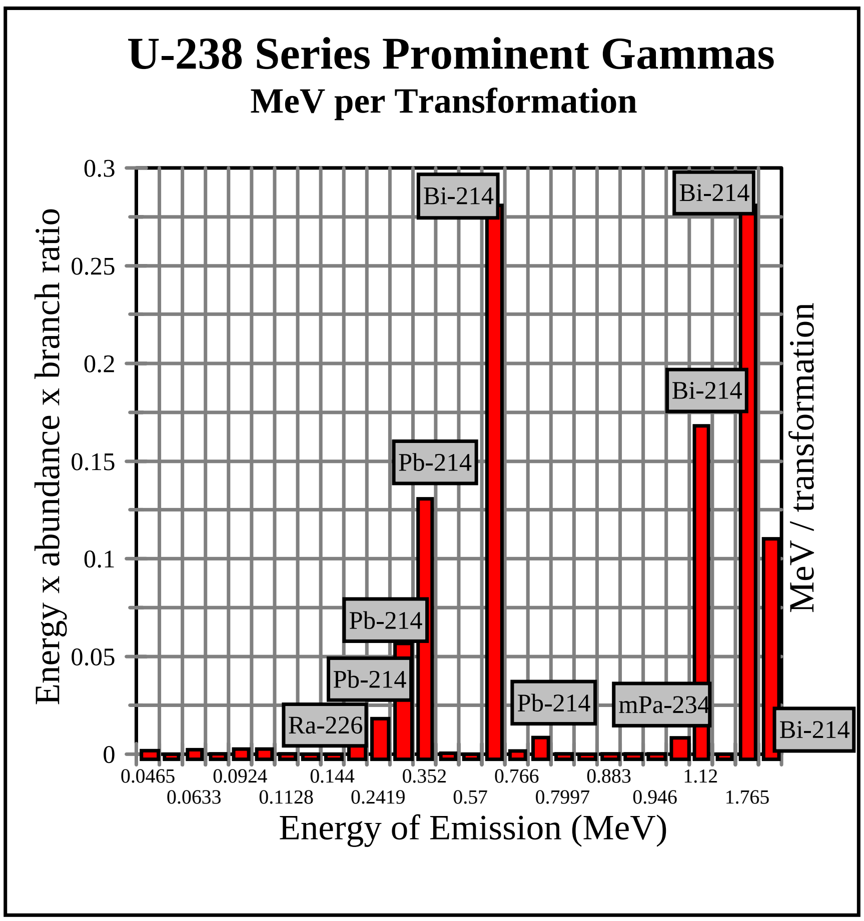


**Figure 20.** **U-238 Series Prominent Gammas and MeV per Transformation**

The "power rating" of MeV per transformation in Figure 20 was derived by multiplication of the gamma emission energy in MeV by the fraction of transformations that occur by that decay mode and by the abundance (another fraction) of that particular gamma emission energy during the decay.

**Source geometries and shielding.** Sources may be present as unconfined materials as small as suspended particulate dust to as large as a gypsum stack of radium-bearing sulfates. Source material may also be contained in vessels such as pipes, sumps, tanks, filter pans, etc. Furthermore, there is a shielding effect from the material containing the radionuclides (self-absorption), any moisture that may be present, the containing vessel (steel, graphite, alloys, etc.), and objects between the source and receptor. This means that it is likely that the energy spectrum will be degraded; i.e., the photons will lose much of the energy from their origin along the path to the receptor.

**Receptors.** The human receptors in this study were predominantly adult males, and fewer adult females. No declared pregnant females were encountered in this study. If that situation had occurred, the fetus would have been the limiting receptor. The orientations of the receptors to the radiation field are PA (posterior to anterior), AP (anterior to posterior), lateral, rotational, isotropic, submersion (in contaminated air), and standing on contaminated ground.

**Radiation field characterization.** During initial field reconnaissance, the sampling methodologies were tested in a small selection of the facilities planned for the larger study. These preliminary data were available early to the project team members to feed into the various other task developments.

The HRS study (Keaton, 1987) primarily addressed the radiological hazards associated with the gypsum filtration systems. It included inspections, measurements, and sampling at two phosphate companies' phosphoric acid plants and at five machine shops servicing the phosphoric acid-related equipment (specifically, filter pans). In order to adequately address the current proposed TENORM regulations, the present study identified the radium-bearing scales on equipment in operation outside of the confines of the filtration areas.

The sampling protocol included the following measurements:

1. Gamma exposure rates.

   - Using micro-R meters intercalibrated to a pressurized ion chamber (PIC).

   - Measurements were made of all typical work areas throughout each facility.

- Measurements were made of equipment determined to have been a source of elevated gamma readings in the work area surveys.

- TLDs were used to monitor integrated exposures.

2. Sampling during specific tasks where there is a potential for radiation exposure.

    - Gamma surveys - gamma exposure rate measurements were made at locations to coincide with worker positions during these tasks.

    - TLDs were used to monitor integrated exposures.

3. Sampling of specific equipment which may be a source of exposure.

    - Gamma surveys - gamma exposure rate measurements were made at the surface and at one meter from the specific equipment.

    - Deposition/precipitate samples - Samples of accumulated build-up of scale or precipitate, and product were taken from locations throughout each facility and at various stages of chemical processes when and where accessible. These were analyzed for radionuclides using gamma spectroscopy.

**Conversion of Ionization in Air to Equivalent Dose.** Assessment of equivalent dose from the external exposure pathway is best accomplished by placing personal dosimeters directly on the individuals whose dose is of interest. This is commonly done using TLDs. In the absence of this type of dosimetry, or as a separate confirmation, investigators often use survey instruments to measure exposure rates and estimate equivalent dose to individuals in that radiation field. The common survey instrument of choice in the phosphate industry is the sodium iodide (NaI) scintillation survey meter (micro-R meter), due to its rugged construction and high efficiency for detecting photons. These instruments are energy-dependent; i.e., at a given energy the exposure rate indicated by the meter may not (and generally *does not*) indicate the true exposure rate. In fact, for micro-R meters the response is much higher than the true exposure rate over the lower energy range encountered with TENORM radionuclides. This is clearly evident in Figure 21 where the response curve only intersects the 1.00 axis at one point. Another problem is the directional response of the instrument; i.e., the orientation of the meter in the radiation field affects the indicated response. A final problem is rate-dependent response. Under conditions of high radiant flux (many gamma and X-rays impacting the NaI crystal per unit area and time) the meter indication may not be true.

Figure 21 displays the responses of the micro-R meter, the PIC, and the Bicron micro-rem meter. A true response would be a horizontal line at 1.00 relative response. The Bicron meter has a flat response from 0.05 to 1 MeV (vendor data) using a tissue-equivalent organic scintillator for detection. Note that this instrument differs from the other two in that the indicated response is in dose equivalent (µrem) instead of exposure (µR). The manufacturer has already applied a dose conversion factor of one, which may or may not be appropriate for the phosphate industry TENORM situation. The instrument is calibrated to the exposure rate due to a known source of $^{137}Cs$. The dose equivalent rate is conservatively assumed to equal the exposure rate (µrem/hr = µR/hr). The PIC also displays a fairly linear response over a wide range of energies, but also suffers at low energies and will not respond to photons that are not energetic enough to penetrate the instrument housing. Since the PIC is large and bulky (designed for stationary use in environmental monitoring), the micro-R meter is the common instrument of choice in the industry. The response problems of energy-dependence and rate-dependence are partially alleviated using a field calibration to the PIC. The instruments are taken to the TENORM site and the sensitive volume of the PIC is situated one meter off the ground in a radiation field. The exposure rate is recorded after sufficient time for stabilization. The PIC is then removed and the micro-R meter is held in the same position formerly occupied by the sensitive volume of the PIC until a stable exposure rate is recorded. This procedure is repeated at different locations until numerous readings are taken that cover the full range of all the scales of the survey instruments being calibrated. Regression analysis is performed to generate a correction algorithm for each instrument and scale, and the best-fit regression line is plotted as seen in Figure 22. This graph shows data graphed to the maximum exposure rate of the PIC. Although the survey meter scale extends to higher exposure rates, the calibration is not valid beyond the last PIC measurement. For lower scales, the entire range is graphed.

Once a reliable exposure rate is acquired, the remaining tasks are conversion to absorbed dose (mrad) and dose equivalent (mrem). The conservative approach is to take the absorbed dose to a volume of standard air of 0.877 rad per roentgen and apply a correction for the interaction of photons in tissue-density material to yield approximately 0.95 rad (and rem) per roentgen. This factor may overestimate the absorbed dose in many situations, as can be seen in Table 10 and Figure 23, which are based on more rigorous calculations found in International Commission on Radiological Protection (ICRP) Report No. 51.

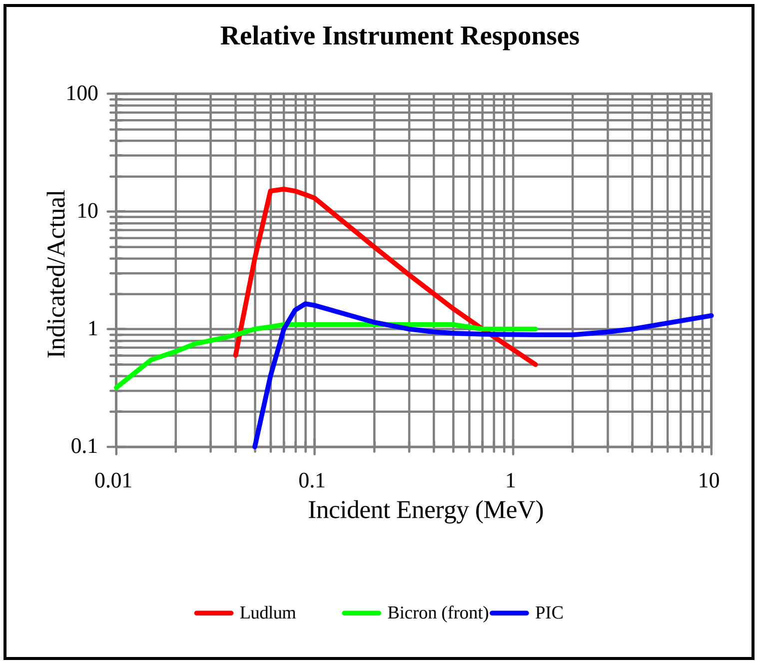


**Figure 21. Instrument Responses Compared to Actual Ionization in Air**

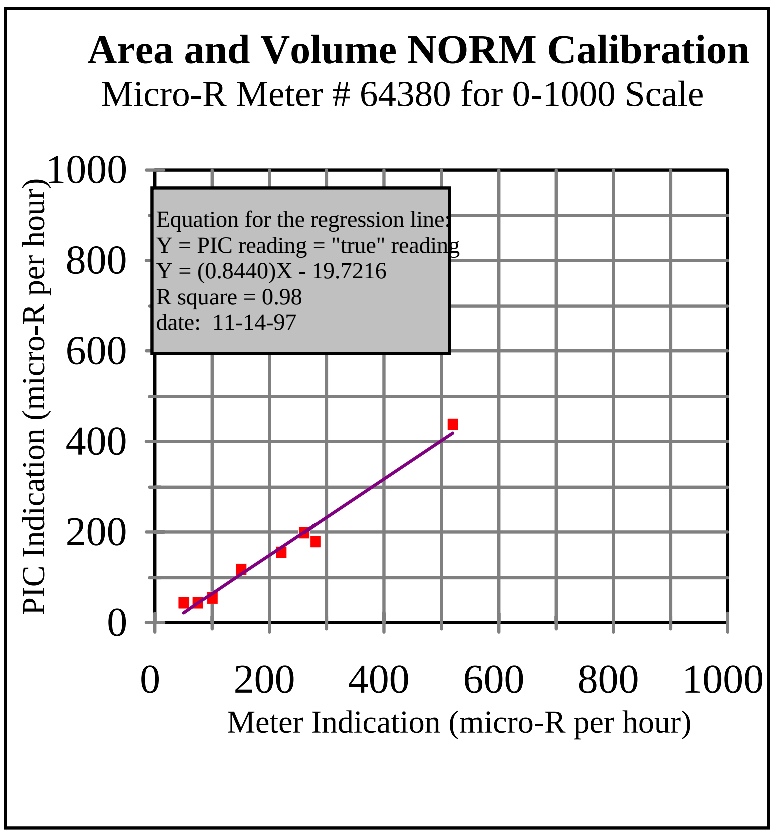


**Figure 22. Micro-R Meter Calibration Against the PIC**

In the energy range of 0.05 to 2 MeV in Table 10, the average dose conversion factor ranges from 0.648 to 0.874 rem/R. It is likely that the average DCF for phosphate TENORM application falls within this range unless the typical energy spectrum is tremendously degraded. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) recommends a DCF of 0.7 rem/$rad_{air}$ for adults in their publications from 1982 to 1993. Therefore, the full conversion from roentgen to rem is:

$$(0.877\ rad_{air}/R) \times (0.7\ rem/rad_{air}) = 0.6\ rem/R.$$

This falls slightly below the range described above and may very well be correct, however the UNSCEAR DCF of 0.7 rem/$rad_{air}$ is scientifically ill-conceived. The 1982 publication is the origin of the DCF as reported in the later publications (and even this one cites Annex A of a 1977 report). At that time, data necessary for derivation of the DCF were in short supply and ICRP-51 was not yet published. The Committee made a best guess based on available information, but more recent data makes continued reliance on that number illogical. The 1982 report derived this value by averaging various disparate literature values as seen in Table 11.

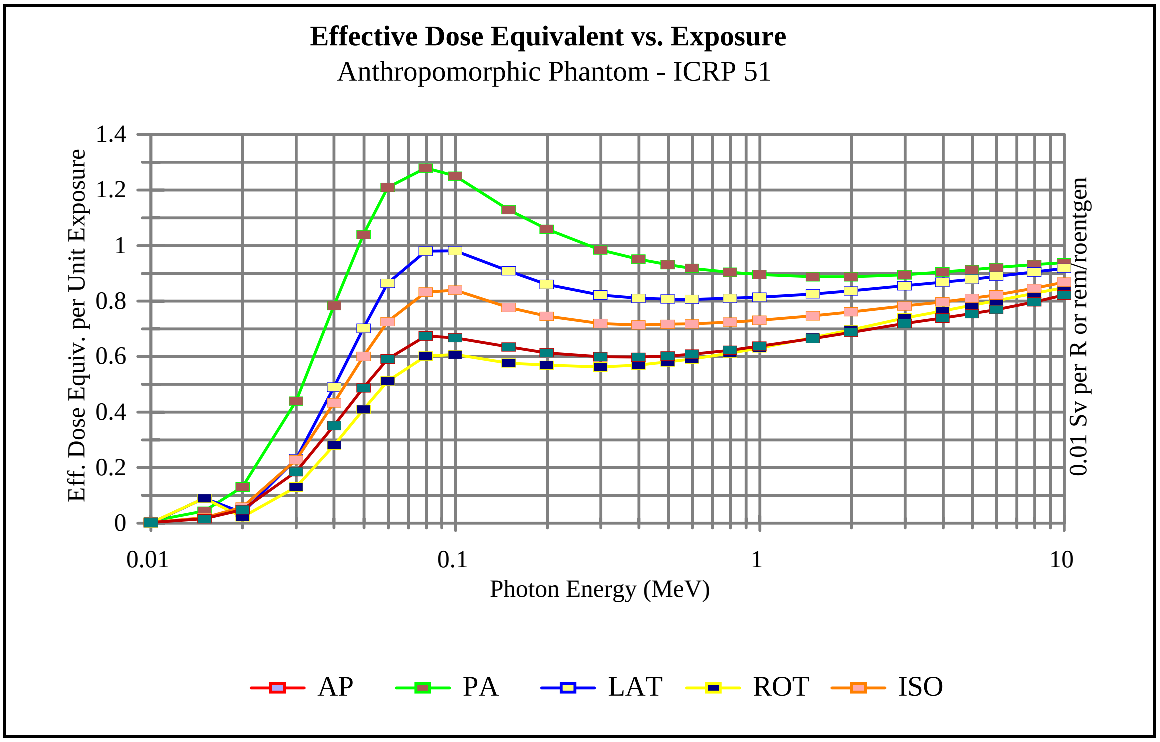


**Figure 23. ICRP 51 Effective Dose Equivalent per Unit Exposure (rem/R)**

**Table 10. ICRP-51 H (rem)/Roentgen Data and Averages**

| Energy (MeV) | Orientation | | | | | Avg. |
|---|---|---|---|---|---|---|
| | AP | PA | LAT | ROT | ISO | |
| 0.01 | 0.0070 | 0.0000 | 0.0020 | 0.0030 | 0.0030 | 0.003 |
| 0.015 | 0.0440 | 0.0900 | 0.0900 | 0.0200 | 0.0160 | 0.052 |
| 0.02 | 0.131 | 0.0392 | 0.0234 | 0.0587 | 0.0495 | 0.060 |
| 0.03 | 0.440 | 0.232 | 0.131 | 0.228 | 0.187 | 0.244 |
| 0.04 | 0.784 | 0.490 | 0.281 | 0.434 | 0.352 | 0.468 |
| 0.05 | 1.04 | 0.703 | 0.410 | 0.601 | 0.488 | 0.648 |
| 0.06 | 1.21 | 0.865 | 0.513 | 0.726 | 0.592 | 0.781 |
| 0.08 | 1.28 | 0.980 | 0.602 | 0.833 | 0.675 | 0.874 |
| 0.1 | 1.25 | 0.982 | 0.608 | 0.840 | 0.668 | 0.870 |
| 0.15 | 1.13 | 0.909 | 0.577 | 0.778 | 0.635 | 0.806 |
| 0.2 | 1.06 | 0.861 | 0.569 | 0.746 | 0.614 | 0.770 |
| 0.3 | 0.984 | 0.823 | 0.563 | 0.720 | 0.600 | 0.738 |
| 0.4 | 0.951 | 0.811 | 0.570 | 0.715 | 0.599 | 0.729 |
| 0.5 | 0.932 | 0.808 | 0.581 | 0.717 | 0.602 | 0.728 |
| 0.6 | 0.919 | 0.807 | 0.592 | 0.719 | 0.609 | 0.729 |
| 0.8 | 0.904 | 0.810 | 0.613 | 0.725 | 0.623 | 0.735 |
| 1 | 0.896 | 0.815 | 0.632 | 0.732 | 0.638 | 0.743 |
| 1.5 | 0.888 | 0.827 | 0.670 | 0.748 | 0.666 | 0.760 |
| 2 | 0.888 | 0.837 | 0.698 | 0.762 | 0.688 | 0.775 |
| 3 | 0.895 | 0.855 | 0.739 | 0.783 | 0.720 | 0.798 |
| 4 | 0.905 | 0.868 | 0.765 | 0.797 | 0.739 | 0.815 |
| 5 | 0.914 | 0.879 | 0.785 | 0.810 | 0.755 | 0.829 |
| 6 | 0.921 | 0.889 | 0.802 | 0.822 | 0.770 | 0.841 |
| 8 | 0.932 | 0.905 | 0.828 | 0.846 | 0.797 | 0.862 |
| 10 | 0.939 | 0.918 | 0.849 | 0.869 | 0.822 | 0.879 |
| Avg. | 0.850 | 0.720 | 0.540 | 0.641 | 0.556 | 0.661 |

**Table 11. Derivation of the UNSCEAR DCF**

| DCF Value ($rem/rad_{air}$) | Comment |
|---|---|
| 0.82 | 1977 Annex A value in outdoor air |
| 0.69 | 1977 Annex A value in indoor air |
| 0.7 | Effective dose equivalent to absorbed dose in air for clouds of gamma emitters of about 1 MeV |
| 0.6 | Gonads only for a semi-infinite cloud |
| 0.7 | Gonads only for an isotropic field |
| 0.8 | Gonads only for a normal field |
| 0.72 | Average of the six values above |

The first two values are described as conversions to "absorbed dose rate in the body," the third is effective dose equivalent, and the last three are for gonads only (not the organs of the whole body) and three different source-receptor geometries. In short, there are at least three different quantities being averaged into one value that is called an effective dose equivalent DCF. Furthermore, the main sources in the phosphate plants are solid volume sources; e.g., pipes, tanks, slabs, etc. which are not analogous to the four cloud geometries. The "outdoors" exposure may be mainly a ground source, and the "indoors" conversion likely involves shielding assumptions not applicable to phosphate plants. The third value in the table is based on only one energy (which is probably high for this TENORM situation) and the wrong source geometry (again, a cloud of gamma emitters). In conclusion, the committee averaged inappropriate DCFs, assumed they would hold for all energies and source geometries, and applied them to both sexes. The 1988 UNSCEAR report simply cites the 1982 report, and the 1993 report again cites the 1982 report and augments that value with reference to more recent research by a single team which claims an overall DCF of 0.72 for effective dose per unit air kerma (Sv per Gy) from terrestrial gamma rays (K-40, Th-232 series, U-238 series). Once again, this is inappropriate because kerma and absorbed dose are different quantities and are calculated differently.

During this study, industry participants offered other publications in support of the UNSCEAR value. One is an article that reports the effective dose equivalent responses based on different beam orientations for plane photon sources on the soil surface (Chen, 1991). The problems are: the data are from Monte Carlo calculations only (no measurements), for photon emitters in soil only with a density assumption of 1 - 2 $g/cm^3$ with uniform distribution, and the results *do not* support the UNSCEAR value. From 0.05 to 2 MeV the $rem/rad_{air}$ conversions are: AP (>1 to 1.4), ROT (>0.6 to >0.9), and ISO (>0.5 to 0.8). The majority of the data points are greater than 0.7 $rem/rad_{air}$.

**Routine External Dose Monitoring.** It should now be clear that the use of survey meters to determine exposure rates and the application of conversion factors present challenging uncertainties. As found later in this section, a more reliable method was chosen to assess the majority of external doses in this study. First, a few items are discussed in review. The relative abundances and activity concentrations of TENORM constituent radionuclides vary according to position in the production process; e.g., mining, phosphoric acid production, and shipping, as described in the discussion for time/motion observations. These radionuclides emit alpha particles, beta particles and associated bremsstrahlung X-rays, and photons (gamma and X-radiation). The radiation absorbed in tissues beneath the dead layer of human skin is due to penetrating gamma and X-rays and the more energetic portion of the beta spectrum. These emissions may be encountered directly by contact with the source material, less directly after some attenuation in air, or indirectly after attenuation and scattering by objects around and in the path between the source and receptor (worker).

The industry "gold standard" for measurement of absorbed dose to the worker is the lithium fluoride (LiF) TLD. This dosimeter is widely used in the nuclear industry because of its similarity in response to tissue over a wide energy range (see Figure 24). The differences in response are resolved by algorithms empirically derived by the manufacturers. Note in the figure that $H_{eff}$ is the effective dose equivalent, D is absorbed dose, and R is exposure in roentgens. As previously discussed, the problem with the LiF TLD is its lack of sensitivity at low doses typical in the phosphate industry. While measurements can be made to a single mrad (or mrem), doses less than ten mrad are not reported due to lack of confidence. For this reason, participants in this study were double-badged with LiF TLDs and more sensitive (tenths of mrem) aluminum oxide carbon ($Al_2O_3$:C) TLDs. This dosimeter fully meets the American National Standards Institute (ANSI) performance, testing, and procedure specifications. The aluminum oxide carbon dosimeter is designed for environmental deployment, and in that regard is more rugged and durable in the field. The drawback is that it does not directly report absorbed dose to a human, and therefore must be corrected.

The badging effort covers six main areas: mine, rock, phosphoric acid, dry products, shipping, and service. The data can be considered as a whole, or in these sets or further subsets of similar duties. The larger sets are more statistically reliable not only because of the sample size, but also due to differences in job classifications between plant sites. For example, phosphoric acid laborers may be assigned different duties from site to site, but the entire set of phosphoric acid workers covers essentially the same duties within their work force and is more reliably scrutinized.

The sampling protocol was developed to yield a statistically defensible number of participants in each of the six main areas derived from at least five sites. Each participant was badged with one LiF TLD for approximately three months, and a series of three aluminum oxide carbon dosimeters (Landauer X9) at least two of which were concurrent to the total LiF period. This co-badging provides an intercomparison between the sensitive X9

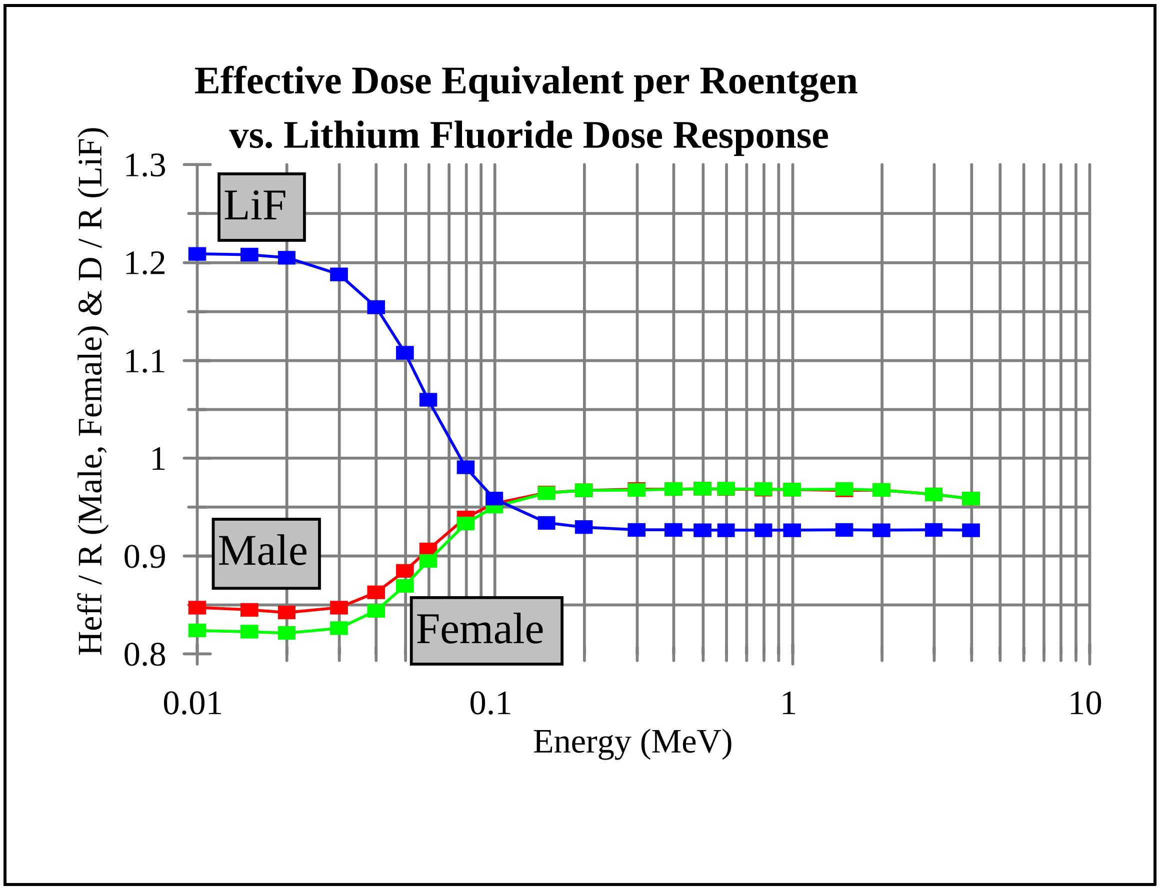


**Figure 24. Dose Response per Roentgen of LiF Compared to Human Tissue Over a Broad Range of Energies**

and the LiF "gold standard." Another advantage is that multiple data sets are available for analysis: (a) the LiF data set, (b) the X9 data set as a total with all three sets combined, and (c) each X9 set as an individual grouping giving three replicates.

**Internal Dosimetry**

1. Air sampling (hi-vol) was performed at specific locations with subsequent radionuclide analysis.

   - Sampling was performed both in areas suspected to have elevated air concentrations of Ra-226 (e.g., phosphoric acid filter areas, filter pan cleaning areas, etc.) and additional working areas.

   - Sampling was performed during specific operations which may elevate air concentrations, such as filter cloth change-out, filter pan cleaning, tank clean-out, and other operations discovered during this study.

- Samples were analyzed for gross alpha and beta, and a subset were chosen for gamma spectroscopy analysis to determine radionuclide constituents.

- Radon samples - in enclosed areas or those areas with limited ventilation, short-term E-Perm Electret ion chambers were used to sample for radon.

2. Sampling during specific tasks where there is a potential for radiation exposure.

   - Hi-vol air samples - samples were taken in the vicinity of the specific task being performed. Gross alpha and beta analysis were performed on all samples. Gamma spectroscopy was performed as necessary.

   - Personal air monitors - workers were enlisted to wear personal air monitors while performing these specific tasks. These air samples were collected on filters which were analyzed for gross alpha and beta.

## DATA ANALYSIS

The subsections that follow explain in detail how the collected data was adjusted for background radiation, and limited so that unrealistically low numbers (like negative absorbed doses) would not occur. Also included are technical discussions when necessary to clarify choices made by the project team regarding assumptions and calculations.

### External Exposure Analysis

Review of the personnel monitoring data supplied by the participating industry companies revealed that most monthly and quarterly doses were below the reporting level of the LiF TLD. This problem and a method for dealing with it are described in Appendix B (Dealing With Censored Data). A more sensitive dosimeter was chosen for this study as described previously. The data derived from these dosimeters were corrected for background radiation and transit to and from the site. A rigorous treatment of the correction techniques can be found in Appendix B under Dosimeter Badge Corrections.

### Internal Dose Analysis

Assessment of internal dose requires knowledge of three quantities: a) working hours in the breathing zone, b) gross alpha and beta concentrations in air (µCi/ml), and c) a breakdown of the radionuclide constituents in the airborne particulates and their fractional contributions to the gross alpha and beta activities. Once these quantities are measured, inhalation DCFs are applied to calculate the dose from that pathway. The working hours were determined in the time and motion portions of the study. The gross alpha and beta concentrations in air were determined by collecting air samples with medium- or high-volume pumps pulling ambient air through paper filters with sub-micron pore sizes (see Figures 25 and 26). These filters were held to allow short-lived radon progeny to fully decay, and then counted for gross alpha and beta activities as described in Appendix B. Since there is no adjustment for particle size in this study, the inhalation doses are conservative; i.e., tend to be greater than the actual dose. Thus, the treatment of all radioactive particles collected on the filter as respirable dose contributors, when it is likely that a significant portion may be larger in terms of activity median aerodynamic diameter (AMAD). In fact, greater than 90% of particles exceeding 10 μm AMAD are deposited in the nasopharyngeal region of the respiratory tract, where the dose would be minimal. Analysis of dust deposited in the working environment, the input materials, or the product materials in the area provide an approximation of the airborne dust collected on the paper filters. These much larger quantities (hundreds of grams) provide the breakdown of radionuclide fractions. Figure 27 depicts preparation of samples in Marinelli beakers. These samples are measured for gamma activity using a high-purity germanium system (HPGe) as seen in Figure 28. The next subsection details the method used to quantify the constituents.

**Prediction of gross alpha and gross beta activity in NORM samples.** In the mid-1980s Dr. Bolch, of Environmental Radiation Group (ERG), was asked to devise a method to predict the gross alpha and gross beta activity in a solid sample. The particular case is confidential, but the sequence of questions applies to many TENORM and natural background situations. Well water samples were submitted to a laboratory for measurement of gross alpha and gross beta activity. This is a rather straightforward analytical technique with a reasonable accuracy for waters with limited dissolved solids, such as drinking water. However, as the dissolved solids (and sometimes undissolved fines) increase, as in some monitor wells, there is a tradeoff on the limit of detection. Too large an aliquot and the solids on the planchet result in very high self-absorption and a high correction factor with its associated errors. Reducing the aliquot to very small volumes avoids some of the self-absorption and corrections to the results. However, this process reduces the activity on the planchet and thus increases the counting error. More important, since the answer in the technique is to be a concentration (pCi/liter, for example) the volume in the denominator becomes smaller and smaller with its direct effect on the MDA (minimum detectable activity) and errors.

The investigation was to determine the source of the activity in the water samples which were taken up gradient and down gradient from a coal ash source as well as some baselines from other locations. The results were inconclusive. The geological consultant suggested core samples of all locations, since some natural geological lenses containing the natural radioactive series (uranium, thorium, $^{40}K$) were a potential source in both the undisturbed and the disposed coal ash. Samples of the ash and the cores were counted on HPGe systems by ERG. Sub-samples (solids) were also sent to the same commercial

**Figure 25. Medium-Volume Air Sampler**

**Figure 26. Air Sample Collection Between Table Filters**

**Figure 27.** **Particulate Sample Preparation**

**Figure 28.** **HPGe Sample Counting System**

laboratory for gross alpha and gross beta on the solid material. This is not a straightforward analytical process and many errors can be introduced. Very small subsamples may not represent the whole. Crushing and mixing may change the radon emanation rate and thus the daughters' distribution. The same self-absorption and concentration problems mentioned above come into the process. The consequence was very inconclusive results, especially with the moderate to low activity materials. Leachate studies were considered but never accomplished. However, there were many unresolved questions about the proposed leachate studies.

The "stakeholders" and the regulators were insisting on gross alpha and gross beta results on the solid materials. The geological consultant inquired as to what ERG could do in this controversy. After giving the problem considerable thought, Dr. Bolch suggested a theoretical calculation. If the gamma spectroscopy yielded the concentrations of many of the natural series radionuclides, and others without gamma peaks could be inferred from equilibrium, then there was hope to sum all the known alpha and known beta emissions. The radiological handbooks provided step-by-step decay series, branching ratios, and thus the rates of alpha decays and beta decays at each stage. This period in history was also a time in which there was a considerable amount of work on radon emanation rates. It is extremely difficult for 100% of the radon to escape natural minerals (20% is a general average for many). Thus the mineral crystal that contains the radium is such that the newly created radon is not close to a surface and will remain and decay into its daughter series. Also materials like slag, fly ash, scales, have unique emanation coefficients, but never 100 percent.

Thirty-eight radionuclides ($^{238}$U series, $^{235}$U series, $^{232}$Th series, and $^{40}$K) were entered into a spreadsheet format. The type of decay (alpha or beta) for each was entered next with due consideration for the branching ratios. The two subsequent columns, alpha activity and beta activity, are tied to equations and assumptions as well as to the primary measurements such as the $^{238}$U, $^{226}$Ra, $^{232}$Th, and $^{40}$K outputs from gamma spectroscopy. The spreadsheet keeps track of assumptions for emanation fractions for the three radon isotopes, the measured and inferred concentrations, and other interrelationships. It then totals the activity for the theoretical gross alpha and gross beta at the bottom of the spreadsheet.

Results of this type derivation of an expected gross alpha and gross beta concentrations on a larger solid sample (500 ml and approximately 700 grams) were presented to the geological firm involved in the project outlined in the previous paragraphs. ERG was informed that the results correlated very well with the total data set of the study. Many of the higher values matched laboratory determinations and the smaller values which did not have a good laboratory value correlated well with the other parameters such as a monitor well and baseline well water analyses. Over the years since that investigation, ERG has been asked to provide these predicted gross alpha and gross beta results in other projects. To date, there has not been any evidence that the system did not make a prediction within the expected accuracy. Most of the gamma results have errors that range from a few percent on the higher activity samples to less than 10% on the very low activity materials, like sand and topsoil. It is difficult to give the gross alpha and gross beta predictions a well-defined percent error. Since the more important samples are the ones with higher activities, there is evidence that the gross alpha and gross beta predictions have generally a 10% error. This would include errors in emanation fractions and other equilibrium errors. ERG does not believe that any values, even the low concentrations, would have errors exceeding 30%.

The primary objective in this subsection is to have a database for comparison to gross alpha and gross beta air samples. It is true that the large samples may not represent potential airborne fractions. However, in an industrial situation it is possible for larger materials to be effectively crushed to sizes that can become airborne by inadvertent events such as moving machinery, forklift tires, etc. Each sample was evaluated with respect to its place of origin and processes at that site. The exercise provides one more analytical result without the large expense of attempting a laboratory analysis with the inherent errors previously discussed.

**Alpha radiation and dose conversion factors.** Some radionuclides emit alpha radiation (see Figure 29) that is of little significance to external dose, but is hazardous when inhaled due to transfer of energy to sensitive tissues (especially the lung) and metabolic factors. For these reasons, radionuclides other than the prominent gamma-emitters

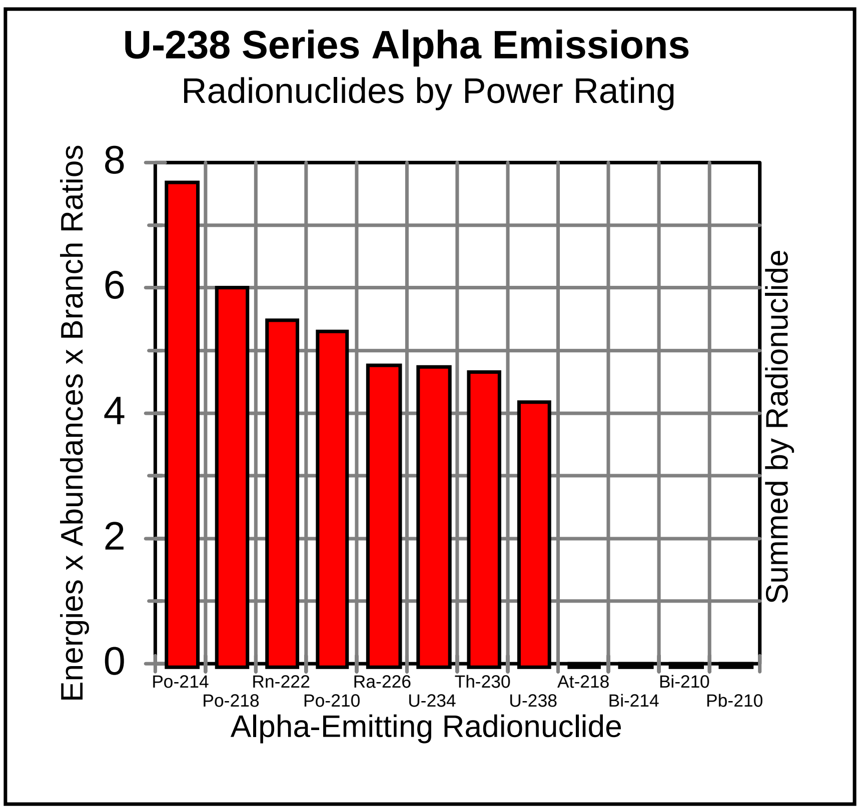


**Figure 29. U-238 Series Prominent Alpha Emissions**

become important once radioactivity is inhaled into the body. Table 12 provides a comparison of two widely used sets of DCFs. One set is from the EPA's Federal Guidance Report No. 11, and the other is from the more recent ICRP Report No. 68. The two data sets have significant differences that are possibly the reflection of more metabolic data published since the EPA report's release. In general, radium isotopes deliver a larger dose commitment than previously reported, and thorium isotopes deliver a smaller dose commitment than previously reported. The highlighted DCFs are very different, and the range extremes are highlighted in the last column which displays the ratio of the two sources. Note that the older report averages 78% higher than the newer one. Since the ICRP tabulation is more recent, that is the source used in the analyses presented in this study.

**Table 12. Comparison of Inhalation DCFs**

| Inhalation Dose Conversion Factors | | | |
|---|---|---|---|
| | mrem/µCi | | FGR/ICRP Ratio |
| | ICRP #68 | FGR #11 | |
| DCF | M | W | W/M |
| $^{238}U$ | 9620 | 7030 | 0.73 |
| $^{234}U$ | 11470 | 7881 | 0.69 |
| $^{230}Th$ | 148000 | 325600 | 2.20 |
| $^{226}Ra$ | 59200 | 8584 | 0.15 |
| $^{235}U$ | 10360 | 7289 | 0.70 |
| $^{231}Pa$ | 481000 | 1283900 | 2.67 |
| $^{227}Th$ | 28860 | 15244 | 0.53 |
| $^{223}Ra$ | 25530 | 7844 | 0.31 |
| $^{232}Th$ | 155400 | 1639100 | 10.55 |
| $^{228}Th$ | 114700 | 249750 | 2.18 |
| $^{224}Ra$ | 10730 | 3156.1 | 0.29 |
| $^{234}Th$ | 23.31 | 29.748 | 1.28 |
| $^{227}Ac$ | 77700 | 1720500 | 2.21 |
| $^{228}Ra$ | 9620 | 4773 | 0.50 |
| | | Avg.→ | 1.78 |

**Uncertainty and Sensitivity Analysis**

It has become routine for organizations performing pathway dose calculations to include uncertainty and sensitivity analysis within the procedure. The Centers for Disease Control and Prevention (CDC) has been a leader in promoting this additional feature in their intensive dose reconstruction efforts at Hanford, Rocky Flats, Marshall Islands, etc. Drs. Emmett Bolch and Brian Birky have completed a two-year contract with the CDC providing that agency with methodologies on three specific aspects of uncertainty and sensitivity analysis. The most popular software program for performing these studies is Crystal Ball (Decisioneering, Inc., Denver, CO).

In the simplest terms, a pathway calculation model can (1) start with the source material (activity in a medium), (2) continue through either direct external exposure or uptake by inhalation or ingestion scenarios (with due consideration of time and motion studies to yield exposure times), and then (4) apply dose conversion factors leading to estimated annual doses to the individual of concern. Such calculations can be performed directly for one individual, or via a spreadsheet such as Microsoft Excel when multiple tasks or many individuals are of concern. Each calculation, often with a very simple equation, yields one value with no report of the error (uncertainty).

The Crystal Ball program allows a much more informative step to be added to the calculation. Each variable, each parameter, and sometimes what is often considered a constant may have some variability. This variability is described either by statistical analysis of the raw data or known errors. Thus, it may be possible to assign each parameter, variable, or constant in the equation an appropriate statistical distribution. For example, media concentrations for a given process may be normally distributed with a given mean and standard deviation, or it may be known to be a log normal distribution of radioactivity with a geometric mean and geometric standard deviation. A time and motion study may yield an average time for a task, but with some well-defined ranges (maximum and minimum).

Crystal Ball allows the user to assign these specific distributions and statistical limits to each part of the pathway-to-dose equation. Then the answer to the model is calculated via a Monte Carlo subroutine that addresses each parameter's assigned distribution randomly for thousands of trials and arrives at a central value (often a mean that may be close to the straight manual calculation). More importantly, a statistical distribution is generated around that central value based upon the input of every parameter in the model that was assigned its particular distribution. Thus, the answer will have confidence limits and other statistical properties. Lastly, Crystal Ball performs a sensitivity analysis by calculating the percent contribution of each parameter to the variability in the final distribution. This is important in that the parameter producing the most variability and hence uncertainty (highest sensitivity) is the parameter that needs the most intense investigation in the next phase of the investigation in order to narrow its statistics (error limits).

# RESULTS

The results of this study are presented with a minimal amount of description, since the previous sections describe data collection and analysis methodologies.

## TASKS BY AREA AND JOB DESCRIPTION

Even in summary tabular form, the descriptions of jobs and tasks by mine and chemical plant subarea are too extensive to include in this main text. Their value lies mainly in determining which data are grouped together, and occupancy times in specific areas. A lengthy tabular summary of results is given in Appendix C, followed by a composite of jobs and tasks across the industry, and finally the raw interview results. The tabular summary provides a listing of 137 duties by area and job title, the maximum and minimum times estimated per duty, the specific location the duty is performed, and the fraction of time that is spent in a dusty breathing zone.

## EXTERNAL DOSE

The sampling protocol was developed to yield a statistically defensible number of participants in each of the six main areas derived from at least five sites. Each participant was badged with one LiF TLD for approximately three months, and a series of three aluminum oxide carbon dosimeters (Landauer X9), at least two of which were concurrent to the total LiF period. Co-badging provided intercomparison between the sensitive X9 and the LiF "gold standard." Another advantage was that multiple data sets were available for analysis: (a) the X9 data set as a total with all three sets combined, (b) the LiF data set, and (c) each X9 set as an individual grouping giving three replicates.

First consider the conditions of data set 'a.' This allows the observation of 360 measurements and their distribution. The measurements in mrem were divided by the deployment time in days to yield a dose rate. Dose bins of a manageable size were constructed and the measurements apportioned to those bins to create a frequency histogram (Figure 30). Note that the distribution is positively skewed (to the left) indicating a lognormal distribution. When the natural logs of the measurements were taken and plotted, the distribution assumed a normal shape, confirming the original lognormal deduction (Figure 31). This is important to augment assumptions for smaller subsets of data that also exhibit lognormal distributions. The statistics of the smaller groupings are therefore generated for lognormal distributions having geometric means and geometric standard deviations. Next, consider data set 'b.' Co-badging with LiF dosimeters allowed comparison to the industry "gold standard" as discussed earlier. The comparison is seen as a ratio in Table 13. Analysis of 106 data pairs results in a mean ratio of 1.22 (aluminum oxide X9/LiF TLD). In other words, the X9 over-responds to the radiation field by 22%. That is the basis for the correction pointed out in the Methodology section.

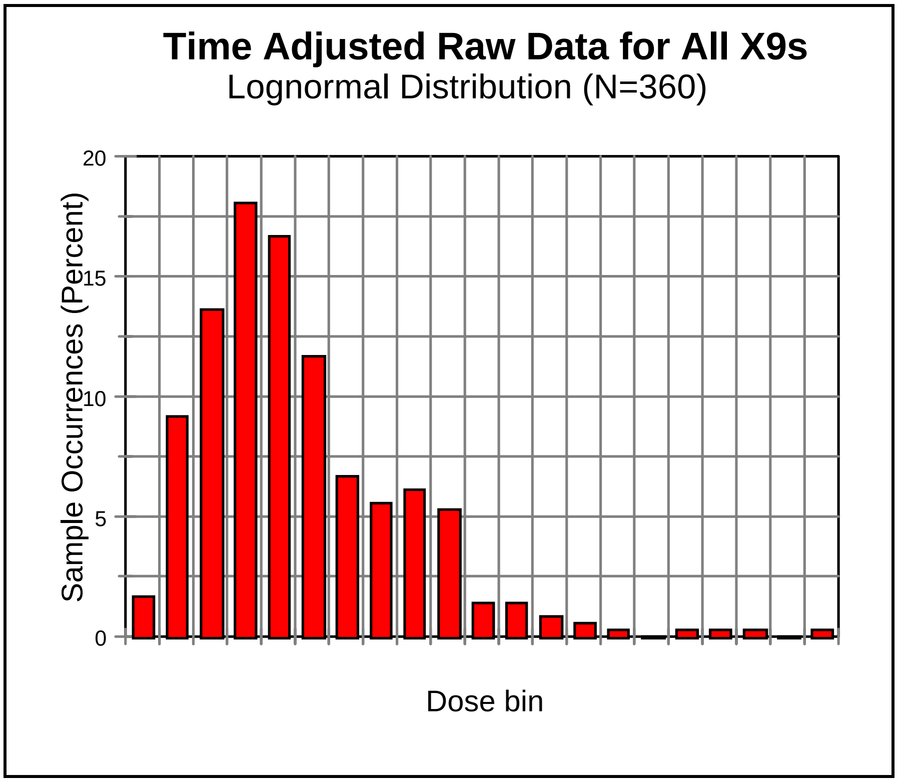


**Figure 30. Log-Normal Distribution of External Dose**

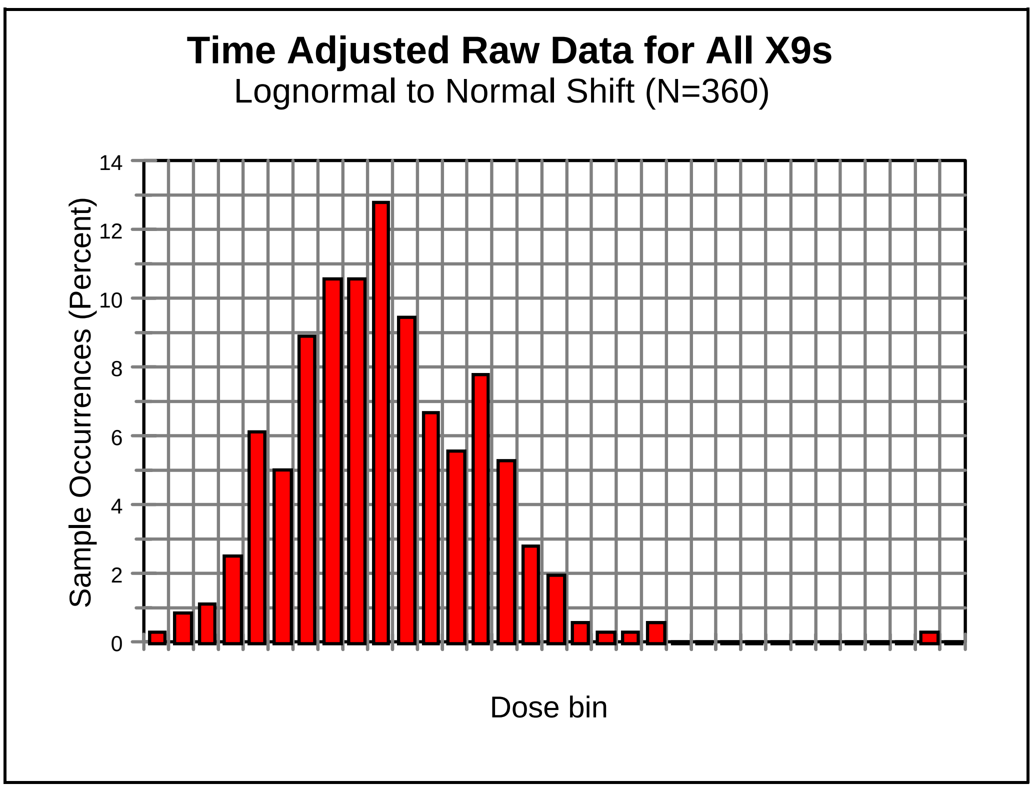


**Figure 31. Confirmation of Log-Normal Distribution**

**Table 13. Dosimeter (Badge) Comparison**

| Personnel Data | X9 / TLD ratio |
|---|---|
| Mean | 1.22 |
| Standard Error | 0.01 |
| Median | 1.18 |
| Mode | 1.18 |
| Standard Deviation | 0.15 |
| Variance | 0.02 |
| Kurtosis | 0.83 |
| Skewness | 0.44 |
| Range | 0.96 |
| Minimum | 0.78 |
| Maximum | 1.73 |
| Count | 106.00 |
| CL (0.950000) | 0.03 |

Condition ‘c’ allows replicate calculations of dose on large data sets without the significant dosimeter losses incurred by workers over larger time frames. Tables 14, 15, and 16 show X9 results extrapolated to annual dose (mrem/yr) presented as a mean, minimum, and maximum for the sampled subareas of the plants and the combined set. The three replicates are in good agreement with only the maxima experiencing wide variability, as is expected in a category where a single data point is so influential. The geometric mean is a better predictor of dose rates and shows that, for external exposures alone, the phosphoric acid production area and the rock handling area produce higher doses than other areas of the plants and mine. However, all mean annual external doses are very low. An examination of condition ‘b’ summary statistics for LiF dosimeters (Table 17) indicates the same trends as the X9 data. The final data summary set is for on-site contractors working a two-week turnaround event cleaning out a phosphoric acid attack tank (reactor), repairing flash coolers and condensers, and disassembling and cleaning a filtration apparatus (Table 18). Note that the doses are *per event* and that the contractors work a variable number of events per year (typically four). Turnaround doses are further evaluated as TEDE dose in the sections that follow.

**Table 14. Summary Statistics for X9 Deployment #1**

| X9 #1 Corr. and Adj. Data (Extrapolated to one year) | Geo. mean mrem/yr | Geo. Std. Dev. | Min. mrem/yr | Max. mrem/yr | Count |
|---|---|---|---|---|---|
| All personnel combined | 15.0 | 2.7 | 4.1 | 184.4 | 151 |
| Dry Product Areas | 10.3 | 2.2 | 5.1 | 78.4 | 30 |
| Shipping Areas | 13.7 | 2.5 | 5.3 | 97.2 | 21 |
| Mine Areas | 9.6 | 2.1 | 4.1 | 32.1 | 21 |
| Phosphoric Acid Areas | 34.4 | 2.5 | 6.9 | 102.7 | 32 |
| Rock Areas | 24.3 | 3.1 | 5.3 | 141.3 | 16 |
| Service Companies | 10.2 | 2.4 | 4.8 | 184.4 | 31 |

**Table 15. Summary Statistics for X9 Deployment #2**

| X9 #2 Corr. and Adj. Data (Extrapolated to one year) | Geo. mean mrem/yr | Geo. Std. Dev. | Min. mrem/yr | Max. mrem/yr | Count |
|---|---|---|---|---|---|
| All personnel combined | 12.8 | 3.1 | 3.5 | 163.2 | 147 |
| Dry Product Areas | 8.1 | 2.7 | 3.6 | 80.9 | 28 |
| Shipping Areas | 12.2 | 2.9 | 3.7 | 124.1 | 20 |
| Mine Areas | 9.5 | 2.2 | 4.2 | 51.5 | 22 |
| Phosphoric Acid Areas | 34.8 | 2.7 | 4.1 | 163.2 | 32 |
| Rock Areas | 21.2 | 3.6 | 3.6 | 135.3 | 16 |
| Service Companies | 6.6 | 2.1 | 3.5 | 116.5 | 29 |

**Table 16. Summary Statistics for X9 Deployment #3**

| X9 #3 Corr. and Adj. Data (Extrapolated to one year) | Geo. mean mrem/yr | Geo. Std. Dev. | Min. mrem/yr | Max. mrem/yr | Count |
|---|---|---|---|---|---|
| All personnel combined | 14.7 | 2.5 | 3.6 | 186.3 | 133 |
| Dry Product Areas | 13.1 | 2.3 | 4.2 | 95.2 | 26 |
| Shipping Areas | 19.2 | 2.5 | 3.6 | 179.5 | 19 |
| Mine Areas | 11.4 | 2.3 | 6.2 | 186.3 | 21 |
| Phosphoric Acid Areas | 26.4 | 2.4 | 5.1 | 172.0 | 25 |
| Rock Areas | 19.4 | 2.9 | 6.2 | 119.7 | 13 |
| Service Companies | 8.7 | 1.8 | 5.7 | 103.8 | 29 |

**Table 17. Summary Statistics for LiF Deployment**

| LiF Corr. and Adj. Data (Extrapolated to one year) | Geo. mean mrem/yr | Geo. Std. Dev. | Min. mrem/yr | Max. mrem/yr | Count |
|---|---|---|---|---|---|
| All personnel combined | 20.9 | 2.0 | 6.5 | 209.9 | 148 |
| Dry Product Areas | 17.1 | 1.9 | 10.6 | 209.9 | 29 |
| Shipping Areas | 19.7 | 1.8 | 12.4 | 66.8 | 21 |
| Mine Areas | 16.8 | 1.5 | 8.1 | 56.5 | 22 |
| Phosphoric Acid Areas | 31.1 | 2.0 | 11.3 | 82.6 | 29 |
| Rock Areas | 30.0 | 2.4 | 6.5 | 128.4 | 16 |
| Service Companies | 17.5 | 1.7 | 8.6 | 166.5 | 31 |

**Table 18. Summary Statistics for X9 Deployment for Turnaround Contractors**

| X9 Corr. and Adj. Data (Dose per Turnaround Event) | Geo. mean mrem per event | Geo. Std. Dev. | Min. mrem per event | Max. mrem per event | Count |
|---|---|---|---|---|---|
| All personnel combined | 1.41 | 1.94 | 0.35 | 6.72 | 29 |
| Machinists, Welders | 1.17 | 1.70 | 0.87 | 3.85 | 9 |
| Hydroblasters | 1.35 | 2.24 | 0.35 | 3.52 | 8 |
| Reactor Repair Workers | 1.48 | 2.43 | 0.52 | 6.72 | 6 |
| Reactor Vacuum Workers | 1.91 | 1.42 | 1.31 | 3.61 | 6 |

In the Methodology section, the problem of calculation of an external radiation dose directly from ambient exposure rate measurements taken by survey meters or PICs is discussed in great detail. This study was designed so that area monitors (X9 dosimeters) placed in the working environment for extended continuous exposure (roughly a month) could be compared to PIC measurements made periodically at the same locations. This would provide a “field dose conversion factor” of “vendor-reported rem” per roentgen. The term “vendor-reported rem” is used because the dosimeter vendor and processor applies some DCF from absorbed dose to the badge to human dose in rem. Since the phosphate industry personnel involved in radiation monitoring must rely on these badge results for the official dose to the worker, and they commonly assess radiation levels using survey meters calibrated against the PIC, this seemed to be a logical and practical approach. The results are displayed in Table 19 as ratio of X9/PIC in units of mrem/mR.

A total of 45 area badges were used in the analysis with a mean of1.53 mrem per mR. This appeared to be unusually high to the project team. Remember from previous discussions that the common TENORM conversion used by others is 0.6 mrem per mR. One of the participating companies supplied its own area badge data (also X9) and co-located (and time encompassed) exposure rate measurements. Over a much longer time period, a total of 276 data points useful for this analysis were collected. The resulting conversion based on that data is 1.56 mrem per mR. This is in surprisingly good agreement with the value of 1.53 mrem per mR found in this study.

**Table 19. Field Approximation of a mrem/mR DCF**

| mrem/mR based on X9 and PIC (area badge data) | |
|---|---|
| Mean | 1.53 |
| Standard Dev. | 0.44 |
| Standard Error | 0.07 |
| Minimum | 0.67 |
| Maximum | 2.87 |
| Count | 45.00 |
| Conf. Level(0.95) | 0.13 |

There are several possibilities for these unusually high results:

- the PIC may be under-responding if the TENORM energy spectrum is degraded to a degree that a large proportion of the radiant flux does not penetrate the outer housing of the instrument to reach the sensitive volume,

- the X9 badge may be over-responding to the TENORM energy spectrum, or the algorithms used by the vendor to report dose may be inappropriate for this particular situation, or

- there may be some combination of the first two possible answers.

In the final analysis it is not suggested that this conversion factor be used, but it does serve to illustrate the need for further research in an effort to define the true mrem/mR conversion factor for the TENORM phosphate environment whether it is 0.6, 1.56 or somewhere between. *In situ* gamma spectroscopy for characterization of the TENORM degraded energy spectrum would be particularly valuable.

Consideration of all of the available external dosimetry data shows which job classifications consistently incur higher doses (arbitrary at >20 mrem/yr) for the study subareas:

- Mine Area - tractor operator, washer operator, dredge crew, maintenance supervisor, float plant operator and assistant operator, and rock tunnel operator

- Rock Area - operator and assistant operator, rail car unloader, chief operator, stacker/reclaimer, maintenance, labor, and ball mill operator

- Phosphoric Acid Area - maintenance, production operator and assistant operator, labor, tank farm operator, hydroblaster, relief operator, maintenance laborer, and supervisor

- Dry Products Area - granular operator, chief operator, maintenance mechanic, bobcat operator/laborer, dry products utility operator, DAP supervisor, and DAP car loader

- Shipping/Storage Area - payload operator, wet rock operator (loading), maintenance, rock/rail supervisor, rock conveyor operator, car loader, rock tractor operator, and shipping process operator

- Service Area - paint yard forklift operator, consultants, welder, sandblaster, pump technician, field supervisor, maintenance, mechanics/machinists, and painters

## INTERNAL DOSE

The internal dose component of the TEDE is the combination of inhalation dose, ingestion dose, and the far less common introduction of radionuclides into the body through intact skin or wounds. The following subsections present results for measurements taken to calculate those pathway contributions.

### Air Particulate Analysis

A total of 86 air samples were collected during routine operations in the industry subareas. The sampling breakdown in numbers of air samples per area is: mine (16), rock (16), phosphoric acid (18), dry products (20), shipping (11), and service (5). The raw results in microcuries of gross alpha and gross beta activities per milliliter of ambient air are included in Appendix C. The means are driven by the lower limit of detection (LLD) of the counting system used; i.e., 1.0 µCi/ml for gross alpha and 1.2 µCi/ml for gross beta. The true means are undoubtedly lower, so the derived doses are conservative (erring toward higher doses). The spread of the distributions, however, is not affected, because the lower end is zero and the upper end is a measured value greater than the LLD. These results alone are not sufficient to calculate an effective dose equivalent. They must be used in conjunction with knowledge of the radionuclides that constitute the particulates. That is the subject of the next subsection.

### Deposition Analysis

The analysis of solid samples is discussed in the Methodology section. Seventeen composite samples were analyzed; i.e., the samples were collected from long-term accumulations of dust. Also, each sample was large (approximately 0.5 kg). A sample of the HPGe analysis results for one sample (Gypsum 1) is shown in Table 20. A summary of the results is displayed in Table 21. The concentrations of the TENORM radionuclides follow published trends discussed in the Introduction section. Radium goes with gypsum while uranium is largely absent, dry products (MAP, DAP) produced with phosphoric acid have enhanced uranium activities, and GTSP retains radium and uranium from input rock and is enhanced with uranium from phosphoric acid. These results and the air particulate sampling are used as activity concentrations for TENORM radionuclides for input into the TEDE uncertainty analysis with occupancy times, breathing rate, protection factor, and dose conversion factors to derive inhalation dose.

**Inhalation Dose**

Using the data as just described and inhalation DCFs, the inhalation component of the TEDE was calculated separately for evaluation. The results are illustrated graphically for the mine area (Figure 32), the rock area (Figure 33), the phosphoric acid area (Figure 34), the dry products area (Figure 35), the shipping area (Figure 36), the pan chipping turnaround activity (Figure 37), and reactor cleaning turnaround activity (Figure 38). In terms of severity of the inhalation dose component by area, the hierarchy is: shipping > rock > dry products > phosphoric acid > mine. Note that the shipping area dose is much greater than the others, and that the dose from the rock and dry products areas are very similar. The turnaround activities are better evaluated using the full TEDE distribution to be reported in a subsequent subsection. An inhalation dose component was not calculated for off-site service companies, because no air sample greater than background was ever recorded. This is not surprising considering the types of working environments encountered; e.g., a typical pan repair area (Figure 39) with open cross ventilation, and the open air of a paint yard seen in Figures 40 and 41.

**Table 20. Activity Measurements and Estimation of Gross Alpha and Beta**

| **Gypsum** | | | | Weight = 403 g |
|---|---|---|---|---|
| Radio-nuclide | Emission type | Est. Rate for: Alphas | Betas | Basis of Estimation |
| U-238 | alpha | 3.38 | | Calculated from three peaks |
| Th-234 | beta | | 3.38 | Assumed equil. for type of sample |
| Pa-234 | beta | | 3.38 | Assumed equil. for type of sample |
| U-234 | alpha | 3.38 | | Assumed equil. for type of sample |
| Th-230 | alpha | 3.38 | | Assumed equil. for type of sample |
| Ra-226 | alpha | 23.83 | | Meas. via sealed equil. w/ radon |
| Rn-222 | alpha | 23.83 | | Meas. via sealed equil. w/ radon |
| Po-218 | alpha | 14.30 | | Scale State, emanation est. 40% |
| Pb-214 | beta | | 14.30 | Scale State, emanation est. 40% |
| Bi-214 | beta | | 14.30 | Scale State, emanation est. 40% |
| Po-214 | alpha | 14.30 | | Equil. w/ remaining radon daughters |
| Pb-210 | beta | | 14.30 | Assum. Max for long-lived daughters |
| Bi-210 | beta | | 14.30 | Assum. Max for long-lived daughters |
| Po-210 | alpha | 14.30 | | Assum. Max for long-lived daughters |
| U-235 | alpha | 0.15 | | Meas. & Ratio of $\gamma$ Abun X U-238 |
| Th-231 | beta | | 0.15 | Assumed equil. for type of sample |
| Pa-231 | alpha | 0.15 | | Assumed equil. for type of sample |
| Ac-227 | beta | | 0.15 | Assumed equil. for type of sample |
| Th-227 | alpha | 0.15 | | Assumed equil. for type of sample |
| Ra-223 | alpha | 0.09 | | Scale State, emanation est. 40% |
| Rn-219 | alpha | 0.09 | | Scale State, emanation est. 40% |
| Po-215 | alpha | 0.09 | | Scale State, emanation est. 40% |
| Pb-211 | beta | | 0.09 | Scale State, emanation est. 40% |
| Bi-211 | beta | | 0.09 | Scale State, emanation est. 40% |
| Po-211 | alpha | 0.09 | | Scale State, emanation est. 40% |
| Th-232 | alpha | 0.54 | | Assumed equil. for type of sample |
| Ra-228 | beta | | 0.54 | Assumed equil. for type of sample |
| Ac-228 | beta | | 0.54 | Max. Ac-228, estim. sample origin |
| Th-228 | alpha | 0.54 | | Assumed equil. for type of sample |
| Ra-224 | alpha | 0.54 | | Assumed equil. for type of sample |
| Rn-220 | alpha | 0.32 | | Scale State, emanation est. 40% |
| Po-216 | alpha | 0.32 | | Scale State, emanation est. 40% |
| Pb-212 | beta | | 0.32 | Scale State, emanation est. 40% |
| Bi-212 | 1/3 alpha | 0.18 | | Assumed equil. for type of sample |
| Bi-212 | 2/3 beta | | 0.36 | Assumed equil. for type of sample |
| Tl-208 | 1/3 beta | | 0.36 | Max. equil. from Ac-228 to Tl-208 |
| Po-212 | 2/3 alpha | 0.36 | | Assumed equil. for type of sample |
| K-40 | 89% beta | | 0.38 | Max. with proper abund. for beta |
| | 0.43 | | | |
| **Max GROSS** | | **104** | **67** | |
| | | **Alpha** | **Beta** | |

**Table 21. Summary of Solid Sample Analyses**

| SOLID SAMPLE ANALYSIS | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Sample | No. | Calculated Emissions/g | | Measured Activity Concentration (pCi/g) | | | |
| | | Alpha | Beta | Ra-226 | U-238 | Th-232 | K-40 |
| Gypsum | 1 | 104 | 67 | 23.83 | 3.38 | 0.54 | 0.43 |
| Gypsum | 2 | 100 | 65 | 20.55 | 6.35 | 0.23 | 1.08 |
| High Grade Rock - Belt | 3 | 233 | 158 | 33.34 | 26.37 | 1.91 | 0.63 |
| GTSP dry | 4 | 260 | 183 | 35.20 | 30.64 | 0.70 | 1.58 |
| High Grade | 5 | 243 | 173 | 31.61 | 29.62 | 1.16 | 2.87 |
| Fines - Baghouse | 6 | 288 | 198 | 21.60 | 57.91 | 0.51 | 1.74 |
| GTSP on Ground | 7 | 328 | 225 | 19.80 | 71.51 | 1.10 | 2.4 |
| GTSP Fines | 8 | 270 | 185 | 16.17 | 59.09 | 0.85 | 2.49 |
| GTSP | 9 | 286 | 195 | 16.39 | 64.13 | 0.47 | 1.96 |
| GTSP Tunnel | 10 | 325 | 223 | 18.55 | 72.85 | 0.75 | 3.51 |
| GTSP | 11 | 131 | 91 | 7.10 | 29.11 | 0.33 | 0.69 |
| MAP Fines | 12 | 241 | 168 | 9.00 | 59.09 | 0.55 | 5.36 |
| MAP Reject | 13 | 237 | 162 | 5.85 | 62.56 | 0.43 | 3.71 |
| Dry Products | 14 | 202 | 135 | 3.33 | 55.83 | 0.29 | 1.09 |
| MAP Area | 15 | 220 | 147 | 1.79 | 63.56 | 0.26 | 1.41 |
| DAP Pre-Screen | 16 | 181 | 121 | 0.62 | 53.51 | 0.30 | 1.57 |
| DAP Screen Reject | 17 | 190 | 126 | 0.60 | 56.26 | 0.28 | 0.62 |

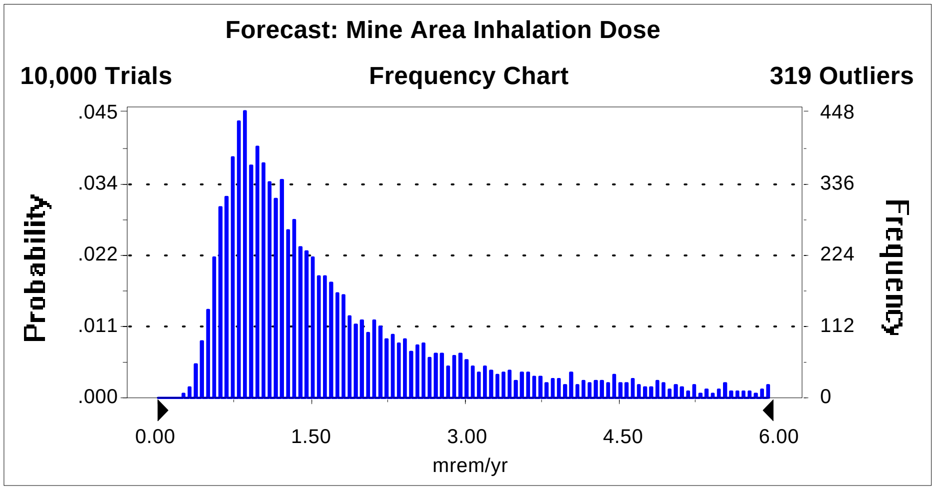


**Figure 32. Mine Area Inhalation Dose Distribution**

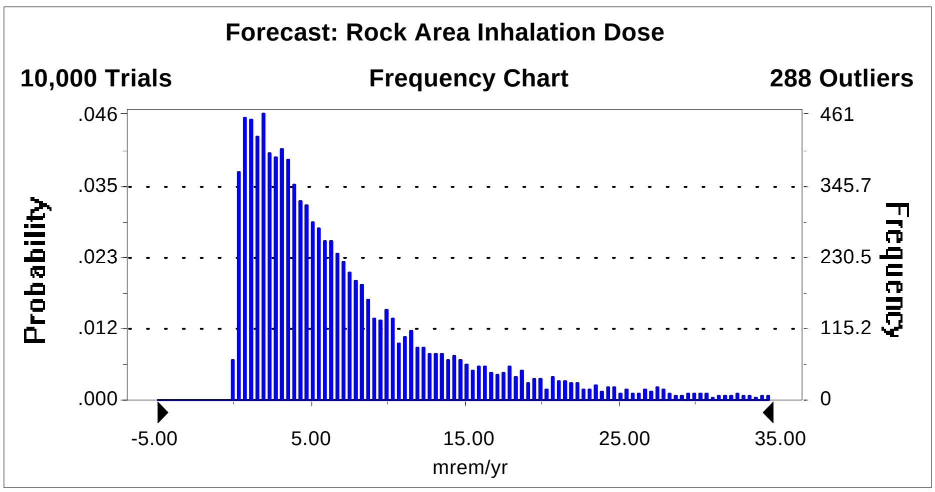


**Figure 33. Rock Area Inhalation Dose Distribution**

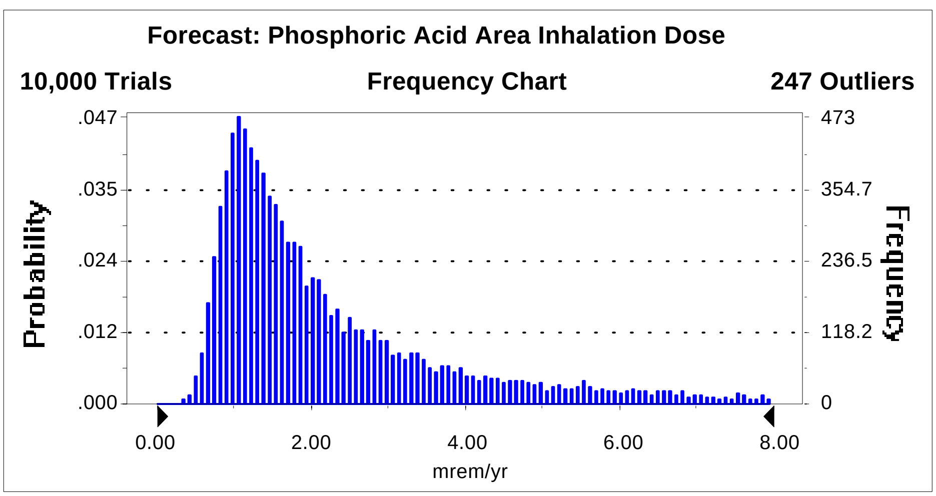


**Figure 34. Phosphoric Acid Area Inhalation Dose Distribution**

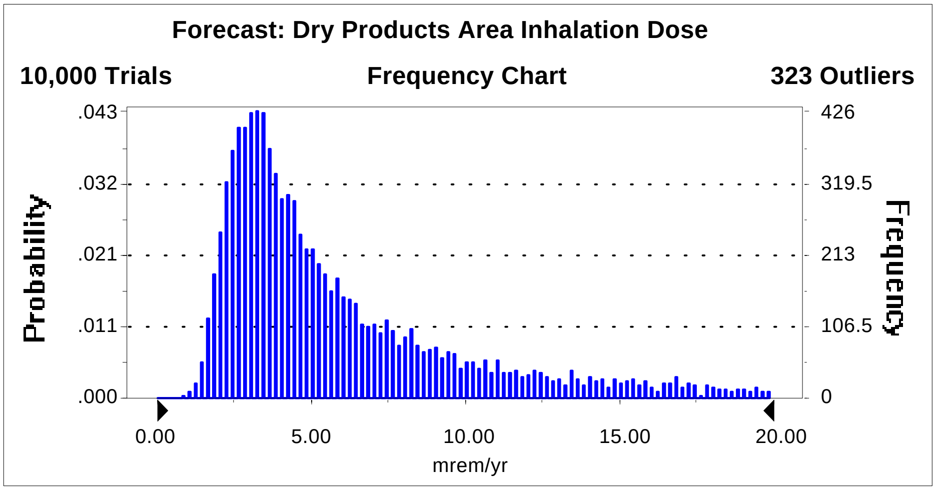


**Figure 35.** **Dry Products Area Inhalation Dose Distribution**

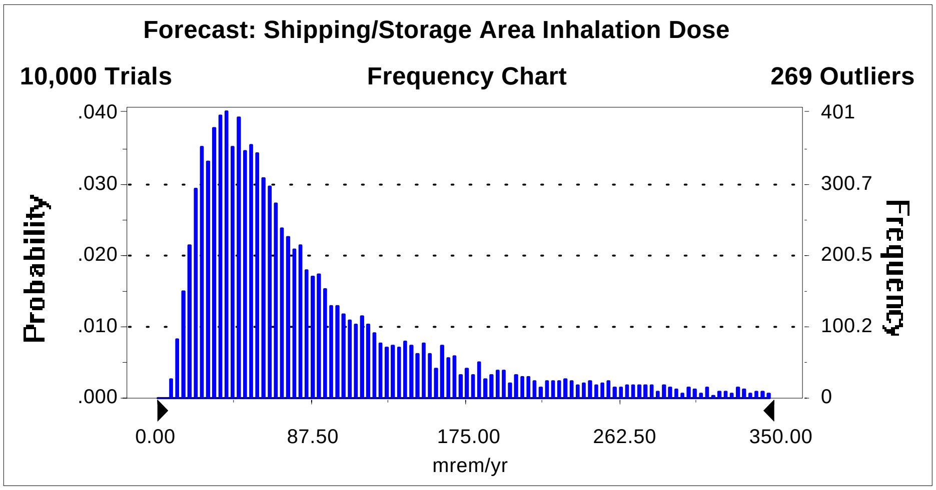


**Figure 36.** **Shipping/Storage Area Inhalation Dose Distribution**

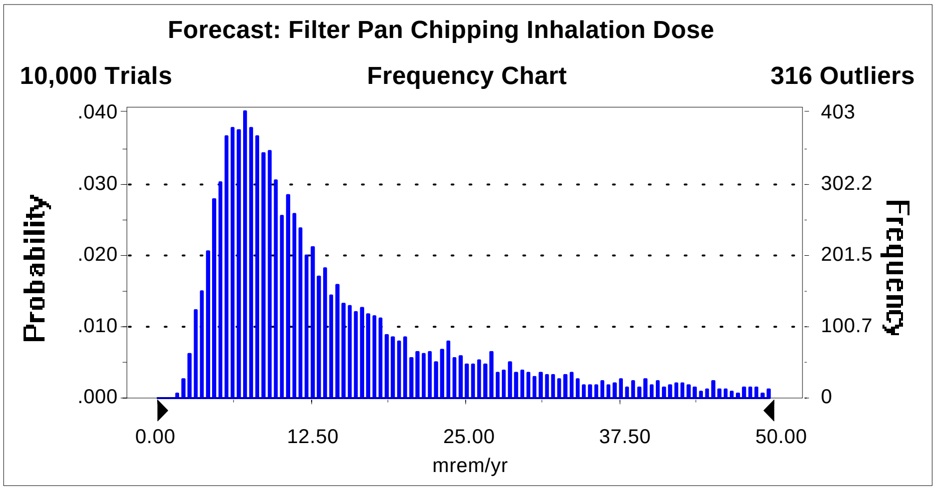


**Figure 37.** **Filter Pan Chipping Inhalation Dose Distribution**

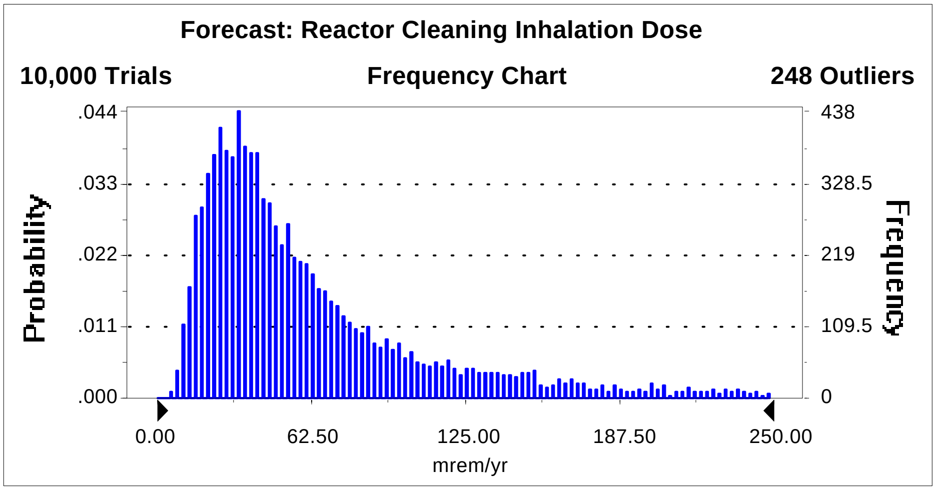


**Figure 38.** **Reactor (Attack Tank) Cleaning Inhalation Dose Distribution**

**Figure 39.** **Filter Pan Repair Area - Open on Both Sides**

**Figure 40. Paint Yard - Open Environment**

**Figure 41. Paint Yard Storage - Open Environment**

## Radon Levels

Radon measurements made in this study using E-perm electret ion chambers were all well below the EPA 4 pCi/l guideline for residences, except for the rock tunnels. A total of 28 samples were collected as follows: mine area (11), rock (5), phosphoric acid (7), dry products (4), and shipping (1). The results can be found in Appendix C. The tremendous volume of industry-generated data already described was also scrutinized by the project team. The EPA uses an extremely conservative scenario of continuous home occupancy and exposure to derive this limit. Therefore, the application of this standard to far less occupancy time and an adult workforce leads to the conclusion that background exposures are not exceeded and an attributable dose above background does not usually occur.

## Working Levels

The working level (WL) is a convenient one-parameter measure of the concentration of radon progeny in air that can be employed as a measure of exposure hazard. One WL is defined as any combination of $^{218}$Po, $^{214}$Pb, $^{214}$Bi, and $^{214}$Po (the short-lived progeny of radon) in one liter of air, under ambient temperature and pressure, that will result in the ultimate emission of 1.3 E+5 MeV of alpha particle energy. This is about the total amount of energy released over a long period of time by the short-lived daughters in equilibrium with 100 pCi of radon. Therefore, the conversion from pCi/l to WL, if one assumes equilibrium in the environment, is made by division by 100. However, most environments are not in equilibrium. The EPA assumes 50% equilibrium of daughters and thus the conversion of 4 pCi/l to 0.02 WL.

Some radon working levels were measured as support for the e-perm results. The raw results are tabulated in Appendix C. The levels were consistently low. Even in rock tunnels where the radon levels can be high, the working levels were less than 0.95 milliWL. This suggests that the tunnels are ventilated frequently enough so that equilibrium concentrations of radon progeny do not accumulate.

## Wound Entry Dose

In the phosphate industry context, the introduction of foreign materials through broken skin is a minor pathway for the entry of radionuclides into the body. The frequency of injuries that involve broken skin; i.e., abrasions, cuts, punctures, and fractures, is quite low. A review of data from 1994 through 1997 indicates 422 accidents occurred during 3,247,588 working hours. This is a rate of 1.3 E-4 accidents per working hour, or 0.26 accidents per 2,000 working hours (a standard working year). That translates to roughly one accident for every four years worked per individual. Of those 422 accidents, only 135 involved *possible* skin breaks. This is a rate of 4.2 E-5 *possible* skin breaks per working hour, or 0.26 *possible* skin breaks per 2,000 working hours; i.e., about one accident for every 12 years worked per worker. In addition to the low frequency of wounds, further consider that not all such wounds incorporate foreign materials containing radioactivity, and such wounds are normally quickly irrigated so that absorption into the circulatory system is decreased. The doses derived from the low activity concentrations of phosphate industry raw materials and products are too hypothetical and trivial to calculate.

### Ingestion Dose

Ingestion dose is a minor pathway for industry workers. Food items are not normally consumed in working environments. Furthermore, even if foods were consumed in those areas and small quantities of raw and product materials contaminated those foods, the resulting doses would be small. There is also a small fraction of the inhaled particulates that are moved up the respiratory system's mucociliary transport mechanism to the throat and swallowed into the gastrointestinal tract. The dose is not only reduced by quantity, but also by quality of dose delivery via this pathway. That is, the DCFs for ingestion are orders of magnitude lower than inhalation DCFs. Comparing ICRP No. 68 DCFs reveals that the average inhalation dose is almost exactly 200 times greater than the corresponding ingestion DCF. The calculation of doses for ingestion would yield tenths of mrem per year in most cases, and is not a worthwhile pursuit. Drinking water is subject to federal standards for radioactivity content. A recent company-sponsored study of a north Florida phosphate operation analyzed well water samples and conducted an ingestion dose analysis for potable water, and found the doses to be trivial (RSS, 1997).

## TOTAL EFFECTIVE DOSE EQUIVALENT (TEDE)

Pathway models describing the movement of TENORM through industrial processes to the general public (in this case, workers affected by production and support) via inhalation, ingestion, wound entry, and external exposure are developed using results from literature and industry data, process information, and time/motion studies. The data previously collected were used to model external exposures and activity concentration in airborne fugitive dust. The finished product of this evaluation is tabulated as annual effective dose equivalents for typical job categories. Doses are presented as attributable to a specific practice, and practices are ranked against one another.

### Uncertainty and Sensitivity Analysis

Pathway models usually do not precisely describe a real situation. Some variables may be unrecognized or not quantified. In addition to the model structure, the parameters of the model each have a degree of uncertainty. A recent NORM report was heavily criticized for its lack of uncertainty analyses, and inadequate justification of parameter values (EPA, 1994). It was the intention of this study to obtain sufficient data to characterize pathway parameters so that assumptive biases were avoided. The Crystal Ball program was used to quantify parameter uncertainty. The software allowed input of statistical functions for each of many parameters in a model and uses a Monte Carlo simulation, or the preferred Latin Hypercube sampling to yield a statistical function for the model endpoint rather than a single value. That is, the result is a range of possible outcomes and the probability of achieving each of them.

A Monte Carlo system uses random numbers to measure the effects of uncertainty in a spreadsheet model. Latin Hypercube sampling is more precise because the entire range of the distribution is sampled in a more even, consistent manner (Decisioneering, Inc., 1993). It will also rank parameters with respect to their importance to the endpoint. Ranking allows more significant parameters to be given more attention and resources while those that do not have much influence on the final dose estimate can be de-emphasized.

In one scenario, *time of stay* at a location could represent the most significant parameter, while another scenario for a different process may indicate that the statistical variation of a source strength may be the critical parameter that needs a more accurate definition. In the former case additional interviews may be in order, whereas the latter would indicate additional sampling of the process. The uncertainty analysis methodology described above and the associated software were recommended in a recent EPA report (EPA, 1994).

The TEDE for a phosphate industry worker is composed of the following parameters: external dose (extrapolated from measurements), radionuclide activities in airborne dust (based on measurements), inhalation dose conversion factors (DCFs from literature), working hours spent in the airborne dust breathing zone, inhalation quantity of air (from literature), protection factor (respirator and its use), radon (progeny) dose, ingestion dose, and wound entry dose. Some assumptions must be incorporated in the dose model.

1. The external dose is a lognormal distribution as shown in the analysis of badge results. The annual dose is an extrapolation based on measured results.

2. Radionuclide concentrations in airborne dust are based on gross alpha and beta concentrations measured in air samples from the sites, and fractions of alpha and beta activities attributed to pre-gaseous members of the three principal decay chains as measured from dust deposition and raw material concentrations.

3. The radionuclide concentrations are assumed to be normal distributions truncated to zero for a low and to three standard deviations from the mean on the upper tail of the distribution (so that the software could not choose values to unreasonable extreme concentrations). The three standard deviation limit corresponds consistently to the maximum concentrations measured at the sites.

4. Dose conversion factors for inhalation are available in three classes (F, M, S) corresponding to solubility of the chemical form of the radionuclide. Class M DCFs are the most extensive (not all radionuclides form compounds in all classes) and are generally, but not always, between classes F and S in magnitude. The phosphate dry products are formulated to be at least somewhat soluble. Class M DCFs were chosen as the most reasonable match to the phosphate compounds, and to provide more

numerous radionuclide contributions to the dose. The DCFs are calculated for standard man. It follows that there must be some variability in this conversion due to individual human differences as well as uncertainties in the physiological model and data that are used to derive it. Since the variability is unknown, the DCFs were modeled as normally distributed about the listed value (mean) and truncated at about ± 10% (see Figure 42).

5. The hours spent in the breathing zone are based on interviews and observations of persons working in the generalized areas. The maximum for each distribution was set at the maximum hours per year spent in dusty areas.

6. The worker ventilation (the quantity of air breathed per year) was taken from literature values of ventilation rates under various levels of exertion from light activity to heavy labor. The mean was set at a moderate level of 35 liters per minute (LPM) with a lower limit of 13 LPM (light activity) and a maximum of 85 LPM (very heavy exertion).

7. The protection factor is based on the standard type of respiratory protection used in the industry: a dust and mist respirator covering the nose and mouth with a maximum protection factor of ten. The parameter is assumed to have a uniform distribution from one (no mask used) to ten (mask on and properly fit). The uniform distribution provides equal probabilities for all situations; e.g., the mask is never worn, sometimes worn, always worn, never properly fit, sometimes properly fit, or never properly fit (see Figure 43). A critic could argue that the assumed distribution is overly conservative by asserting that the protection factor is already conservatively based on typical use conditions which include degraded fit. Furthermore, quantitative fit testing, using a protocol involving a range of facial movements, typically shows much higher protection; i.e., a factor of greater than 3,000 (HEPA filter). However, the assumed distribution provides allowance for the conditions of infrequent or no usage. Also, this study assesses doses in the same manner that phosphate industry radiation safety officers must follow, which does not permit a higher protection factor for the indicated respirator.

8. The radon dose contribution to the TEDE is not included, because the measured levels are at background in most situations. As shown previously, the radon/daughter concentrations do not exceed background due to the open and drafty construction of the sites. The rock tunnels are the only locations of high concentrations, but are seldom occupied (usually laborers) and are vented.

9. The ingestion dose contribution to the TEDE is not included. In this context, ingestion is a minor pathway to internal dose. The products are not consumable and food is not eaten in work areas. Drinking water is not derived from working sites.

10. Although wound entry provides a direct path to the circulatory system of the body, wounds as documented herein are rare and injected quantities would be very small.

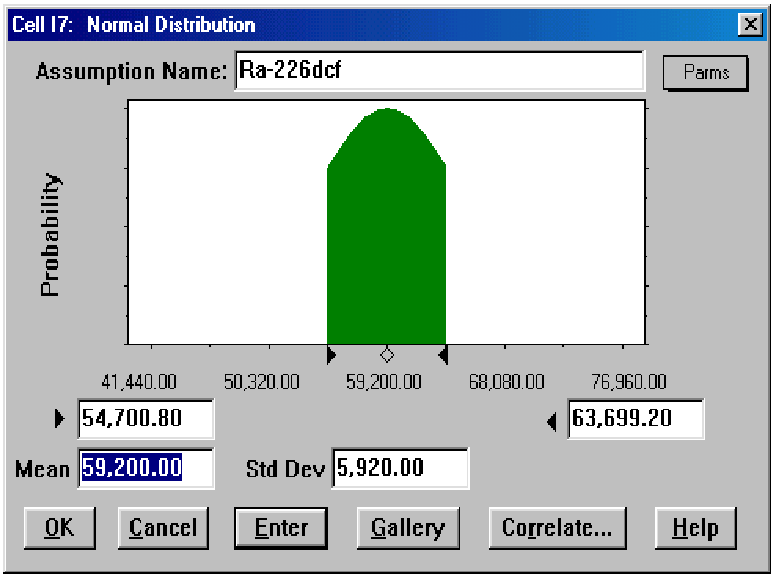


**Figure 42. Example of a Truncated Distribution for a DCF**

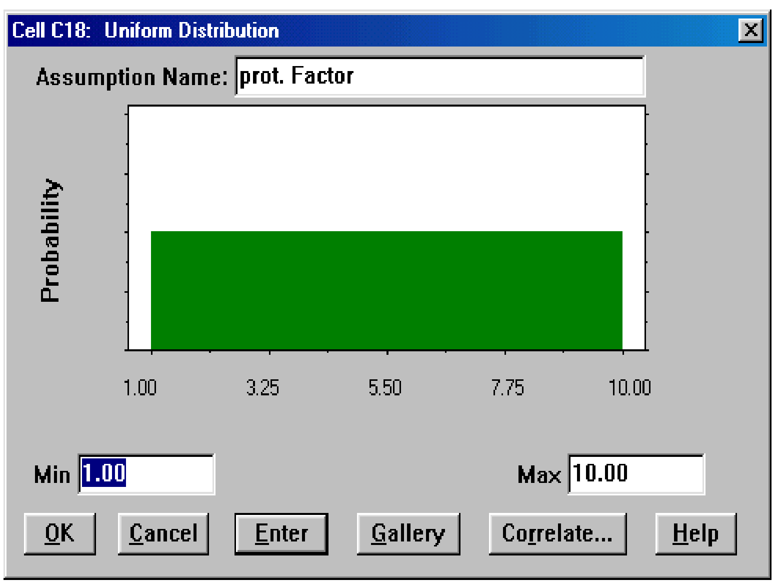


**Figure 43. Uniform Distribution for a Respirator Protection Factor**

The TEDE equation used in the generation of dose distributions and sensitivity analyses contains 30 parameters (variables) that are each described as statistical distributions. The dose for each area is the result of 10,000 separate calculations of the dose by computer selection of random values from each of the distributions. That gives a final result for each area of a dose distribution in units of mrem per year.

For example, a typical statistical distribution for a parameter may have a lognormal or normal distribution as shown in Figure 44, and the computer selects a value from that distribution (and the numerous other parameters) to generate a calculated dose. After 10,000 such calculations, the computer plots the final TEDE dose distribution as seen by example in Figure 45. Use of this uncertainty analysis technique also gives insight into effects of each parameter on the variability of the final dose. That is, of particular interest is to find which parameters tend to increase the spread of the distribution to higher dose levels. For example, in the mine TEDE distribution, the sensitivity analysis shows that the external dose as determined by TLD badge contributes 35% of variance, and the protection factor allowed for respirator use contributes about 55% (see Sensitivity Chart Figure 46). Different parameters are more important in different areas. The value of this analysis is that it becomes clear that workers in areas of airborne dust or mist should wear a basic NIOSH/MSHA approved respirator (and wear it properly fit).

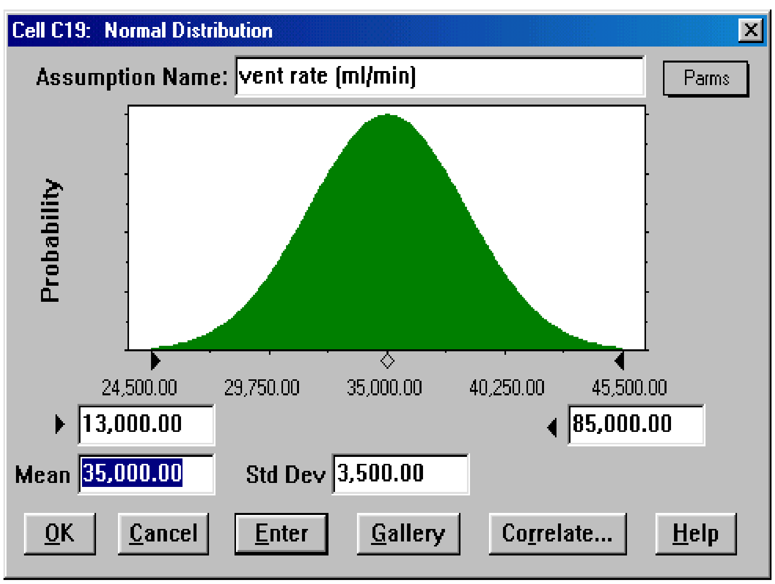


**Figure 44. Typical Parameter with Normal Distribution**

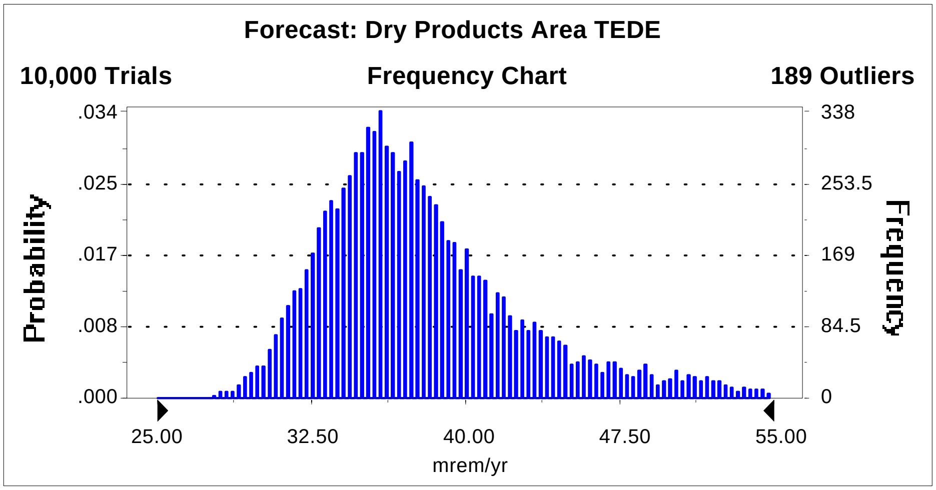


**Figure 45. Sample TEDE Dose Distribution**

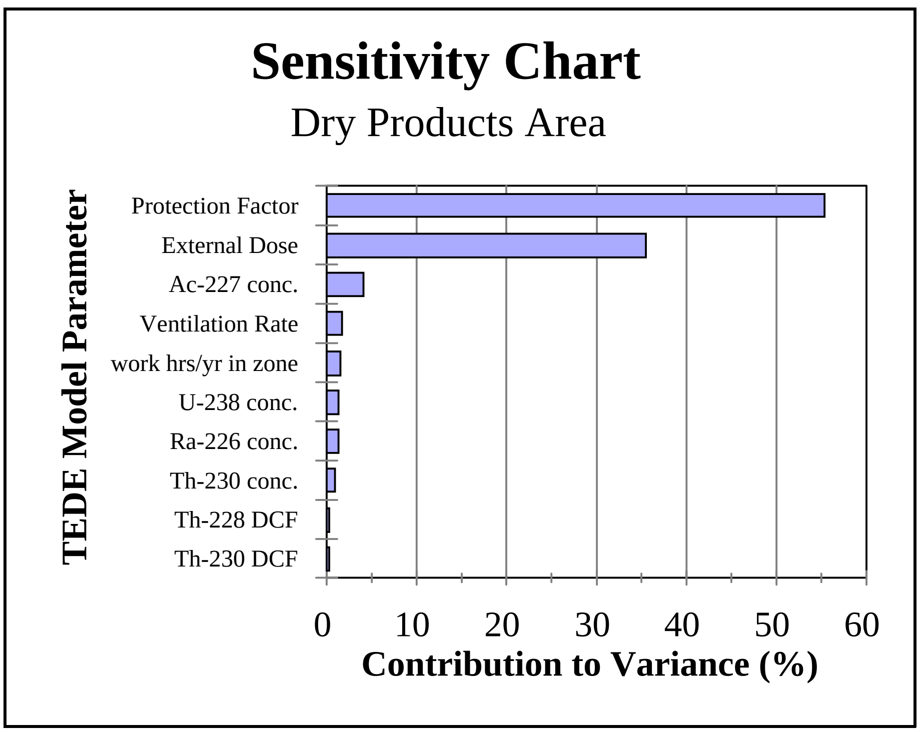


**Figure 46. Sample Sensitivity Analysis**

The final output TEDE distributions for the main industry areas and support activities are shown for the mine area (Figure 47), rock area (Figure 48), phosphoric acid area (Figure 49), dry products area (Figure 50), shipping area (Figure 51), pan chipping turnaround activity (Figure 52), and reactor cleaning turnaround activity (Figure 53). The graphical results are displayed to the $99^{th}$ percentile (two σ). Table 22 gives the same results in tabular form, and also indicates the maximum calculated doses beyond the visible ranges of the graphs. The maxima, while theoretically possible, are the result of multiple linked and unlikely events;

e.g., the maximum occupancy in an area with maximum external exposure rates, and maximum radionuclide concentrations inhaled with the maximum ventilation rate with no respiratory protection. Outcomes greater than 100 mrem/yr are highlighted. A more reasonable upper extreme is the 99$^{th}$ percentile; i.e., the dose rate below which 99 percent of the workers in that category will fall. Again, outcomes greater than 100 mrem/yr are highlighted. The shipping area is the most likely area where a worker could exceed the standard, and some may exceed the standard in the rock area. Less than one percent of the workers in the shipping area are expected to exceed 350 mrem/yr. The maximum of 184 mrem/yr in the service sector is due to one badged individual working in a paint yard who received consistently elevated external exposures. This appears to be a site-specific problem not applicable to the service sector as a whole. Contractors disassembling filtration equipment on chemical plant sites, those chipping gypsum from the associated pans, and those cleaning scale from reactor vessels (mainly hydroblasters) may all possibly exceed the standard. Less than 1% of those involved in reactor vessel (attack tank) cleaning should exceed 250 mrem/yr.

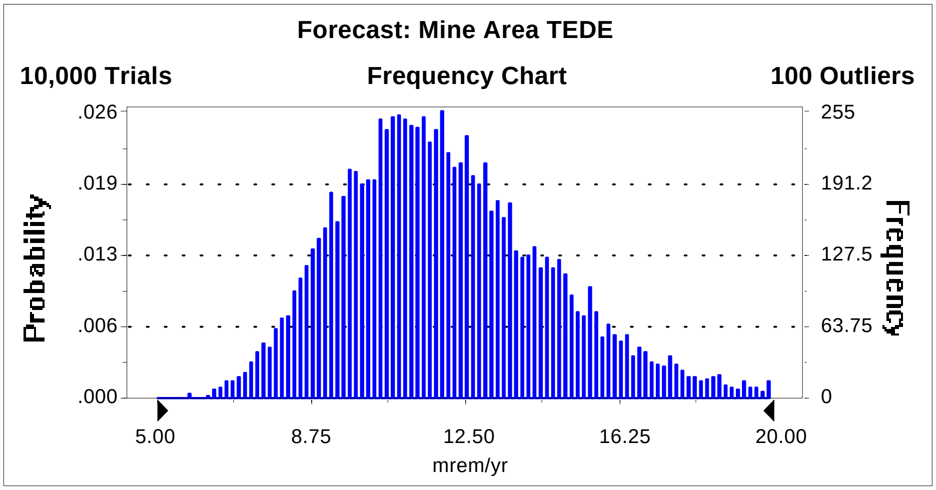


**Figure 47. Mine Area TEDE Dose Distribution**

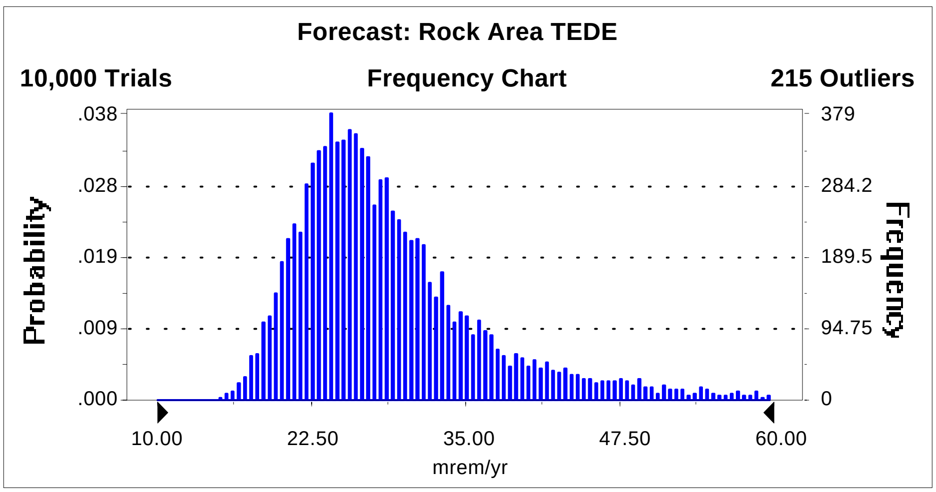


**Figure 48. Rock Area TEDE Dose Distribution**

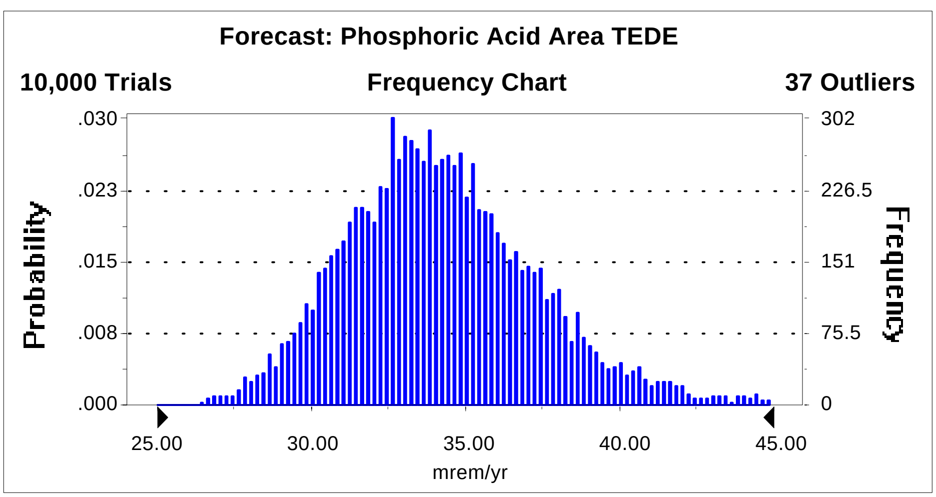


**Figure 49. Phosphoric Acid Area TEDE Dose Distribution**

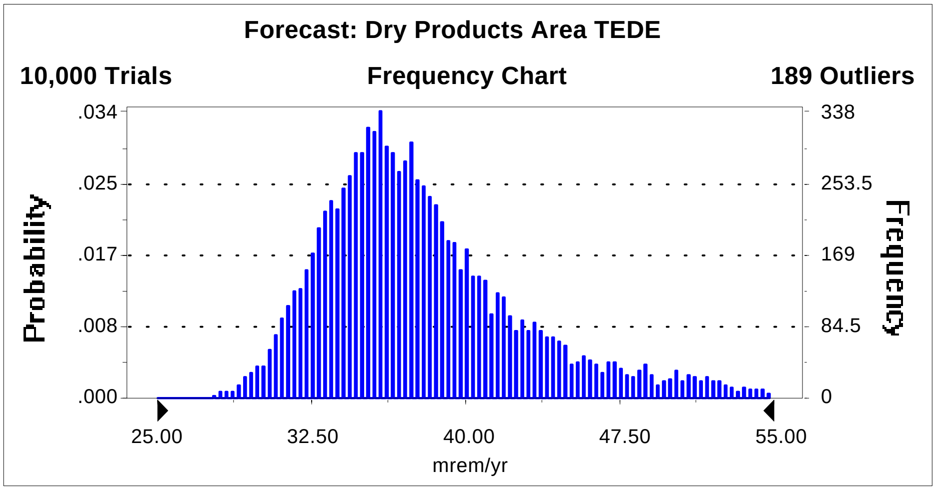


**Figure 50. Dry Products Area TEDE Dose Distribution**

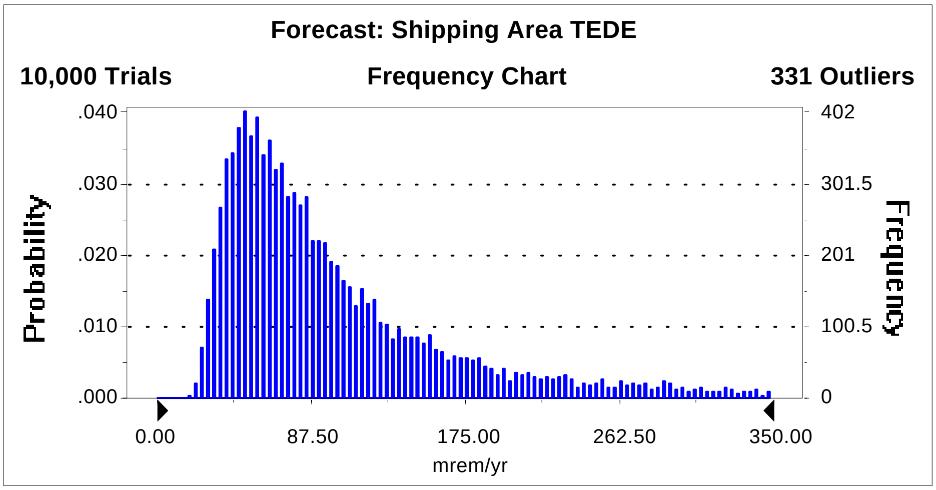


**Figure 51. Shipping Area TEDE Dose Distribution**

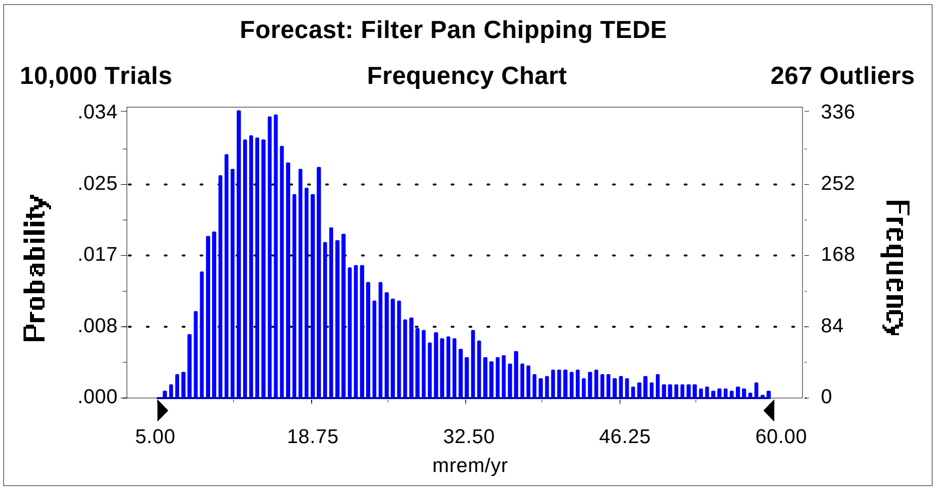


**Figure 52. Filter Pan Chipping TEDE Dose Distribution**

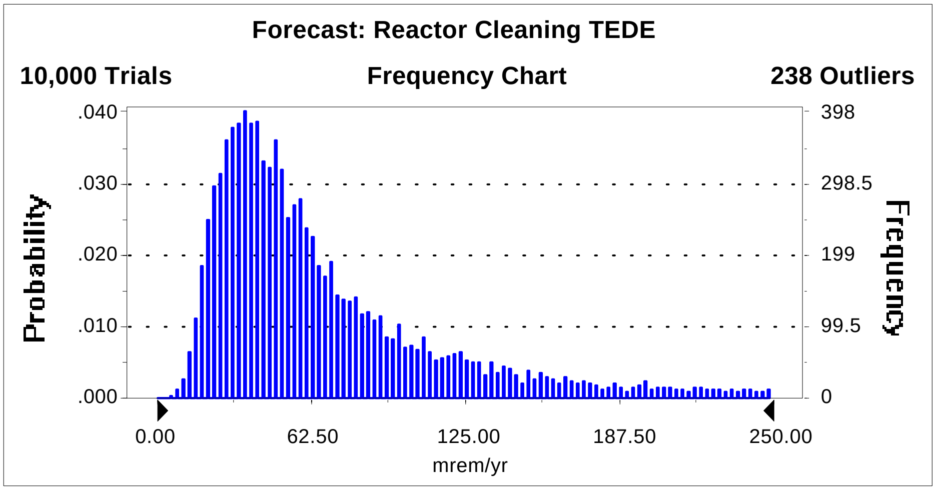


**Figure 53.** **Reactor Cleaning TEDE Dose Distribution**

**Table 22. TEDE Results**

| TEDE Statistics by Area or Task (mrem/yr) | | | | | |
|---|---|---|---|---|---|
| **Area or Task** | **Mean** | **Std. Err.** | **Min.** | **Max.** | **99th Percentile (2.60 σ)** |
| Mine | 12.11 | 0.03 | 5.78 | 26.93 | 20 |
| Rock | 29.86 | 0.10 | 14.23 | 136.96 | 60 |
| Phos. Acid | 34.28 | 0.03 | 25.51 | 50.33 | 45 |
| Dry P. | 38.32 | 0.06 | 26.39 | 77.07 | 55 |
| Ship. | 111.64 | 0.91 | 20.44 | 889.99 | 350 |
| Service | 8.50 | 1.10 | 4.80 | 184.40 | 11 |
| Pan Assembly | 31.60 | 0.18 | 9.06 | 129.31 | 80 |
| Pan Cleaning | 22.45 | 0.14 | 5.36 | 130.71 | 60 |
| Reactor Cleaning | 73.44 | 0.61 | 5.46 | 700.37 | 250 |

Parameter sensitivity analyses are graphically represented in Figures 54 through 61. These analyses show percent contributions of the parameters to the overall variability of the TEDE outcome; i.e., which parameters tend to widen the spread of the distribution (especially to the higher dose end). Identification of the larger contributors allows radiation safety specialists to target those factors for expenditure of resources (money and/or training) to reduce doses to ALARA levels. Precious few parameters are amenable to this type of influence. For example, ventilation (breathing) rates of workers, dose conversion factors, and radionuclide concentrations are not alterable. Adjusting working hours in breathing zones would likely hurt production. Reduction of external doses through shielding would require large expenses for even a modest effect. The only viable option is the "protection factor" parameter. This is the dose allowance given by properly wearing the minimum NIOSH/MSHA-approved dust and mist respirator. Since inhalation doses are important contributors to the TEDE, this parameter is frequently identified as a large contributor to variance.

In the mine area, external exposure accounts for 76% and the protection factor 19% of the variance in the TEDE distribution. For the rock area, the $^{226}Ra$ concentration is 47% (but cannot be changed), the external exposure is 25%, and the protection factor is 27%. In the phosphoric acid area, external exposure is 75%, and the protection factor (mainly inhalation of gypsum dust and mist) accounts for 21% of the variance. The TEDE for the dry products area is influenced by the protection factor (55%), and external dose (35%). Figure 62 shows the project team preparing to take an air sample in a truck loading area when the next truck moves into position to receive product. The shipping area TEDE is heavily influenced by the inhalation component and its parameters. In the shipping area, the protection factor contributes 56% to the variability, while the $^{227}Ac$ concentration is 37%. Even though there is not much $^{227}Ac$ present as expected from and actinium series radionuclide, it has an extremely large DCF due to its bone surface-seeking nature and biological retention. That DCF is directly multiplied to the concentration, thus increasing its importance. This phenomenon prompted the researchers to take a look at DCFs in general and the relative importance of TENORM radionuclides. Table 23 shows that seven of the highest 10 DCFs of the 296 listed in Federal Guidance Report 11 (Eckerman, et al, 1988) are TENORM radionuclides, and that $^{227}Ac$ DCFs occupy the first, fourth, and seventh positions. Furthermore, 29 of the top 69 DCFs are NORM radionuclides. The task of filter assembly cleaning receives 87% of its variability from the protection factor, and 7% from external dose. Filter pan cleaning (usually dry chipping with an air hammer) has a 64% contribution from the protection factor, 16% from $^{226}Ra$ concentration (inhalation), and 12% due to external dose. Finally, the task of reactor (attack tank) cleaning owes 64% of its TEDE variability to the protection factor, and 26% to the $^{226}Ra$ concentration. Figure 63 is a photograph of a hydroblaster working beneath the removed agitator of an attack tank compartment. Figure 64 shows the finished product of his labor; the cleaned brick lining of the vessel.

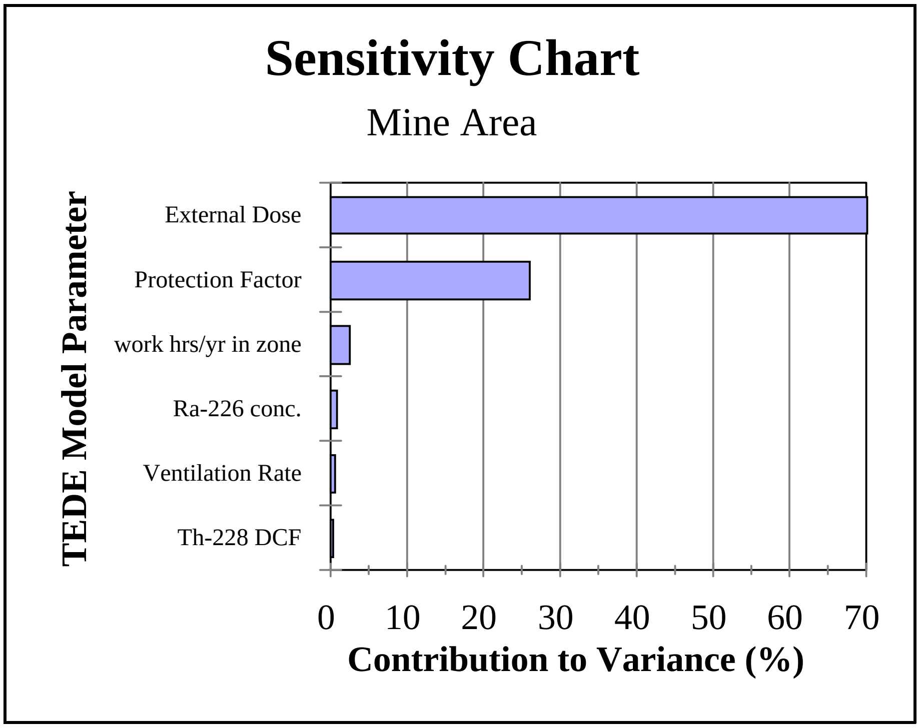


**Figure 54. Mine Area: Parameter Sensitivity Analysis**

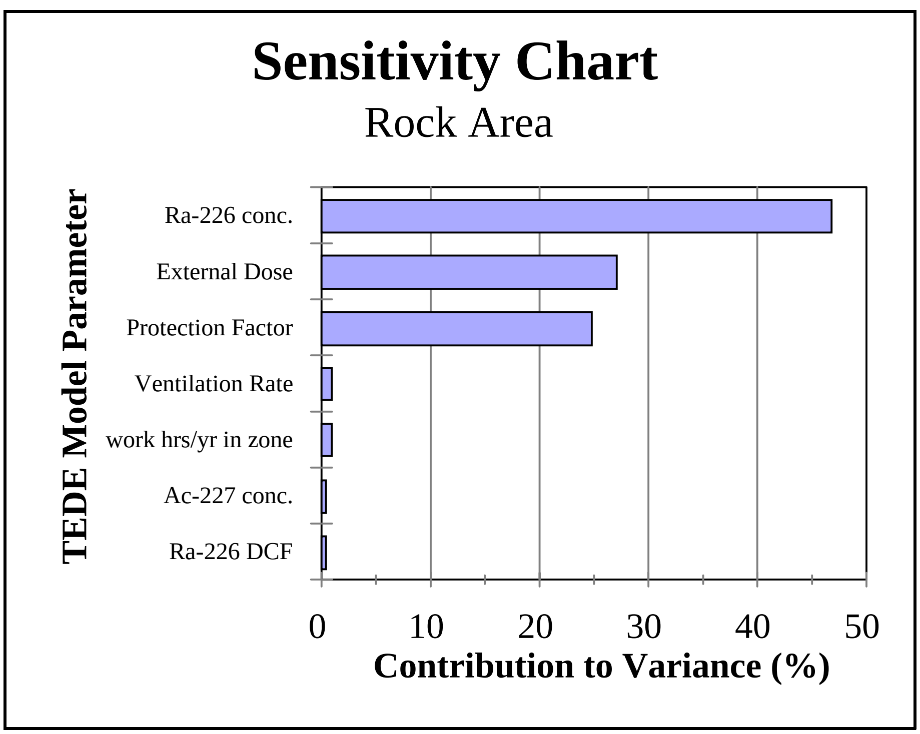


**Figure 55. Rock Area: Parameter Sensitivity Analysis**

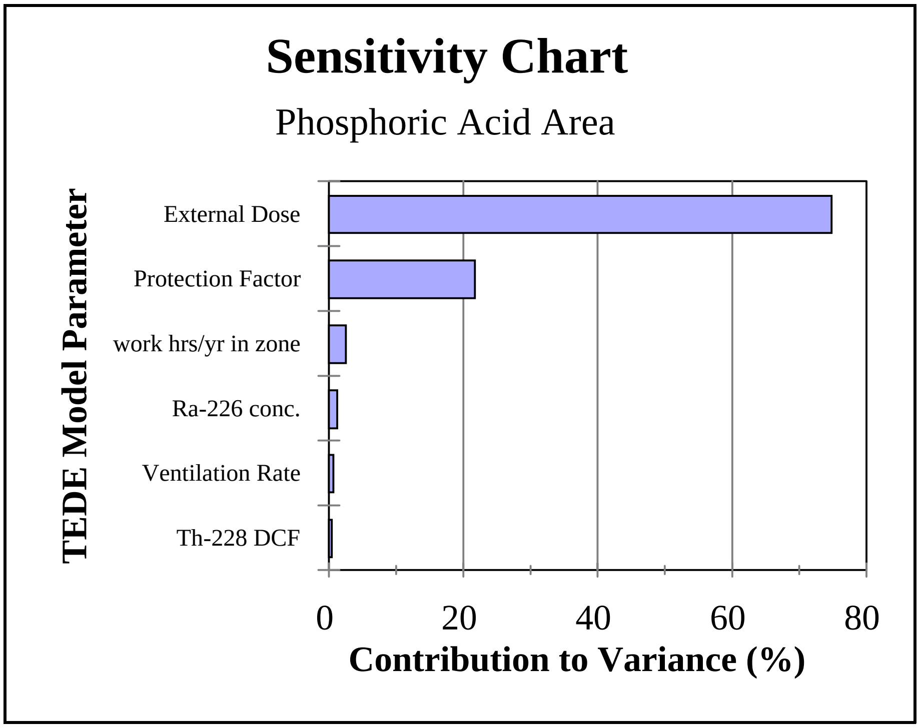


**Figure 56. Phosphoric Acid Area: Parameter Sensitivity Analysis**

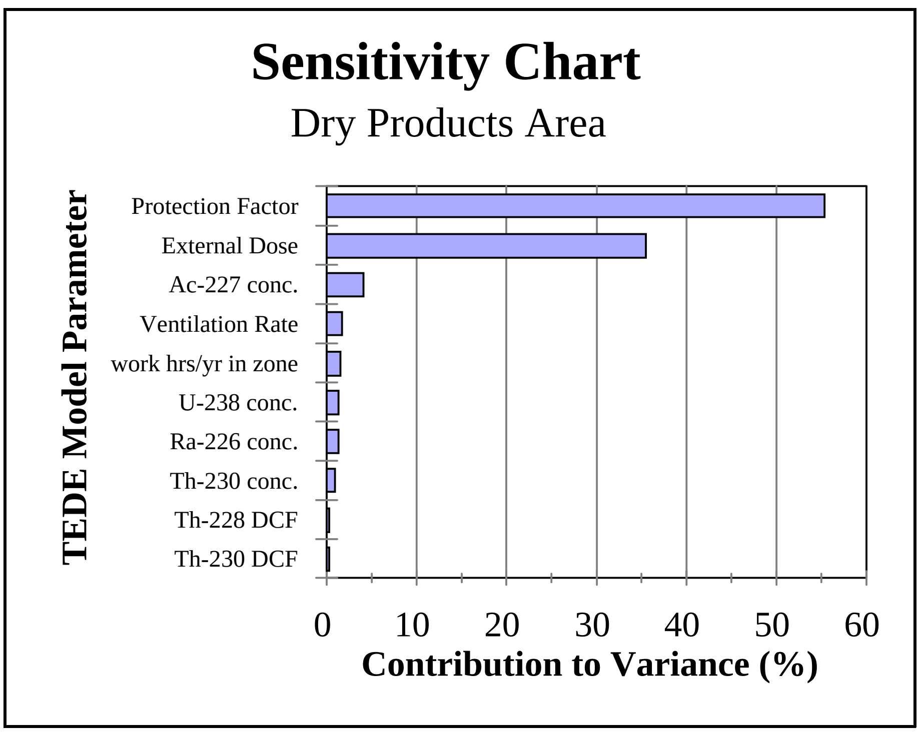


**Figure 57. Dry Products Area: Parameter Sensitivity Analysis**

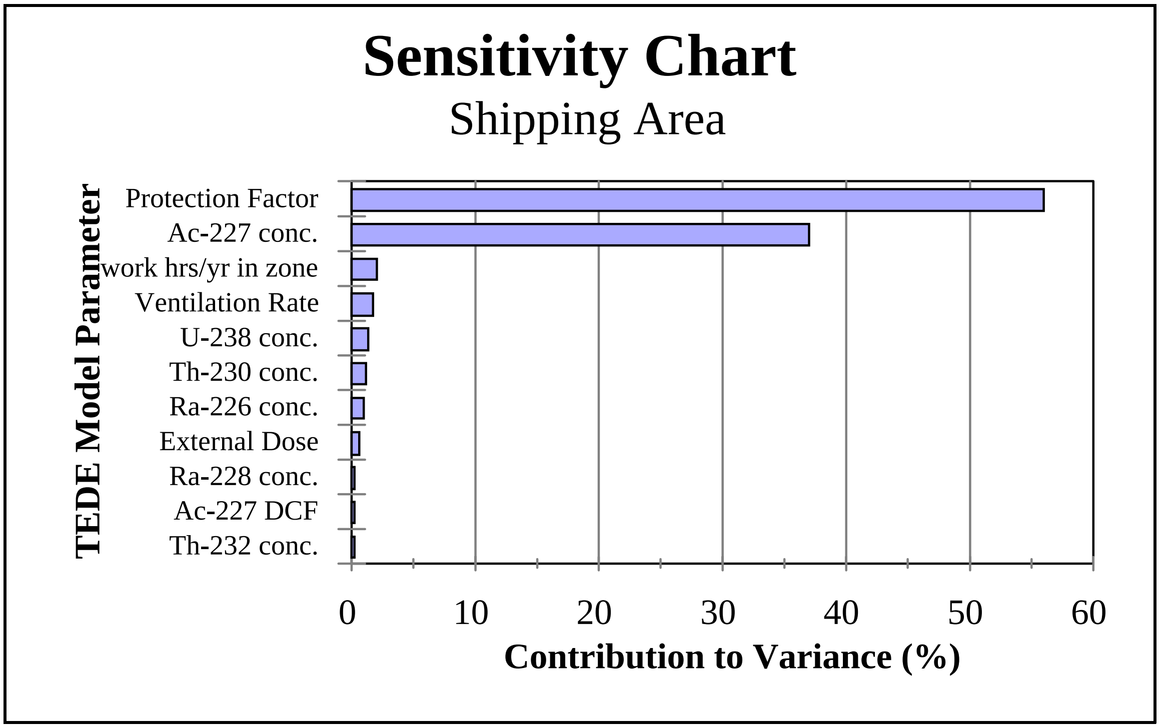


**Figure 58. Shipping Area: Parameter Sensitivity Analysis**

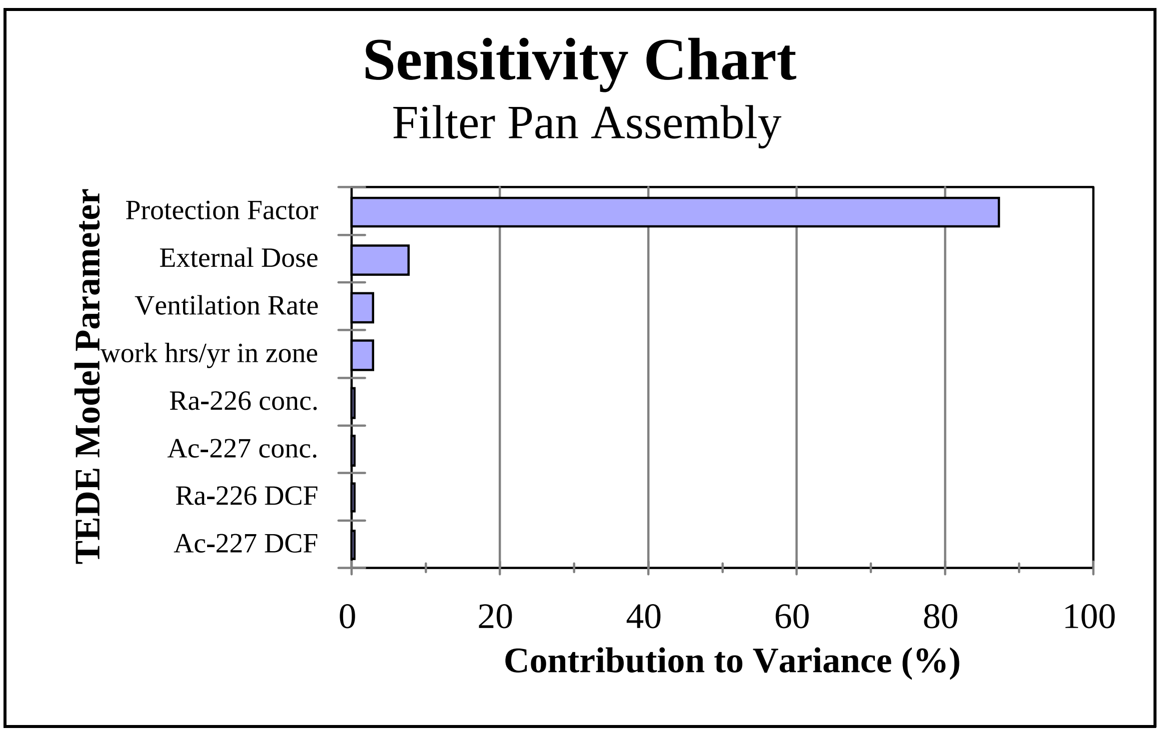


**Figure 59. Filter Pan Assembly: Parameter Sensitivity Analysis**

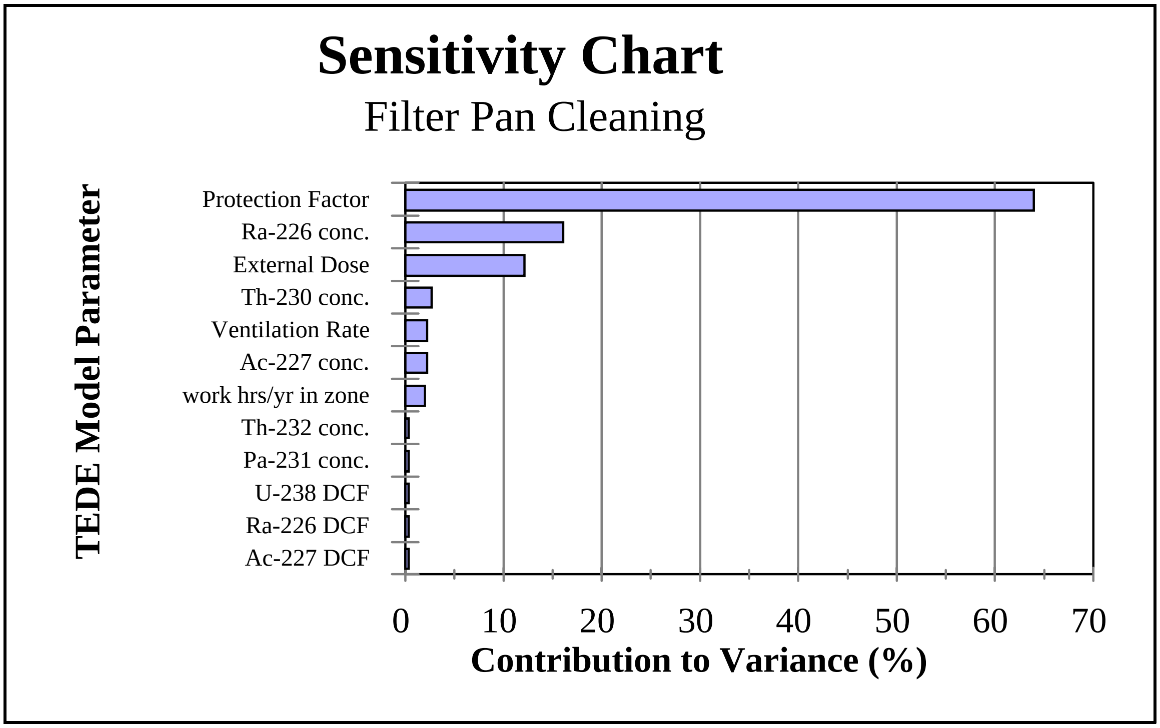


**Figure 60. Filter Pan Cleaning: Parameter Sensitivity Analysis**

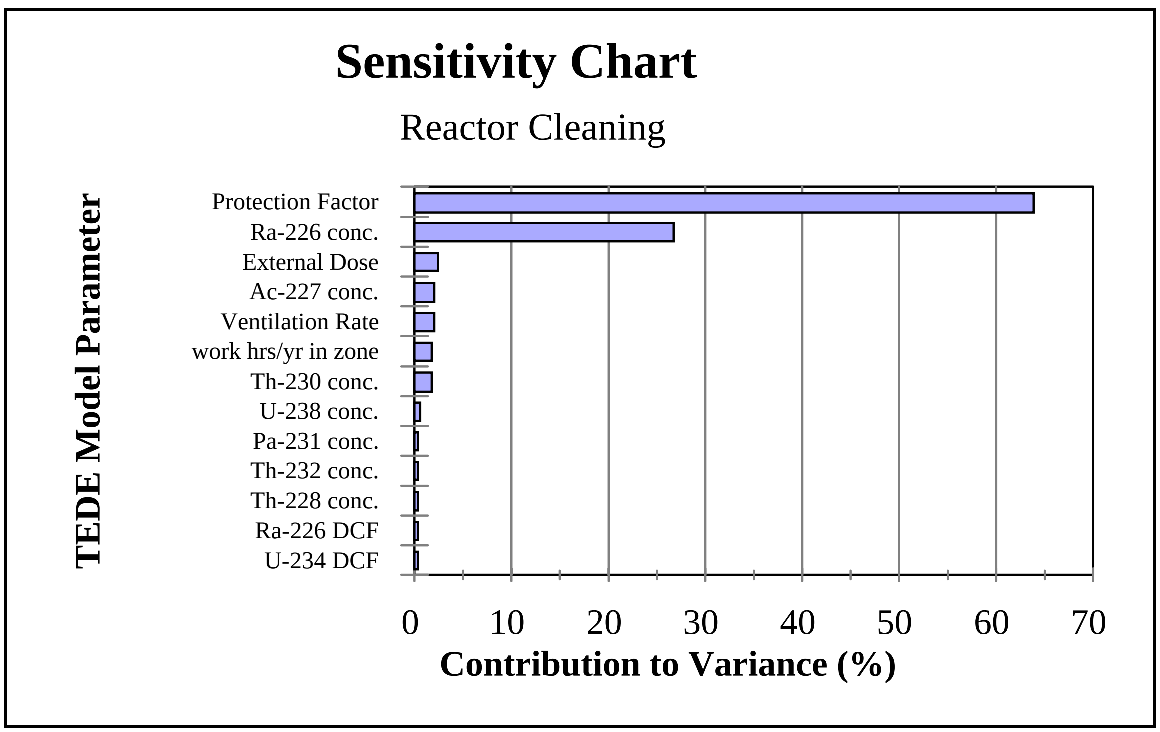


**Figure 61. Reactor Cleaning: Parameter Sensitivity Analysis**

**Table 23. Ranking of NORM Radionuclide DCFs**

| FGR #11 Inhalation CDE | | | |
|---|---|---|---|
| **Nuclide** | **Class** | **$H_{eff}$ (Sv/Bq)** | **Rank (of 296)** |
| Ac-227 | D | 1.81E-03 | 1 |
| Th-229 | W | 5.80E-04 | 2 |
| Th-229 | Y | 4.67E-04 | 3 |
| Ac-227 | W | 4.65E-04 | 4 |
| Cm-248 | W | 4.47E-04 | 5 |
| Th-232 | W | 4.43E-04 | 6 |
| Ac-227 | Y | 3.49E-04 | 7 |
| Pa-231 | W | 3.47E-04 | 8 |
| Th-232 | Y | 3.11E-04 | 9 |
| Pa-231 | Y | 2.32E-04 | 10 |

**Figure 62. Truck Loading Station: Air Particulate Sampling**

**Figure 63. Reactor Cleaning: Hydroblasting**

**Figure 64. Reactor Cleaning: Cleaned Brick Lining**

## CONCLUSIONS AND RECOMMENDATIONS

Many of the conclusions of this report have been discussed in the Results section. Those conclusions are presented again in this section with the addition of further conclusions that are drawn indirectly from them. The Recommendations subsection presents suggestions by the project team regarding improved industrial procedures, regulatory issues, and additional future research needs.

The best way to interpret results in a scientific study is through the guidance of an organization of professionals specializing in the field of study. The Health Physics Society (HPS) is a scientific organization concerned with the protection of people and the environment from unnecessary exposure to radiation. The society's concern is also understanding, evaluating and controlling the risks from radiation exposure relative to the benefits derived from the activities that produce the exposures. The published scientific positions of this society are cited to support conclusions of the project team.

### CONCLUSIONS

Conclusions are made regarding three levels of dosimetry: external radiation dose, internal radiation dose, and the TEDE to workers.

#### External Dose

1. Analysis of multiple data sets demonstrates that the <u>average</u> phosphate industry worker, regardless of assigned area, receives an annual radiation dose from sources external to the body that is far less than current limits for members of the public.

2. Personnel working for companies that service the phosphate industry receive annual radiation doses from sources external to the body that are at the low end of the spectrum for the industry. The only exception is for workers involved in a particular paint yard who are projected to have the highest exposures in the industry. This may be a site-specific problem, and can be solved with mechanical measures and new procedures.

3. Any industry area categorized in this study can produce a worker whose <u>extrapolated</u> annual dose exceeds 100 mrem if the monitoring duration is approximately one month; i.e., short-term sampling versus quarterly sampling exaggerates higher dose fluctuations. Over a year's monitoring period, individual cumulative annual doses would tend come back to the mean; i.e., extrapolated highs or lows based on short-term sampling are smoothed out.

4. The higher external dose occupations are found in phosphoric acid production and rock handling areas, but few exceed the annual dose limit for a member of the public.

## Internal Dose

**Airborne particulate dose.** Solid sample analyses confirm the trends found in the literature. Radium goes with gypsum while uranium is largely absent, dry products (MAP, DAP) produced with phosphoric acid have enhanced uranium activities, and GTSP retains radium and uranium from input rock and is enhanced with uranium from phosphoric acid. In terms of severity of the inhalation dose component by area, the hierarchy is: shipping > rock > dry products > phosphoric acid > mine. Note that the shipping area yields much greater inhalation doses than the others, and that the rock and dry products areas produce very similar doses. An inhalation dose component was not calculated for off-site service companies, because no air sample greater than background was ever recorded. This is not surprising considering the types of open-air working environments encountered, and the fact that objects are cleaned to low release exposure rates before transportation from the chemical plants.

**Turnaround activities.** Analysis of airborne particulates during reactor vessel work shows levels similar to routine operations until the spike at > 2.25 E-11 μCi/ml representing the early stages of hydroblasting (no respiratory protection worn). The full analysis of reactor cleaning inhalation dose considering the yearly frequency the workers perform the task yields a mean of 68 mrem/yr; and 99% of workers are below 250 mrem/yr.

During dry pan chipping and scraping (minimal protection worn, if any) the incurred inhalation dose is a mean of 16 mrem/yr with 99% of workers below 50 mrem/yr. The associated task of filtration apparatus disassembly, cleaning, and refitting shows concentration levels close to normal operating conditions except for the spike at > 6.75 E-12 μCi/ml representing Black Beauty blasting. Black Beauty is the trade name for an abrasive granular material used for sand blasting that also contains TENORM radionuclides. This airborne radionuclide concentration spike is not a problem, because workers used supplied air. This task delivers a mean inhalation dose of 24 mrem/yr with 99% of workers less than 80 mrem/yr.

**Radon.** Although scientists have been aware of radon for many years, it was not until recently that it was realized that the largest radiation exposures received by most individuals come from natural sources of radiation, primarily radon and its radioactive decay products. This new understanding of the role of radon has led to anxiety over radiation exposures among members of the general public and considerable and often inaccurate statements in the media. Radon/radon daughter analysis indicates levels well below concern, especially considering the open air working environment. The levels in rock tunnels are high (10s of pCi/l), as found in previous studies, although working levels are not excessive (< 1 mWL) suggesting that equilibrium factors are generally low (not measured in this study).

Radon measurements made in this study using E-perm electret ion chambers were all well below the EPA guideline for residences of 4 pCi/l, except for rock tunnels. The EPA uses an extremely conservative scenario for the home of continuous family occupancy and exposure to derive this limit. Therefore, the application of this standard to far less occupancy time and an adult workforce leads to the conclusion that background exposures are not exceeded and an attributable dose above background does not usually occur.

**Wound entry.** The introduction of foreign materials through broken skin is a minor pathway for the entry of radionuclides into the body in the phosphate industry context. Analysis of industry data provided a rate of 4.2 E-05 *possible* skin breaks per working hour, or 0.26 *possible* skin breaks per 2,000 working hours; i.e., about one accident for every twelve years worked per worker. In addition to the low frequency of wounds, further consider that not all such wounds incorporate foreign materials containing radioactivity, and such wounds are normally quickly irrigated so that absorption into the circulatory system is decreased. The doses derived from the low activity concentrations of phosphate industry raw materials and products are too hypothetical and trivial to calculate.

**Ingestion dose.** Ingestion dose is a minor pathway for industry workers. Food items are not normally consumed in working environments. Furthermore, even if foods were consumed in those areas and small quantities of raw and product materials contaminated those foods, the resulting doses would be small. There is also a small fraction of the inhaled particulates that are moved up the respiratory system's mucociliary transport mechanism to the throat and swallowed into the gastrointestinal tract. The dose is not only reduced by quantity, but also by quality of dose delivery via this pathway. That is, the DCFs for ingestion are orders of magnitude lower than inhalation DCFs. Comparing ICRP No. 68 DCFs reveals that the average inhalation dose is almost exactly 200 times greater than the corresponding ingestion DCF. The calculation of doses for ingestion would yield tenths of mrem per year in most cases, and is not a worthwhile pursuit. Drinking water is subject to federal standards for radioactivity content. A recent company-sponsored study of a north Florida phosphate operation analyzed well water samples and conducted an ingestion dose analysis for potable water, and found the doses to be trivial (RSS, 1997).

"The Health Physics Society recommends that regulations for radiation protection be based on the scientific consensus contained in the recommendations of the ICRP and NCRP. In particular, we recommend that constraints be applied to all regulated, nonmedical, nonoccupational sources of radiation exposure to the general public, excluding indoor radon (hereinafter referred to as "constrained sources"), such that no individual member of the public will receive in any one year a committed effective dose equivalent (CEDE) exceeding 100 mrem (1 mSv) from all such sources combined" (HPS, 1992). Constraints refer to restrictions placed on sources or practices in order to achieve the dose limits that apply to individuals (ICRP 1991). The CEDE, as used in this text by the HPS, is the sum of the absorbed doses that will be delivered to the separate organs or tissues during the lifetime of an individual from one year's intake of radionuclides, with each organ or tissue dose weighted for the type of radiation producing the dose and the relative tissue susceptibility, using the weighting factors recommended by the ICRP. The CEDE has been replaced as a quantity by the committed effective dose.

Even though this is an occupational application, many members of the workforce are not trained as radiation workers (especially in the service sector), and as such are members of the general public. An important implication in the cited HPS passage is that indoor radon (radon progeny) dose is not included in the CEDE, and consequently is regarded as a separate treatment, as is done in this study.

**Total Effective Dose Equivalent**

The mean annual doses (mrem/yr) to the critical groups are: mine area (12), rock area (30), phosphoric acid area (34), dry products area (38), shipping area (111), routine service by off-site contractors (8), filtration assembly cleaning (32), filter pan cleaning and chipping (22), and attack tank cleaning (73). The mine and service areas would not need further evaluation according to the HPS statement above, but those evaluations were made in this study.

The shipping area is the most likely area where a worker, as a member of the public, could exceed the standard. The rock area is one where some individuals may exceed the standard. Less than 1% of the workers in the shipping area are expected to exceed 350 mrem/yr. Contractors disassembling filtration equipment on chemical plant sites, chipping gypsum from the associated pans, and cleaning scale from reactor vessels (mainly hydroblasters) may all possibly exceed the standard. Less than 1% of those involved in reactor vessel (attack tank) cleaning should exceed 250 mrem/yr.

The sensitivity analysis revealed respirator usage and the external dose distribution are the main factors affecting the variability in the TEDE distribution. For the respirator usage (protection factor), the contributions to the TEDE variability are: mine area (19%), rock area (27%), phosphoric acid area (21%), dry products area (55%), shipping area (56%), filtration assembly cleaning (87%), filter pan cleaning and chipping (64%), and attack tank cleaning (64%). For the external dose distribution, the contributions to the TEDE variability are: mine area (76%), rock area (25%), phosphoric acid area (75%), dry products area (35%), shipping area (<1%), filtration assembly cleaning (7%), filter pan cleaning and chipping (12%), and attack tank cleaning (2%). The only other first or second ranked contributors are $^{226}$Ra concentration in the rock area (47%), pan cleaning (16%), and attack tank cleaning (26%); and $^{227}$Ac concentration in the shipping area (37%). These concentrations are an inherent characteristic of the mined matrix and are influenced inadvertently by mechanical and chemical processing. They are not amenable to reduction efforts.

An item of interest noticed by the project team is that seven of the highest 10 DCFs of the 296 listed in Federal Guidance Report 11 (Eckerman, et al, 1988) are TENORM radionuclides, and $^{227}$Ac DCFs occupy the first, fourth, and seventh positions. Furthermore, the top 69 DCFs are dominated by TENORM radionuclides.

The HPS strongly recommends that dose limits be applied only to individual members of the public, not to the collective dose to population groups. However, evaluation of constrained sources should be based on the mean annual dose to the critical population group, defined as the most highly exposed homogeneous group affected by a specific constrained radiation source. This is the approach used in this study by consolidating "homogenous groups" of workers by subareas such as the phosphoric acid area. The society recommends that if the mean annual dose to the critical group is likely to exceed 25 mrem CEDE, an evaluation should be made to ensure that no individual is likely to receive an annual dose exceeding 100 mrem from all constrained sources combined. Since the 100 mrem/yr TEDE is in regulatory effect for Florida, the evaluation used in this study is even more restrictive than the HPS benchmark.

## RECOMMENDATIONS

Recommendations for industrial procedures and practices to comply with regulatory limits as well as maintaining doses ALARA, regulatory issues to be considered, and future research needed to reduce uncertainties in the TEDE calculations are all presented in the next three subsections.

### Industrial Procedures

Monitoring of external exposures to personnel in the phosphate industry has commonly been accomplished through use of LiF TLD badges. External exposures in the industry are so low that this dosimeter is not sensitive enough to register doses for most workers in a quarterly period. It is recommended that more sensitive dosimeters should be the standard issue, and that control badges should be stored in a very low background location. The choice of dosimeter vendor is up to the various companies. Landauer is discontinuing their LiF badges entirely in favor of the more sensitive aluminum oxide dosimeter that is processed using laser technology called the "Luxel dosimetry system." This dosimeter is capable of detecting gamma energies as low as 5 keV and beta energies down to 150 keV. It has a dose range of 1.0 mrem to 1,000 rad for high and low energy photons and betas (over 1 MeV). In addition, this badge is much more durable than the LiF badge; an important consideration for the phosphate environment.

According to ALARA principles, the TEDE must be minimized. The first line of defense is implementation of engineering controls. If it is practical to do so, dust emissions should be restricted or contained at the source. In the absence of, or in addition to such controls, use of a respirator can offer protection against inhalation of the airborne activity. However, wearing a respirator decreases the worker's efficiency and increases the time necessary to complete a job. Thus, the decision about whether or not to use respiratory protection depends on the actual levels of ambient airborne radioactivity and the effect of respirator use on the TEDE distribution. In areas where the TEDE distribution variability is very sensitive to the protection factor of the respirator and doses approach or surpass the standard, the use of respirators and instruction in their proper fit and replacement is recommended. This definitely applies to the shipping area and the attack tank cleaning turnaround activity. The rock handling area and the dry products area personnel should use respirators if they routinely work in dust conditions. The phosphoric acid activities involving airborne dust and mist, the early stages of filtration disassembly and scale removal, and pan chipping activities would all benefit from respirator use. In most cases, the companies already encourage respirator use, and workers voluntarily comply in situations where dust loading is high enough to cause irritation. In regard to the expense of a respiratory protection program, the HPS statement on what is reasonable in ALARA expenditures states: "For doses near the individual dose limits recommended by the ICRP and the NCRP in clearly identified populations, the appropriate expenditure may be as much as a few hundred dollars per person-rem avoided. Where larger sums are spent to avoid radiation doses to any population group, such expenditures should not be attributed to health protection and should be clearly identified and justified separately." Since the individual dose limit is 100 mrem/yr, the reasonable amount to spend in dose reduction is a few hundred dollars for every group of ten workers expected to approach or marginally exceed the limit. This amount should be weighed against the cost of implementing a respiratory protection program to determine if ALARA doses are maintained with or without it. The HPS also recognizes that it would be inappropriate to devote the same magnitude of effort or resources to reducing undetectable risks as are appropriate for risks that produce observable health effects.

Recommendations regarding radon made in earlier studies still apply; i.e., ventilation of the tunnels and limited stay times. Workers who enter the rock tunnels are usually laborers who infrequently clean up spills, and maintenance personnel who repair conveyor systems. It is recommended that the ventilation system be operated in advance of any entry so that the entire volume of air in the tunnel is replaced, and that the fans remain in operation while the tunnel is occupied.

**Regulatory Issues**

The TEDE limit of 100 mrem is in regulatory effect and is therefore enforceable. However, it should be realized that an annual dose of 100 mrem is much too small to produce any detectable biological effects in any exposed individual. It is clear that in some cases, as discussed in the previous subsection, use of a respirator is recommended as an ALARA precaution. The respirator of choice is the minimum NIOSH/MSHA-approved model with a protection factor of 10 for particulates and mist.

In conclusion, most workers employed by the phosphate companies receive training commensurate with the level of radiation hazard they encounter. Those workers are subject to the occupational exposure limit of 5,000 mrem/yr TEDE. The finding of this study is that it is extremely unlikely that this limit would be approached or exceeded. Engineering controls and the use of respirators should be considered part of the ALARA commitment.

Service industry workers are often not trained in radiation safety, and are consequently subject to public dose limits. This study found that service industry workers working on phosphate company sites, and more often at remote service company locations, receive doses far below the 100 mrem/yr TEDE limit for a member of the public. The only exception to this finding is workers involved in attack tank cleaning. The most significant component of the TEDE for those individuals is the inhalation dose. It is recommended that a more targeted study be conducted to reduce uncertainties in that dose component, so that appropriate actions may be taken.

**Future Research**

In the Methodology section, the problem of calculation of an external radiation dose directly from ambient exposure rate measurements taken by survey meters or PICs was discussed in great detail. This study was designed so that area monitors (X9 dosimeters) placed in the working environment for extended continuous exposure (roughly a month) could be compared to PIC measurements made periodically at the same locations. This would provide a field dose conversion factor of "vendor-reported rem" per roentgen. The term "vendor-reported rem" is used because the dosimeter vendor and processor applies some DCF from absorbed dose to the badge to human dose in rem. Since the phosphate industry personnel involved in radiation monitoring must rely on these badge results for the official dose to the worker, and they commonly assess radiation levels using survey meters calibrated against the PIC, this seemed to be a logical and practical approach.

In the final analysis, the conversion factor calculated in this study only further confuses the issue and was not used in any data analysis herein, but it does serve to illustrate the need for further research in an effort to define the true mrem/mR conversion factor for the TENORM phosphate environment whether it is 0.6, 1.56 or somewhere between. This has been an ongoing problem in separate phosphate-industry-related studies such as the land application of phosphogypsum, and a consensus scientifically based decision should be reached.

The importance of the inhalation dose component to the TEDE is well documented in this text. Research should be conducted to reduce uncertainties in its calculation. This includes measurement of particle size distributions in the various working environments using cascade impaction air samplers. This type of study was conducted for a wet process facility (Ryan and Cotter, 1980), but the results were extremely variable. That study found that 45-85% of the $^{226}$Ra, 5-75% of the uranium, and 7-75% of the $^{230}$Th were associated with particles of equivalent aerodynamic diameter of 0.5 microns or less. Dust particles in dry product areas were much larger. There is also a need to study dissolution times of the sample and size combinations in simulated human lung fluid to define clearance classes for choosing proper dose conversion factors.

**RISK ASSESSMENT**

In a dose analysis of this nature it is appropriate to address the associated risks of health detriment. "In accordance with current knowledge of radiation health risks, the Health

Physics Society recommends against quantitative estimation of health risk below an individual dose of 5 rem in one year or a lifetime dose of 10 rem in addition to background radiation. Risk estimation in this dose range should be strictly qualitative accentuating a range of hypothetical health outcomes with an emphasis on the likely possibility of zero adverse health effects. The current philosophy of radiation protection is based on the assumption that any radiation dose, no matter how small, may result in human health effects, such as cancer and hereditary genetic damage. There is substantial and convincing scientific evidence for health risks at high dose. Below 10 rem (which includes occupational and environmental exposures), risks of health effects are either too small to be observed or are non-existent." (HPS, 1996).

In other words, for doses below 5,000 mrem/yr, risk estimates should not be used, and expressions of risk should only be qualitative, emphasizing the inability to detect any increased health detriment (i.e., zero health effects is the most likely outcome). All TEDE results in this study are far below the risk calculation baseline. Radiation protection efforts are usually directed to the control of doses for which the assumed effects in humans are stochastic and assumed not to require a threshold dose. The mechanisms of biological damage observed at high doses have led to the assumption that any radiation dose, no matter how small, may be capable of causing some detriment. On the other hand, there is also some evidence for the possibility of biological benefit at low doses, i.e, the radiation hormesis effect (Luckey, 1991).

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# APPENDIX A - SUPPORTING DATA FOR THE INTRODUCTION SECTION

**LITERATURE DATA**

**Table A-1. Data from the HRS Study (Keaton, 1987)**

| No. | Description of Objects Surveyed | Micro-R Meter Measurement (µR/hr) | | | Ion Chamber Measurement (µR/hr) | |
|---|---|---|---|---|---|---|
| | | avg or min | | max | avg or min | max |
| 1 | inside uncleaned pan at ribbed surface | > | 3000 | | | |
| 2 | outside surface of uncleaned pan | | 1700 | | | |
| 3 | 2 meter from inside of uncleaned pan | > | 3000 | | | |
| 4 | uncleaned pan retention area | | 100 | 3000 | | |
| 5 | uncleaned pan retention area 5 feet from two pans | | 800 | | | |
| 6 | inside cleaned pans at ribbed surface | > | 3000 | | | |
| 7 | outside surface cleaned pan | | 800 | 1500 | | |
| 8 | surface of cleaned pan with section of ribs removed | | 100 | | | |
| 9 | surface of above pan where ribs not removed | | 1000 | | | |
| 11 | scrap bin with removed ribs in it | | 800 | | | |
| 14 | caulking pile in pan retention area | | 800 | | | |
| 15 | filter cloths in pan retention area | | 1500 | | | |
| 16 | agitator blade from reactor vessel | | 40 | 150 | | |
| 17 | 15 feet from pan retention area S.W. corner of shop 2 feet from surface of road | | 90 | | | |
| 18 | 50 feet from pan retention area | | 15 | | | |
| 19 | hydroblast area 2 feet from ground surface | | 800 | 1200 | | |
| 20 | readings in plant excluding pan repair area | | 7 | 15 | | |
| 21 | cleaned pan with rib sections removed | | | | 2.2 | |
| 22 | above cleaned pan where rib sections not removed | | | | 3 | |
| 23 | pan retention area (no pans in area) | | 20 | 30 | | |
| 24 | pile of removed filters (at surface) | | | | 3.4 | |
| 25 | waste pile of ribs | | | | 1.5 | |

| No. | Description of Objects Surveyed | Micro-R Meter Measurement (μR/hr) | | Ion Chamber Measurement (μR/hr) | |
|---|---|---|---|---|---|
| | | avg or min | max | avg or min | max |
| 26 | hydroblast area | | | 1 | 2.5 |
| 27 | pile of scale on shop floor | | | 5 | |
| 28 | hydroblast area being washed and cleaned | | | 0.2 | |
| 29 | pile of material cleaned from hydroblast area | | | 1 | 9 |
| 30 | Parking lot | 7 | | | |
| 31 | repaired pan on contact with old section not moved | 2000 | | 2.3 | |
| 32 | repaired pan at a distance of 1 meter with old section not moved | 600 | | 0.5 | |
| 33 | repaired pan on contact with rebuilt section 2 feet wide | 400 | | | |
| 34 | repaired pan over trough | 800 | | 0.7 | |
| 35 | repaired pan at a distance of 1 meter | 500 | | 0.4 | |
| 36 | cleaned out but not repaired pan (large) | | | | |
| 37 | cleaned out but not repaired contact with pan over trough | > 3000 | | 4.2 | |
| 38 | cleaned out but not repaired contact with pan not at trough | 1900 | | 2.4 | |
| 39 | small filter pan | | | | |
| 40 | contact with pan at trough | > 3000 | | 12 | |
| 41 | contact with pan not at trough | > 3000 | | 11.5 | |
| 42 | at 1 meter from pan | | | 2.2 | |

**Table A-2. UF U-238 (pCi/g)Analysis of Phosphate Material in Central Florida**

| Location | Sample Type | No. | Mean | Min. | Max. |
|---|---|---|---|---|---|
| Phosphoric Acid Plant | 30% Tank Sediment | 1 | 1 | 0 | 0 |
| Phosphoric Acid Plant | 5% Phosphoric Acid | 1 | 6.3 | 0 | 0 |
| Phosphoric Acid Plant | Gypsum | 6 | 0.5 | 0.4 | 0.7 |
| Phosphoric Acid Plant | Filtrate Tank Scale | 1 | 28.1 | 0 | 0 |
| Phosphoric Acid Plant | 15% Phosphoric Acid | 1 | 17.1 | 0 | 0 |
| Phosphoric Acid Plant | 30% Phosphoric Acid | 1 | 30 | 0 | 0 |
| Mining and Rock Operations | Rock Dust | 5 | 33.4 | 24.2 | 45.4 |
| Mining and Rock Operations | Matrix | 6 | 38.5 | 20.2 | 83.4 |
| Mining and Rock Operations | Pebble | 13 | 45.8 | 36 | 68.1 |
| Mining and Rock Operations | Rock Concentrate | 12 | 28.4 | 20.1 | 43.5 |
| Mining and Rock Operations | Tailings | 24 | 4.7 | 1.5 | 10.4 |
| Mining and Rock Operations | Total Rock | 5 | 37.1 | 20.1 | 68.1 |
| Mining and Rock Operations | Rock Unspecified | 5 | 38.9 | 33.4 | 49.8 |
| Fertilizer | Triple Superphosphate | 5 | 57 | 40.1 | 72.7 |
| Fertilizer | Total (MAP, DAP) | 8 | 70.2 | 46 | 81.8 |
| Fertilizer | DAP | 6 | 69.3 | 46 | 81.8 |

| Location | Sample Type | No. | Mean | Min. | Max. |
| --- | --- | --- | --- | --- | --- |
| Fertilizer | Total (TSP-ROP) | 10 | 56.5 | 40.1 | 72.7 |
| Fertilizer | Triple Superphosphate | 5 | 55.9 | 41.1 | 67.7 |
| Fertilizer | MAP | 2 | 72.8 | 66.9 | 78.7 |
| Electric Furnace | Phosphate Fines | 1 | 73.5 | 0 | 0 |
| Electric Furnace | Ferro-phos. | 1 | 40.9 | 0 | 0 |
| Electric Furnace | Coke | 1 | 1.7 | 0 | 0 |
| Electric Furnace | Slag | 1 | 63.4 | 0 | 0 |

**Table A-3. UF Study: 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 | 0 |
| G | 12 | 0.059 | 0.35 | 0.00077 |
| 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 |

**INDUSTRY DATA**

The data supplied by the participating companies are included in this section. Tabular and statistical summaries are arranged in the following sequence:

- LiF TLD badge personnel monitoring statistics for the year 1981
- Personnel monitoring summary statistics for the phosphoric acid production area
- area monitoring results for 1993 - 1996
- radon measurements for 1989 - 1994 summary statistics
- radon measurements summary for 1995 - 1996
- radon measurements in rock tunnels for 1996
- radon measurements in rock tunnels for 1996 summary statistics
- radon measurements using E-perms for 1996
- radon measurements using E-perms for 1996 summary statistics
- Teradex radon measurements for 1982 - 1996 summary statistics
- chemical plant track etch results for 1993 - 1996

**Table A-4. LiF TLD Badge Personnel Monitoring Statistics for the Year 1981**

| Summary Statistics for 5 months for the Indicated Area: 1981 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Administration | | Electrical Main. | | Acid Production | | Instrument Main. | |
| | Gamma | Beta | Gamma | Beta | Gamma | Beta | Gamma | Beta |
| Mean* | 6.3 | 7.8 | 5.5 | 5.0 | 6.2 | 5.8 | 6.7 | 5.6 |
| Std Err | 0.6 | 1.7 | 0.2 | 0.0 | 0.4 | 0.4 | 0.5 | 0.4 |
| Median | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| Mode | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| Std Dev | 4.4 | 11.6 | 1.6 | 0.0 | 3.1 | 2.9 | 3.5 | 2.5 |
| Variance | 19.0 | 134.6 | 2.4 | 0.0 | 9.7 | 8.5 | 12.3 | 6.1 |
| Kurtosis | 21.1 | 34.4 | 5.2 | NA | 11.3 | 17.9 | 7.3 | 25.8 |
| Skewness | 4.4 | 5.7 | 2.6 | NA | 3.2 | 4.2 | 2.6 | 4.8 |
| Range | 25.0 | 75.0 | 5.0 | 0.0 | 15.0 | 15.0 | 15.0 | 15.0 |
| Min | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| Max | 30.0 | 80.0 | 10.0 | 5.0 | 20.0 | 20.0 | 20.0 | 20.0 |
| Count | 47.0 | 47.0 | 47.0 | 47.0 | 61.0 | 61.0 | 47.0 | 47.0 |
| CL 95% | 1.2 | 3.3 | 0.4 | NA | 0.8 | 0.7 | 1.0 | 0.7 |
| * All the units are in mrem/month | | | | | | | | |

| Summary Statistics for 5 months for the Indicated Area: 1981 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Laboratory | | Phos Acid M-1 | | Sulfuric Acid | | Phos Acid M-2 | |
| | Gamma | Beta | Gamma | Beta | Gamma | Beta | Gamma | Beta |
| Mean* | 6.7 | 5.5 | 6.5 | 5.9 | 7.1 | 5.9 | 8.2 | 5.6 |
| Std Err | 0.4 | 0.2 | 0.9 | 0.8 | 0.7 | 0.5 | 0.9 | 0.5 |
| Median | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| Mode | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| Std Dev | 4.6 | 2.7 | 6.4 | 6.1 | 4.7 | 3.7 | 5.3 | 2.7 |
| Variance | 21.1 | 7.2 | 41.5 | 37.1 | 22.2 | 13.7 | 28.6 | 7.2 |
| Kurtosis | 22.4 | 54.2 | 40.0 | 53.6 | 12.2 | 37.6 | 1.1 | 27.1 |
| Skewness | 4.2 | 7.0 | 6.1 | 7.3 | 3.3 | 5.9 | 1.6 | 5.1 |
| Range | 35.0 | 25.0 | 45.0 | 45.0 | 25.0 | 25.0 | 15.0 | 15.0 |
| Min | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| Max | 40.0 | 30.0 | 50.0 | 50.0 | 30.0 | 30.0 | 20.0 | 20.0 |
| Count | 159.0 | 159.0 | 55.0 | 55.0 | 51.0 | 51.0 | 34.0 | 34.0 |
| CL 95% | 0.7 | 0.4 | 1.7 | 1.6 | 1.3 | 1.0 | 1.8 | 0.9 |
| * All the units are in mrem/month | | | | | | | | |

| Summary Statistics for 5 months for the Indicated Area: 1981 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Fert. Shipping** | | **Utility Crew** | | **Fert. Production** | | **Equipment Main.** | |
| | **Gamma** | **Beta** | **Gamma** | **Beta** | **Gamma** | **Beta** | **Gamma** | **Beta** |
| Mean* | 5.9 | 5.0 | 5.4 | 5.4 | 7.1 | 5.8 | 8.5 | 7.1 |
| Std Err | 0.3 | 0.0 | 0.3 | 0.3 | 0.5 | 0.4 | 0.9 | 0.9 |
| Median | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| Mode | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| Std Dev | 2.8 | 0.5 | 2.1 | 2.1 | 5.7 | 4.6 | 5.4 | 5.0 |
| Variance | 7.9 | 0.2 | 4.3 | 4.3 | 32.1 | 21.4 | 28.9 | 25.0 |
| Kurtosis | 45.9 | 119.0 | 37.5 | 37.5 | 26.1 | 67.9 | 0.8 | 3.4 |
| Skewness | 5.9 | 10.9 | 5.8 | 5.8 | 4.4 | 7.9 | 1.5 | 2.2 |
| Range | 25.0 | 5.0 | 15.0 | 15.0 | 45.0 | 45.0 | 15.0 | 15.0 |
| Min | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| Max | 30.0 | 10.0 | 20.0 | 20.0 | 50.0 | 50.0 | 20.0 | 20.0 |
| Count | 119.0 | 119.0 | 67.0 | 67.0 | 136.0 | 136.0 | 33.0 | 33.0 |
| CL 95% | 0.5 | 0.1 | 0.5 | 0.5 | 1.0 | 0.8 | 1.8 | 1.7 |
| * All the units are in mrem/month | | | | | | | | |

| Summary Statistics for 5 months for the Indicated Area: 1981 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Machine Shop** | | **Phos Acid New** | | **Sulfuric Acid** | | **Fert. Shipping** | |
| | **Gamma** | **Beta** | **Gamma** | **Beta** | **Gamma** | **Beta** | **Gamma** | **Beta** |
| Mean* | 6.3 | 6.0 | 6.9 | 6.5 | 6.3 | 5.1 | 6.3 | 5.3 |
| Std Err | 0.3 | 0.4 | 0.3 | 1.0 | 0.4 | 0.1 | 0.2 | 0.1 |
| Median | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| Mode | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| Std Dev | 3.1 | 4.7 | 4.9 | 15.3 | 5.2 | 0.8 | 3.8 | 2.2 |
| Variance | 9.7 | 22.2 | 23.9 | 233.8 | 27.2 | 0.6 | 14.2 | 4.7 |
| Kurtosis | 10.1 | 63.9 | 13.4 | 222.9 | 70.2 | 37.9 | 31.1 | 79.6 |
| Skewness | 3.0 | 7.4 | 3.4 | 14.6 | 7.5 | 6.3 | 4.9 | 8.5 |
| Range | 15.0 | 45.0 | 35.0 | 235.0 | 55.0 | 5.0 | 35.0 | 25.0 |
| Min | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| Max | 20.0 | 50.0 | 40.0 | 240.0 | 60.0 | 10.0 | 40.0 | 30.0 |
| Count | 124.0 | 124.0 | 248.0 | 248.0 | 167.0 | 167.0 | 552.0 | 552.0 |
| CL 95% | 0.5 | 0.8 | 0.6 | 1.9 | 0.8 | 0.1 | 0.3 | 0.2 |
| * All the units are in mrem/month | | | | | | | | |

| Summary Statistics for 5 months for the Indicated Area: 1981 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Fert. Production** | | **Warehouse** | | **Fertilizer Main.** | | **General Main.** | |
| | **Gamma** | **Beta** | **Gamma** | **Beta** | **Gamma** | **Beta** | **Gamma** | **Beta** |
| Mean* | 6.5 | 5.8 | 5.5 | 5.0 | 7.1 | 5.8 | 6.5 | 5.6 |
| Std Err | 0.2 | 0.2 | 0.2 | 0.0 | 0.5 | 0.4 | 0.3 | 0.2 |
| Median | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| Mode | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| Std Dev | 3.8 | 3.5 | 1.5 | 0.0 | 5.7 | 4.6 | 5.9 | 3.4 |
| Variance | 14.6 | 12.4 | 2.2 | 0.0 | 32.1 | 21.4 | 35.2 | 11.6 |
| Kurtosis | 17.3 | 43.4 | 6.7 | NA | 26.1 | 67.9 | 69.8 | 101.1 |
| Skewness | 3.8 | 6.1 | 2.9 | NA | 4.4 | 7.9 | 7.2 | 9.2 |
| Range | 25.0 | 35.0 | 5.0 | 0.0 | 45.0 | 45.0 | 75.0 | 45.0 |
| Min | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| Max | 30.0 | 40.0 | 10.0 | 5.0 | 50.0 | 50.0 | 80.0 | 50.0 |
| Count | 372.0 | 372.0 | 43.0 | 43.0 | 136.0 | 136.0 | 401.0 | 401.0 |
| CL 95% | 0.4 | 0.4 | 0.4 | NA | 1.0 | 0.8 | 0.6 | 0.3 |
| * All the units are in mrem/month | | | | | | | | |

**Table A-5. Personnel Monitoring in Phosphoric Acid Production**

| Area | Station | | Dose Eq. (mrem) | | | Total No. Months | Avg. Dose per month | Rank |
|---|---|---|---|---|---|---|---|---|
| | | | Deep | Eye | Shallow | | | |
| A Phos Acid | #1 | Sum | 167 | 167 | 167 | 33 | 5.06 | 4 |
| | | Min | 9 | 9 | 9 | 33 | 0.27 | |
| | | Max | 40 | 40 | 40 | 33 | 1.21 | |
| | #2 | Sum | 124 | 124 | 124 | 30 | 4.13 | 7 |
| | | Min | 9 | 9 | 9 | 30 | 0.30 | |
| | | Max | 20 | 20 | 20 | 30 | 0.67 | |
| | #3 | Sum | 161 | 161 | 161 | 42 | 3.83 | 8 |
| | | Min | 9 | 9 | 9 | 42 | 0.21 | |
| | | Max | 20 | 20 | 20 | 42 | 0.48 | |
| | #4 | Sum | 19 | 19 | 19 | 6 | 3.17 | 9 |
| | | Min | 9 | 9 | 9 | 6 | 1.50 | |
| | | Max | 10 | 10 | 10 | 6 | 1.67 | |
| Acid Clean up | #1 | Sum | 88 | 88 | 88 | 15 | 5.87 | 2 |
| | | Min | 9 | 9 | 9 | 15 | 0.60 | |
| | | Max | 30 | 30 | 30 | 15 | 2.00 | |
| B Phos Acid | #3 | Sum | 159 | 159 | 159 | 21 | 7.57 | 1 |
| | | Min | 9 | 9 | 9 | 21 | 0.43 | |
| | | Max | 50 | 50 | 50 | 21 | 2.38 | |
| | #4 | Sum | 164 | 164 | 164 | 33 | 4.97 | 5 |
| | | Min | 9 | 9 | 9 | 33 | 0.27 | |
| | | Max | 40 | 40 | 40 | 33 | 1.21 | |
| Hydroblast Day Crew | | Sum | 343 | 343 | 353 | 63 | 5.44 | 3 |
| | | Min | 9 | 9 | 9 | 63 | 0.14 | |
| | | Max | 40 | 40 | 40 | 63 | 0.63 | |
| Utility | | Sum | 76 | 76 | 76 | 18 | 4.22 | 6 |
| | | Min | 9 | 9 | 9 | 18 | 0.50 | |
| | | Max | 30 | 30 | 30 | 18 | 1.67 | |

**Table A-6. Area Monitoring Results for 1993 - 1996**

| Month/Yr | Control Avg. (mrem) | Control Calc. Exp. rate (μR/hr) | Location | Avg. Meas. Exp. rate (μR/hr) | Avg. TLD (mrem) | TLD Calc. Exp. rate (μR/hr) |
|---|---|---|---|---|---|---|
| Feb-93 | 9.00 | 6.70 | PA #1 | 22.50 | 14.00 | 14.14 |
| Mar-93 | 10.20 | 6.25 | PA #1 | 20.00 | 16.00 | 14.31 |
| Apr-93 | 9.60 | 5.80 | PA #1 | 21.00 | 18.20 | 17.74 |
| May-93 | 7.80 | 5.60 | PA #1 | 26.00 | 12.20 | 12.39 |
| Jun-93 | 11.20 | 6.57 | PA #1 | 25.00 | 17.00 | 13.48 |
| Jul-93 | 15.40 | 9.58 | PA #1 | 22.00 | 15.80 | 10.19 |
| Aug-93 | 9.60 | 5.80 | PA #1 | 24.00 | 16.40 | 12.71 |
| Sep-93 | 9.20 | 5.11 | PA #1 | 22.00 | 15.40 | 15.88 |
| Oct-93 | 11.80 | 6.22 | PA #1 | 17.50 | 17.40 | 13.52 |
| Nov-93 | 7.40 | 4.40 | PA #1 | 17.50 | 12.80 | 12.16 |
| Dec-93 | 13.80 | 8.10 | PA #1 | 20.00 | 20.00 | 15.70 |
| Feb-93 | 9.00 | 6.70 | PA #2 | 185.00 | 121.80 | 174.55 |
| Mar-93 | 10.20 | 6.25 | PA #2 | 145.00 | 131.00 | 174.03 |
| Apr-93 | 9.60 | 5.80 | PA #2 | 165.00 | 123.60 | 164.13 |
| May-93 | 7.80 | 5.60 | PA #2 | 237.50 | 126.20 | 188.32 |
| Jun-93 | 11.20 | 6.57 | PA #2 | 232.50 | 146.40 | 167.53 |
| Jul-93 | 15.40 | 9.58 | PA #2 | 225.00 | 123.60 | 176.55 |
| Aug-93 | 9.60 | 5.80 | PA #2 | 210.00 | 158.80 | 157.42 |
| Sep-93 | 9.20 | 5.11 | PA #2 | 205.00 | 56.00 | 86.36 |
| Oct-93 | 11.80 | 6.22 | PA #2 | 220.00 | 145.00 | 179.66 |
| Nov-93 | 7.40 | 4.40 | PA #2 | 240.00 | 132.40 | 184.00 |
| Dec-93 | 13.80 | 8.10 | PA #2 | 225.00 | 179.60 | 211.28 |
| Feb-93 | 9.00 | 6.70 | PA #3 | 95.00 | 49.60 | 67.11 |
| Mar-93 | 10.20 | 6.25 | PA #3 | 70.00 | 47.00 | 57.36 |
| Apr-93 | 9.60 | 5.80 | PA #3 | 85.00 | 49.20 | 60.80 |
| May-93 | 7.80 | 5.60 | PA #3 | 105.00 | 42.40 | 59.00 |
| Jun-93 | 11.20 | 6.57 | PA #3 | 120.00 | 60.40 | 65.14 |
| Jul-93 | 15.40 | 9.58 | PA #3 | 135.00 | 51.60 | 65.44 |
| Aug-93 | 9.60 | 5.80 | PA #3 | 135.00 | 55.20 | 52.14 |
| Sep-93 | 9.20 | 5.11 | PA #3 | 125.00 | 20.00 | 23.86 |
| Oct-93 | 11.80 | 6.22 | PA #3 | 135.00 | 65.20 | 75.75 |
| Nov-93 | 7.40 | 4.40 | PA #3 | 150.00 | 49.60 | 65.04 |
| Dec-93 | 13.80 | 8.10 | PA #3 | 140.00 | 73.80 | 81.63 |
| Feb-93 | 9.00 | 6.70 | PA #4 | 34.00 | 21.00 | 24.55 |
| Mar-93 | 10.20 | 6.25 | PA #4 | 25.00 | 19.20 | 18.75 |

| Month/Yr | Control Avg. (mrem) | Control Calc. Exp. rate (µR/hr) | Location | Avg. Meas. Exp. rate (µR/hr) | Avg. TLD (mrem) | TLD Calc. Exp. rate (µR/hr) |
|---|---|---|---|---|---|---|
| Apr-93 | 9.60 | 5.80 | PA #4 | 20.00 | 19.80 | 19.96 |
| May-93 | 7.80 | 5.60 | PA #4 | 25.00 | 15.60 | 17.64 |
| Jun-93 | 11.20 | 6.57 | PA #4 | 32.50 | 22.20 | 19.67 |
| Jul-93 | 15.40 | 9.58 | PA #4 | 33.50 | 20.60 | 17.60 |
| Aug-93 | 9.60 | 5.80 | PA #4 | 36.00 | 20.60 | 16.98 |
| Sep-93 | 9.20 | 5.11 | PA #4 | 35.00 | 23.60 | 30.11 |
| Oct-93 | 11.80 | 6.22 | PA #4 | 25.00 | 25.60 | 24.19 |
| Nov-93 | 7.40 | 4.40 | PA #4 | 22.50 | 18.80 | 20.78 |
| Dec-93 | 13.80 | 8.10 | PA #4 | 27.50 | 28.20 | 25.75 |
| Feb-93 | 9.00 | 6.70 | PA #5 | 145.00 | 83.00 | 116.82 |
| Mar-93 | 10.20 | 6.25 | PA #5 | 125.00 | 99.00 | 129.58 |
| Apr-93 | 9.60 | 5.80 | PA #5 | 145.00 | 86.20 | 112.19 |
| May-93 | 7.80 | 5.60 | PA #5 | 185.00 | 85.20 | 125.05 |
| Jun-93 | 11.20 | 6.57 | PA #5 | 230.00 | 163.00 | 187.29 |
| Jul-93 | 15.40 | 9.58 | PA #5 | 250.00 | 134.60 | 193.53 |
| Aug-93 | 9.60 | 5.80 | PA #5 | 242.50 | 160.60 | 159.25 |
| Sep-93 | 9.20 | 5.11 | PA #5 | 242.50 | 91.60 | 148.17 |
| Oct-93 | 11.80 | 6.22 | PA #5 | 250.00 | 159.40 | 198.41 |
| Nov-93 | 7.40 | 4.40 | PA #5 | 250.00 | 127.20 | 176.53 |
| Dec-93 | 13.80 | 8.10 | PA #5 | 240.00 | 181.80 | 213.98 |
| Feb-93 | 9.00 | 6.70 | PA #6 | 60.00 | 25.80 | 31.70 |
| Mar-93 | 10.20 | 6.25 | PA #6 | 50.00 | 27.60 | 30.42 |
| Apr-93 | 9.60 | 5.80 | PA #6 | 45.00 | 27.80 | 31.07 |
| May-93 | 7.80 | 5.60 | PA #6 | 50.00 | 25.60 | 33.07 |
| Jun-93 | 11.20 | 6.57 | PA #6 | 31.00 | 40.40 | 41.33 |
| Jul-93 | 15.40 | 9.58 | PA #6 | 36.00 | 31.60 | 34.58 |
| Aug-93 | 9.60 | 5.80 | PA #6 | 62.50 | 35.20 | 31.81 |
| Sep-93 | 9.20 | 5.11 | PA #6 | 67.50 | 31.60 | 44.00 |
| Oct-93 | 11.80 | 6.22 | PA #6 | 70.00 | 37.20 | 39.30 |
| Nov-93 | 7.40 | 4.40 | PA #6 | 70.00 | 28.40 | 34.58 |
| Dec-93 | 13.80 | 8.10 | PA #6 | 65.00 | 40.00 | 40.21 |
| Feb-93 | 9.00 | 6.70 | PA #7 | 185.00 | 113.40 | 162.05 |
| Mar-93 | 10.20 | 6.25 | PA #7 | 190.00 | 132.80 | 176.53 |
| Apr-93 | 9.60 | 5.80 | PA #7 | 230.00 | 120.00 | 159.13 |
| May-93 | 7.80 | 5.60 | PA #7 | 230.00 | 117.00 | 174.12 |
| Jun-93 | 11.20 | 6.57 | PA #7 | 230.00 | 200.00 | 231.33 |

| Month/Yr | Control Avg. (mrem) | Control Calc. Exp. rate (µR/hr) | Location | Avg. Meas. Exp. rate (µR/hr) | Avg. TLD (mrem) | TLD Calc. Exp. rate (µR/hr) |
|---|---|---|---|---|---|---|
| Jul-93 | 15.40 | 9.58 | PA #7 | 290.00 | 155.20 | 225.32 |
| Aug-93 | 9.60 | 5.80 | PA #7 | 350.00 | 204.00 | 203.36 |
| Sep-93 | 9.20 | 5.11 | PA #7 | 340.00 | 104.00 | 169.69 |
| Oct-93 | 11.80 | 6.22 | PA #7 | 280.00 | 154.80 | 192.42 |
| Nov-93 | 7.40 | 4.40 | PA #7 | 300.00 | 104.00 | 143.20 |
| Dec-93 | 13.80 | 8.10 | PA #7 | 310.00 | 213.60 | 252.95 |
| Feb-93 | 9.00 | 6.70 | PA #8 | 75.00 | 65.60 | 90.92 |
| Mar-93 | 10.20 | 6.25 | PA #8 | 45.00 | 58.20 | 72.92 |
| Apr-93 | 9.60 | 5.80 | PA #8 | 50.00 | 54.60 | 68.30 |
| May-93 | 7.80 | 5.60 | PA #8 | 80.00 | 49.20 | 69.49 |
| Jun-93 | 11.20 | 6.57 | PA #8 | 90.00 | 75.80 | 83.48 |
| Jul-93 | 15.40 | 9.58 | PA #8 | 90.00 | 57.60 | 74.70 |
| Aug-93 | 9.60 | 5.80 | PA #8 | 100.00 | 79.20 | 76.53 |
| Sep-93 | 9.20 | 5.11 | PA #8 | 110.00 | 47.20 | 71.08 |
| Oct-93 | 11.80 | 6.22 | PA #8 | 105.00 | 69.40 | 81.22 |
| Nov-93 | 7.40 | 4.40 | PA #8 | 105.00 | 52.60 | 69.35 |
| Dec-93 | 13.80 | 8.10 | PA #8 | 100.00 | 82.80 | 92.66 |
| Feb-93 | 9.00 | 6.70 | Pan Sand. | 80.00 | 38.80 | 51.04 |
| Mar-93 | 10.20 | 6.25 | Pan Sand. | 75.00 | 47.20 | 57.64 |
| Apr-93 | 9.60 | 5.80 | Pan Sand. | 90.00 | 44.60 | 54.41 |
| May-93 | 7.80 | 5.60 | Pan Sand. | 97.50 | 34.60 | 46.96 |
| Jun-93 | 11.20 | 6.57 | Pan Sand. | 82.50 | 46.80 | 48.95 |
| Jul-93 | 15.40 | 9.58 | Pan Sand. | 90.00 | 47.40 | 58.96 |
| Aug-93 | 9.60 | 5.80 | Pan Sand. | 100.00 | 59.00 | 56.00 |
| Sep-93 | 9.20 | 5.11 | Pan Sand. | 105.00 | 43.80 | 65.18 |
| Oct-93 | 11.80 | 6.22 | Pan Sand. | 110.00 | 61.40 | 70.81 |
| Nov-93 | 7.40 | 4.40 | Pan Sand. | 115.00 | 41.80 | 53.83 |
| Feb-93 | 9.00 | 6.70 | RT #1 | 19.00 | 14.40 | 14.73 |
| Mar-93 | 10.20 | 6.25 | RT #1 | 25.00 | 20.60 | 20.69 |
| Apr-93 | 9.60 | 5.80 | RT #1 | 16.00 | 16.20 | 14.96 |
| May-93 | 7.80 | 5.60 | RT #1 | 18.50 | 13.20 | 13.94 |
| Jun-93 | 11.20 | 6.57 | RT #1 | 17.50 | 18.60 | 15.38 |
| Jul-93 | 15.40 | 9.58 | RT #1 | 10.00 | 19.60 | 16.06 |
| Aug-93 | 9.60 | 5.80 | RT #1 | 9.00 | 17.40 | 13.72 |
| Sep-93 | 9.20 | 5.11 | RT #1 | 7.50 | 14.80 | 14.83 |
| Oct-93 | 11.80 | 6.22 | RT #1 | 8.50 | 18.00 | 14.30 |

| Month/Yr | Control Avg. (mrem) | Control Calc. Exp. rate (µR/hr) | Location | Avg. Meas. Exp. rate (µR/hr) | Avg. TLD (mrem) | TLD Calc. Exp. rate (µR/hr) |
|---|---|---|---|---|---|---|
| Nov-93 | 7.40 | 4.40 | RT #1 | 10.00 | 16.20 | 17.05 |
| Dec-93 | 13.80 | 8.10 | RT #1 | 10.00 | 21.60 | 17.66 |
| Feb-93 | 9.00 | 6.70 | RT #2 | 29.50 | 19.20 | 21.88 |
| Mar-93 | 10.20 | 6.25 | RT #2 | 22.50 | 20.60 | 20.69 |
| Apr-93 | 9.60 | 5.80 | RT #2 | 21.00 | 22.20 | 23.30 |
| May-93 | 7.80 | 5.60 | RT #2 | 18.50 | 16.40 | 18.88 |
| Jun-93 | 11.20 | 6.57 | RT #2 | 25.00 | 23.20 | 20.86 |
| Jul-93 | 15.40 | 9.58 | RT #2 | 32.50 | 18.80 | 14.82 |
| Aug-93 | 9.60 | 5.80 | RT #2 | 32.50 | 20.80 | 17.18 |
| Sep-93 | 9.20 | 5.11 | RT #2 | 24.00 | 18.00 | 20.39 |
| Oct-93 | 11.80 | 6.22 | RT #2 | 31.50 | 22.80 | 20.55 |
| Nov-93 | 7.40 | 4.40 | RT #2 | 42.50 | 13.20 | 12.74 |
| Dec-93 | 13.80 | 8.10 | RT #2 | 37.50 | 26.60 | 23.78 |
| Jan-94 | 10.20 | 5.67 | PA #1 | 20.00 | 18.00 | 16.87 |
| Feb-94 | 9.20 | 6.28 | PA #1 | 20.00 | 12.60 | 11.17 |
| Mar-94 | 12.60 | 7.00 | PA #1 | 20.00 | 18.00 | 14.03 |
| Apr-94 | 18.60 | 10.62 | PA #1 | 20.00 | 19.00 | 11.28 |
| May-94 | 11.60 | 7.00 | PA #1 | 20.00 | 15.60 | 12.21 |
| Jun-94 | 11.60 | 6.36 | PA #1 | 19.00 | 14.00 | 9.59 |
| Jul-94 | 9.80 | 5.59 | PA #1 | 19.00 | 14.80 | 12.10 |
| Aug-94 | 13.80 | 8.21 | PA #1 | 20.00 | 18.20 | 13.45 |
| Sep-94 | 11.60 | 6.20 | PA #1 | 27.50 | 18.80 | 16.20 |
| Oct-94 | 8.40 | 5.07 | PA #1 | 28.50 | 16.40 | 17.89 |
| Nov-94 | 11.60 | 6.90 | PA #1 | 21.00 | 15.60 | 12.65 |
| Dec-94 | 10.40 | 6.19 | PA #1 | 20.00 | 21.20 | 19.05 |
| Jan-94 | 10.20 | 5.67 | PA #2 | 215.00 | 128.20 | 175.21 |
| Feb-94 | 9.20 | 6.28 | PA #2 | 220.00 | 133.40 | 184.73 |
| Mar-94 | 12.60 | 7.00 | PA #2 | 220.00 | 159.00 | 197.63 |
| Apr-94 | 18.60 | 10.62 | PA #2 | 180.00 | 74.20 | 103.28 |
| May-94 | 11.60 | 7.00 | PA #2 | 140.00 | 72.40 | 86.17 |
| Jun-94 | 11.60 | 6.36 | PA #2 | 120.00 | 65.20 | 78.40 |
| Jul-94 | 9.80 | 5.59 | PA #2 | 95.00 | 39.80 | 44.66 |
| Aug-94 | 13.80 | 8.21 | PA #2 | 95.00 | 54.60 | 56.79 |
| Sep-94 | 11.60 | 6.20 | PA #2 | 100.00 | 43.20 | 50.09 |
| Oct-94 | 8.40 | 5.07 | PA #2 | 150.00 | 101.00 | 153.47 |
| Nov-94 | 11.60 | 6.90 | PA #2 | 210.00 | 110.20 | 148.57 |

| Month/Yr | Control Avg. (mrem) | Control Calc. Exp. rate (µR/hr) | Location | Avg. Meas. Exp. rate (µR/hr) | Avg. TLD (mrem) | TLD Calc. Exp. rate (µR/hr) |
|---|---|---|---|---|---|---|
| Dec-94 | 10.40 | 6.19 | PA #2 | 180.00 | 193.80 | 224.52 |
| Jan-94 | 10.20 | 5.67 | PA #3 | 140.00 | 52.40 | 66.30 |
| Feb-94 | 9.20 | 6.28 | PA #3 | 135.00 | 50.20 | 65.19 |
| Apr-94 | 18.60 | 10.62 | PA #3 | 105.00 | 47.20 | 58.28 |
| May-94 | 11.60 | 7.00 | PA #3 | 85.00 | 49.80 | 56.74 |
| Jun-94 | 11.60 | 6.36 | PA #3 | 110.00 | 46.40 | 53.13 |
| Jul-94 | 9.80 | 5.59 | PA #3 | 125.00 | 64.40 | 76.69 |
| Aug-94 | 13.80 | 8.21 | PA #3 | 100.00 | 102.20 | 113.45 |
| Sep-94 | 11.60 | 6.20 | PA #3 | 85.00 | 88.60 | 113.14 |
| Oct-94 | 8.40 | 5.07 | PA #3 | 95.00 | 36.80 | 50.59 |
| Nov-94 | 11.60 | 6.90 | PA #3 | 120.00 | 48.40 | 59.78 |
| Dec-94 | 10.40 | 6.19 | PA #3 | 130.00 | 64.60 | 70.71 |
| Jan-94 | 10.20 | 5.67 | PA #4 | 32.50 | 21.80 | 22.33 |
| Feb-94 | 9.20 | 6.28 | PA #4 | 30.00 | 19.80 | 21.51 |
| Mar-94 | 12.60 | 7.00 | PA #4 | 25.00 | 25.20 | 23.41 |
| May-94 | 11.60 | 7.00 | PA #4 | 32.50 | 17.80 | 15.08 |
| Jun-94 | 11.60 | 6.36 | PA #4 | 30.00 | 16.40 | 12.81 |
| Jul-94 | 9.80 | 5.59 | PA #4 | 25.00 | 17.20 | 15.23 |
| Aug-94 | 13.80 | 8.21 | PA #4 | 25.00 | 25.40 | 22.02 |
| Sep-94 | 11.60 | 6.20 | PA #4 | 32.50 | 21.20 | 19.53 |
| Oct-94 | 8.40 | 5.07 | PA #4 | 33.50 | 17.60 | 19.82 |
| Nov-94 | 11.60 | 6.90 | PA #4 | 31.00 | 19.40 | 18.11 |
| Dec-94 | 10.40 | 6.19 | PA #4 | 30.00 | 23.20 | 21.43 |
| Jan-94 | 10.20 | 5.67 | PA #5 | 245.00 | 128.00 | 174.92 |
| Feb-94 | 9.20 | 6.28 | PA #5 | 245.00 | 140.00 | 194.22 |
| Mar-94 | 12.60 | 7.00 | PA #5 | 240.00 | 133.60 | 164.55 |
| Apr-94 | 18.60 | 10.62 | PA #5 | 30.00 | 107.20 | 158.28 |
| May-94 | 11.60 | 7.00 | PA #5 | 200.00 | 71.00 | 84.35 |
| Jun-94 | 11.60 | 6.36 | PA #5 | 165.00 | 84.80 | 104.75 |
| Jul-94 | 9.80 | 5.59 | PA #5 | 145.00 | 85.40 | 104.03 |
| Aug-94 | 13.80 | 8.21 | PA #5 | 210.00 | 112.00 | 125.12 |
| Sep-94 | 11.60 | 6.20 | PA #5 | 200.00 | 86.60 | 110.36 |
| Oct-94 | 8.40 | 5.07 | PA #5 | 110.00 | 75.20 | 112.12 |
| Nov-94 | 11.60 | 6.90 | PA #5 | 120.00 | 73.20 | 95.41 |
| Dec-94 | 10.40 | 6.19 | PA #5 | 110.00 | 94.20 | 105.95 |
| Jan-94 | 10.20 | 5.67 | PA #6 | 60.00 | 36.40 | 43.31 |

| Month/Yr | Control Avg. (mrem) | Control Calc. Exp. rate (µR/hr) | Location | Avg. Meas. Exp. rate (µR/hr) | Avg. TLD (mrem) | TLD Calc. Exp. rate (µR/hr) |
|---|---|---|---|---|---|---|
| Feb-94 | 9.20 | 6.28 | PA #6 | 60.00 | 29.80 | 35.88 |
| Mar-94 | 12.60 | 7.00 | PA #6 | 60.00 | 36.40 | 37.99 |
| May-94 | 11.60 | 7.00 | PA #6 | 55.00 | 24.60 | 23.93 |
| Jun-94 | 11.60 | 6.36 | PA #6 | 50.00 | 27.60 | 27.87 |
| Jul-94 | 9.80 | 5.59 | PA #6 | 45.00 | 21.20 | 20.44 |
| Aug-94 | 13.80 | 8.21 | PA #6 | 45.00 | 39.20 | 38.45 |
| Sep-94 | 11.60 | 6.20 | PA #6 | 45.00 | 19.80 | 17.59 |
| Oct-94 | 8.40 | 5.07 | PA #6 | 50.00 | 54.20 | 78.47 |
| Nov-94 | 11.60 | 6.90 | PA #6 | 70.00 | 33.00 | 37.65 |
| Dec-94 | 10.40 | 6.19 | PA #6 | 70.00 | 43.40 | 45.48 |
| Jan-94 | 10.20 | 5.67 | PA #7 | 300.00 | 163.00 | 225.21 |
| Feb-94 | 9.20 | 6.28 | PA #7 | 295.00 | 120.80 | 166.63 |
| Mar-94 | 12.60 | 7.00 | PA #7 | 290.00 | 171.40 | 213.77 |
| Apr-94 | 18.60 | 10.62 | PA #7 | 255.00 | 137.60 | 208.95 |
| May-94 | 11.60 | 7.00 | PA #7 | 200.00 | 90.40 | 109.61 |
| Jun-94 | 11.60 | 6.36 | PA #7 | 190.00 | 100.20 | 125.45 |
| Jul-94 | 9.80 | 5.59 | PA #7 | 185.00 | 102.20 | 125.91 |
| Aug-94 | 13.80 | 8.21 | PA #7 | 140.00 | 116.00 | 129.88 |
| Sep-94 | 11.60 | 6.20 | PA #7 | 125.00 | 114.80 | 149.53 |
| Oct-94 | 8.40 | 5.07 | PA #7 | 200.00 | 94.80 | 143.53 |
| Nov-94 | 11.60 | 6.90 | PA #7 | 250.00 | 149.60 | 205.18 |
| Dec-94 | 10.40 | 6.19 | PA #7 | 215.00 | 203.40 | 235.95 |
| Jan-94 | 10.20 | 5.67 | PA #8 | 105.00 | 67.40 | 87.85 |
| Feb-94 | 9.20 | 6.28 | PA #8 | 110.00 | 69.60 | 93.07 |
| Mar-94 | 12.60 | 7.00 | PA #8 | 110.00 | 68.60 | 79.92 |
| May-94 | 11.60 | 7.00 | PA #8 | 95.00 | 56.40 | 65.34 |
| Jun-94 | 11.60 | 6.36 | PA #8 | 85.00 | 51.80 | 60.39 |
| Jul-94 | 9.80 | 5.59 | PA #8 | 75.00 | 45.60 | 52.21 |
| Aug-94 | 13.80 | 8.21 | PA #8 | 65.00 | 64.80 | 68.93 |
| Sep-94 | 11.60 | 6.20 | PA #8 | 72.50 | 51.20 | 61.20 |
| Oct-94 | 8.40 | 5.07 | PA #8 | 82.50 | 47.40 | 67.57 |
| Nov-94 | 11.60 | 6.90 | PA #8 | 80.00 | 56.20 | 70.99 |
| Dec-94 | 10.40 | 6.19 | PA #8 | 75.00 | 72.20 | 79.76 |
| Jan-94 | 10.20 | 5.67 | Pan Sand. | 100.00 | 52.80 | 66.87 |
| Feb-94 | 9.20 | 6.28 | Pan Sand. | 90.00 | 46.60 | 60.02 |
| Mar-94 | 12.60 | 7.00 | Pan Sand. | 80.00 | 51.60 | 57.78 |

| Month/Yr | Control Avg. (mrem) | Control Calc. Exp. rate (μR/hr) | Location | Avg. Meas. Exp. rate (μR/hr) | Avg. TLD (mrem) | TLD Calc. Exp. rate (μR/hr) |
|---|---|---|---|---|---|---|
| Apr-94 | 18.60 | 10.62 | Pan Sand. | 90.00 | 54.80 | 70.95 |
| May-94 | 11.60 | 7.00 | Pan Sand. | 105.00 | 48.60 | 55.18 |
| Jun-94 | 11.60 | 6.36 | Pan Sand. | 100.00 | 49.60 | 57.43 |
| Jul-94 | 9.80 | 5.59 | Pan Sand. | 80.00 | 47.20 | 54.29 |
| Aug-94 | 13.80 | 8.21 | Pan Sand. | 70.00 | 64.80 | 68.93 |
| Sep-94 | 11.60 | 6.20 | Pan Sand. | 75.00 | 50.60 | 60.36 |
| Oct-94 | 8.40 | 5.07 | Pan Sand. | 90.00 | 46.20 | 65.65 |
| Nov-94 | 11.60 | 6.90 | Pan Sand. | 105.00 | 54.60 | 68.69 |
| Dec-94 | 10.40 | 6.19 | Pan Sand. | 87.50 | NA | NA |
| Jan-94 | 10.20 | 5.67 | RT #1 | 10.00 | 21.60 | 22.05 |
| Feb-94 | 9.20 | 6.28 | RT #1 | 9.00 | 16.20 | 16.34 |
| Mar-94 | 12.60 | 7.00 | RT #1 | 8.00 | 21.00 | 17.94 |
| Apr-94 | 18.60 | 10.62 | RT #1 | 8.00 | 19.20 | 11.62 |
| May-94 | 11.60 | 7.00 | RT #1 | 10.00 | 17.20 | 14.30 |
| Jun-94 | 11.60 | 6.36 | RT #1 | 11.00 | 16.80 | 13.35 |
| Jul-94 | 9.80 | 5.59 | RT #1 | 10.00 | 15.40 | 12.89 |
| Aug-94 | 13.80 | 8.21 | RT #1 | 14.00 | 21.80 | 17.74 |
| Sep-94 | 11.60 | 6.20 | RT #1 | 19.00 | 20.80 | 18.97 |
| Oct-94 | 8.40 | 5.07 | RT #1 | 13.00 | 15.80 | 16.93 |
| Nov-94 | 11.60 | 6.90 | RT #1 | 8.00 | 15.00 | 11.79 |
| Dec-94 | 10.40 | 6.19 | RT #1 | 11.00 | 18.60 | 15.95 |
| Jan-94 | 10.20 | 5.67 | RT #2 | 30.00 | 20.60 | 20.61 |
| Feb-94 | 9.20 | 6.28 | RT #2 | 25.00 | 17.80 | 18.64 |
| Mar-94 | 12.60 | 7.00 | RT #2 | 30.00 | 23.60 | 21.32 |
| Apr-94 | 18.60 | 10.62 | RT #2 | 25.00 | 22.00 | 16.28 |
| May-94 | 11.60 | 7.00 | RT #2 | 25.00 | 19.60 | 17.42 |
| Jun-94 | 11.60 | 6.36 | RT #2 | 30.00 | 18.00 | 14.96 |
| Jul-94 | 9.80 | 5.59 | RT #2 | 32.50 | 18.60 | 17.05 |
| Aug-94 | 13.80 | 8.21 | RT #2 | 25.00 | 22.40 | 18.45 |
| Sep-94 | 11.60 | 6.20 | RT #2 | 22.50 | 23.20 | 22.31 |
| Oct-94 | 8.40 | 5.07 | RT #2 | 35.00 | 19.00 | 22.06 |
| Nov-94 | 11.60 | 6.90 | RT #2 | 31.00 | 18.40 | 16.67 |
| Dec-94 | 10.40 | 6.19 | RT #2 | 21.00 | 23.60 | 21.90 |
| Jan-95 | 20.40 | 11.97 | PA #1 | 22.5 | 30.80 | 28.02 |
| Feb-95 | 10.00 | 5.95 | PA #1 | 22.5 | 16.80 | 15.72 |
| Mar-95 | 14.00 | 7.88 | PA #1 | 22.5 | 19.00 | 13.84 |

| Month/Yr | Control Avg. (mrem) | Control Calc. Exp. rate (µR/hr) | Location | Avg. Meas. Exp. rate (µR/hr) | Avg. TLD (mrem) | TLD Calc. Exp. rate (µR/hr) |
|---|---|---|---|---|---|---|
| Apr-95 | 10.00 | 6.04 | PA #1 | 22.5 | 16.80 | 16.53 |
| May-95 | 10.20 | 5.99 | PA #1 | 22.5 | 16.20 | 14.32 |
| Jun-95 | 9.40 | 5.60 | PA #1 | 20 | 15.60 | 12.98 |
| Jul-95 | 11.40 | 6.69 | PA #1 | 22.5 | 15.60 | 12.94 |
| Aug-95 | 8.80 | 5.73 | PA #1 | 27.5 | 14.80 | 13.08 |
| Sep-95 | 14.00 | 7.58 | PA #1 | 22.5 | 15.80 | 10.35 |
| Oct-95 | 12.80 | 7.51 | PA #1 | 19 | NA | NA |
| Nov-95 | 7.20 | 5.26 | PA #1 | 15 | 13.40 | 14.49 |
| Dec-95 | 12.6 | 7.29 | PA #1 | 13.5 | 21.20 | 17.83 |
| Jan-95 | 20.40 | 11.97 | PA #2 | 135 | 239.00 | 349.32 |
| Feb-95 | 10.00 | 5.95 | PA #2 | 145 | 134.00 | 184.11 |
| Mar-95 | 14.00 | 7.88 | PA #2 | 160 | 159.80 | 181.45 |
| Apr-95 | 10.00 | 6.04 | PA #2 | 140 | 141.80 | 209.43 |
| May-95 | 10.20 | 5.99 | PA #2 | 120 | 152.60 | 203.76 |
| Jun-95 | 9.40 | 5.60 | PA #2 | 120 | 158.20 | 182.74 |
| Jul-95 | 11.40 | 6.69 | PA #2 | 140 | 126.00 | 177.23 |
| Aug-95 | 8.80 | 5.73 | PA #2 | 150 | 139.60 | 166.02 |
| Sep-95 | 14.00 | 7.58 | PA #2 | 180 | 126.00 | 180.42 |
| Oct-95 | 12.80 | 7.51 | PA #2 | 210 | 137.00 | 174.45 |
| Nov-95 | 7.20 | 5.26 | PA #2 | 190 | 112.60 | 162.11 |
| Dec-95 | 12.6 | 7.29 | PA #2 | 180 | 137.80 | 160.72 |
| Jan-95 | 20.40 | 11.97 | PA #3 | 120 | 90.80 | 120.61 |
| Feb-95 | 10.00 | 5.95 | PA #3 | 120 | 63.20 | 82.39 |
| Mar-95 | 14.00 | 7.88 | PA #3 | 120 | 48.00 | 48.36 |
| Apr-95 | 10.00 | 6.04 | PA #3 | 132.5 | 56.20 | 77.33 |
| May-95 | 10.20 | 5.99 | PA #3 | 135 | 54.80 | 67.93 |
| Jun-95 | 9.40 | 5.60 | PA #3 | 110 | 60.00 | 65.83 |
| Jul-95 | 11.40 | 6.69 | PA #3 | 120 | 52.60 | 68.00 |
| Aug-95 | 8.80 | 5.73 | PA #3 | 120 | 51.00 | 57.44 |
| Sep-95 | 14.00 | 7.58 | PA #3 | 135 | 41.00 | 49.24 |
| Oct-95 | 12.80 | 7.51 | PA #3 | 190 | 50.60 | 58.32 |
| Nov-95 | 7.20 | 5.26 | PA #3 | 190 | 44.00 | 60.03 |
| Dec-95 | 12.6 | 7.29 | PA #3 | 190 | 88.20 | 99.94 |
| Jan-95 | 20.40 | 11.97 | PA #4 | 32.5 | 34.20 | 33.27 |
| Feb-95 | 10.00 | 5.95 | PA #4 | 32.5 | 17.80 | 17.16 |
| Mar-95 | 14.00 | 7.88 | PA #4 | 30 | 20.60 | 15.74 |

| Month/Yr | Control Avg. (mrem) | Control Calc. Exp. rate (μR/hr) | Location | Avg. Meas. Exp. rate (μR/hr) | Avg. TLD (mrem) | TLD Calc. Exp. rate (μR/hr) |
|---|---|---|---|---|---|---|
| Apr-95 | 10.00 | 6.04 | PA #4 | 30 | 16.80 | 16.53 |
| May-95 | 10.20 | 5.99 | PA #4 | 35 | 19.80 | 19.32 |
| Jun-95 | 9.40 | 5.60 | PA #4 | 27.5 | 18.80 | 16.79 |
| Jul-95 | 11.40 | 6.69 | PA #4 | 22.5 | 19.00 | 18.00 |
| Aug-95 | 8.80 | 5.73 | PA #4 | 30 | 7.30 | 3.89 |
| Sep-95 | 14.00 | 7.58 | PA #4 | 30 | 17.20 | 12.51 |
| Oct-95 | 12.80 | 7.51 | PA #4 | 27.5 | 20.60 | 18.00 |
| Nov-95 | 7.20 | 5.26 | PA #4 | 25 | 22.20 | 27.58 |
| Dec-95 | 12.6 | 7.29 | PA #4 | 27.5 | 28.00 | 26.16 |
| Jan-95 | 20.40 | 11.97 | PA #5 | 110 | 119.00 | 164.13 |
| Feb-95 | 10.00 | 5.95 | PA #5 | 120 | 70.60 | 93.02 |
| Mar-95 | 14.00 | 7.88 | PA #5 | 130 | 83.20 | 90.26 |
| Apr-95 | 10.00 | 6.04 | PA #5 | 170 | 71.60 | 101.10 |
| May-95 | 10.20 | 5.99 | PA #5 | 210 | 83.00 | 107.10 |
| Jun-95 | 9.40 | 5.60 | PA #5 | 150 | 92.80 | 104.88 |
| Jul-95 | 11.40 | 6.69 | PA #5 | 90 | 61.80 | 81.69 |
| Aug-95 | 8.80 | 5.73 | PA #5 | 90 | 10.90 | 8.30 |
| Sep-95 | 14.00 | 7.58 | PA #5 | 100 | 60.80 | 79.80 |
| Oct-95 | 12.80 | 7.51 | PA #5 | 130 | 65.60 | 78.48 |
| Nov-95 | 7.20 | 5.26 | PA #5 | 130 | 26.00 | 33.24 |
| Dec-95 | 12.6 | 7.29 | PA #5 | 115 | 84.80 | 95.77 |
| Jan-95 | 20.40 | 11.97 | PA #6 | 70 | 58.40 | 70.61 |
| Feb-95 | 10.00 | 5.95 | PA #6 | 70 | 41.80 | 51.64 |
| Mar-95 | 14.00 | 7.88 | PA #6 | 60 | 57.00 | 59.07 |
| Apr-95 | 10.00 | 6.04 | PA #6 | 55 | 31.60 | 39.37 |
| May-95 | 10.20 | 5.99 | PA #6 | 50 | 61.40 | 77.10 |
| Jun-95 | 9.40 | 5.60 | PA #6 | 125 | 89.80 | 101.31 |
| Jul-95 | 11.40 | 6.69 | PA #6 | 155 | 38.00 | 46.27 |
| Aug-95 | 8.80 | 5.73 | PA #6 | 95 | 3.00 | NA |
| Sep-95 | 14.00 | 7.58 | PA #6 | 100 | 28.80 | 30.42 |
| Oct-95 | 12.80 | 7.51 | PA #6 | 125 | 40.80 | 45.15 |
| Nov-95 | 7.20 | 5.26 | PA #6 | 115 | 32.60 | 43.06 |
| Dec-95 | 12.6 | 7.29 | PA #6 | 100 | 68.20 | 75.43 |
| Jan-95 | 20.40 | 11.97 | PA #7 | 195 | 99.40 | 133.89 |
| Feb-95 | 10.00 | 5.95 | PA #7 | 190 | 86.00 | 115.15 |
| Mar-95 | 14.00 | 7.88 | PA #7 | 175 | 91.80 | 100.50 |

| Month/Yr | Control Avg. (mrem) | Control Calc. Exp. rate (µR/hr) | Location | Avg. Meas. Exp. rate (µR/hr) | Avg. TLD (mrem) | TLD Calc. Exp. rate (µR/hr) |
|---|---|---|---|---|---|---|
| Apr-95 | 10.00 | 6.04 | PA #7 | 165 | 71.00 | 100.17 |
| May-95 | 10.20 | 5.99 | PA #7 | 150 | 74.40 | 95.15 |
| Jun-95 | 9.40 | 5.60 | PA #7 | 130 | 91.40 | 103.21 |
| Jul-95 | 11.40 | 6.69 | PA #7 | 155 | 78.80 | 106.99 |
| Aug-95 | 8.80 | 5.73 | PA #7 | 215 | 8.80 | 5.73 |
| Sep-95 | 14.00 | 7.58 | PA #7 | 240 | 56.60 | 73.32 |
| Oct-95 | 12.80 | 7.51 | PA #7 | 260 | 91.60 | 113.43 |
| Nov-95 | 7.20 | 5.26 | PA #7 | 260 | 56.60 | 78.78 |
| Dec-95 | 12.6 | 7.29 | PA #7 | 230 | 78.60 | 88.17 |
| Jan-95 | 20.40 | 11.97 | PA #8 | 75 | 159.60 | 226.79 |
| Mar-95 | 14.00 | 7.88 | PA #8 | 110 | 81.60 | 88.36 |
| Apr-95 | 10.00 | 6.04 | PA #8 | 110 | 46.20 | 61.90 |
| May-95 | 10.20 | 5.99 | PA #8 | 100 | 57.80 | 72.10 |
| Jun-95 | 9.40 | 5.60 | PA #8 | 80 | 65.80 | 72.74 |
| Jul-95 | 11.40 | 6.69 | PA #8 | 85 | 50.50 | 64.87 |
| Aug-95 | 8.80 | 5.73 | PA #8 | 140 | 6.70 | 3.16 |
| Sep-95 | 14.00 | 7.58 | PA #8 | 135 | 28.30 | 29.64 |
| Oct-95 | 12.80 | 7.51 | PA #8 | 110 | 56.80 | 66.65 |
| Nov-95 | 7.20 | 5.26 | PA #8 | 120 | 52.40 | 72.53 |
| Dec-95 | 12.6 | 7.29 | PA #8 | 110 | 77.60 | 86.95 |
| Jan-95 | 20.40 | 11.97 | Pan Sand. | 67.5 | 88.00 | 116.29 |
| Feb-95 | 10.00 | 5.95 | Pan Sand. | 70 | 46.00 | 57.68 |
| Mar-95 | 14.00 | 7.88 | Pan Sand. | 70 | 57.00 | 59.07 |
| Apr-95 | 10.00 | 3.93 | Pan Sand. | 70 | 102.40 | 146.52 |
| May-95 | 10.20 | 5.99 | Pan Sand. | 90 | 44.80 | 54.04 |
| Jun-95 | 9.40 | 5.60 | Pan Sand. | 75 | 51.00 | 55.12 |
| Jul-95 | 11.40 | 6.69 | Pan Sand. | 60 | 42.80 | 53.42 |
| Aug-95 | 8.80 | 5.73 | Pan Sand. | 75 | 39.40 | 43.23 |
| Sep-95 | 14.00 | 7.58 | Pan Sand. | 90 | 63.60 | 84.12 |
| Oct-95 | 12.80 | 7.51 | Pan Sand. | 120 | 37.20 | 40.31 |
| Nov-95 | 7.20 | 5.26 | Pan Sand. | 130 | 41.40 | 56.16 |
| Dec-95 | 12.6 | 7.29 | Pan Sand. | 100 | 73.00 | 81.31 |
| Jan-95 | 20.40 | 11.97 | RT #1 | 12 | 25.00 | 19.07 |
| Feb-95 | 10.00 | 5.95 | RT #1 | 12 | 16.20 | 14.86 |
| Mar-95 | 14.00 | 7.88 | RT #1 | 11 | 18.40 | 13.12 |
| Apr-95 | 10.00 | 6.04 | RT #1 | 16 | 14.00 | 12.21 |

| Month/Yr | Control Avg. (mrem) | Control Calc. Exp. rate (µR/hr) | Location | Avg. Meas. Exp. rate (µR/hr) | Avg. TLD (mrem) | TLD Calc. Exp. rate (µR/hr) |
|---|---|---|---|---|---|---|
| May-95 | 10.20 | 5.99 | RT #1 | 23.5 | 15.00 | 12.65 |
| Jun-95 | 9.40 | 5.60 | RT #1 | 16 | 16.00 | 13.45 |
| Jul-95 | 11.40 | 6.69 | RT #1 | 9.5 | 15.80 | 13.24 |
| Aug-95 | 8.80 | 5.73 | RT #1 | 13.5 | 11.60 | 9.16 |
| Sep-95 | 14.00 | 7.58 | RT #1 | 11.5 | 14.40 | 8.19 |
| Oct-95 | 12.80 | 7.51 | RT #1 | 9 | 14.60 | 9.93 |
| Nov-95 | 7.20 | 5.26 | RT #1 | 11 | 18.40 | 21.93 |
| Dec-95 | 12.6 | 7.29 | RT #1 | 13.5 | 18.20 | 14.15 |
| Jan-95 | 20.40 | 11.97 | RT #2 | 20 | 35.00 | 34.50 |
| Feb-95 | 10.00 | 5.95 | RT #2 | 20 | 20.20 | 20.61 |
| Mar-95 | 14.00 | 7.88 | RT #2 | 20 | 22.00 | 17.41 |
| Apr-95 | 10.00 | 6.04 | RT #2 | 25 | 15.00 | 13.75 |
| May-95 | 10.20 | 5.99 | RT #2 | 30 | 19.40 | 18.76 |
| Jun-95 | 9.40 | 5.60 | RT #2 | 22.5 | 22.80 | 21.55 |
| Jul-95 | 11.40 | 6.69 | RT #2 | 22.5 | 21.40 | 21.57 |
| Aug-95 | 8.80 | 5.73 | RT #2 | 25 | 14.20 | 12.35 |
| Sep-95 | 14.00 | 7.58 | RT #2 | 27 | 19.20 | 15.60 |
| Oct-95 | 12.80 | 7.51 | RT #2 | 31 | 18.80 | 15.58 |
| Nov-95 | 7.20 | 5.26 | RT #2 | 31.5 | 14.60 | 16.28 |
| Dec-95 | 12.6 | 7.29 | RT #2 | 37.5 | 20.60 | 17.10 |
| Jan-96 | 8.80 | 5.02 | PA #1 | 15 | 15.60 | 14.79 |
| Feb-96 | 5.80 | 4.17 | PA #1 | 15 | 2.80 | 0.26 |
| Mar-96 | 12.80 | 6.58 | PA #1 | 15 | 16.40 | 11.94 |
| Apr-96 | 7.80 | 4.22 | PA #1 | 15 | 25.80 | 29.22 |
| May-96 | 11.40 | 6.69 | PA #1 | 22.5 | 17.40 | 14.27 |
| Jun-96 | | | PA #1 | 19 | 18.80 | 27.98 |
| Jan-96 | 8.80 | 5.02 | PA #2 | 170 | 93.20 | 126.29 |
| Feb-96 | 5.80 | 4.17 | PA #2 | 160 | 17.00 | 18.75 |
| Mar-96 | 12.80 | 6.58 | PA #2 | 115 | 107.20 | 147.06 |
| Apr-96 | 7.80 | 4.22 | PA #2 | 70 | 123.20 | 164.50 |
| May-96 | 11.40 | 6.69 | PA #2 | 90 | 134.20 | 161.74 |
| Jun-96 | | | PA #2 | 70 | 49.60 | 73.81 |
| Jan-96 | 8.80 | 5.02 | PA #3 | 200 | 64.40 | 84.91 |
| Feb-96 | 5.80 | 4.17 | PA #3 | 200 | 4.40 | 2.34 |
| Mar-96 | 12.80 | 6.58 | PA #3 | 150 | 55.40 | 69.98 |
| Apr-96 | 7.80 | 4.22 | PA #3 | 80 | 65.40 | 84.22 |

| Month/Yr | Control Avg. (mrem) | Control Calc. Exp. rate (µR/hr) | Location | Avg. Meas. Exp. rate (µR/hr) | Avg. TLD (mrem) | TLD Calc. Exp. rate (µR/hr) |
|---|---|---|---|---|---|---|
| May-96 | 11.40 | 6.69 | PA #3 | 60 | 55.00 | 61.74 |
| Jun-96 | | | PA #3 | 50 | 135.00 | 200.89 |
| Jan-96 | 8.80 | 5.02 | PA #4 | 35 | 19.40 | 20.25 |
| Feb-96 | 5.80 | 4.17 | PA #4 | 40 | 5.50 | 3.78 |
| Mar-96 | 12.80 | 6.58 | PA #4 | 30 | 25.00 | 24.74 |
| Apr-96 | 7.80 | 4.22 | PA #4 | 19 | 27.60 | 31.72 |
| May-96 | 11.40 | 6.69 | PA #4 | 19 | 28.20 | 27.90 |
| Jun-96 | | | PA #4 | 20 | 28.20 | 41.96 |
| Jan-96 | 8.80 | 5.02 | PA #5 | 115 | 50.40 | 64.79 |
| Feb-96 | 5.80 | 4.17 | PA #5 | 120 | 10.10 | 9.77 |
| Mar-96 | 12.80 | 6.58 | PA #5 | 110 | 58.20 | 74.14 |
| Apr-96 | 7.80 | 4.22 | PA #5 | 70 | 55.80 | 70.89 |
| May-96 | 11.40 | 6.69 | PA #5 | 60 | 67.40 | 77.40 |
| Jun-96 | | | PA #5 | 62.5 | 64.20 | 95.54 |
| Jan-96 | 8.80 | 5.02 | PA #6 | 100 | 35.20 | 42.95 |
| Feb-96 | 5.80 | 4.17 | PA #6 | 100 | 2.30 | NA |
| Mar-96 | 12.80 | 6.58 | PA #6 | 75 | 45.40 | 55.10 |
| Apr-96 | 7.80 | 4.22 | PA #6 | 45 | 50.20 | 63.11 |
| May-96 | 11.40 | 6.69 | PA #6 | 37.5 | 43.20 | 46.84 |
| Jun-96 | | | PA #6 | 25 | 36.80 | 54.76 |
| Jan-96 | 8.80 | 5.02 | PA #7 | 230 | 45.20 | 57.32 |
| Feb-96 | 5.80 | 4.17 | PA #7 | 240 | 4.60 | 2.60 |
| Mar-96 | 12.80 | 6.58 | PA #7 | 200 | 55.00 | 69.38 |
| Apr-96 | 7.80 | 4.22 | PA #7 | 150 | 69.40 | 89.78 |
| May-96 | 11.40 | 6.69 | PA #7 | 110 | 56.80 | 64.01 |
| Jun-96 | | | PA #7 | 62.5 | 54.60 | 81.25 |
| Jan-96 | 8.80 | 5.02 | PA #8 | 100 | 44.80 | 56.75 |
| Mar-96 | 12.80 | 6.58 | PA #8 | 90 | 58.80 | 75.04 |
| Apr-96 | 7.80 | 4.22 | PA #8 | 80 | 71.60 | 92.83 |
| May-96 | 11.40 | 6.69 | PA #8 | 65 | 59.20 | 67.04 |
| Jun-96 | | | PA #8 | 45 | 62.40 | 92.86 |
| Jan-96 | 8.80 | 5.02 | Pan Sand. | 85 | 35.80 | 43.82 |
| Feb-96 | 5.80 | 4.17 | Pan Sand. | 40 | 41.20 | 50.26 |
| Mar-96 | 12.80 | 6.58 | Pan Sand. | 82.5 | 35.60 | 40.51 |
| Apr-96 | 7.80 | 4.22 | Pan Sand. | 48.5 | 44.00 | 54.50 |
| May-96 | 11.40 | 6.69 | Pan Sand. | 33.5 | 40.80 | 43.81 |

| Month/Yr | Control Avg. (mrem) | Control Calc. Exp. rate (µR/hr) | Location | Avg. Meas. Exp. rate (µR/hr) | Avg. TLD (mrem) | TLD Calc. Exp. rate (µR/hr) |
|---|---|---|---|---|---|---|
| Jun-96 | | | Pan Sand. | 45 | 35.00 | 52.08 |
| Jan-96 | 8.80 | 5.02 | RT #1 | 17.5 | 16.20 | 15.66 |
| Feb-96 | 5.80 | 4.17 | RT #1 | 100 | 14.80 | 15.89 |
| Mar-96 | 12.80 | 6.58 | RT #1 | 15 | 29.00 | 30.69 |
| Apr-96 | 7.80 | 4.22 | RT #1 | 18 | 34.40 | 41.17 |
| May-96 | 11.40 | 6.69 | RT #1 | 17.5 | 25.60 | 24.62 |
| Jun-96 | | | RT #1 | 9 | 25.00 | 37.20 |
| Jan-96 | 8.80 | 5.02 | RT #2 | 40 | 16.40 | 15.94 |
| Feb-96 | 5.80 | 4.17 | RT #2 | 20 | 19.20 | 21.61 |
| Mar-96 | 12.80 | 6.58 | RT #2 | 25 | 20.40 | 17.89 |
| Apr-96 | 7.80 | 4.22 | RT #2 | 9 | 25.00 | 28.11 |
| May-96 | 11.40 | 6.69 | RT #2 | 11.5 | 19.60 | 17.04 |
| Jun-96 | | | RT #2 | 13.5 | 19.00 | 28.27 |

The following is a summary of the one chemical plant's radon readings between the years 1989-1994. Included is the full statistical summary for each monitoring location.

**Table A-7. Radon Measurements for 1989 - 1994**

| 1989-1994 Chemical Plant Radon Readings | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Monitoring Location | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Mean* | 2.43 | 2.89 | 0.35 | 1.89 | 1.90 | 2.60 | 6.52 | 2.08 |
| Std Err | 0.45 | 0.65 | 0.08 | 0.48 | 0.49 | 0.74 | 1.01 | 0.63 |
| Median | 0.75 | 2.12 | 0.18 | 0.40 | 0.54 | 0.75 | 4.41 | 0.91 |
| Mode | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Std Dev | 4.30 | 4.87 | 0.47 | 5.23 | 5.04 | 7.43 | 4.95 | 5.18 |
| Variance | 18.45 | 23.73 | 0.22 | 27.39 | 25.36 | 55.26 | 24.52 | 26.85 |
| Kurtosis | 9.10 | 20.14 | 12.03 | 29.97 | 40.15 | 32.12 | 0.68 | 19.41 |
| Skewness | 2.94 | 4.16 | 3.10 | 5.04 | 6.05 | 5.35 | 1.36 | 4.48 |
| Range | 21.74 | 30.60 | 2.38 | 40.87 | 40.84 | 56.76 | 15.82 | 27.61 |
| Min | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.07 | 0.00 |
| Max | 21.74 | 30.61 | 2.38 | 40.87 | 40.84 | 56.76 | 17.89 | 27.61 |
| Count | 90.00 | 56.00 | 31.00 | 118.00 | 105.00 | 101.00 | 24.00 | 68.00 |
| CL 95% | 0.89 | 1.28 | 0.16 | 0.94 | 0.96 | 1.45 | 1.98 | 1.23 |
| * All the units are in pCi/l | | | | | | | | |

Monitoring Locations:
1) NE Gypsum Stack Well
2) Auto Shop SE Fence
3) SW of Plant
4) Burn Area Fence
5) Liming Station Ladder
6) Environmental Monitoring Well
7) Gypsum Stack Flux Test
8) Cooling Pond Hand Rail

The following is a summary of the a chemical plant's radon readings between the years 1995-1996.

**Table A-8. Radon Measurements Summary for 1995 - 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 |

**Table A-9.  1996 Radon Readings in Rock Tunnels**

| Start Date | End Date | µR/hr | pCi/l | Area | Location |
|---|---|---|---|---|---|
| 01/05 | 02/06 | 6 | 7.284 | Tunnel | North |
| 01/05 | 02/06 | 6 | 8.600 | Tunnel | Middle |
| 01/05 | 02/06 | 6 | 6.938 | Tunnel | South Lower |
| 01/05 | 02/06 | 6 | 10.121 | Tunnel | South Upper |
| 02/06 | 03/13 | 7 | 8.669 | Tunnel | North |
| 02/06 | 03/13 | 10 | 7.094 | Tunnel | Middle |
| 02/06 | 03/13 | 10 | 4.819 | Tunnel | South Lower |
| 02/06 | 03/13 | 7 | 10.479 | Tunnel | South Upper |
| 03/13 | 04/19 | 7 | 28.137 | Tunnel | North |
| 03/13 | 04/19 | 10 | 5.295 | Tunnel | Middle |
| 03/13 | 04/19 | 10 | 4.228 | Tunnel | South Lower |
| 03/13 | 04/19 | 7 | 5.157 | Tunnel | South Upper |
| 04/19 | 05/14 | 9 | 16.626 | Tunnel | North |
| 04/19 | 05/14 | 16 | 6.272 | Tunnel | Middle |
| 04/19 | 05/14 | 14 | 3.441 | Tunnel | South Lower |
| 04/19 | 05/14 | 10 | 4.621 | Tunnel | South Upper |
| 05/14 | 06/18 | 9 | 5.574 | Tunnel | North |
| 05/14 | 06/18 | 16 | 3.349 | Tunnel | Middle |
| 05/14 | 06/18 | 14 | 1.380 | Tunnel | South Lower |
| 05/14 | 06/18 | 10 | 2.135 | Tunnel | South Upper |
| 06/18 | 07/17 | 9 | 7.572 | Tunnel | North |
| 06/18 | 07/17 | 16 | 9.144 | Tunnel | Middle |
| 06/18 | 07/17 | 14 | 0.785 | Tunnel | South Lower |
| 06/18 | 07/17 | 10 | 1.563 | Tunnel | South Upper |
| 07/17 | 08/08 | 9 | 7.031 | Tunnel | North |
| 07/17 | 08/08 | 16 | 3.295 | Tunnel | Middle |
| 07/17 | 08/08 | 14 | 0.985 | Tunnel | South Lower |
| 07/17 | 08/08 | 10 | 2.562 | Tunnel | South Upper |
| 08/08 | 09/23 | 5 | 59.599 | Tunnel | North |
| 08/08 | 09/23 | 10 | 3.399 | Tunnel | Middle |
| 08/08 | 09/23 | 10 | 1.630 | Tunnel | South Lower |
| 08/08 | 09/23 | 10 | 2.007 | Tunnel | South Upper |
| 09/23 | 10/15 | 8 | 61.330 | Tunnel | South Upper |
| 09/23 | 10/15 | 10 | 4.355 | Tunnel | South Upper |
| 09/23 | 10/15 | 12 | 0.964 | Tunnel | South Upper |
| 09/23 | 10/15 | 10 | 1.937 | Tunnel | South Upper |

**Table A-10. Radon Measurements in Rock Tunnels for 1996 Summary Statistics**

| 1996 Rock Tunnel Radon Readings | | | | |
|---|---|---|---|---|
| | Monitoring Location | | | |
| | **1** | **2** | **3** | **4** |
| Mean* | 5.81 | 3.03 | 17.56 | 8.94 |
| Std Err | 0.84 | 0.78 | 6.57 | 4.85 |
| Median | 5.78 | 2.54 | 8.12 | 3.46 |
| Mode | NA | NA | NA | NA |
| Std Dev | 2.37 | 2.20 | 18.59 | 16.8 |
| Variance | 5.60 | 4.85 | 345.57 | 282.24 |
| Kurtosis | -1.65 | -0.53 | 4.28 | 10.91 |
| Skewness | 0.24 | 0.72 | 2.07 | 3.25 |
| Range | 5.85 | 6.15 | 54.02 | 60.37 |
| Min | 3.30 | 0.78 | 5.57 | 0.96 |
| Max | 9.14 | 6.94 | 59.60 | 61.33 |
| Count | 8 | 8 | 8 | 12 |
| CL 95% | 1.64 | 1.53 | 12.88 | 9.50 |
| * All the units are in pCi/l | | | | |

Monitoring Locations:
1) Middle Tunnel
2) South Lower Tunnel
3) North Tunnel
4) South Upper Tunnel

**Table A-11. Radon Readings in Rock Tunnels Using E-Perms for the Year 1996**

| Start Date | End Date | μR/hr | pCi/l | Location |
|---|---|---|---|---|
| 01/10 | 02/20 | 50 | 9.621 | Chute 1 |
| 01/10 | 02/20 | 50 | 8.723 | Chute 1 |
| 01/10 | 02/20 | 50 | 11.229 | Chute 10 |
| 01/10 | 02/20 | 50 | 16.025 | Chute 10 |
| 01/10 | 02/20 | 50 | 4.535 | Chute 20 |
| 01/10 | 02/20 | 50 | 6.540 | Chute 20 |
| 02/20 | 03/08 | 30 | 11.410 | Chute 1 |
| 02/20 | 03/08 | 30 | 8.496 | Chute 1 |
| 02/20 | 03/08 | 40 | 10.633 | Chute 10 |
| 02/20 | 03/08 | 40 | 10.908 | Chute 10 |
| 02/20 | 03/08 | 50 | 4.174 | Chute 20 |
| 02/20 | 03/08 | 50 | 5.584 | Chute 20 |
| 03/08 | 04/03 | 40 | 9.701 | Chute 1 |
| 03/08 | 04/03 | 40 | 7.056 | Chute 1 |
| 03/08 | 04/03 | 35 | 15.259 | Chute 10 |
| 03/08 | 04/03 | 35 | 24.598 | Chute 10 |
| 03/08 | 04/03 | 50 | 9.287 | Chute 20 |
| 03/08 | 04/03 | 50 | 11.199 | Chute 20 |
| 04/03 | 05/06 | 35 | 9.227 | Chute 1 |
| 04/03 | 05/06 | 35 | 5.051 | Chute 1 |
| 04/03 | 05/06 | 35 | 14.144 | Chute 10 |
| 04/03 | 05/06 | 35 | 17.244 | Chute 10 |
| 04/03 | 05/06 | 40 | 9.999 | Chute 20 |
| 04/03 | 05/06 | 40 | 18.015 | Chute 20 |
| 05/06 | 06/17 | 35 | 14.591 | Chute 1 |
| 05/06 | 06/17 | 35 | 5.458 | Chute 1 |
| 05/06 | 06/17 | 35 | 21.567 | Chute 10 |
| 05/06 | 06/17 | 35 | 30.285 | Chute 10 |
| 05/06 | 06/17 | 40 | 5.083 | Chute 20 |
| 05/06 | 06/17 | 40 | 16.273 | Chute 20 |
| 06/17 | 07/31 | 40 | 28.164 | Chute 1 |
| 06/17 | 07/31 | 40 | 8.853 | Chute 1 |
| 06/17 | 07/31 | 40 | 20.975 | Chute 10 |
| 06/17 | 07/31 | 40 | 63.616 | Chute 10 |
| 06/17 | 07/31 | 40 | 8.590 | Chute 20 |
| 06/17 | 07/31 | 40 | 9.434 | Chute 20 |
| 07/31 | 08/27 | 35 | 15.978 | Chute 1 |
| 07/31 | 08/27 | 35 | 8.390 | Chute 1 |

| Start Date | End Date | μR/hr | pCi/l | Location |
|---|---|---|---|---|
| 07/31 | 08/27 | 35 | 29.499 | Chute 10 |
| 07/31 | 08/27 | 35 | 22.962 | Chute 10 |
| 07/31 | 08/27 | 40 | 6.741 | Chute 20 |
| 07/31 | 08/27 | 40 | 6.983 | Chute 20 |
| 08/27 | 09/13 | 35 | 14.949 | Chute 1 |
| 08/27 | 09/13 | 35 | 14.686 | Chute 1 |
| 08/27 | 09/13 | 35 | 17.147 | Chute 10 |
| 08/27 | 09/13 | 35 | 33.107 | Chute 10 |
| 08/27 | 09/13 | 40 | 8.839 | Chute 20 |
| 08/27 | 09/13 | 40 | 31.428 | Chute 20 |
| 09/13 | 10/08 | 35 | 20.242 | Chute 1 |
| 09/13 | 10/08 | 35 | 10.033 | Chute 1 |
| 09/13 | 10/08 | 35 | 42.713 | Chute 10 |
| 09/13 | 10/08 | 35 | 74.706 | Chute 10 |
| 09/13 | 10/08 | 40 | 71.348 | Chute 20 |
| 09/13 | 10/08 | 40 | 79.540 | Chute 20 |

**Table A-12. Radon Measurements Using E-Perms for 1996 Summary Statistics**

| 1996 Rock Tunnel E-Perm Radon | | | |
|---|---|---|---|
| | Monitoring Location | | |
| | Chute 1 | Chute 10 | Chute 20 |
| Mean* | 11.70 | 26.48 | 17.42 |
| Std Err | 1.34 | 4.20 | 5.21 |
| Median | 9.66 | 21.27 | 9.06 |
| Mode | 0.00 | 0.00 | 0.00 |
| Std Dev | 5.69 | 17.81 | 22.12 |
| Variance | 32.38 | 317.19 | 489.15 |
| Kurtosis | 3.09 | 2.74 | 4.64 |
| Skewness | 1.60 | 1.76 | 2.35 |
| Range | 23.11 | 64.07 | 75.37 |
| Min | 5.05 | 10.63 | 4.17 |
| Max | 28.16 | 74.71 | 79.54 |
| Count | 18.00 | 18.00 | 18.00 |
| CL 95% | 2.63 | 8.23 | 10.22 |
| * All the units are in pCi/l | | | |

The following is a summary of the Teradex Radon readings 1982-1996. In the following page is the full statistical summary of each site.

**Table A-13. Terradex Radon Measurements for 1982 - 1996 Summary Statistics**

| Area | Mean (pCi/l) |
|---|---|
| Area-10 Control Room S.C.B.A. | 0.52 |
| Area-20 | 0.61 |
| Area-40 Control Room | 0.72 |
| Area-40 Storage | 0.30 |
| Area-40 5th Floor | 0.27 |
| Area-50 Lunch Room | 0.28 |
| Auto Shop | 0.27 |
| Ball Mill Electric Room | 0.61 |
| Ball Mill Cont. Room S. Wall | 0.78 |
| DAP Storage W. of Conveyor | 0.52 |
| DAP#1 Control Room | 0.20 |
| DAP#1 Storage | 0.27 |
| DAP#1 Shipping Control Room | 0.30 |
| Dozer Inside Cab | 1.20 |
| Dragline Inside Cab | 0.86 |
| Environmental Lab | 1.40 |
| GSTP | 0.61 |
| H.P. Lab | 0.43 |
| Hall | 0.53 |
| MAP-DAP Shipping Office | 0.34 |
| MAP-DAP Control Room E. Wall | 0.67 |
| Main Office | 0.58 |
| MAP Storage N.E. Corner | 0.71 |
| Met Tower Lower Level (3ft) | 0.71 |
| Met Tower Upper Level (30ft) | 0.30 |
| Phos-Acid | 0.64 |
| West Rock Tunnel Chute 1 | 12.51 |
| Phosphate Council | 3.20 |
| West Rock Tunnel Chute 5 | 13.07 |
| West Rock Tunnel Chute 10 | 14.78 |
| West Rock Tunnel Chute 8 | 47.56 |
| West Rock Tunnel Chute 15 | 11.89 |
| West Rock Tunnel Chute 20 | 10.24 |

| Area | Mean (pCi/l) |
|---|---|
| West Rock Tunnel Chute 16 | 40.23 |
| West Rock Tunnel Chute 21 | 43.75 |
| West Rock Tunnel Chute 25 | 8.95 |
| West Rock Tunnel Chute 27 | 32.91 |
| West Rock Tunnel Chute 30 | 5.76 |
| West Rock Tunnel Chute 33 | 19.96 |
| Pilot Plant | 0.40 |
| Background | 1.88 |
| Safety Receptionist’s Window | 0.59 |
| MAP-DAP E. Wall Control Room | 0.23 |
| Wet Rock Lower Level | 6.62 |
| Wet Rock Behind Refrigerator | 1.10 |
| Wet Rock Lower Level | 8.60 |
| Wet Rock S. Entrance | 0.98 |
| East Rock Tunnel Chute 30 | 11.11 |
| East Rock Tunnel Chute 25 | 10.94 |
| East Rock Tunnel Chute 20 | 18.24 |
| East Rock Tunnel Chute 15 | 25.97 |
| East Rock Tunnel Chute 10 | 19.56 |
| East Rock Tunnel Chute 5 | 26.07 |
| East Rock Tunnel Chute 1 | 23.80 |

**Table A-14. Chemical Plant Track Etch Radon Results for 1993 - 1996**

| 1993 | | | |
|---|---|---|---|
| **Start** | **End** | **Area** | **pCi/l** |
| 01/22 | 07/22 | Environmental Tech Office | 1 |
| 01/22 | 07/22 | Office | 0.3 |
| 01/22 | 07/22 | Office | 0.6 |
| 01/22 | 07/22 | Administrative Assistant Trailer | 1 |
| 01/22 | 07/22 | Main Office Bldg | 0.2 |
| 01/22 | 07/22 | Office | 0.3 |
| 01/22 | 07/22 | Electric Shop | 0.7 |
| 01/22 | 07/22 | Phos-acid Control Room | 0.9 |
| 01/22 | 07/22 | Filter Pan Level Offices | 0.6 |
| 07/22 | 01/24 | Environmental Tech Office | 1.8 |
| 07/22 | 01/24 | Office | 0.4 |
| 07/22 | 01/24 | Office | 0.8 |
| 07/22 | 01/24 | Administrative Assistant Trailer | 1.5 |
| 07/22 | 01/24 | Main Office Bldg | 1 |
| 07/22 | 01/24 | Employee's Residence | 1.2 |
| 07/22 | 01/24 | Electric Shop | 0.8 |
| 07/22 | 01/24 | Phos-acid Control Room | 0.7 |
| 07/22 | 01/24 | Filter Pan Level Offices | 0.7 |
| **1994** | | | |
| **Start** | **End** | **Area** | **pCi/l** |
| 01/24 | 07/21 | Environmental Tech Office | 1.2 |
| 01/24 | 07/21 | Trailer | 0.5 |
| 01/24 | 07/21 | Trailer | 0.7 |
| 01/24 | 07/21 | Administrative Assistant Trailer | 0.9 |
| 01/24 | 07/21 | Lab Bldg(main Office Bldg) | 0.8 |
| 01/24 | 07/21 | Residence | 0.5 |
| 01/24 | 07/21 | Electric Shop | 0.5 |
| 01/24 | 07/21 | Phos-acid Control Room | 0.6 |
| 01/24 | 07/21 | Filter Pan Level Offices | 0.6 |
| 07/21 | 01/31 | Safety Office | 0.7 |
| 07/21 | 01/31 | Lab Bldg(main Office Bldg) | 1.1 |
| 07/21 | 01/31 | Environmental Tech Office | 1.2 |
| 07/21 | 01/31 | Electric Shop | 0.3 |
| 07/21 | 01/31 | Instrument Shop | 0.8 |
| 07/21 | 01/31 | Phos-acid Control Room | 0.6 |
| 07/21 | 01/31 | Filter Pan Level Offices | 0.3 |

| 1995 | | | |
|---|---|---|---|
| **Start** | **End** | **Area** | **pCi/l** |
| 01/31 | 07/21 | Filter Pan Level Offices | 0.4 |
| 01/31 | 07/21 | Employee's House | 2.1 |
| 01/31 | 07/21 | Ball Mill Control Room | 0.3 |
| 01/31 | 07/21 | Instrument Shop | 0.6 |
| 01/31 | 07/21 | Sulfuric Maintenance Office | 1.2 |
| 01/31 | 07/21 | Lab Bldg(main Office Bldg) | 1 |
| 01/31 | 07/21 | Phos-acid Control Room | 0.9 |
| 01/31 | 07/21 | Electric Shop | 0.5 |
| 01/31 | 07/21 | DAP Maintenance Lunchroom | 0.3 |
| 01/31 | 07/21 | Services | 0.6 |
| 01/31 | 07/21 | Rock Tunnel | 5.8 |
| 01/31 | 07/21 | Sulfuric Control Room | 0.7 |
| 01/31 | 07/21 | Safety | 0.6 |
| 07/21 | 01/22 | Filter Pan Level Offices | 0.5 |
| 07/21 | 01/22 | Ball Mill Control Room | 0.4 |
| 07/21 | 01/22 | Instrument Shop | 0.6 |
| 07/21 | 01/22 | Sulfuric Maintenance Office | 2.9 |
| 07/21 | 01/22 | Lab Bldg(main Office Bldg) | 0.9 |
| 07/21 | 01/22 | Phos-acid Control Room | 0.6 |
| 07/21 | 01/22 | Electric Shop | 0.5 |
| 07/21 | 01/22 | DAP Maintenance Lunchroom | 0.3 |
| 07/21 | 01/22 | Services | 0.5 |
| 07/21 | 01/22 | Rock Tunnel | 5.2 |
| 07/21 | 01/22 | Sulfuric Control Room | 0.6 |
| 07/21 | 01/22 | Safety | 0.5 |

| 1996 | | | |
|---|---|---|---|
| **Start** | **End** | **Area** | **pCi/l** |
| 01/17 | 07/17 | Sulfuric Maintenance Office | 1.4 |
| 01/17 | 07/17 | Safety | 0.7 |
| 01/17 | 07/17 | DAP Maintenance Lunchroom | 0.4 |
| 01/17 | 07/17 | Sulfuric Control Room | 0.7 |
| 01/17 | 07/17 | Phos-acid Control Room | 1 |
| 01/17 | 07/17 | Services | 0.8 |
| 01/17 | 07/17 | Main Office | 1.4 |
| 01/17 | 07/17 | Filter Pan Level Offices | 0.7 |
| 01/17 | 07/17 | Electric Shop | 0.6 |
| 01/17 | 07/17 | Ball Mill Control Room | 1 |
| 01/17 | 07/17 | Instrument Shop | 0.8 |

# APPENDIX B - SUPPORT MATERIALS FOR THE METHODOLOGY SECTION

## DEALING WITH CENSORED DATA

### Personnel Monitoring Devices, Limit of Detection and Statistical Evaluation

**Personnel Monitoring Devices.** It is important in the nuclear industry to have workers wear a personal radiation monitoring device. The pocket dosimeter, either self-reading or one that is read from a charging station, represents one type of device often issued upon entry into a radiation area. Historically, a photographic film badge was used to monitor the entire work day. Badges were often worn on the chest area and returned to a control station at the end of the shift. The film badge was evaluated on the basis that radiation exposure darkened the film much as it would if exposed to light outside of the sealed packet. The film became a permanent record to the radiation exposure. More recently, however, the thermoluminescent dosimeter (TLD) has become the standard personal dosimeter for the nuclear industry and is often used in tandem with the pocket dosimeter. Each has its advantages and disadvantages.

**TLDs.** TLDs match their intended use in many ways. They respond well to gamma and X-radiations, and with proper filtration and calibration can be reported out in units of mrem (or mSv) of deep dose and/or shallow dose. The TLD material stores light in proportion to the energy absorbed from the radiation's interaction with the "crystal." Once this crystal is heated, the light released is proportional to the radiation exposure. The graph of light emission over time as the crystal is heated is called the glow curve. If the information from the glow curve is recorded, correctly quantified, and correlated to an appropriate standard exposure, the is accepted as a permanent record of the dose to the individual who has worn that badge. Lithium fluoride (LiF) is a common dosimeter material. It can be made with uniform characteristics, in precise shapes, and with the capability of being reused hundreds of times by appropriate annealing (heating release stored energy). Very important is the fact that the LiF is approximately tissue equivalent (effective atomic number = 8.1 versus that of human soft tissue = 7.4). Vendors of these badges are now accredited through the National Voluntary Laboratory Accreditation Program (NVLAP).

**Controls, Background and Net Exposures.** In an ideal situation, TLDs issued to a work crew in the nuclear industry are worn during their shifts over a period of time to integrate the total external dose. The time period is most commonly one month. The vendor provides both the number of badges needed for the crew and a control badge. This control badge is placed in a suitable non-radiation area. The vendor will utilize the control badge to subtract both the background and any transit exposure. Again, in the ideal situation, the net dose for each worker is an "above background" dose. It is obviously a difficult decision to pick an ideal control location. In the phosphate industry, it is even a more difficult choice. Almost any location for the control badges (also where the workers' badges should be stored during non-working hours) can be criticized because the materials from which the radioactivity of concern is derived can be almost anywhere in some form at the facility. A locker room or administrative office is the usual choice, but a severe critic could argue that the true background for the phosphate facilities would be a similar plant processing a phosphate ore containing no uranium, thorium, or decay products of each. This is, of course, an extreme and unattainable position. However, it does stress the importance of a carefully considered control location.

Selecting a location with terrestrial gamma levels well above what is normally considered background in Florida (about 5 - 7 µR/hr ) will lower the net workers' exposure. Selecting a location with a background even lower than that of the administrative staff of the facility will increase the net workers' exposure above what should be fairly assigned to the person working with TENORM.

**TLD Badging in the Phosphate Industry.** Historically, various companies in the phosphate industry have instituted a series of TLD studies to (1) investigate the levels of exposure to NORM for their own understanding of the potential, (2) provide assurance to their workers that their doses were sufficiently low in comparison to acceptable standards at that time, (3) provide the company a degree of liability protection against a future claim of disability or medical problems, and (4) in some cases, fulfill a license requirement. Much of the historical TLD badging in the phosphate industry was conducted with a monthly exchange frequency. This is a logical rotation period because it provides more immediate feedback to the investigation and especially any higher than expected dose value for a particular worker or work assignment. Longer times of integration, quarterly badges for example, do not have the above advantages and may create more problems with lost or damaged badges. In such cases, the data for three months may be missing or very questionable (damaged badges from heat, water, physical damage, etc.).

This current investigation was most fortunate in being given access to past TLD badging campaigns of several of the phosphate companies. Please see the Acknowledgment section for more detail on the high degree of cooperation and assistance provided with regard to both historical data and the intensive monitoring and surveys conducted in the last two years at the companies. Some general statements can be made about the historical TLD badging projects of the phosphate companies: (1) many of the workers did not receive doses of concern with respect to the standards at that time, (2) those workers with somewhat elevated doses could be associated with particular processes in the industry, and (3) all worker doses were at least an order of magnitude lower than the 5,000 mrem/yr allowable in the commercial nuclear industry. The most common conclusion of the historical studies was that a few particular processes (filter pan cleaning and refurbishing, for example) need to be of concern to the industry.

**Limits of Detection on TLD Badges.** The standard personnel TLD badge has a normal limit of less than 10 mrem net. This is the limit irrespective of the time frame of integration. For a monthly badge this means 10 mrem per month and for a quarterly badge this means 10 mrem/quarter. The vendor companies read both the worker's TLD badge and a control badge for a particular set provided for the rotation. For example, one crew of twelve receives thirteen badges, wear one each for a month, and keep a control badge on a storage board along with their badge when they leave for home. The vendor reads, analyzes, and records all thirteen badges in the set. If the difference between the control and a particular worker's badge is 10 mrem or above, the net dose is reported. If the difference is less than 10 mrem, the vendor suggests that the statistics of the reading, analysis, algorithms, calibrations for both the control and actual badge indicate that only a limit of detection can be reported. For the purpose of the rest of the discussion that follows, this limit of detection will be "M," a marker substituted for a numeral value of a net of ten or less. The actual difference reported as "M" could be any dose value from nine mrem to zero and even to a small negative number. A few small negative differences are theoretically expected even though scientifically, differences would be limited to zero. That is, one cannot reasonably incur an exposure less than that of the working environs. Obviously, any set of badges with large number of negative values would indicate some problem or abnormality in the control badge, and the vendor notifies the client of the potential error in the data set.

**Interpretation of TLD Data Set with Imbedded Limits of Detection "M."** Consider the hypothetical data set in Table B-1. This worker received only two positive results

**Table B-1. Hypothetical TENORM Worker's Radiation Dose**

| Year | Month | TLD Badge | mrem/mo |
|---|---|---|---|
| 1991 | Jan | 1234001 | M |
| 1991 | Feb | 1234002 | M |
| 1991 | Mar | 1234003 | 12 |
| 1991 | Apr | 1234004 | M |
| 1991 | May | 1234005 | M |
| 1991 | June | 1234006 | 15 |
| 1991 | July | 1234007 | M |
| 1991 | Aug | 1234008 | M |
| 1991 | Sept | 1234009 | M |
| 1991 | Oct | 1234010 | M |
| 1991 | Nov | 1234011 | M |
| 1991 | Dec | 1234012 | M |

during the calendar year of 1991. The data set indicates that the external, deep dose exposure was low. However, there remains the question on how to handle this data set in more detailed statistical analyzes. Also in investigations that attempt to understand and evaluate task exposures, there needs to be some numerical value assigned to this worker's dose.

Surveys for gamma levels and area monitors, coupled with time and motion studies, are a valuable asset to verification of personal badging. Once again there is a need to assign the most technically valid level for each of the "M" doses or lower limit of detection recorded.

**Methods of Interpreting "M" Values in a Set of TLD Readings**

**NRC Surveillance Data Analogy.** There a number of ways in which this data table would be handled by industry. The Nuclear Regulatory Commission faced this problem years ago in environmental surveillance for radioactivity, where many of the analyzes of potential pathway items were returned as <MDA (less than the minimum detectable activity). The NRC specified that a data set (if it were in concentrations) such as in Table B-1 would be reported as follows:

| | |
|---|---|
| Number positive/number sampled: | 2/12 |
| Average of the positive values: | 13.5 mrem/month |

This is not a particularly useful system for further analysis of larger sets of data. It has the potential for an investigator or critic to report out the year dose as twelve times 13.5 or 162 mrem/yr. Clearly this is an unacceptable value.

**Direct Use of the LLD in Data Sets.** The harshest critic of the nuclear or phosphate industry could suggest that the ten "M" readings in Table B-1 be considered as 9.4 mrem/month each. This assumes that a 9.5 mrem net would be rounded to 10 mrem and reported as a positive value. Thus the yearly dose to the hypothetical worker in Table B-1 would be reported as follows:

| | |
|---|---|
| Ten limits of detection, 9.4 mrem each | 94 mrem |
| Two positive values, 12 and 15 mrem each | 27 mrem |
| **Yearly dose** | **121 mrem** |

This approach is common in other types of data sets since it should set an upper limit for the analysis. However, it is not statistically valid and does little to confirm a parallel study such as the area surveys coupled to time and motion data.

**Assignment of Zero Dose to LLD Entries.** The opposite end of the spectrum is the most liberal view, suggesting that the ten "M" values should be recorded as zero mrem. Thus, the yearly dose to this hypothetical worker is recorded as follows:

| | |
|---|---|
| Ten net values below LLD, 0 mrem each | 0 mrem |
| Two positive values, 12 and 15 mrem each | 27 mrem |
| **Yearly dose** | **27 mrem** |

It is clear that this approach has the same validation problems noted in the previous paragraph. It is likely the least scientific approach and tends to give this worker a false sense of security.

**Confidence Limit Approach.** Another approach borrowed from the surveillance for radioactivity reporting system is the concept of a Confidence Limit (CL). This CL technique has a well defined statistical basis and has gained some use in the summary of large environmental data sets containing many imbedded analyses below the analytical LLD or MDA. Samples without the same LLD or MDA as sample size, delay times, chemical recoveries, etc., may differ from sample to sample. The CL is essentially one half of the lower limit of detection for the particular analysis. With actual values then available for all samples, it is possible to compare, for example, averages, standard deviations, and ranges between data sets from two different locations. A process that uses this concept for the data in Table B-1 would result in a prediction about halfway between the two previous extremes is calculated:

| | |
|---|---|
| Ten Confidence Limit values, 4.7 mrem each | 47 mrem |
| Two positive values, 12 and 15 mrem each | 27 mrem |
| **Yearly dose** | **74 mrem** |

**Advantages and Disadvantages of Longer Badge Cycles.** Clearly, conversion to quarterly badges would have the advantage of increasing the sensitivity, since the badge would integrate over a longer time frame. It should also be noted that the quarterly rotation is less expensive. A quarterly badge that reads 15 mrem would imply an average of five mrem per month. If the hypothetical worker shown in Table 1 had worn three monthly badges instead of twelve monthly badges, the data may have been similar to that in Table B-2.

In Table B-1 is was evident that the tasks and work environment assigned to this worker produced a higher exposure in the months of March and May. This observation is of some value to future planning and evaluation of risk. In Table B-2, there is evidence for more elevated exposures in the first half of 1991 than in the second half of the year, but the resolution of which month has been lost.

**Table B-2. Hypothetical TENORM Worker's Radiation Dose**

| Year | Quarter | TLD Badge | mrem/qtr. |
|---|---|---|---|
| 1991 | Jan, Feb, Mar | 1235001 | 28 |
| 1991 | Apr, May Jun | 1235002 | 29 |
| 1991 | Jul, Aug, Sep | 1235003 | 15 |
| 1991 | Oct, Nov, Dec | 1235004 | 11 |

Consider also the consequence of losing a badge (or a damaged badge) in late May under both scenarios. In Table B-1 the lost "M" is not critical. Losing the second quarter badge data in Table B-2 is more significant. Any loss of a badge is of concern where the potential for even higher doses exists. The probability of an acute event in the phosphate industry is less likely, but should be considered in the management of the schedule of badging. If a more acute event occurs at the beginning of a quarterly badge cycle, there is obviously a loss of time to implement corrective actions. The savings in expense may not be worth the potential loss of data (high or low readings).

**Regulatory Implications.** When the permissible radiation dose (1) to the occupational radiation worker was 5,000 mrem/yr (with administrative controls demanding much less in actual practice), (2) to the industry employee not specified as a radiation worker was 500 mrem/yr, and (3) to the general off-site public was a third less (170 mrem/yr), the arguments in the preceeding pages had much less meaning to the industry. When the exposure limit for a non-radiation worker was reduced to100 mrem/yr, the handling of the "M" values became a more important consideration. At the same time, the TEDE concept was also introduced. In its simplest form, both the external dose (normally the deep dose result from the TLD badge and a calculation of any internal dose from inhalation and ingestion) must be added to obtain the TEDE.

The internal dose by ingestion or inhalation will be ignored during the following discussions, but will be addressed in detail in other portions of this report. Referring back to the four methods outlined for handling the annual data to the hypothetical worker in Table B-1, there are four different outcomes:

| | |
|---|---|
| NRC Surveillance Analogy | 162 mrem/yr |
| Direct Use of the LLD | 121 mrem/yr |
| Assignment of Zero for <LLDs | 27 mrem/yr |
| Confidence Limit Approach | 74 mrem/yr |

Two of the three cases would place this worker out of the non-radiation worker's category if the limit were the 100 mrem/yr. The Confidence Limit Approach is in the center of the hypothetical annual doses of the set and would allow 26 mrem/yr of internal dose to be added before a TEDE of 100 mrem/yr would be exceeded. None of the scenarios have a satisfactory statistical basis and thus are not scientifically correct. An alternative interpretation is required. One suggestion was to seek advice from the vendor.

**Treatment of the "M" Values by the TLD Vendor.** The chief scientist (personal communication, Zelac, 1997) at Landauer suggested that the history of the positive readings for a site indicates something about the value to assign an "M" in any statistical summary of the site data. If, for example, any 11, 13, 14, 15, etc., values intermixed with a larger array of "M" values, then each "M" could be assigned an upper value of about eight or nine mrem in an accumulative total or statistical summary. However, if a site or set rarely reports any positive values, then an "M" should be assigned a more modest value of about 4, 4.5 or 5.

Dr. Zelac did not think that assigning a zero to "M" in any set is correct. The true baseline for the workers in an industry with a TENORM component should be a similar facility processing the same raw materials with a very low TENORM content. This, of course, is not possible, but indicates that the control badges are likely in an environment elevated somewhat by TENORM. That is, even the control level of a working site with a TENORM component may be greater than the background exposure level at the site prior to the processing activities, there should be a small inherent, non-zero, occupational exposure. With all the aforementioned difficulties and uncertainties in mind, methods were researched to assign more scientifically both an expected mean and a statistical characteristic to the "M" values observed in the historical data gathered in the badging studies of the phosphate industry.

**Actual Historical Phosphate TLD Badging Data Sets.** One phosphate company considered in this study had historical records for both monthly and quarterly badging results. Although these two sets of data were for different time periods that did not overlap, they were for the same general worker's population, the same plant and likely for the same environmental and occupational conditions. From 1979 to 1983, more than 31,200 monthly TLD results were reported. For this set of data, only 17% of the results were above the vendor's reporting limits, that is, 83% of readings were "M" values. From 1994 to 1996, 85 quarterly TLD results were reported. For this set of data, 54 percent of the results were above the vendor's reporting limits, (46% were "M" values). These two data sets provide an opportunity to use a scientific method to obtain a more valid estimate of the statistical characteristics of the missing data. A professional statistician advised directing the investigation to literature concerned with "censored data" (personal communication with Carter, 1997).

**Application of Censored Data Statistics.** The first step in the investigation is to hypothesize the type of statistical distribution expected from the data. Consider again the hypothetical monthly TLD data set from Table B-1. For the purpose of graphical presentation, the hypothetical worker's data in Table B-1 is plotted in Figure B-1 as non-scaled bar chart. The "M" values are shown, but this presentation is not extremely helpful in the comparison of another worker or a second year of the same worker. It does not assist in understanding the task exposures in a survey.

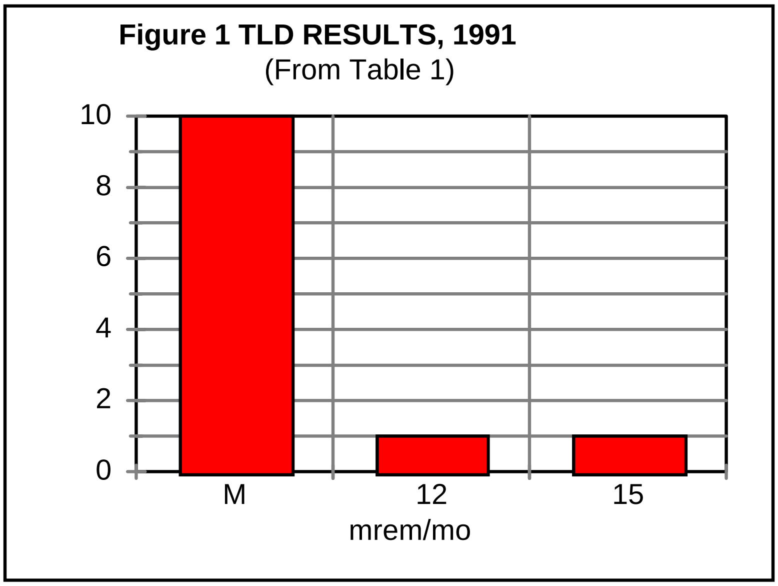


**Figure B-1. Hypothetical TLD Results**

Figure B-2 is the same data using the CL assumption for the "M" values. This allows the abscissa to be scaled and suggests more about the potential distribution of the data set. Again, it is not too helpful in the larger investigations when there is a need to compare data sets.

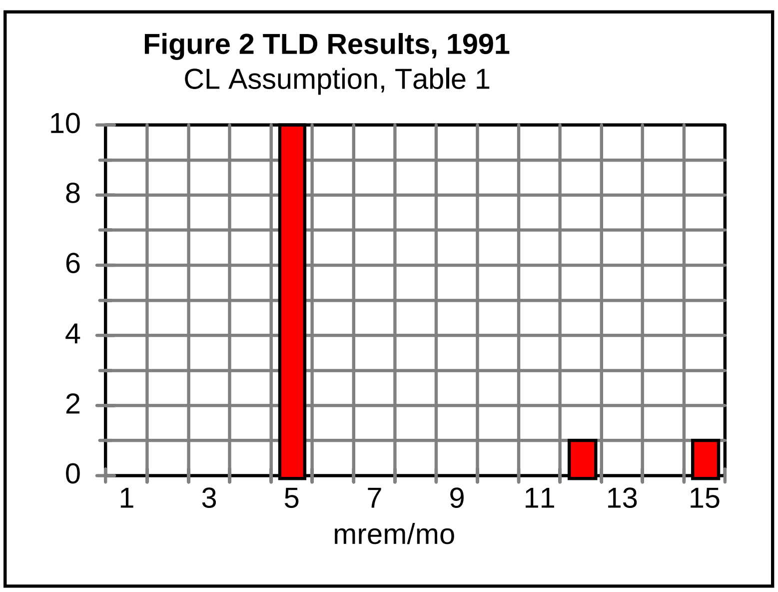


**Figure B-2. TLD Results with CL Assumption**

Many data sets are assumed to be normal distributions. Averages and standard deviations are calculated and used to compare to other data sets or to use in larger aggregates of data. This is often not a valid assumption for environmental data, especially those where there is a limit of zero and negative values are basically incorrect or mistakes. The next two figures attempt to demonstrate the type of distribution to be chosen for the data sets containing a large percent of "M" values.

Figure 3 uses the Table B-1 data and the CL assumption. An average (6.2 mrem/month) and a standard deviation (3.3 mrem/month) was calculated for the set. The raw data is plotted using the large crosshatched rectangle: ten values at 4.7 mrem/month and the two positive values at 12 and 15 mrem/month. Overlain on Figure B-3 is the normal distribution with the same mean and standard deviation. There are some problems evident with choosing the normal distribution. The first is the number of theoretical values close to zero or actually negative. This characteristic has been previously discussed.

The second problem with the normal distribution assumption for Figure B-3 is that the shape does not appear to fit well with the two positive values. In fact, the 15 mrem/month is one basic reason for the average to be so high (6.2 mrem/month) in comparison to the ten values at the assumed CL value of 4.7 mrem/month. The shape and area above the "M" value of 9.4 mrem/month can also be roughly analyzed. The area under the curve in Figure 3 above 9.4 mrem/month is about 13%. The two positive values in the set of twelve account for 17%. The distribution skews the average high, but does not fit the higher positive numbers as a mathematical model. This phenomenon becomes more evident with even more positive results in a set.

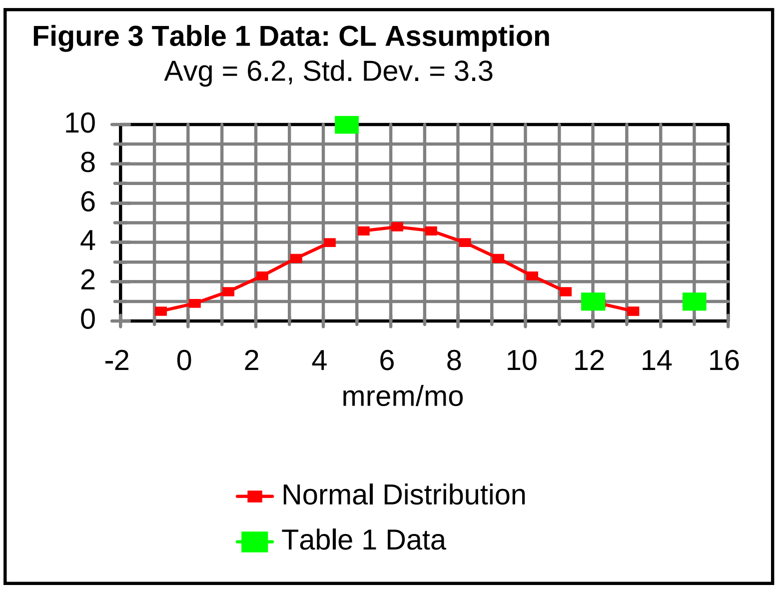


**Figure B-3. TLD Results with Overlain Normal Distribution**

**Lognormal Distributions.** Many environmental data sets are considered to be lognormal. This is true for the very low value data sets at or near the limit of detection. It is also true of many data sets with larger values. It is a basic premise of why log values are used to describe pHs, earthquakes, noise levels, etc. The geometric mean of such a set is the nth root of the product of all values in the set. This is more difficult to accomplish by hand calculator or even on a computer spread sheet. More direct, is that the natural log of the data set is normally distributed. This type of distribution is characterized by a geometric mean and a geometric standard deviation. The Table B-1 values with a CL assumption would be analyzed as in Table B-3.

**Table B-3. Hypothetical NORM Worker's Radiation Dose**

| **Calculation of Geometric Mean and Geometric Standard Deviation with CLs for "M" Values** | | | | |
|---|---|---|---|---|
| **Year** | **TLD Badge** | **mrem/ month** | **Value** | **Ln (value)** |
| 1991 | 1234001 | M | 4.7 | 1.5476 |
| 1991 | 1234002 | M | 4.7 | 1.5476 |
| 1991 | 1234003 | 12 | 12 | 2.4849 |
| 1991 | 1234004 | M | 4.7 | 1.5476 |
| 1991 | 1234005 | M | 4.7 | 1.5476 |
| 1991 | 1234006 | 15 | 15 | 2.7080 |
| 1991 | 1234007 | M | 4.7 | 1.5476 |
| 1991 | 1234008 | M | 4.7 | 1.5476 |
| 1991 | 1234009 | M | 4.7 | 1.5476 |
| 1991 | 1234010 | M | 4.7 | 1.5476 |
| 1991 | 1234011 | M | 4.7 | 1.5476 |
| 1991 | 1234012 | M | 4.7 | 1.5476 |
| Mean Ln value = 1.7224 | | | | |
| Standard Deviation = 0.3936 | | | | |
| Exponent of Mean = **Geo. Mean = 5.6 mrem/month** | | | | |
| Exponent of Std. Dev. = Geo.Std. Dev. = 1.48 * or / | | | | |

Note: Geometric standard deviations are factors to multiply or divide the geometric mean by to note the locations of one standard deviation in the data set.

Figure B-4 is similar to Figure B-3 except now the overlay is a lognormal distribution. Note that the geometric mean is closer to the large set of CL values and is not as affected by the two high positive values. However, the shape of the distribution more closely matches the data and especially at the high end where the 12 and 15 mrem/month values are plotted. The match of the percent of the area above the "M" value is also acceptable. The area under the curve above 9.4 mrem/month is approximately 19%. This compares to the 17% (two of 12) of positive values in the Table B-1 data set. More positive and somewhat higher data values may bring this percent even closer in agreement. Also, this distribution falls off drastically below the geometric mean and never will have a zero or negative value. Other data sets with even more positive values will behave similarly. That is, with a larger geometric standard deviation the low end may approach zero, but never passes over into the negative numbers.

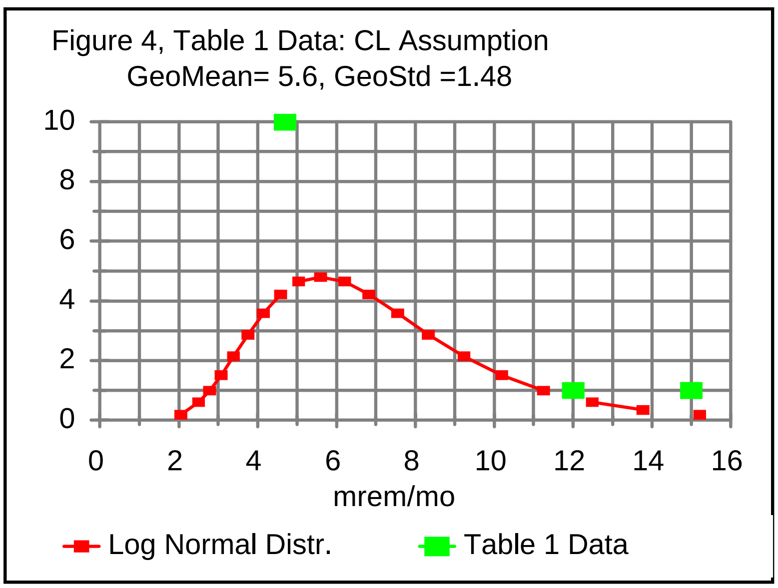


**Figure B-4. TLD Results with Overlain Lognormal Distribution**

The choice of a lognormal distribution for the censored data sets appears logical and scientifically justified. The basic theory of applying censored data statistics to the available data is to attempt to fit those positive data points to the higher tail of the theoretical distribution, much as was done in analyzing the two positive values in Figure B-4. There is, of course, a need for a larger data set in order to be scientifically valid. Therefore, the investigation and discussion that follow returns to the two actual industry data sets previously mentioned. The researchers also located a software tool to assist in fitting the non-censored distributions to a total theoretical distribution, from which geometric means and geometric standard deviations can be obtained. Only the positive data are utilized along with the lognormal function to arrive at a geometric mean without prejudging the value of the "M" or censored value. Once these statistical parameters are available, the data "missing" because of the recorded "M" values can be used in the much wider investigation with confidence.

**Application of Censored Data Statistics to the Industry Badging Data.** The mathematical model is therefore assumed to have a lognormal distribution with an unknown geometric mean (GM) and an unknown geometric standard deviation (GSD). However, since there are two sets of data, and it should be possible to solve for the best analytical fit. The monthly badging set of 31,200 TLD results from one industry is a very useful set to apply the censored data concepts. A lognormal distribution (normalized to a unit area under the curve) must be fit to an area under the curve of 0.17 above 9.4 mrem/month, which corresponds to the 17% of the positive exposures greater than an "M" value. The quarterly set previously mentioned is a smaller set, only 85 values. But it more accurately represents the distribution above its on "M" value.

It is reasonable to assume that the monthly and quarterly sets have the same distribution, just different limits of detection. The quarterly set can be examined from a monthly point of view. An "M" value in the quarterly set is indicative of a censored reading in the monthly set below 3.1 mrem (9.4 mrem per quarter divided by three months per quarter). This set defines the distribution more clearly since only 46% of the data was censored. The geometric mean should be near this defining value of 3.1 mrem/month than to the approaches using a normal distribution. Again, a lognormal distribution (normalized to a unit area under the curve) must have an area under the curve of 0.54 above 3.1 mrem/month effective "M."

There are two ways to solve this hypothesis: direct mathematics and iterative techniques. A straight mathematical approach was tried, but became unwieldy in the integration. The iterative approach using the computer forecasting program Crystal Ball® was found to be simple, direct, and scientifically defensible (Decisioneering, 1996). The software approach is outlined next.

**Crystal Ball as a Censored Data Tool.** The Crystal Ball software package runs under Microsoft Excel. If the equation in Excel is A = 1 x B, then B is the variable Crystal Ball can be instructed to give both a distribution and some statistical characteristics. A lognormal distribution is selected and a trial geometric mean and geometric standard deviation is inserted for the parameter B. When a "Forecast" is selected for A, an output distribution like Figure B-5 is generated. One can then drag the left range marker to the Lower Limit of Detection and Crystal Ball will automatically display the fractional area between this LLD and the right marker, which approaches infinity. If this fraction is the same as the fraction of uncensored data, then the two chosen parameters (GM and GSD) represent one solution for the distribution and parameters that match the data. Trial and error iterations can be attempted for other potential fits. However, the trials converge rather quickly. Either the parameter does not make physical sense or the fraction above the LLD does not match the actual percent of positive data.

**Crystal Ball Trial Fits to the Monthly and Quarterly Data Sets.** The month data set was attempted first. After a several trials, a geometric mean of 3.0 mrem/month and a geometric standard deviation of 3.0 (recall this is a factor to multiply or divide) was shown to have a reasonable shape and fit. When the left range marker was moved to 9.4 mrem/month on the bar graph generated by the one thousand Monte Carlo trials, the area under the curve to the left of the 9.4 LLD was 16%, which closely matched the 17% goal for the non-censored positive results. It should be noted that the bar graphs were not continuous and moving the left range maker did not produce a continuous small step. This trial was considered a success. The 23 outliers represent 23 values of the 1,000 that were above the setting of the right range marker.

By the same process, the quarterly industry data was also analyzed using the same GM (3.0) and same GSD (3.0). The Monte Carlo output for this trial is shown in Figure B-6. Moving the left marker to 3.1 mrem/month, the apparent monthly LLD, the quarterly badges yielded 49.7% above 3.1 mrem/month, which closely matched the goal of 54% of positive non-censored results. Fine tuning of choices for either the GM or the GSD would yield a higher degree of agreement, but the data and the system were not sufficient to yield values statistically significant to more than one digit.

The investigation found that the lognormal distribution is scientifically acceptable. The best fit of the two sets of data obtained by the trial and error fit was a geometric mean of 3.0 mrem/month and a geometric standard deviation of */ 3.0. Thus, in any investigations where there is no other method to interpret “M” values, it is scientifically acceptable to use 3.0 mrem/month for each “M” when the smaller data set is incorporated into a larger one or there is a need to compare one worker-tasks combination to another.

**Another Crystal Ball Solution to Censored Data.** After the above iterative method was applied to the data, another option was discovered in the Crystal Ball menu system. One menu allows the input of two areas of the same set of data which have a known range of values and a known expected area under the lognormal distribution curve. In this menu, Crystal Ball automatically calculated a GM and a GSD that best fit the data. A review of both the industry monthly and industry quarterly sets of data indicated that in both cases no more than 5% of the data were above 20 mrem/month. Thus, there was a second input set: 20 mrem/month to infinity is equal to 5% or 0.05 for a unit area distribution. Crystal Ball was pulsed for a Monte Carlo solution with the previous data set and this additional observation. The yield was the result shown in Table B-4.

**Table B-4. Estimation of Distribution Parameters for Censored TLD Data**

| Trial | Range | Area | Range | Area | Geo. Mean | Geo.Std. |
|---|---|---|---|---|---|---|
| 1 | 9.4 - infinity | 0.17 | 20 - infinity | 0.05 | 2.96 | 3.19 |
| 2 | 3.1 - infinity | 0.54 | 20 - infinity | 0.05 | 3.45 | 2.91 |
| **Average** | | | | | **3.2 mrem** | **3.1** */ |

This independent calculation suggests that the manual iteration process is also valid for estimating of the distribution and its parameters. There is little justification for reporting the results to more than two significant figures; i.e., 3.2 for the GM and 3.1 for the GSD. In many cases, as in the phosphate industry, one significant figure (3) for both may be sufficient. Thus, all four methods yield results that are very close.

A visual representation is valuable. Thus, Figure B-7 is similar to the previous presentations of Table B-1 values with an overlay of a lognormal distribution with the results of the Crystal Ball investigation as the parameters. The science seems to fit nicely. The peak is, of course, at the geometric mean. The distribution drops rapidly below that toward zero and does not go negative. The two single positive values in the hypothetical Table B-1 are at approximately the right location even though the parameters were based on data sets with a larger number of positive values.

A final step was to fill out a table similar to those of the earlier discussions. A calculation of the yearly dose to the worker in Table B-1 would be as follows.

| | |
|---|---|
| Ten censored data values, 3.2 mrem each | 32 mrem |
| Two positive values, 12 and 15 mrem each | 27 mrem |
| **Yearly dose** | **59 mrem** |

This calculation is for the external dose and there is a considerable cushion, 41 mrem, for any internal dose from inhalation or ingestion for this hypothetical worker.

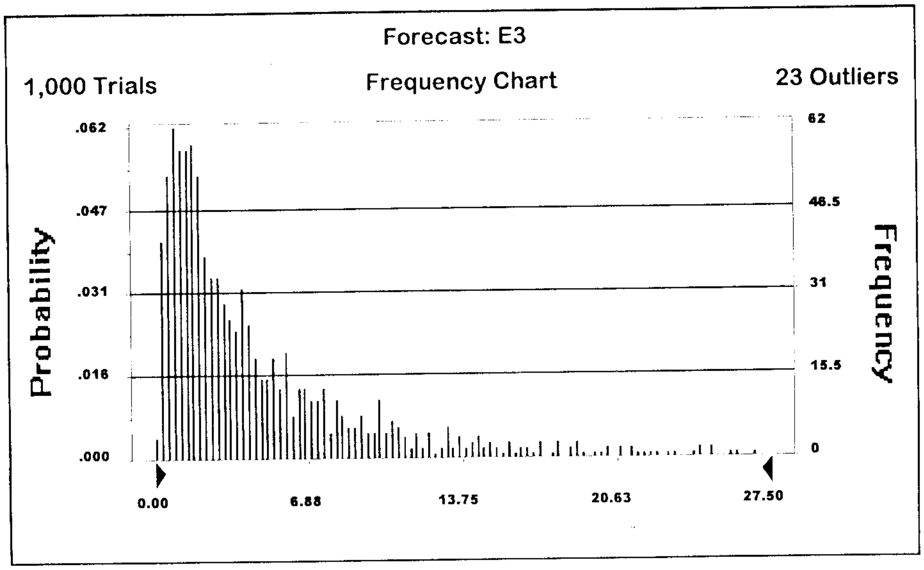


**Figure B-5. Crystal Ball Distribution for Quarterly TLD Data**

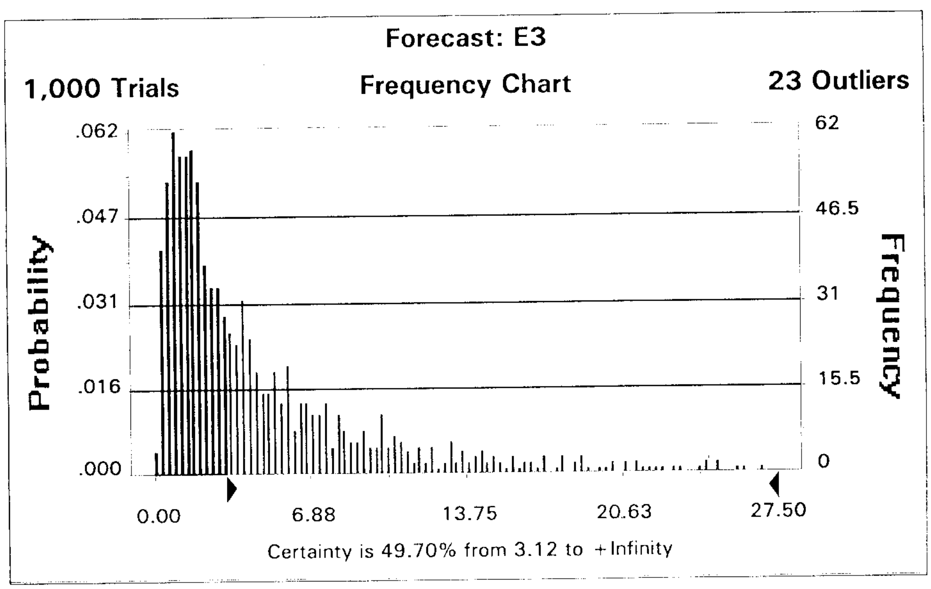


**Figure B-6. Pulsing Crystal Ball Distribution for Quarterly TLD Data**

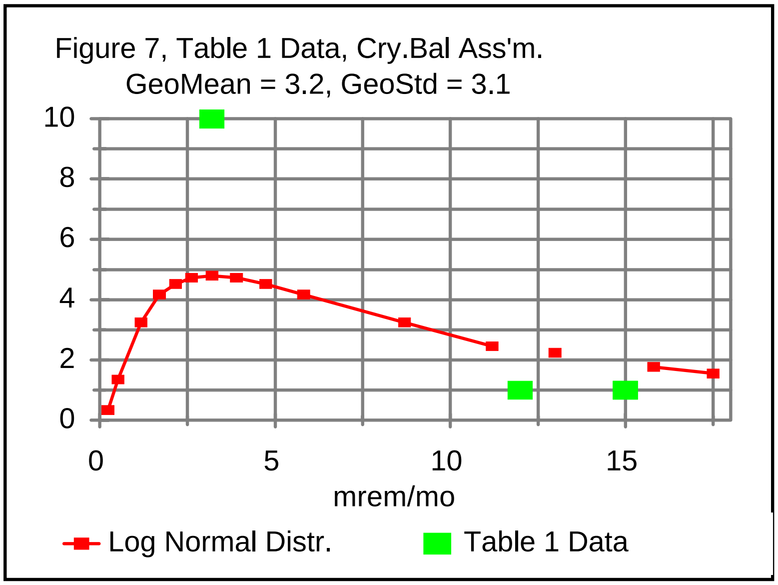


**Figure B-7. Crystal Ball Results with Overlain Lognormal Distribution**

**Conclusions on the Management of "M" Values in TLD Data Sets**

This investigation recommends the use of 3 mrem for any monthly badge that is given an "M" LLD instead of a positive value. The statistical analysis of the previous pages strongly suggests that a "Zero" for an "M" value is not appropriate. Likewise the assignment of the LLD value of 9.4 mrem is equally inappropriate to include as a value in a larger set for averages and comparisons. The 3 mrem/month for badges at the limit of detection also yields some measure of regulatory relief if the TENORM limit were to be set at 100 mrem/yr TEDE.

The choice of a lognormal distribution also makes scientific sense. This study and other investigations should use a lognormal distribution with a GM and a GSD of 3 in uncertainty and sensitivity analysis sections. The sensitivity analysis will demonstrate if this is a critical parameter that requires additional work, or whether another parameter(s) yield(s) more of the error in the final dose. The choices of a more sensitive dosimeter, or assigning a group to wear pairs of badges (monthly and quarterly) is addressed in the Methodology section of the main text. The solution using Crystal Ball software has potential for examining other types of censored data encountered in a variety of industries and especially environmental samples were some of the laboratory data will be at, or below, the detection limit.

## DOSIMETER BADGE CORRECTIONS

Each row corresponds to a single deployed dosimeter. Please refer to Tables B-5 and B-6 for examples from the worksheets.

Column H: the starting date for the badge deployment. The date is encoded to allow direct subtraction from the ending date.

Column I: the ending date for the badge deployment.

Column J: the gross reported dose to the badge in mrem for the entire deployment time.

Column K: the result of the gross absorbed dose minus the site control absorbed dose.

Column L: at times the result in Column K is a negative number (the badge result is lower than the control). It is not reasonable to allow this to remain a negative number; i.e., a dose less than background. A reasonable substitute value can be derived using the reported error (deviation) for this type of dosimeter. The site control value is multiplied by the error and the result is divided by two (since the error can apply in either direction). This must be imbedded in a logical conditional argument. The proper function is the conditional "@IF(Cond, TrueExpr, FalseExpr)." In this expression, "Cond" is the value from Column K to be tested as <0 or ≥0; "TrueExpr" is substitute value to be returned if the condition is true (<0); and "FalseExpr" is the original value in Column K to be returned if the condition is not met (≥0).

Column M: if the test condition in Column L is not met (the test value is ≥0), and the value is less than the substitute value, then the substitute value is returned (higher and more conservative). If the test value is greater than the substitute value, then the test value is returned without change.

Column N: the total number of days the dosimeter is deployed is calculated by subtraction of the numerically coded dates in Columns I and H.

Column O: the net dose in mrem from Column M is divided by the total deployment in days in Column N to yield a dose rate in mrem/day.

Column P: extrapolation to a full year's dose is made by multiplying the dose rate in mrem/day by 365 days/year to yield mrem/year.

Column Q: for aluminum oxide dosimeters the result in Column P is standardized to the industry standard LiF dosimeter by division by 1.22 (to account for the 22% over-response observed in this study).

**Table B-5. Sample External Dose Worksheet**

| H | I | J | K | L | |
|---|---|---|---|---|---|
| X-9 # 1 | | | Subtract Control | First Argument | |
| #1 From | #1 To | X9 # 1 | | | |
| 09/11/97 | 10/10/97 | 22.7 | 7.6 | 7.6 | **3** |
| 09/08/97 | 10/07/97 | 16.8 | 5.4 | 5.4 | **4** |
| 09/11/97 | 10/10/97 | 19.1 | 4.0 | 4.0 | **5** |
| 09/25/97 | 10/24/97 | 15.4 | 3.1 | 3.1 | **6** |
| 09/25/97 | 10/24/97 | 15.0 | 2.7 | 2.7 | **7** |
| 09/25/97 | 11/05/97 | 15.7 | 3.4 | 3.4 | **8** |
| 09/08/97 | 10/07/97 | 13.5 | 2.1 | 2.1 | **9** |
| 09/11/97 | 10/10/97 | 16.9 | 1.8 | 1.8 | **10** |

| M | N | O | P | Q | |
|---|---|---|---|---|---|
| Second Argument | Total days | Rate mrem/day | Annual mrem/yr | TLD Adjust | |
| 7.6 | 29 | 0.262 | 95.655 | 78.41 | **3** |
| 5.4 | 29 | 0.186 | 67.966 | 55.71 | **4** |
| 4.0 | 29 | 0.138 | 50.345 | 41.27 | **5** |
| 3.1 | 29 | 0.107 | 39.017 | 31.98 | **6** |
| 2.7 | 29 | 0.093 | 33.983 | 27.85 | **7** |
| 3.4 | 41 | 0.083 | 30.268 | 24.81 | **8** |
| 2.1 | 29 | 0.072 | 26.431 | 21.66 | **9** |
| 1.8 | 29 | 0.062 | 22.655 | 18.57 | **10** |

The value cells and formula cells entered in the worksheet are displayed in Table B-6 for reference to the verbal explanation for the columns provided (H to Q) and correlation with Table B-5 above. Note that analogous formulas do not necessarily contain the same numerical values due to differences in local background exposure rates from site to site.

**Table B-6. External Dose Worksheet Value Cells and Formula Cells**

| | |
|---|---|
| new Xl sort: H3: | 35684 |
| new Xl sort: I3: | 35713 |
| new Xl sort: J3: | 22.7 |
| new Xl sort: K3: | 7.6 |
| new XI sort: L3: | @IF(K3<01((l5.1*0.09)/2),K3) |
| new Xl sort: M3: | @IF(L3<((l5.1*0.09)/2),((15.1*0.09)/2),L3) |
| new Xl sort: N3: | +I3-H3 |
| new Xl sort: O3: | +M3/N3 |
| new Xl sort: P3: | +O3*365 |
| new Xl sort: Q3: | +P3/1.22 |
| new Xl sort: H4: | 35681 |
| new Xl sort: I4: | 35710 |
| new Xl sort: J4: | 16.8 |
| new Xl sort: K4: | 5.4 |
| new Xl sort: L4: | @IF(K4<0,((l1.4*0.09)/2),K4) |
| new Xl sort: M4: | @IF(L4<((l1.4*0.09)/2),((11.4*0.09)/2),L4) |
| new Xl sort: N4: | +I4-H4 |
| new Xl sort: O4: | +M4/N4 |
| new Xl sort: P4: | +O4*365 |
| new Xl sort: Q4: | +P4/1.22 |

**TIME AND MOTION QUESTIONNAIRES**

**PLANT AREA:**
NAME:_____________________________________________ SEX: (M F)
AGE:_____
**JOB TITLE_______________________________________ SMOKER / NONSM.**
How long have you smoked or not smoked?
How many shifts do you supervise?____ Time of shift(s): _________
What are the job classifications of the people you supervise?

______________________________________________________________________

______________________________________________________________________

How many workers (and what sex) are in each job classification?

______________________________________________________________________

______________________________________________________________________

Which jobs (tasks) are performed by plant workers and which by contractors (and who are they)?

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

Have any of the workers you supervise ever worn a radiation monitoring device? If yes, who are they?

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

How often do your workers change shifts or rotate to different plant areas?

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

What equipment is maintained on site and what is taken off site for repair or cleaning?

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

Is any of the equipment rubber lined?

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

- choose one-quarter in each job classification to be interviewed
- Make sure that the supervisors and workers understand that this is not a job performance review, and nothing they say will affect duties or employment.

**PLANT AREA:**
NAME:_____________________________________________ SEX: (M F)
AGE:_____
**JOB TITLE___________________________________ SMOKER / NONSM.**
If smoker, for how long?

______________________________________________________________

If non-smoker, for how long?

______________________________________________________________

Do you work more than one shift (number)?____ Times:

______________________________________________________________

How many hours per week do you work on average?

______________________________________________________________

Have you ever worn a radiation monitoring device? If yes, when and where?

______________________________________________________________

______________________________________________________________

How often do you rotate to different plant areas?

______________________________________________________________

______________________________________________________________

Describe the duties you perform:

- e.g., on foot, in bobcat, etc.; physical location, physical activity (strenuous, etc.)
- Is the area dusty and is any respiratory protection worn?
- Describe clothing worn (coveralls, gloves, etc.)
- How long does this task usually take?- How often is it done? Hourly, daily, weekly, etc.

______________________________________________________________

______________________________________________________________

______________________________________________________________

______________________________________________________________

______________________________________________________________

______________________________________________________________

______________________________________________________________

______________________________________________________________

______________________________________________________________

______________________________________________________________

**PCHU SAMPLING AND ANALYSIS PROCEDURES**

**HI-VOL SAMPLING PROCEDURES**

SAMPLE COLLECTION

EQUIPMENT USED

1. Collection of samples with F&J, Inc. Hi Vol air sampler, Model HV1S, SN 997
2. Filters used: Whatman 41, 11.0 cm, paper filters

SAMPLING TECHNIQUE

1. Filter loaded into screw-on filter holder.

2. Side of filter facing out is marked with pen to indicate filter side for analysis.

3. Air sampler placed on stable, level surface, 20 inches to 6 feet above floor level.

4. Sampling information recorded on “Air Sample" form as follows:

   - Facility
   - Date
   - Collector
   - Sample number
   - Location
   - Activities in area
   - People in area
   - Weather conditions

5. Air sampler turned on. Record:

   - Time started (to the second)
   - Flow rate (liters per min.)

6. After 4 1/2 minutes, observe and record the final flow rate (lpm).

7. After 5 minutes, turn air sampler off and record the time ended (to the second).

8. Place filter in zip lock baggie permanently marked with sample number.

## ANALYSIS

### EQUIPMENT USED

Tennelec, Inc. Model LB 1000, low background proportional counting system

### ANALYSIS PROCEDURE

1. Cut out a 5 cm. diameter circle from the middle of the 9 cm. diameter sampling area of the filter. (The filter is 11 cm., but the diameter of the air sampler filter housing is 9 cm.)

2. Place the cut-out in a planchet and load in the counting chamber.

3. Acquire a 10 min. count.

4. Record the following on the "Air Sample" form:

   - Date counted
   - Time counted
   - Count time (10 min.)
   - Person performing analysis
   - Gross count (alpha)
   - Gross count (beta)

5. Calculate the alpha activity in air (µCi/ml) using the following equation:

$$\alpha = \frac{\text{Net CPM}}{(2.22)(0.180)(\text{vol})} \times 3.24 \times 1\text{E-}9$$

Where:

| | |
|---|---|
| Net CPM | = Gross counts per min - Background counts per min |
| 2.22 | = Conversion of dpm/pCi |
| 0.180 | = counter efficiency cpm/dpm for alpha activity |
| vol | = volume of air sampled in liters (time sampled X avg. flow rate) |
| 3.24 | = correction for filter area counted: $(4.5\ \text{cm})^2/(2.5\ \text{cm})^2$ |
| 1E-9 | = conversion to ml from liters and µCi from pCi: (1 liter/1000 ml) (1 µCi/1E6 pCi) |

6. Calculate the beta activity in air (µCi/ml) using the following equation:

$$\beta = \frac{\text{Net CPM}}{(2.22)(0.304)(vol)} \times 3.24 \times 1E\text{-}9$$

Where:

0.304 = counter efficiency cpm/dpm for beta activity and all other variables are as described for the alpha in air activity.

**Short Term Electret Ion Chamber Radon Detectors (E-Perms)**

The E-Perm contains a charged electret (an electrostatically-charged disk of Teflon) which collects ions formed in the chamber by radiation emitted from radon and radon decay products. When the device is exposed, radon diffuses into the chamber through filtered openings. Ions which are generated continuously by the decay of radon and radon decay products are drawn to the surface of the electret and reduce its surface voltage. The amount of voltage reduction is related directly to the average radon concentration and the duration of the exposure period.

**Guidelines for Detector Deployment**

Radon detection devices (charcoal canisters or E-Perms) are to be placed within a facility according to the following criteria:

1. In the lowest liveable area of the building (i.e., an inhabited basement, bedroom, living room, family room, or dining room).

2. In an area where it will not be disturbed during the measurement period.

3. Away from drafts caused by heating, ventilating, and A/C vents, doors, fans, and windows.

4. Away from areas of excessive heat, direct sunlight, and high humidity.

5. Not within 3 feet of windows or other openings in the exterior wall and not within 1 foot of any exterior wall.

6. At least 20 inches from the floor and at least 4 inches from other objects. An optimal height for placement is in the general breathing zone, such as 6 to 8 feet from the floor.

7. Not in kitchens, laundry rooms, closets, or bathrooms.

## Measurement Conditions

Short-term measurements should be made under closed-building conditions. All windows, outside vents, and external doors should be closed (except for normal entrance and exit) for 12 hours prior to and during the measurement period. External doors should not be kept open for more than a few minutes.

Internal/external air exchange systems such as high-volume attic and window fans should not be operating during measurements and for at least 12 hours before measurements are initiated. Air conditioning systems that recycle interior air may be operating.

In buildings where permanent radon mitigation systems have been installed, these systems should be functioning during the measurement period.

Tests lasting 2 or 3 days should not be conducted if severe storms with high winds greater than 30 mph or rapidly changing barometric pressure are predicted during the measurement period.

## Preparation of E-Perms

E-Perms with short-term electrets are used by investigators for in-field measurements. Electrets are stored separately from E-Perm devices, each within the counting room closet. On the day needed, electrets are removed from the closet, uncapped, and read on the surface voltage electret reader (after QA has been performed for the reader). The electret reading is recorded in the Short Term Electret Log Book and on the Sample Information Form (For E-Perm Radon Tests). The electret number is also recorded on this form. The electret is then attached to an E-perm, bagged and boxed for transport. The employee performing the infield measurement is responsible for performing the above stated preparation of the E-Perm.

## Short Term Electret Analysis

The E-Perm Analysis log in the radon lab is used for recording analysis data used in the calculation of radon results. Within this log are the E-Perm Analysis forms used for recording data. As an E-Perm arrives in the lab, the following information is recorded on this form:

1. Lab sample number

2. Electret number

3. Location

4. Exposure rate at sample location (μR/hr)

5. Date and time deployed

6. Date and time retrieved

The electret voltage reader is placed on a flat and level surface and zeroed as it is in the daily QA procedures.

The electret is then unscrewed from the E-Perm chamber and placed face down on the electret voltage reader. The lever is pulled all the way back, then gently released. Volts are read out on the display. This procedure is repeated until the reader gives the same volts reading twice in a row. This voltage is recorded as the final voltage on the E-Perm analysis form. The electret is then capped and placed in the appropriate electret storage container in the counting room closet. The E-Perm chamber is bagged and boxed and also stored in this closet. The voltage read from the electret is also recorded in the Short-Term Electret Log. This log is also dated and initialed.

**<u>Short Term Electrets</u>**

Radon results for short term electrets are calculated using the following equation:

$$Rn = [(V_I+V_F)/((((V_I+V_F)/2)(.000638)+1.886)(\# \text{ days}))] - [.09911 - ((V_I+V_F)/2)(.00002914)] [\text{exposure rate}]$$

Where:

| | | |
|---|---|---|
| $V_I$ | = | initial voltage |
| $V_F$ | = | final voltage |
| # days | = | number of sample days (number of days opened) |
| exposure rate | = | exposure rate at sample location in micro-R per hour |

The above calculation may be performed by using the TI-95 calculator program "EBL."

## KUSNETZ METHOD WORKING LEVEL SAMPLING

This sampling method is as described in the Health Physics and Radiation Protection training manual of the Oak Ridge Associated Universities' Professional Training Programs.

SAMPLE COLLECTION

Equipment

SAIC RADECO, Inc. Model H809V- 1, SN 5776, medium volume air sampler (0 - 10 cfm)

0.7 µm membrane filter or Gelman A/E glass fiber filter.

Procedure

1. Complete the following on the "Kusnetz Method Working Level Sampling" form:
   - Facility
   - Date
   - Conditions
   - Location
   - Sample number
2. Load filter onto filter holder of air sampler.
3. Place the air sampler on a level, flat surface, between 20 inches and 6 feet above the floor.
4. Turn on sampler, adjust and record flow rate (cfm) and record time started.
5. At end of 5 minute sample, record ending flow rate and time ended, and turn off pump.
6. Transport sample back to the lab as quickly as possible. Sample must be counted within 90 minutes after sampling.

SAMPLE ANALYSIS

NMC, Model PC-5, gas flow proportional counter

Procedure

1. Record the following on the "Kusnetz Method Working Level Sampling" form:

   - Lab proportional counter used
   - Background cpm for that counter

2. Load filter into a stainless steel planchet and place in counting chamber.

3. Set counter for 10 min. count.

4. Begin 144 sec. purge for counter.

5. When purge ends, record time when count begins.

6. At end of 10 min. count, record gross count.

7. Calculate the volume and use the following equation:

   WL= C / KVE

   Where:

   C = net alpha count rate (gross cpm - bkgd cpm)
   V = volume of air sampled in liters (avg cfm x time sampled x 28.32 l/cf)
   E = counting efficiency (cpm / dpm)
   K = correction factor as supplied on the "Kusnetz Method Working Level Sampling" form

**Table B-7. Kusnetz Correction Factors**

| Time after Sampling | K | Time after Sampling | K |
|---|---|---|---|
| 40 | 150 | 66 | 98 |
| 42 | 146 | 68 | 94 |
| 44 | 142 | 70 | 90 |
| 46 | 138 | 72 | 87 |
| 48 | 134 | 74 | 84 |
| 50 | 130 | 76 | 82 |
| 52 | 126 | 78 | 78 |
| 54 | 122 | 80 | 75 |
| 56 | 118 | 82 | 73 |
| 58 | 114 | 84 | 69 |
| 60 | 110 | 86 | 66 |
| 62 | 106 | 88 | 63 |
| 64 | 102 | 90 | 60 |

# APPENDIX C - SUPPORT MATERIALS FOR THE RESULTS SECTION

## EXTERNAL DOSIMETRY RESULTS

**Table C-1. Personnel Badge Results for the First Deployment**

| G | Job Type | X-9 # 1 | | | Estimated* |
|---|---|---|---|---|---|
| A | Or Area | #1 from | #1 to | mrem | mrem/yr |
| D | Granular operator | 09/11/97 | 10/10/97 | 22.7 | 78.4 |
| D | Maintenance mech west end | 09/08/97 | 10/07/97 | 16.8 | 55.7 |
| D | Granular chief operator | 09/11/97 | 10/10/97 | 19.1 | 41.3 |
| D | DAP mech. | 09/25/97 | 10/24/97 | 15.4 | 32.0 |
| D | DAP mech | 09/25/97 | 10/24/97 | 15.0 | 27.9 |
| D | DAP process operator | 09/25/97 | 11/05/97 | 15.7 | 24.8 |
| D | Maintenance mech y-train | 09/08/97 | 10/07/97 | 13.5 | 21.7 |
| D | Granular chief operator | 09/11/97 | 10/10/97 | 16.9 | 18.6 |
| D | Services/production | 09/09/97 | 10/14/97 | 14.3 | 15.4 |
| D | Tank farm operator | 09/08/97 | 10/07/97 | 12.4 | 10.3 |
| D | Granular operator trainee | 09/09/97 | 10/09/97 | 13.5 | 10.0 |
| D | Granular operator | 09/11/97 | 10/10/97 | 16.0 | 9.3 |
| D | 5&9 mill operator-dry prod. | 09/18/97 | 10/15/97 | 12.7 | 7.8 |
| D | Dry prod.asst.operator | 09/17/97 | 10/15/97 | 13.4 | 6.9 |
| D | Asst operator loading | 09/17/97 | 10/15/97 | 13.0 | 6.9 |
| D | Loading operator | 09/17/97 | 10/15/97 | 14.5 | 6.9 |
| D | Dry prod.utility operator | 09/17/97 | 10/15/97 | 11.9 | 6.9 |
| D | Supervisor #4 DAP | 09/17/97 | 10/15/97 | 13.3 | 6.9 |
| D | GTSP maintenance mech | 09/18/97 | 10/15/97 | 11.6 | 6.0 |
| D | 3&4 MAP mechanic | 09/18/97 | 10/15/97 | 11.8 | 6.0 |
| D | GTSP bobcat & labor | 09/18/97 | 10/15/97 | 11.3 | 6.0 |
| D | 3&4 MAP lead operator | 09/18/97 | 10/15/97 | 11.6 | 6.0 |
| D | AFI operator trainee | 09/09/97 | 10/09/97 | 11.5 | 5.6 |
| D | Car loader | 09/09/97 | 10/09/97 | 11.7 | 5.6 |
| D | Payloader operator | 09/09/97 | 10/09/97 | 12.5 | 5.6 |
| D | Dry side operator X-train | 09/09/97 | 10/07/97 | 11.6 | 5.5 |
| D | Z-train operator | 09/08/97 | 10/07/97 | 10.9 | 5.3 |
| D | Area 4 operator | 09/08/97 | 10/07/97 | 9.8 | 5.3 |
| D | Area 4 board operator | 09/08/97 | 10/07/97 | 11.3 | 5.3 |
| D | AFI operator | 09/09/97 | 10/14/97 | 13.1 | 5.1 |
| H | Shipping payloader | 09/25/97 | 10/31/97 | 24.0 | 97.2 |
| H | Wet rock field operator | 09/18/97 | 10/15/97 | 17.1 | 56.5 |
| H | Loading field operator | 09/18/97 | 10/16/97 | 16.4 | 47.0 |
| H | Wet rock field operator | 09/18/97 | 10/15/97 | 15.3 | 36.6 |
| H | Area 3 maintenance | 09/08/97 | 10/07/97 | 14.9 | 36.1 |

| G | Job Type | X-9 # 1 | | | Estimated* |
|---|---|---|---|---|---|
| A | Or Area | #1 from | #1 to | mrem | mrem/yr |
| H | Supervisor rock/rail | 09/17/97 | 10/15/97 | 17.4 | 32.1 |
| H | Rock conveyor operator | 09/17/97 | 10/15/97 | 16.5 | 22.4 |
| H | Area 3 maintenance | 09/08/97 | 10/07/97 | 13.4 | 20.6 |
| H | Prod load operator | 09/18/97 | 10/15/97 | 13.2 | 13.3 |
| H | Area 3 maintenance | 09/08/97 | 10/07/97 | 12.4 | 10.3 |
| H | Rail field operator | 09/18/97 | 10/15/97 | 12.7 | 7.8 |
| H | Ship process operator | 09/11/97 | 10/10/97 | 15.6 | 7.0 |
| H | Carloader | 09/11/97 | 10/10/97 | 15.4 | 7.0 |
| H | Locomotive operator | 09/17/97 | 10/15/97 | 13.0 | 6.9 |
| H | Mobile equip operator | 09/17/97 | 10/15/97 | 11.8 | 6.9 |
| H | Lead flag man - rail | 09/17/97 | 10/15/97 | 13.8 | 6.9 |
| H | Utility operator-rock/rail | 09/17/97 | 10/15/97 | 14.0 | 6.9 |
| H | Tractor operator Rock | 09/17/97 | 10/16/97 | 13.7 | 6.7 |
| H | Locomotive operator | 09/18/97 | 10/15/97 | 12.6 | 6.6 |
| H | Area 3 maintenance | 09/08/97 | 10/07/97 | 10.9 | 5.3 |
| H | B shipping operator | 09/08/97 | 10/07/97 | 10.4 | 5.3 |
| M | Tractor operator | 09/23/97 | 11/03/97 | 15.7 | 32.1 |
| M | Washer operator | 10/02/97 | 11/07/97 | 15.4 | 31.6 |
| M | Dredge crew (all over) | 09/30/97 | 10/30/97 | 17.1 | 29.9 |
| M | Maintenance super (all over) | 10/02/97 | 10/28/97 | 13.9 | 29.9 |
| M | Float plant operator | 09/23/97 | 10/30/97 | 13.7 | 19.4 |
| M | Float plant operator | 10/02/97 | 10/28/97 | 13.2 | 18.4 |
| M | Rock tractor operator | 09/23/97 | 11/06/97 | 20.6 | 17.7 |
| M | Tractor operator | 10/02/97 | 11/03/97 | 13.1 | 14.0 |
| M | Tractor operator | 09/30/97 | 10/30/97 | 13.4 | 6.3 |
| M | Washer operator | 09/30/97 | 10/30/97 | 14.5 | 6.3 |
| M | Float operator | 09/30/97 | 10/30/97 | 14.0 | 6.3 |
| M | Utility operator (all over) | 09/22/97 | 10/29/97 | 14.1 | 6.1 |
| M | Tailings tractor operator | 09/22/97 | 10/29/97 | 10.1 | 6.1 |
| M | Washer operator | 09/22/97 | 10/29/97 | 13.6 | 6.1 |
| M | Float plant asst. | 09/22/97 | 10/29/97 | 12.3 | 6.1 |
| M | Supervisor (all over) | 10/02/97 | 10/28/97 | 11.6 | 6.0 |
| M | Ship.foreman (all over) | 09/23/97 | 10/28/97 | 12.0 | 6.0 |
| M | Tailings tractor operator | 09/22/97 | 10/29/97 | 13.1 | 4.6 |
| M | Float plant asst. | 09/22/97 | 10/29/97 | 12.4 | 4.6 |
| M | Washer operator | 09/22/97 | 10/29/97 | 12.9 | 4.6 |
| M | Gen tractor operator | 09/22/97 | 11/03/97 | 12.1 | 4.1 |

| G<br>A | Job Type<br>Or Area | X-9 # 1 | | | Estimated*<br>mrem/yr |
|---|---|---|---|---|---|
| | | #1 from | #1 to | mrem | |
| P | Phos acid maintenance | 09/17/97 | 10/24/97 | 25.0 | 102.7 |
| P | Phos acid operator | 09/09/97 | 10/09/97 | 22.6 | 100.7 |
| P | Phos acid labor | 09/09/97 | 10/09/97 | 21.6 | 90.8 |
| P | Phos acid proc. Operator | 09/11/97 | 10/10/97 | 23.5 | 86.7 |
| P | Phos acid operator | 09/25/97 | 10/24/97 | 20.6 | 85.6 |
| P | Tank farm operator | 09/11/97 | 10/10/97 | 23.3 | 84.6 |
| P | Phos acid labor | 09/09/97 | 10/09/97 | 20.3 | 77.8 |
| P | Phos acid maintenance mech | 09/18/97 | 10/15/97 | 18.5 | 72.0 |
| P | Phos acid maintenance mech | 09/17/97 | 10/15/97 | 21.1 | 71.6 |
| P | Phos acid mech | 09/18/97 | 10/15/97 | 18.3 | 69.8 |
| P | Hydroblaster | 09/08/97 | 10/07/97 | 17.4 | 61.9 |
| P | Phos acid maintenance | 09/25/97 | 10/30/97 | 19.5 | 61.5 |
| P | Phos acid maintenance mech | 09/08/97 | 10/07/97 | 17.3 | 60.9 |
| P | Relief operator | 09/18/97 | 10/15/97 | 16.9 | 54.3 |
| P | Phos acid maintenance | 09/25/97 | 10/24/97 | 17.4 | 52.6 |
| P | Production operator | 09/08/97 | 10/07/97 | 16.0 | 47.5 |
| P | Hydroblaster | 09/08/97 | 10/07/97 | 15.9 | 46.4 |
| P | Phos acid maint. super. | 09/25/97 | 10/30/97 | 16.9 | 39.3 |
| P | Phos acid maintenance labor | 09/17/97 | 10/15/97 | 18.0 | 38.5 |
| P | Phos acid relief operator | 09/18/97 | 10/15/97 | 15.2 | 35.5 |
| P | Production operator | 09/08/97 | 10/07/97 | 14.5 | 32.0 |
| P | Phos acid proc. operator | 09/11/97 | 10/10/97 | 18.0 | 29.9 |
| P | Production operator | 09/08/97 | 10/07/97 | 13.5 | 21.7 |
| P | Phos acid field operator | 09/18/97 | 10/15/97 | 13.3 | 14.4 |
| P | Phos acid asst operator | 09/17/97 | 10/27/97 | 16.3 | 14.2 |
| P | Phos acid labor | 09/11/97 | 10/10/97 | 16.4 | 13.4 |
| P | Phos acid proc. operator | 09/11/97 | 10/20/97 | 16.3 | 9.2 |
| P | Phos acid maintenance | 09/09/97 | 10/09/97 | 13.4 | 9.0 |
| P | Phos acid maint. mech. | 09/11/97 | 10/10/97 | 15.6 | 7.0 |
| P | Phos acid maintenance labor | 09/17/97 | 10/15/97 | 14.6 | 6.9 |
| P | Phos acid maintenance mech | 09/17/97 | 10/15/97 | 14.9 | 6.9 |
| P | Phos acid asst operator | 09/17/97 | 10/15/97 | 13.4 | 6.9 |
| R | Rock asst. operator | 09/11/97 | 10/10/97 | 28.8 | 141.3 |
| R | Rock rail car unloader | 09/11/97 | 10/20/97 | 30.1 | 115.1 |
| R | Rock operator | 09/25/97 | 10/24/97 | 20.9 | 88.7 |
| R | Rock chief operator | 09/25/97 | 10/24/97 | 20.0 | 79.4 |
| R | Rock asst. operator | 09/11/97 | 10/10/97 | 21.9 | 70.2 |

| G<br>A | Job Type<br>Or Area | X-9 # 1 | | | Estimated*<br>mrem/yr |
|---|---|---|---|---|---|
| | | #1 from | #1 to | mrem | |
| R | Stacker/reclaimer | 09/09/97 | 10/20/97 | 18.1 | 40.9 |
| R | Rock maintenance | 09/09/97 | 10/09/97 | 15.9 | 33.9 |
| R | Rock labor | 09/09/97 | 10/09/97 | 15.7 | 31.9 |
| R | Rock maintenance | 09/17/97 | 10/24/97 | 14.8 | 20.2 |
| R | Rock maintenance | 09/09/97 | 10/09/97 | 13.8 | 13.0 |
| R | Rock maintenance | 09/12/97 | 10/10/97 | 16.1 | 10.7 |
| R | Rock labor | 09/09/97 | 10/09/97 | 13.5 | 10.0 |
| R | Wet rock operator | 09/08/97 | 10/07/97 | 12.2 | 8.3 |
| R | Ball mill operator | 09/18/97 | 10/15/97 | 12.5 | 6.0 |
| R | Rock operator | 09/09/97 | 10/09/97 | 12.9 | 5.6 |
| R | Rock maintenance | 09/12/97 | 10/20/97 | 14.8 | 5.3 |
| S | Paint yard | 09/15/97 | 10/22/97 | 40.4 | 184.4 |
| S | Consultant | 09/15/97 | 10/22/97 | 26.1 | 50.1 |
| S | Welder | 09/12/97 | 10/14/97 | 17.2 | 48.6 |
| S | Sandblaster | 09/13/97 | 10/14/97 | 18.1 | 35.7 |
| S | Pump tech. | 09/12/97 | 10/14/97 | 16.9 | 23.4 |
| S | Field super. | 09/16/97 | 10/22/97 | 20.2 | 21.6 |
| S | maintenance | 09/15/97 | 10/22/97 | 22.5 | 21.0 |
| S | RSO/estimator | 09/12/97 | 10/14/97 | 16.0 | 15.0 |
| S | Consultant | 09/15/97 | 10/22/97 | 21.7 | 14.6 |
| S | Mechanic-machinist | 09/12/97 | 10/14/97 | 14.7 | 10.3 |
| S | Shop foreman | 09/12/97 | 10/14/97 | 12.8 | 7.5 |
| S | NDT consultant | 09/15/97 | 10/22/97 | 18.6 | 7.2 |
| S | Balance tech. - shop | 09/15/97 | 10/22/97 | 14.7 | 7.2 |
| S | Consultant | 09/15/97 | 10/22/97 | 16.9 | 7.2 |
| S | Consultant | 09/15/97 | 10/23/97 | 15.0 | 7.1 |
| S | NDT dept. Mgr | 09/15/97 | 10/23/97 | 15.6 | 7.1 |
| S | Consultant | 09/15/97 | 10/23/97 | 14.1 | 7.1 |
| S | Field super. | 09/16/97 | 10/22/97 | 17.8 | 6.6 |
| S | Material handling | 09/12/97 | 10/14/97 | 12.7 | 6.5 |
| S | Mechanic | 09/17/97 | 10/22/97 | 14.3 | 6.5 |
| S | Rubber shop | 09/15/97 | 10/22/97 | 12.9 | 6.4 |
| S | Pan shop fabrication | 09/12/97 | 10/14/97 | 14.0 | 6.1 |
| S | Pan shop lead-man | 09/12/97 | 10/14/97 | 12.1 | 6.1 |
| S | Machinist | 09/12/97 | 10/14/97 | 13.1 | 6.1 |
| S | Shipper-receiver | 09/12/97 | 10/14/97 | 12.9 | 5.7 |
| S | Shop supervisor | 09/24/97 | 10/30/97 | 14.4 | 5.4 |

| G<br>A | Job Type<br>Or Area | X-9 # 1 | | | Estimated*<br>mrem/yr |
|---|---|---|---|---|---|
| | | #1 from | #1 to | mrem | |
| S | Machinist | 09/24/97 | 10/30/97 | 13.6 | 5.4 |
| S | Sandblaster | 09/18/97 | 10/30/97 | 14.3 | 5.4 |
| S | Press brake operator | 09/12/97 | 10/14/97 | 10.2 | 5.0 |
| S | Painter | 09/12/97 | 10/14/97 | 11.8 | 5.0 |
| S | Valve tech. | 09/24/97 | 11/03/97 | 14.5 | 4.8 |

* Includes site-specific control corrections, time adjustment and extrapolation, transformation of negative values to reasonable positives, and correction to LiF "standard" based on empirical data.

G/A = General Area
D = Dry Products
H = Shipping
M = Mine
P = Phosphoric Acid
R = Rock
S = Service

**Table C-2. Personnel Badge Results for the Second Deployment**

| G<br>A | Job Type<br>Or Area | X-9 # 2 | | | Estimated*<br>mrem/yr |
|---|---|---|---|---|---|
| | | #2 From | #1 to | mrem | |
| D | Granular chief operator | 10/10/97 | 12/03/97 | 31.6 | 80.89 |
| D | Granular operator | 10/10/97 | 12/03/97 | 24.7 | 42.66 |
| D | Granular chief operator | 10/10/97 | 12/17/97 | 26.6 | 42.24 |
| D | DAP mech. | 10/24/97 | 01/06/98 | 27.7 | 39.62 |
| D | GTSP bobcat & labor | 10/15/97 | 12/19/97 | 24.5 | 35.90 |
| D | Maintenance mech y-train | 10/07/97 | 12/01/97 | 21.2 | 33.73 |
| D | Maintenance mech west end | 10/07/97 | 12/01/97 | 18.1 | 16.86 |
| D | 3&4 MAP lead operator | 10/15/97 | 12/09/97 | 19.3 | 14.14 |
| D | GTSP maintenance mech | 10/15/97 | 12/09/97 | 19.0 | 12.51 |
| D | Dry prod.asst.operator | 10/15/97 | 12/08/97 | 19.4 | 7.20 |
| D | DAP carloader | 10/30/97 | 12/09/97 | 16.2 | 6.02 |
| D | Tank farm operator | 10/07/97 | 12/01/97 | 16.0 | 5.44 |
| D | Supervisor #4 DAP | 10/15/97 | 12/08/97 | 19.0 | 4.99 |
| D | Services/production | 10/14/97 | 12/04/97 | 18.0 | 4.78 |
| D | Asst operator loading | 10/15/97 | 12/08/97 | 15.2 | 4.51 |
| D | Loading operator | 10/15/97 | 12/08/97 | 17.1 | 4.51 |
| D | AFI operator trainee | 10/09/97 | 12/02/97 | 16.9 | 4.51 |
| D | Payloader operator | 10/09/97 | 12/02/97 | 14.7 | 4.51 |
| D | 5&9 mill operator-dry prod. | 10/15/97 | 12/09/97 | 16.0 | 4.09 |
| D | 3&4 MAP mechanic | 10/15/97 | 12/09/97 | 15.2 | 4.09 |
| D | #5 DAP labor | 10/15/97 | 12/09/97 | 15.1 | 4.09 |
| D | Dry prod.utility operator | 10/15/97 | 12/14/97 | 14.1 | 4.06 |
| D | Area 4 operator | 10/07/97 | 12/01/97 | 13.7 | 3.67 |
| D | Z-train operator | 10/07/97 | 12/01/97 | 13.8 | 3.67 |
| D | Area 4 board operator | 10/07/97 | 12/01/97 | 13.5 | 3.67 |
| D | Dry side operator X-train | 10/07/97 | 12/01/97 | 14.2 | 3.67 |
| D | AFI operator | 10/09/97 | 12/16/97 | 12.9 | 3.58 |
| D | Car loader | 10/09/97 | 12/16/97 | 14.9 | 3.58 |
| H | Carloader | 10/10/97 | 12/03/97 | 39.4 | 124.10 |
| H | Rock conveyor operator | 10/15/97 | 12/08/97 | 35.3 | 95.29 |
| H | Supervisor rock/rail | 10/15/97 | 12/08/97 | 24.3 | 34.35 |
| H | Wet rock field operator | 10/15/97 | 12/09/97 | 22.0 | 28.83 |
| H | Area 3 maintenance | 10/07/97 | 12/01/97 | 20.2 | 28.29 |
| H | Area 3 maintenance | 10/07/97 | 12/01/97 | 18.6 | 19.58 |
| H | Locomotive operator | 10/15/97 | 12/09/97 | 19.9 | 17.41 |
| H | Area 3 maintenance | 10/07/97 | 12/01/97 | 17.9 | 15.77 |

| G | Job Type | X-9 # 2 | | | Estimated* |
|---|---|---|---|---|---|
| A | Or Area | #2 From | #1 to | mrem | mrem/yr |
| H | Shipping process operator | 10/27/97 | 12/09/97 | 19.9 | 13.92 |
| H | Ship process operator | 10/10/97 | 12/04/97 | 19.5 | 13.60 |
| H | Tractor operator Rock | 10/16/97 | 12/14/97 | 20.6 | 12.68 |
| H | Wet rock field operator | 10/15/97 | 12/09/97 | 18.9 | 11.97 |
| H | Mobile equip operator | 10/15/97 | 12/08/97 | 17.8 | 4.51 |
| H | Lead flag man - rail | 10/15/97 | 12/08/97 | 18.7 | 4.51 |
| H | Utility operator-rock/rail | 10/15/97 | 12/08/97 | 15.7 | 4.51 |
| H | Locomotive operator | 10/15/97 | 12/12/97 | 18.1 | 4.20 |
| H | Loading field operator | 10/16/97 | 12/09/97 | 15.6 | 4.16 |
| H | Prod load operator | 10/15/97 | 12/09/97 | 17.3 | 4.09 |
| H | Rail field operator | 10/15/97 | 12/09/97 | 17.1 | 4.09 |
| H | B shipping operator | 10/07/97 | 12/01/97 | 13.6 | 3.67 |
| M | Tractor operator | 10/28/97 | 12/03/97 | 22.4 | 51.53 |
| M | Float plant asst. | 10/29/97 | 12/16/97 | 22.7 | 49.86 |
| M | Washer operator | 10/29/97 | 12/15/97 | 20.0 | 33.74 |
| M | Float plant operator | 10/28/97 | 12/04/97 | 19.7 | 33.15 |
| M | Supervisor (all over) | 10/28/97 | 12/04/97 | 17.8 | 17.79 |
| M | Maintenance super (all over) | 10/28/97 | 12/03/97 | 17.6 | 11.63 |
| M | Tractor operator | 11/03/97 | 12/03/97 | 16.6 | 9.97 |
| M | Float plant operator | 10/30/97 | 12/05/97 | 17.3 | 9.14 |
| M | Washer operator | 11/07/97 | 12/04/97 | 16.0 | 7.78 |
| M | Rock tractor operator | 10/28/97 | 12/03/97 | 19.5 | 7.37 |
| M | Rock tunnel operator | 10/28/97 | 12/04/97 | 19.8 | 7.17 |
| M | Utility operator (all over) | 10/29/97 | 12/15/97 | 21.3 | 6.85 |
| M | Float plant asst. | 10/29/97 | 12/15/97 | 18.6 | 6.85 |
| M | Tailings tractor operator | 10/29/97 | 12/15/97 | 22.7 | 6.85 |
| M | Washer operator | 10/29/97 | 12/15/97 | 17.0 | 6.85 |
| M | Ship.foreman (all over) | 10/28/97 | 12/03/97 | 14.7 | 6.06 |
| M | Dredge crew (all over) | 10/31/97 | 12/19/97 | 16.2 | 5.00 |
| M | Washer operator | 10/31/97 | 12/19/97 | 17.8 | 5.00 |
| M | Tractor operator | 10/31/97 | 12/19/97 | 14.5 | 5.00 |
| M | Float operator | 10/31/97 | 12/19/97 | 16.8 | 5.00 |
| M | Tailings tractor operator | 10/29/97 | 12/15/97 | 15.0 | 4.21 |
| M | Gen tractor operator | 10/29/97 | 12/15/97 | 15.1 | 4.21 |
| P | Phos acid proc. operator | 10/20/97 | 12/03/97 | 41.0 | 163.19 |
| P | Relief operator | 10/15/97 | 12/09/97 | 42.2 | 138.71 |
| P | Phos acid proc. Operator | 10/10/97 | 12/03/97 | 36.1 | 105.82 |

| G | Job Type | X-9 # 2 | | | Estimated* |
|---|---|---|---|---|---|
| A | Or Area | #2 From | #1 to | mrem | mrem/yr |
| P | Phos acid operator | 10/09/97 | 12/02/97 | 34.8 | 92.52 |
| P | Phos acid maintenance mech | 10/15/97 | 12/09/97 | 33.5 | 91.39 |
| P | Hydroblaster | 10/07/97 | 12/01/97 | 28.8 | 75.07 |
| P | Phos acid mech | 10/15/97 | 12/09/97 | 30.4 | 74.52 |
| P | Phos acid operator | 10/24/97 | 01/06/98 | 36.0 | 73.18 |
| P | Phos acid maintenance | 10/09/97 | 12/03/97 | 30.9 | 69.63 |
| P | Hydroblaster | 10/07/97 | 12/01/97 | 27.4 | 67.45 |
| P | Phos acid labor | 10/09/97 | 12/02/97 | 29.6 | 63.71 |
| P | Phos acid maintenance mech | 10/07/97 | 12/01/97 | 25.8 | 58.75 |
| P | Phos acid proc. operator | 10/10/97 | 12/03/97 | 27.2 | 56.51 |
| P | Tank farm operator | 10/10/97 | 12/17/97 | 27.1 | 44.44 |
| P | Phos acid maintenance labor | 10/15/97 | 12/08/97 | 25.5 | 41.00 |
| P | Production operator | 10/07/97 | 12/01/97 | 22.5 | 40.80 |
| P | Phos acid relief operator | 10/15/97 | 12/09/97 | 24.2 | 40.80 |
| P | Phos acid labor | 10/09/97 | 12/02/97 | 25.0 | 38.23 |
| P | Phos acid asst operator | 10/27/97 | 12/08/97 | 23.4 | 37.75 |
| P | Phos acid maintenance | 10/24/97 | 01/06/98 | 27.0 | 36.79 |
| P | Production operator | 10/07/97 | 12/01/97 | 21.7 | 36.45 |
| P | Phos acid maintenance mech | 10/15/97 | 12/10/97 | 23.1 | 26.71 |
| P | Phos acid labor | 10/10/97 | 12/03/97 | 21.7 | 26.04 |
| P | Phos acid maintenance mech. | 10/10/97 | 12/17/97 | 22.8 | 25.52 |
| P | Phos acid maintenance super. | 10/30/97 | 12/09/97 | 20.0 | 15.71 |
| P | Phos acid maintenance | 10/24/97 | 02/04/98 | 22.4 | 13.07 |
| P | Production operator | 10/07/97 | 12/01/97 | 17.2 | 11.97 |
| P | Phos acid field operator | 10/15/97 | 12/09/97 | 18.8 | 11.42 |
| P | Phos acid maintenance mech | 10/15/97 | 12/08/97 | 20.0 | 10.53 |
| P | Phos acid maintenance | 10/09/97 | 12/02/97 | 17.8 | 4.51 |
| P | Phos acid asst operator | 10/15/97 | 12/08/97 | 16.0 | 4.51 |
| P | Phos acid maintenance labor | 10/15/97 | 12/14/97 | 17.9 | 4.06 |
| R | Rock rail car unloader | 10/20/97 | 12/03/97 | 36.9 | 135.31 |
| R | Rock asst. operator | 10/10/97 | 12/03/97 | 32.8 | 87.54 |
| R | Rock asst. operator | 10/10/97 | 12/03/97 | 32.7 | 86.98 |
| R | Rock chief operator | 10/24/97 | 01/08/98 | 39.5 | 85.03 |
| R | Ball mill operator | 10/15/97 | 12/09/97 | 30.0 | 72.35 |
| R | Rock operator | 10/24/97 | 01/06/98 | 34.4 | 66.71 |
| R | Stacker/reclaimer | 10/20/97 | 12/04/97 | 21.7 | 23.93 |
| R | Rock prep maintenance | 10/24/97 | 02/04/98 | 25.8 | 22.95 |

| G | Job Type | X-9 # 2 | | | Estimated* |
|---|---|---|---|---|---|
| A | Or Area | #2 From | #1 to | mrem | mrem/yr |
| R | Rock maintenance | 10/09/97 | 12/03/97 | 21.3 | 17.41 |
| R | Wet rock operator | 10/07/97 | 12/01/97 | 17.9 | 15.77 |
| R | Rock maintenance | 10/24/97 | 12/09/97 | 19.4 | 9.76 |
| R | Rock maintenance | 10/10/97 | 12/03/97 | 18.3 | 7.20 |
| R | Rock maintenance | 10/10/97 | 12/03/97 | 18.1 | 6.09 |
| R | Rock labor | 10/09/97 | 12/02/97 | 18.5 | 4.51 |
| R | Rock operator | 10/09/97 | 12/15/97 | 15.2 | 3.64 |
| R | Rock maintenance | 10/09/97 | 12/15/97 | 17.2 | 3.64 |
| S | Paint yard | 10/22/97 | 12/18/97 | 45.3 | 116.52 |
| S | Mechanic-machinist | 10/14/97 | 12/18/97 | 24.7 | 36.36 |
| S | Material handling | 10/14/97 | 01/12/98 | 25.6 | 15.62 |
| S | Sandblaster | 10/22/97 | 12/18/97 | 20.6 | 10.50 |
| S | NDT dept. Mgr | 10/22/97 | 12/18/97 | 28.6 | 6.80 |
| S | Consultant | 10/22/97 | 12/18/97 | 28.3 | 6.80 |
| S | Consultant | 10/22/97 | 12/18/97 | 27.3 | 6.80 |
| S | Consultant | 10/22/97 | 12/18/97 | 27.6 | 6.80 |
| S | Consultant | 10/22/97 | 12/18/97 | 16.8 | 6.80 |
| S | Maintenance | 10/22/97 | 12/18/97 | 28.1 | 6.80 |
| S | Consultant | 10/22/97 | 12/19/97 | 16.6 | 6.69 |
| S | Consultant | 10/22/97 | 12/19/97 | 18.9 | 6.69 |
| S | Balance tech. - shop | 10/22/97 | 12/19/97 | 23.8 | 6.69 |
| S | RSO/estimator | 10/14/97 | 12/18/97 | 20.1 | 5.98 |
| S | Field super. | 10/22/97 | 12/18/97 | 23.9 | 5.46 |
| S | Rubber shop | 10/22/97 | 12/18/97 | 16.7 | 5.46 |
| S | Field super. | 10/22/97 | 12/19/97 | 22.5 | 5.36 |
| S | Valve tech. | 10/30/97 | 12/18/97 | 16.2 | 4.56 |
| S | Machinist | 10/30/97 | 12/18/97 | 15.2 | 4.56 |
| S | Shop supervisor | 10/30/97 | 12/18/97 | 13.2 | 4.56 |
| S | Mechanic | 10/22/97 | 12/18/97 | 15.9 | 4.39 |
| S | Welder | 10/14/97 | 12/18/97 | 17.9 | 4.33 |
| S | Press brake operator | 10/14/97 | 12/18/97 | 14.5 | 4.33 |
| S | Pan shop lead-man | 10/14/97 | 12/18/97 | 18.3 | 3.89 |
| S | Pan shop fabrication | 10/14/97 | 12/18/97 | 17.5 | 3.89 |
| S | Pump tech. | 10/14/97 | 12/18/97 | 18.2 | 3.89 |
| S | Sandblaster | 10/14/97 | 12/18/97 | 14.7 | 3.89 |
| S | Machinist | 10/14/97 | 12/18/97 | 13.8 | 3.89 |
| S | Shipper-receiver | 10/14/97 | 12/18/97 | 16.7 | 3.48 |

* Includes site-specific control corrections, time adjustment and extrapolation, transformation of negative values to reasonable positives, and correction to LiF "standard" based on empirical data.

G/A = General Area
D = Dry Products
H = Shipping
M = Mine
P = Phosphoric Acid
R = Rock
S = Service

Table C-3.  Personnel Badge Results for the Third Deployment

| G<br>A | Job Type<br>Or Area | X-9 # 3 | | | Estimated*<br>mrem/yr |
|---|---|---|---|---|---|
| | | #3 From | #1 to | mrem | |
| D | Supervisor #4 DAP | 12/08/97 | 01/10/98 | 35.3 | 95.2 |
| D | Dry prod.utility operator | 12/08/97 | 01/16/98 | 36.0 | 85.9 |
| D | Granular chief operator | 12/17/97 | 01/22/98 | 29.5 | 54.8 |
| D | DAP mech. | 01/06/98 | 02/04/98 | 26.4 | 51.6 |
| D | DAP carloader | 12/09/97 | 02/04/98 | 25.2 | 19.9 |
| D | DAP mech | 12/09/97 | 02/04/98 | 25.2 | 19.9 |
| D | 5&9 mill operator-dry prod. | 12/09/97 | 03/05/98 | 28.0 | 18.4 |
| D | Granular operator | 12/03/97 | 01/22/98 | 25.9 | 18.0 |
| D | Granular operator | 12/03/97 | 01/22/98 | 24.9 | 12.0 |
| D | Asst operator loading | 12/08/97 | 01/08/98 | 21.2 | 10.8 |
| D | Loading operator | 12/08/97 | 01/08/98 | 22.5 | 10.8 |
| D | Dry prod.asst.operator | 12/08/97 | 01/08/98 | 23.9 | 10.8 |
| D | Z-train operator | 12/01/97 | 12/31/97 | 21.7 | 9.4 |
| D | Maintenance mech west end | 12/01/97 | 12/31/97 | 19.4 | 9.4 |
| D | Tank farm operator | 12/01/97 | 12/31/97 | 20.1 | 9.4 |
| D | Dry side operator X-train | 12/01/97 | 12/31/97 | 21.0 | 9.4 |
| D | Area 4 board operator | 12/01/97 | 12/31/97 | 21.7 | 9.4 |
| D | Maintenance mech y-train | 12/01/97 | 12/31/97 | 21.9 | 9.4 |
| D | Car loader | 12/16/97 | 01/21/98 | 20.1 | 9.1 |
| D | GTSP bobcat & labor | 12/09/97 | 03/05/98 | 25.2 | 8.7 |
| D | AFI operator | 12/16/97 | 03/18/98 | 26.5 | 7.2 |
| D | AFI operator trainee | 12/02/97 | 01/21/98 | 20.8 | 6.5 |
| D | Payloader operator | 12/02/97 | 01/21/98 | 22.1 | 6.5 |
| D | Area 4 operator | 12/01/97 | 01/14/98 | 20.8 | 6.4 |
| D | Services/production | 12/04/97 | 02/04/98 | 22.9 | 5.3 |
| D | 3&4 MAP mechanic | 12/09/97 | 02/19/98 | 20.3 | 4.2 |
| H | Carloader | 01/16/98 | 01/22/98 | 26.5 | 179.5 |
| H | Rock conveyor operator | 12/08/97 | 01/08/98 | 30.7 | 56.9 |
| H | Tractor operator Rock | 12/08/97 | 01/21/98 | 31.6 | 46.2 |
| H | B shipping operator | 12/01/97 | 12/31/97 | 25.2 | 41.9 |
| H | Area 3 maintenance | 12/01/97 | 12/31/97 | 24.4 | 33.9 |
| H | Supervisor rock/rail | 12/08/97 | 01/08/98 | 27.9 | 29.9 |
| H | Shipping payloader | 01/06/98 | 03/18/98 | 27.0 | 23.6 |
| H | Wet rock field operator | 12/09/97 | 03/05/98 | 29.2 | 22.6 |
| H | Shipping process operator | 12/09/97 | 03/18/98 | 28.4 | 21.2 |
| H | Wet rock field operator | 12/09/97 | 03/05/98 | 28.6 | 20.5 |

| G<br>A | Job Type<br>Or Area | X-9 # 3 | | | Estimated*<br>mrem/yr |
|---|---|---|---|---|---|
| | | #3 From | #1 to | mrem | |
| H | Ship process operator | 12/04/97 | 01/22/98 | 26.1 | 19.5 |
| H | Utility operator-rock/rail | 12/08/97 | 01/08/98 | 24.6 | 10.8 |
| H | Mobile equip operator | 12/08/97 | 01/08/98 | 23.9 | 10.8 |
| H | Lead flag man - rail | 12/08/97 | 01/08/98 | 22.9 | 10.8 |
| H | Locomotive operator | 12/08/97 | 01/12/98 | 23.6 | 9.5 |
| H | Area 3 maintenance | 12/01/97 | 12/31/97 | 21.2 | 9.4 |
| H | Area 3 maintenance | 12/01/97 | 12/31/97 | 21.6 | 9.4 |
| H | Area 3 maintenance | 12/01/97 | 01/09/98 | 19.8 | 7.2 |
| H | Locomotive operator | 12/09/97 | 03/05/98 | 23.1 | 3.6 |
| M | Tractor operator | 12/03/97 | 01/07/98 | 45.2 | 186.3 |
| M | Float operator | 12/22/97 | 01/29/98 | 31.6 | 71.6 |
| M | Maintenance super (all over) | 12/03/97 | 01/06/98 | 26.1 | 23.8 |
| M | Rock tractor operator | 12/03/97 | 01/07/98 | 28.5 | 13.7 |
| M | Washer operator | 12/04/97 | 01/06/98 | 26.0 | 10.4 |
| M | Float plant operator | 12/04/97 | 01/06/98 | 24.4 | 10.4 |
| M | Supervisor (all over) | 12/04/97 | 01/06/98 | 22.0 | 10.4 |
| M | Tractor operator | 12/22/97 | 01/29/98 | 23.8 | 10.2 |
| M | Float plant operator | 12/05/97 | 01/06/98 | 21.4 | 9.8 |
| M | Tractor operator | 12/03/97 | 01/08/98 | 24.0 | 9.6 |
| M | Ship.foreman (all over) | 12/03/97 | 01/06/98 | 23.2 | 9.3 |
| M | Washer operator | 12/15/97 | 01/29/98 | 22.0 | 8.6 |
| M | Dredge crew (all over) | 12/22/97 | 01/29/98 | 22.9 | 8.0 |
| M | Washer operator | 12/22/97 | 01/29/98 | 21.1 | 8.0 |
| M | Washer operator | 12/15/97 | 01/29/98 | 21.8 | 7.6 |
| M | Utility operator (all over) | 12/15/97 | 01/29/98 | 24.2 | 7.6 |
| M | Float plant asst. | 12/15/97 | 01/29/98 | 23.1 | 7.6 |
| M | Tailings tractor operator | 12/15/97 | 02/04/98 | 22.3 | 6.7 |
| M | Tailings tractor operator | 12/15/97 | 01/29/98 | 18.7 | 6.2 |
| M | Float plant asst. | 12/15/97 | 01/29/98 | 21.5 | 6.2 |
| M | Gen tractor operator | 12/15/97 | 01/29/98 | 21.2 | 6.2 |
| P | Phos acid maintenance labor | 12/08/97 | 01/09/98 | 43.2 | 172.0 |
| P | Phos acid proc. Operator | 12/03/97 | 01/22/98 | 39.0 | 96.3 |
| P | Phos acid labor | 12/02/97 | 01/21/98 | 37.9 | 81.4 |
| P | Phos acid proc. operator | 12/17/97 | 01/22/98 | 31.9 | 74.8 |
| P | Phos acid labor | 12/02/97 | 01/21/98 | 36.0 | 70.0 |
| P | Phos acid proc. operator | 12/03/97 | 01/22/98 | 33.5 | 63.4 |
| P | Phos acid maintenance mech | 12/08/97 | 01/08/98 | 29.8 | 48.3 |

| G | Job Type | X-9 # 3 | | | Estimated* |
|---|---|---|---|---|---|
| A | Or Area | #3 From | #1 to | mrem | mrem/yr |
| P | Production operator | 12/01/97 | 12/31/97 | 24.9 | 38.9 |
| P | Tank farm operator | 12/17/97 | 02/04/98 | 28.4 | 33.6 |
| P | Phos acid field operator | 12/09/97 | 03/05/98 | 31.3 | 29.9 |
| P | Phos acid operator | 01/06/98 | 02/04/98 | 24.1 | 27.9 |
| P | Hydroblaster | 12/01/97 | 12/31/97 | 23.6 | 25.9 |
| P | Phos acid maintenance | 12/09/97 | 02/04/98 | 26.2 | 25.2 |
| P | Phos acid maintenance mech | 12/08/97 | 01/08/98 | 27.4 | 25.1 |
| P | Phos acid maintenance | 01/06/98 | 02/04/98 | 23.6 | 22.7 |
| P | Production operator | 12/01/97 | 01/22/98 | 24.7 | 21.3 |
| P | Production operator | 12/01/97 | 12/31/97 | 22.8 | 18.0 |
| P | Phos acid maintenance mech | 12/01/97 | 12/31/97 | 22.7 | 17.0 |
| P | Hydroblaster | 12/01/97 | 01/22/98 | 23.7 | 15.5 |
| P | Phos acid maintenance labor | 12/14/97 | 01/12/98 | 23.2 | 11.5 |
| P | Phos acid asst operator | 12/08/97 | 01/08/98 | 22.4 | 10.8 |
| P | Phos acid asst operator | 12/08/97 | 01/08/98 | 22.0 | 10.8 |
| P | Phos acid maintenance mech. | 12/17/97 | 01/22/98 | 23.1 | 8.6 |
| P | Phos acid maintenance | 12/02/97 | 01/21/98 | 24.6 | 6.5 |
| P | Phos acid maintenance super. | 12/09/97 | 02/04/98 | 20.5 | 5.1 |
| R | Rock asst. operator | 12/03/97 | 01/22/98 | 42.9 | 119.7 |
| R | Rock chief operator | 01/08/98 | 02/04/98 | 31.2 | 108.6 |
| R | Rock asst. operator | 12/03/97 | 01/22/98 | 33.8 | 65.2 |
| R | Rock operator | 01/06/98 | 02/04/98 | 24.9 | 36.1 |
| R | Rock maintenance | 12/03/97 | 01/22/98 | 27.8 | 29.3 |
| R | Rock labor | 12/02/97 | 02/04/98 | 28.6 | 20.1 |
| R | Rock labor | 12/02/97 | 01/21/98 | 27.1 | 16.8 |
| R | Wet rock operator | 12/01/97 | 12/31/97 | 21.2 | 9.4 |
| R | Rock maintenance | 12/15/97 | 01/21/98 | 25.3 | 8.8 |
| R | Rock maintenance | 12/03/97 | 01/21/98 | 25.6 | 7.9 |
| R | Rock maintenance | 12/09/97 | 02/04/98 | 22.7 | 6.8 |
| R | Rock operator | 12/15/97 | 02/04/98 | 22.9 | 6.4 |
| R | Rock maintenance | 12/03/97 | 01/22/98 | 22.4 | 6.2 |
| S | Paint yard | 12/18/97 | 02/05/98 | 48.4 | 103.8 |
| S | Material handling | 01/12/98 | 01/28/98 | 21.9 | 19.2 |
| S | Pump tech. | 12/18/97 | 01/28/98 | 25.2 | 19.0 |
| S | Shipper-receiver | 12/18/97 | 01/28/98 | 25.1 | 12.4 |
| S | Consultant | 12/18/97 | 02/27/98 | 33.0 | 11.4 |
| S | Rubber shop | 12/18/97 | 02/05/98 | 21.5 | 8.6 |

| G | Job Type | X-9 # 3 | | | Estimated* |
|---|---|---|---|---|---|
| A | Or Area | #3 From | #1 to | mrem | mrem/yr |
| S | Consultant | 12/18/97 | 02/05/98 | 30.6 | 8.3 |
| S | NDT dept. Mgr | 12/18/97 | 02/05/98 | 22.5 | 8.3 |
| S | Maintenance | 12/18/97 | 02/05/98 | 30.8 | 8.3 |
| S | Consultant | 12/18/97 | 02/05/98 | 30.7 | 8.3 |
| S | Sandblaster | 12/18/97 | 01/28/98 | 23.7 | 8.0 |
| S | Valve tech. | 12/18/97 | 01/28/98 | 24.5 | 7.9 |
| S | Mechanic-machinist | 12/18/97 | 01/28/98 | 22.2 | 7.7 |
| S | Welder | 12/18/97 | 01/28/98 | 23.7 | 7.5 |
| S | Shop foreman | 12/18/97 | 01/28/98 | 21.4 | 7.5 |
| S | Pan shop fabrication | 12/18/97 | 01/28/98 | 22.7 | 7.4 |
| S | Pan shop lead-man | 12/18/97 | 01/28/98 | 22.1 | 7.4 |
| S | Machinist | 12/18/97 | 01/28/98 | 19.0 | 7.4 |
| S | RSO/estimator | 12/18/97 | 01/28/98 | 23.0 | 7.4 |
| S | Shop supervisor | 12/18/97 | 02/05/98 | 19.3 | 6.6 |
| S | Machinist | 12/18/97 | 02/05/98 | 21.8 | 6.6 |
| S | Sandblaster | 12/18/97 | 02/05/98 | 25.0 | 6.6 |
| S | Mechanic | 12/18/97 | 02/05/98 | 21.4 | 6.6 |
| S | Press brake operator | 12/18/97 | 02/05/98 | 20.3 | 6.3 |
| S | Field super. | 12/19/97 | 02/27/98 | 24.7 | 6.0 |
| S | Balance tech. - shop | 12/19/97 | 02/27/98 | 28.0 | 5.8 |
| S | Consultant | 12/19/97 | 02/27/98 | 27.4 | 5.8 |
| S | Consultant | 12/19/97 | 02/27/98 | 31.3 | 5.8 |
| S | Consultant | 12/18/97 | 02/27/98 | 28.1 | 5.7 |

* Includes site-specific control corrections, time adjustment and extrapolation, transformation of negative values to reasonable positives, and correction to LiF "standard" based on empirical data.

G/A = General Area
D = Dry Products
H = Shipping
M = Mine
P = Phosphoric Acid
R = Rock
S = Service

**Table C-4. Personnel Badge Results for the LiF TLD Deployment**

| G A | Job Type Or Area | TLD # | TLD From | TLD to | TLD mrem | Estimated* mrem/yr |
|---|---|---|---|---|---|---|
| D | DAP carloader | 153 | 10/30/97 | 12/09/97 | 47 | 209.9 |
| D | Granular chief operator | 50 | 09/11/97 | 12/17/97 | 45 | 67.7 |
| D | Granular operator | 49 | 09/11/97 | 12/03/97 | 40 | 57.2 |
| D | DAP mech. | 158 | 09/25/97 | 01/06/98 | 33 | 31.9 |
| D | Maintenance mech y-train | 12 | 09/08/97 | 12/01/97 | 29 | 30.4 |
| D | #5 DAP labor | 74 | 10/15/97 | 12/09/97 | 25 | 19.9 |
| D | Payloader operator | 77 | 09/30/97 | 12/02/97 | 24 | 17.4 |
| D | Dry prod.asst.operator | 190 | 09/17/97 | 12/08/97 | 29 | 13.4 |
| D | 3&4 MAP lead operator | 109 | 09/18/97 | 12/09/97 | 27 | 13.4 |
| D | 5&9 mill operator-dry prod. | 110 | 09/18/97 | 12/09/97 | 26 | 13.4 |
| D | 3&4 MAP mechanic | 129 | 09/18/97 | 12/09/97 | 24 | 13.4 |
| D | Asst operator loading | 54 | 09/17/97 | 12/08/97 | 21 | 13.4 |
| D | GTSP maintenance mech | 120 | 09/18/97 | 12/09/97 | 23 | 13.4 |
| D | Supervisor #4 DAP | 56 | 09/17/97 | 12/08/97 | 24 | 13.4 |
| D | Loading operator | 57 | 09/17/97 | 12/08/97 | 23 | 13.4 |
| D | Dry side operator X-train | 21 | 09/09/97 | 12/01/97 | 22 | 13.2 |
| D | Z-train operator | 9 | 09/08/97 | 12/01/97 | 21 | 13.0 |
| D | Maintenance mech west end | 8 | 09/08/97 | 12/01/97 | 24 | 13.0 |
| D | Area 4 operator | 3 | 09/08/97 | 12/01/97 | 21 | 13.0 |
| D | Area 4 board operator | 14 | 09/08/97 | 12/01/97 | 20 | 13.0 |
| D | AFI operator trainee | 27 | 09/09/97 | 12/02/97 | 21 | 13.0 |
| D | Tank farm operator | 5 | 09/08/97 | 12/01/97 | 25 | 13.0 |
| D | Services/production | 37 | 09/09/97 | 12/04/97 | 22 | 12.7 |
| D | Granular chief operator | 48 | 09/11/97 | 01/06/98 | 31 | 12.5 |
| D | Dry prod.utility operator | 186 | 09/17/97 | 12/14/97 | 22 | 12.4 |
| D | GTSP bobcat & labor | 123 | 09/18/97 | 12/19/97 | 34 | 11.9 |
| D | Car loader | 30 | 09/09/97 | 12/16/97 | 22 | 11.2 |
| D | AFI operator | 32 | 09/09/97 | 12/16/97 | 22 | 11.2 |
| D | DAP process operator | 136 | 09/25/97 | 01/06/98 | 23 | 10.6 |
| H | Supervisor rock/rail | 174 | 09/17/97 | 12/08/97 | 43 | 66.8 |
| H | Rock conveyor operator | 59 | 09/17/97 | 12/08/97 | 41 | 57.9 |
| H | Area 3 maintenance | 13 | 09/08/97 | 12/01/97 | 34 | 52.1 |
| H | Carloader | 165 | 09/11/97 | 01/06/98 | 40 | 40.6 |
| H | Shipping payloader | 161 | 09/25/97 | 02/04/98 | 37 | 35.9 |
| H | Area 3 maintenance | 11 | 09/08/97 | 12/01/97 | 30 | 34.8 |
| H | Area 3 maintenance | 16 | 09/08/97 | 12/01/97 | 29 | 30.4 |

| G<br>A | Job Type<br>Or Area | TLD<br># | TLD<br>From | <br>to | <br>mrem | Estimated*<br>mrem/yr |
|---|---|---|---|---|---|---|
| H | Utility operator-rock/rail | 55 | 09/17/97 | 12/08/97 | 27 | 13.4 |
| H | Wet rock field operator | 124 | 09/18/97 | 12/09/97 | 31 | 13.4 |
| H | Lead flag man - rail | 175 | 09/17/97 | 12/08/97 | 26 | 13.4 |
| H | Prod load operator | 130 | 09/18/97 | 12/09/97 | 29 | 13.4 |
| H | Locomotive operator | 189 | 09/18/97 | 12/09/97 | 26 | 13.4 |
| H | Loading field operator | 131 | 09/18/97 | 12/09/97 | 24 | 13.4 |
| H | Rail field operator | 114 | 09/18/97 | 12/09/97 | 26 | 13.4 |
| H | Wet rock field operator | 116 | 09/18/97 | 12/09/97 | 29 | 13.4 |
| H | Mobile equip operator | 168 | 09/17/97 | 12/08/97 | 21 | 13.4 |
| H | Area 3 maintenance | 10 | 09/08/97 | 12/01/97 | 25 | 13.0 |
| H | Ship process operator | 162 | 09/11/97 | 12/04/97 | 29 | 13.0 |
| H | B shipping operator | 7 | 09/08/97 | 12/01/97 | 20 | 13.0 |
| H | Locomotive operator | 58 | 09/17/97 | 12/12/97 | 27 | 12.7 |
| H | Tractor operator Rock | 187 | 09/17/97 | 12/14/97 | 30 | 12.4 |
| M | Gen tractor operator | 127 | 09/22/97 | 12/15/97 | 35 | 56.5 |
| M | Rock tunnel operator | 64 | 10/28/97 | 12/04/97 | 31 | 29.6 |
| M | Tractor operator | 132 | 09/23/97 | 11/03/97 | 29 | 26.7 |
| M | Float operator | 155 | 09/30/97 | 12/19/97 | 29 | 22.8 |
| M | Washer operator | 73 | 09/30/97 | 12/19/97 | 28 | 18.3 |
| M | Dredge crew (all over) | 152 | 09/30/97 | 12/19/97 | 28 | 18.3 |
| M | Tractor operator | 105 | 10/02/97 | 12/03/97 | 22 | 17.7 |
| M | Supervisor (all over) | 98 | 10/02/97 | 12/04/97 | 27 | 17.4 |
| M | Float plant operator | 106 | 10/02/97 | 12/04/97 | 28 | 17.4 |
| M | Washer operator | 96 | 10/02/97 | 12/04/97 | 26 | 17.4 |
| M | Maintenance super (all over) | 97 | 09/23/97 | 12/03/97 | 27 | 15.4 |
| M | Rock tractor operator | 134 | 09/23/97 | 12/03/97 | 29 | 15.4 |
| M | Ship.foreman (all over) | 141 | 09/23/97 | 12/03/97 | 28 | 15.4 |
| M | Float plant operator | 138 | 09/23/97 | 12/05/97 | 28 | 15.0 |
| M | Tractor operator | 72 | 09/30/97 | 12/19/97 | 27 | 13.7 |
| M | Float plant asst. | 117 | 09/22/97 | 12/15/97 | 27 | 13.0 |
| M | Utility operator (all over) | 118 | 09/22/97 | 12/15/97 | 27 | 13.0 |
| M | Tailings tractor operator | 122 | 09/22/97 | 12/15/97 | 24 | 13.0 |
| M | Washer operator | 143 | 09/22/97 | 12/15/97 | 26 | 13.0 |
| M | Washer operator | 142 | 09/22/97 | 12/15/97 | 22 | 13.0 |
| M | Float plant asst. | 119 | 09/22/97 | 12/16/97 | 24 | 12.9 |
| M | Tailings tractor operator | 128 | 09/22/97 | 02/04/98 | 22 | 8.1 |
| P | Phos acid labor | 29 | 09/09/97 | 12/02/97 | 42 | 82.6 |

| G A | Job Type Or Area | TLD # | TLD From | to | mrem | Estimated* mrem/yr |
|---|---|---|---|---|---|---|
| P | Phos acid proc. Operator | 44 | 09/11/97 | 12/03/97 | 45 | 79.2 |
| P | Phos acid operator | 25 | 09/09/97 | 12/02/97 | 41 | 78.2 |
| P | Phos acid labor | 26 | 09/09/97 | 12/02/97 | 40 | 73.9 |
| P | Phos acid maintenance mech | 17 | 09/08/97 | 12/01/97 | 36 | 60.8 |
| P | Phos acid maintenance mech | 171 | 09/17/97 | 12/10/97 | 42 | 60.8 |
| P | Phos acid operator | 145 | 09/25/97 | 01/06/98 | 41 | 60.2 |
| P | Phos acid maintenance mech | 125 | 09/18/97 | 12/09/97 | 46 | 57.9 |
| P | Phos acid proc. operator | 42 | 09/11/97 | 12/03/97 | 39 | 52.8 |
| P | Phos acid proc. operator | 52 | 09/11/97 | 12/17/97 | 41 | 52.7 |
| P | Phos acid mech | 108 | 09/18/97 | 12/09/97 | 44 | 49.0 |
| P | Production operator | 1 | 09/08/97 | 12/01/97 | 32 | 43.5 |
| P | Phos acid maintenance labor | 179 | 09/17/97 | 12/08/97 | 37 | 40.1 |
| P | Hydroblaster | 6 | 09/08/97 | 12/01/97 | 31 | 39.1 |
| P | Production operator | 15 | 09/08/97 | 12/01/97 | 30 | 34.8 |
| P | Relief operator | 113 | 09/18/97 | 03/05/98 | 46 | 28.2 |
| P | Phos acid maintenance | 156 | 09/25/97 | 02/04/98 | 34 | 27.7 |
| P | Phos acid labor | 43 | 09/11/97 | 12/03/97 | 32 | 22.0 |
| P | Production operator | 22 | 09/08/97 | 12/01/97 | 27 | 21.7 |
| P | Phos acid maintenance | 163 | 09/17/97 | 01/06/98 | 30 | 19.7 |
| P | Tank farm operator | 53 | 09/11/97 | 12/17/97 | 32 | 18.8 |
| P | Phos acid maintenance super. | 137 | 09/25/97 | 12/09/97 | 26 | 14.6 |
| P | Phos acid asst operator | 172 | 09/17/97 | 12/08/97 | 24 | 13.4 |
| P | Phos acid field operator | 188 | 09/18/97 | 12/09/97 | 29 | 13.4 |
| P | Phos acid relief operator | 115 | 09/18/97 | 12/09/97 | 35 | 13.4 |
| P | Phos acid maintenance mech | 177 | 09/17/97 | 12/08/97 | 30 | 13.4 |
| P | Phos acid maintenance | 47 | 09/10/97 | 12/02/97 | 25 | 13.2 |
| P | Phos acid maintenance labor | 181 | 09/17/97 | 12/14/97 | 28 | 12.4 |
| P | Phos acid maintenance mech. | 39 | 09/11/97 | 12/17/97 | 25 | 11.3 |
| R | Rock asst. operator | 75 | 10/10/97 | 12/03/97 | 46 | 128.4 |
| R | Rock rail car unloader | 45 | 09/11/97 | 12/03/97 | 52 | 109.9 |
| R | Rock asst. operator | 40 | 09/11/97 | 12/03/97 | 46 | 83.6 |
| R | Rock chief operator | 149 | 09/25/97 | 01/08/98 | 46 | 76.5 |
| R | Rock operator | 140 | 09/25/97 | 01/06/98 | 38 | 49.6 |
| R | Wet rock operator | 2 | 09/08/97 | 12/01/97 | 32 | 43.5 |
| R | Rock maintenance | 164 | 09/12/97 | 12/03/97 | 36 | 40.1 |
| R | Rock labor | 18 | 09/09/97 | 12/02/97 | 30 | 30.4 |
| R | Rock prep maintenance | 150 | 09/25/97 | 02/04/98 | 34 | 27.7 |

| G<br>A | Job Type<br>Or Area | TLD<br># | TLD<br>From | <br>to | <br>mrem | Estimated*<br>mrem/yr |
|---|---|---|---|---|---|---|
| R | Rock labor | 19 | 09/09/97 | 12/02/97 | 29 | 26.1 |
| R | Rock maintenance | 20 | 09/09/97 | 12/15/97 | 27 | 15.1 |
| R | Rock maintenance | 167 | 09/12/97 | 12/03/97 | 29 | 13.4 |
| R | Rock maintenance | 41 | 09/17/97 | 12/09/97 | 23 | 13.2 |
| R | Rock maintenance | 35 | 09/09/97 | 12/03/97 | 25 | 12.9 |
| R | Rock operator | 33 | 09/09/97 | 12/15/97 | 26 | 11.3 |
| R | Ball mill operator | 112 | 09/18/97 | 03/05/98 | 35 | 6.5 |
| S | Paint yard | 62 | 10/22/97 | 12/18/97 | 55 | 166.5 |
| S | Painter | 182 | 09/12/97 | 10/14/97 | 26 | 34.2 |
| S | NDT dept. Mgr | 69 | 10/22/97 | 12/18/97 | 38 | 32.0 |
| S | Welder | 169 | 09/12/97 | 12/18/97 | 33 | 22.6 |
| S | Rubber shop | 85 | 10/22/97 | 12/18/97 | 25 | 19.2 |
| S | Field super. | 86 | 10/22/97 | 12/18/97 | 25 | 19.2 |
| S | Consultant | 60 | 10/22/97 | 12/18/97 | 32 | 19.2 |
| S | Consultant | 63 | 10/22/97 | 12/18/97 | 32 | 19.2 |
| S | Sandblaster | 68 | 10/22/97 | 12/18/97 | 28 | 19.2 |
| S | Mechanic | 88 | 10/22/97 | 12/18/97 | 24 | 19.2 |
| S | Consultant | 84 | 10/22/97 | 12/18/97 | 34 | 19.2 |
| S | Balance tech. - shop | 71 | 10/22/97 | 12/18/97 | 32 | 19.2 |
| S | Consultant | 87 | 10/22/97 | 12/18/97 | 25 | 19.2 |
| S | Maintenance | 78 | 10/22/97 | 12/18/97 | 32 | 19.2 |
| S | Field super. | 89 | 10/22/97 | 12/19/97 | 27 | 18.9 |
| S | Pan shop lead-man | 83 | 10/14/97 | 12/18/97 | 28 | 16.8 |
| S | Pump tech. | 81 | 10/14/97 | 12/18/97 | 25 | 16.8 |
| S | Machinist | 103 | 10/14/97 | 12/18/97 | 25 | 16.8 |
| S | RSO/estimator | 82 | 10/14/97 | 12/18/97 | 25 | 16.8 |
| S | Sandblaster | 79 | 10/14/97 | 12/18/97 | 25 | 16.8 |
| S | Pan shop fabrication | 80 | 10/14/97 | 12/18/97 | 28 | 16.8 |
| S | Mechanic-machinist | 184 | 09/12/97 | 12/18/97 | 28 | 15.1 |
| S | Shop supervisor | 146 | 09/24/97 | 12/18/97 | 26 | 12.9 |
| S | Valve tech. | 135 | 09/24/97 | 12/18/97 | 25 | 12.9 |
| S | Machinist | 139 | 09/24/97 | 12/18/97 | 22 | 12.9 |
| S | Press brake operator | 170 | 09/12/97 | 12/18/97 | 22 | 11.3 |
| S | Shipper-receiver | 183 | 09/12/97 | 12/18/97 | 26 | 11.3 |
| S | Shop foreman | 173 | 09/12/97 | 12/18/97 | 24 | 11.3 |
| S | Material handling | 185 | 09/12/97 | 01/12/98 | 29 | 9.0 |
| S | Consultant | 65 | 10/22/97 | 02/27/98 | 36 | 8.6 |

| G<br>A | Job Type<br>Or Area | TLD<br># | TLD<br>From | <br>to | <br>mrem | Estimated*<br>mrem/yr |
|---|---|---|---|---|---|---|
| S | Consultant | 66 | 10/22/97 | 02/27/98 | 35 | 8.6 |

* Includes site-specific control corrections, time adjustment and extrapolation, and transformation of negative values to reasonable positives.

G/A = General Area
D = Dry Products
H = Shipping
M = Mine
P = Phosphoric Acid
R = Rock
S = Service

**Table C-5. Personnel Badge Results for a Turnaround**

| Job Type Or Area | X-9 Absorbed Dose | | Corrected Dose (mrem) |
|---|---|---|---|
| | Event | (mrem) | |
| Mach/m/w supervisor | TURN | 18.0 | 0.87 |
| Mach/m/w supervisor | TURN | 24.2 | 0.87 |
| Mach/mech/welder | TURN | 24.7 | 0.90 |
| Mach/mech/welder | TURN | 14.7 | 0.87 |
| Mach/mech/welder | TURN | 19.9 | 0.87 |
| Mach/mech/welder | TURN | 24.9 | 1.07 |
| Mach/mech/welder | TURN | 28.3 | 3.85 |
| Mach/mech/welder | TURN | 24.7 | 0.90 |
| Mach/mech/welder | TURN | 26.2 | 2.13 |
| Hydroblaster | TURN | 10.7 | 0.98 |
| Hydroblaster | TURN | 13.8 | 3.52 |
| Hydroblaster | TURN | 13.2 | 3.03 |
| Hydroblaster | TURN | 10.8 | 1.07 |
| Hydroblaster | TURN | 11.1 | 1.31 |
| Hydroblaster | TURN | 9.0 | 0.35 |
| Hydroblaster | TURN | 10.4 | 0.74 |
| Hydroblaster | TURN | 13.1 | 2.95 |
| Reactor repair | TURN | 16.1 | 1.72 |
| Reactor repair | TURN | 22.2 | 6.72 |
| Reactor repair | TURN | 15.6 | 1.31 |
| Reactor repair | TURN | 14.0 | 0.52 |
| Reactor repair | TURN | 14.9 | 0.74 |
| Reactor repair | TURN | 16.2 | 1.80 |
| Reactor vacuuming | TURN | 14.0 | 1.80 |
| Reactor vacuuming | TURN | 14.4 | 2.13 |
| Reactor vacuuming | TURN | 16.2 | 3.61 |
| Reactor vacuuming | TURN | 13.7 | 1.56 |
| Reactor vacuuming | TURN | 13.9 | 1.72 |
| Reactor vacuuming | TURN | 13.4 | 1.31 |

**PARTICULATES SAMPLING RESULTS**

**Table C-6. Airborne Particulates Sampling Results**

| G<br>A | Plant Area | Activities in Area | Alpha* µCi/ml | Beta* µCi/ml |
|---|---|---|---|---|
| C | Guard Shack | Ambient air at entry to plant, normal traffic | 1E-12 | 1.2E-12 |
| D | Dry product, cage mill | Normal production | 2.8E-12 | 1.3E-12 |
| D | Dry product | Normal production | 1.7E-12 | 2.5E-12 |
| D | Dry product, top level | Normal production | 1.6E-12 | 2.6E-12 |
| D | Dry product, 1st floor | Normal production | 1.5E-12 | 1.2E-12 |
| D | Granular-2nd floor | Normal production (dusty) | 1.2E-12 | 2.2E-12 |
| D | XYZ Granulator | Limited production - this granulator not in operation | 1.1E-12 | 1.2E-12 |
| D | GTSP Production | Normal production | 1E-12 | 1.8E-12 |
| D | GTSP Storage | Normal activities | 1E-12 | 1.2E-12 |
| D | XYZ Work Bench | Limited production | 1E-12 | 1.2E-12 |
| D | XYZ Ground floor | Washing down area - limited operations | 1E-12 | 1.2E-12 |
| D | XYZ Belt | Limited production - this belt not currently in operation | 1E-12 | 1.2E-12 |
| D | Dry products | Maintenance on shaker screens | 1E-12 | 1.2E-12 |
| D | Dry products #4 | Granulator maintenance - Plant down | 1E-12 | 1.2E-12 |
| D | DAP Storage-Reclaimer | Inside reclaimer car - Normal production | 1E-12 | 1.2E-12 |
| D | DAP | | 1.5E-12 | 1.2E-12 |
| D | MAP | | 2.0E-12 | 1.7E-12 |
| D | GTSP | | 4.2E-12 | 4.1E-12 |
| D | DAP Ammonia | | 1E-12 | 1.2E-12 |
| D | DAP Ammonia Belt | | 1.2E-12 | 1.7E-12 |
| D | DAP Storage | | 1E-12 | 1.2E-12 |
| H | Product Shipping | Granular, 2nd level, NE side, norm. prod. | 1.59E-11 | 4.96E-11 |
| H | Product Shipping | GTSP Storage building, steps next to belt, heavy equipment | 1.38E-12 | 1.93E-12 |
| H | Shipping - rail load | Normal activity | 1.1E-12 | 1.2E-12 |
| H | Shipping-Truck loading | Normal loading activities | 1E-12 | 2E-12 |
| H | Product Shipping | Shipping, Truck loader operator, 2nd level, norm. act. | 1E-12 | 1.2E-12 |
| H | Shipping-Rail loading | No loading currently | 1E-12 | 1.5E-12 |

| G<br>A | Plant Area | Activities in Area | Alpha*<br>µCi/ml | Beta*<br>µCi/ml |
|---|---|---|---|---|
| H | Product shipping-truck | Normal activities | 1E-12 | 1.2E-12 |
| H | Product Shipping | Truck loading operator, area above operator, norm. act. | 1E-12 | 1.2E-12 |
| H | Product Shipping | DAP Storage/Shipping Bldg., Reclaimer operating | 1E-12 | 1.24E-12 |
| H | Shipping rail car unload. | No loading currently | 1E-12 | 1.2E-12 |
| H | Shipping - truck load | Currently no activity | 1E-12 | 1.5E-12 |
| M | Washer | Normal operation | 2.2E-12 | 1.2E-12 |
| M | Float plant | Normal production | 2.2E-12 | 1.6E-12 |
| M | Float plant lab | Normal activities | 1.9E-12 | 1.8E-12 |
| M | Ball Mill | Very little activity currently | 1.4E-12 | 1.3E-12 |
| M | Washer | Normal production | 1.1E-12 | 1.2E-12 |
| M | Rail car load out | No loading currently | 1E-12 | 1.2E-12 |
| M | Washer | Normal production | 1E-12 | 1.2E-12 |
| M | Dryer - Tank house | Normal production | 1E-12 | 1.2E-12 |
| M | Dryer 2nd floor | Normal production | 1E-12 | 1.2E-12 |
| M | Float plant | Normal production | 1E-12 | 1.2E-12 |
| M | Float plant | Normal production | 1E-12 | 1.2E-12 |
| M | Washer | Normal production | 1E-12 | 1.2E-12 |
| M | Float plant | Normal production | 1E-12 | 1.2E-12 |
| M | Rock tunnel | Normal activities | 1E-12 | 1.2E-12 |
| M | Washer | Normal production | 1E-12 | 1.2E-12 |
| M | Rail shipping | No load out currently | 1E-12 | 1.2E-12 |
| P | Phos Acid | Filter pan floor, between B&C filters, normal production | 1.97E-12 | 1.2E-12 |
| P | Phos Acid filter area | Normal production | 1.8E-12 | 1.2E-12 |
| P | Phos Acid evaporators | Normal production | 1.6E-12 | 1.2E-12 |
| P | Phos Acid 2nd floor | Above seal tank area - Normal production | 1.3E-12 | 1.2E-12 |
| P | Phos Acid ground floor | Normal production | 1.2E-12 | 1.6E-12 |
| P | Phos Acid B | Ground floor - crossover near evaporators | 1.2E-12 | 1.7E-12 |
| P | Phos Acid B | Filter pan area - normal operation | 1.2E-12 | 1.4E-12 |
| P | Phos Acid | Filter pan floor, between A&B filters, normal production | 1E-12 | 1.59E-12 |
| P | Phos Acid filter pan | Filter cloth change-out activities | 1E-12 | 1.2E-12 |
| P | Phos Acid B | Stairs handrail - normal production | 1E-12 | 1.2E-12 |

| G<br>A | Plant Area | Activities in Area | Alpha*<br>µCi/ml | Beta*<br>µCi/ml |
|---|---|---|---|---|
| P | Phos Acid B | Seal tank area,<br>normal production | 1E-12 | 1.2E-12 |
| P | Phos Acid | E Train 2nd floor, Outside locker room, normal production | 1E-12 | 1.2E-12 |
| P | Phos Acid seal tank | Normal production | 1E-12 | 1.2E-12 |
| P | Phos Acid seal tank | Normal production | 1E-12 | 1.5E-12 |
| P | Phos Acid filter pans | Normal production | 1E-12 | 1.2E-12 |
| P | Phos Acid reactor roof | Normal production | 1E-12 | 1.2E-12 |
| P | Phos Acid | E Train, Filter Pan Floor, between systems, normal production | 1E-12 | 1.2E-12 |
| P | Phos Acid attack tank | Normal production | 1E-12 | 1.2E-12 |
| R | Rock receiving, 3rd floor | Normal production | 2.3E-11 | 1.5E-11 |
| R | Rock 3rd floor | Normal production | 3E-12 | 1.2E-12 |
| R | Rock ball mill | Normal production | 2E-12 | 1.9E-12 |
| R | Rock loading | Rock 2nd level, top ball mill level, SW, normal production | 1.67E-12 | 1.2E-12 |
| R | Rock tunnel | Normal production | 1.6E-12 | 1.2E-12 |
| R | Ball mill slurry tanks | Normal production | 1.2E-12 | 1.2E-12 |
| R | Rock loading | Rock ball mill area, ground floor, north side, normal production | 1.08E-12 | 1.2E-12 |
| R | Rock ball mill ground floor | Between X-9 locations 92 & 155; Normal production | 1E-12 | 1.4E-12 |
| R | Rock slurry tanks | Normal production | 1E-12 | 1.2E-12 |
| R | Rock-Rail unloading | Car unloading | 1E-12 | 1.6E-12 |
| R | Ball mill | Normal production | 1E-12 | 1.8E-12 |
| R | Ball mill platform | Normal production | 1E-12 | 1.2E-12 |
| R | Rock tunnel | Normal production | 1E-12 | 1.2E-12 |
| R | Rail car unloading | No unloading at this time | 1E-12 | 1.2E-12 |
| R | Rock loading | Rock unloading-Rail Car, normal activities | 1E-12 | 1.2E-12 |
| R | Rail car unloading | No unloading at this time | 1E-12 | 1.2E-12 |
| S | Burn-out area | Pipe rubber liner burn-out; 8 ft. downwind amid smoke | 1.04E-12 | 1.2E-12 |
| S | Burn-out area | Pipe rubber liner burn-out; 4 ft. away where men are; upwind | 1E-12 | 1.2E-12 |
| S | Burn-out area | Pipe rubber liner burn-out; 8 ft. downwind amid smoke | 1E-12 | 1.2E-12 |

| G<br>A | Plant Area | Activities in Area | Alpha*<br>µCi/ml | Beta*<br>µCi/ml |
|---|---|---|---|---|
| S | Burn-out area | Pipe rubber liner burn-out; 10 ft. downwind/crosswind | 1E-12 | 1.2E-12 |
| S | Burn-out area | 100 ft. upwind from pipe burn-out; background sample | 1E-12 | 1.2E-12 |
| Note: alpha LLD = 1.0 E-12 and beta LLD = 1.2 E-12 | | | | |

## SOLID SAMPLE ANALYSIS RESULTS

**Table C-7. Summary of Solid Sample Analyses**

| SOLID SAMPLE ANALYSES | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Sample Numbers | | Gross (per g) | | (pCi/g) | | | |
| | | Alpha | Beta | Ra-226 | U-238 | Th-232 | K-40 |
| Gypsum | 1 | 104 | 67 | 23.83 | 3.38 | 0.54 | 0.43 |
| Gypsum | 2 | 100 | 65 | 20.55 | 6.35 | 0.23 | 1.08 |
| High Grade - Belt | 3 | 233 | 158 | 33.34 | 26.37 | 1.91 | 0.63 |
| GTSP dry | 4 | 260 | 183 | 35.20 | 30.64 | 0.70 | 1.58 |
| High Grade | 5 | 243 | 173 | 31.61 | 29.62 | 1.16 | 2.87 |
| Fines - Baghouse | 6 | 288 | 198 | 21.60 | 57.91 | 0.51 | 1.74 |
| GTSP on Ground | 7 | 328 | 225 | 19.80 | 71.51 | 1.10 | 2.4 |
| GTSP Fines | 8 | 270 | 185 | 16.17 | 59.09 | 0.85 | 2.49 |
| GTSP | 9 | 286 | 195 | 16.39 | 64.13 | 0.47 | 1.96 |
| GTSP Tunnel | 10 | 325 | 223 | 18.55 | 72.85 | 0.75 | 3.51 |
| GTSP | 11 | 131 | 91 | 7.10 | 29.11 | 0.33 | 0.69 |
| MAP Fines | 12 | 241 | 168 | 9.00 | 59.09 | 0.55 | 5.36 |
| MAP Reject | 13 | 237 | 162 | 5.85 | 62.56 | 0.43 | 3.71 |
| Dry Products 2nd Floor | 14 | 202 | 135 | 3.33 | 55.83 | 0.29 | 1.09 |
| MAP Area | 15 | 220 | 147 | 1.79 | 63.56 | 0.26 | 1.41 |
| DAP Pre-Screen | 16 | 181 | 121 | 0.62 | 53.51 | 0.30 | 1.57 |
| DAP Screen Reject | 17 | 190 | 126 | 0.60 | 56.26 | 0.28 | 0.62 |

**RADON SAMPLING RESULTS**

All testing performed with Rad Elec, Inc., Short-term "E-Perms."
Analysis performed with Rad Elec Inc., Electret Voltage Reader, SN D89-RE-139 .

**Table C-8. E-Perm Radon Results**

| | Location | Date Start | Date End | Result pCi/l | Comments |
|---|---|---|---|---|---|
| D | Granular 2nd floor at stairs | 12/03/97 | 12/09/97 | 1.1 | |
| D | Reclaimer - DAP Shipping | 12/02/97 | 12/05/97 | 1.0 | |
| D | DAP #4 Granulator | 12/08/97 | 12/12/97 | 0.5 | |
| D | XYZ; 3rd floor workbench | 12/01/97 | 12/05/97 | < 0.5 | |
| H | B Ship.; Platform over conv. | 12/01/97 | 12/05/97 | 0.7 | |
| M | Rock Tunnel | 12/04/97 | 12/09/97 | 21.5 | |
| M | Float Plant | 12/15/97 | 12/19/97 | 1.6 | Duplicate |
| M | Float Plant (Retest) | 01/09/98 | 01/13/98 | 1.5 | Duplicate |
| M | Rail Car Load-Out | 12/04/97 | 12/09/97 | 1.4 | |
| M | Rock Tunnel | 12/04/97 | 12/09/97 | 1.4 | Duplicate |
| M | Pit Car #14 | 12/15/97 | 12/19/97 | 1.1 | Duplicate |
| M | Float Plant | 12/15/97 | 12/19/97 | 0.8 | |
| M | Pit-Car | 12/04/97 | 12/09/97 | 0.7 | |
| M | Pit Car# 12 | 12/15/97 | 12/19/97 | 0.7 | |
| M | Float Plant Lab | 12/04/97 | 12/09/97 | < 0.5 | |
| M | Pit-Car | 12/04/97 | 12/09/97 | < 0.5 | |
| P | Phos Acid E-Train filter p. area | 12/02/97 | 12/05/97 | 1.7 | E-Perm wet |
| P | Phos Acid Control Room | 12/03/97 | 12/09/97 | 1.4 | Dup. with bag |
| P | Phos Acid Control Room | 12/08/97 | 12/12/97 | 1.4 | Dup. with bag |
| P | Phos Acid B filter pan area | 12/03/97 | 12/09/97 | 0.9 | |
| P | Phos Acid Control Room | 12/09/97 | 12/12/97 | < 0.5 | Dup. with bag |
| P | Phos Acid Control Room | 12/02/97 | 12/05/97 | < 0.5 | Dup. with bag |
| P | Phos Acid Control Room | 12/01/97 | 12/05/97 | < 0.5 | Dup. with bag |
| R | Rock Tunnel | 12/08/97 | 12/12/97 | 40.0 | Duplicate |
| R | Rock Tunnel | 12/02/97 | 12/05/97 | 28.8 | |
| R | Rock Tunnel | 12/09/97 | 12/12/97 | 15.8 | Duplicate |
| R | Rock Tunnel | 12/19/97 | 12/23/97 | 5.8 | Duplicate |
| R | Wet rock unload; QC/Breakr. | 12/02/97 | 12/05/97 | 2.4 | |

Working Level Monitor: EDA Instruments, Inc., Mod. WLM 30, SN A 118.
Kusnetz samples counted on NMC proportional counters, Mod. PC-5.
Kusnetz filters either 0.7 micron membrane or Gelman A/E glass fiber.

**Table C-9. Working Level Measurements in Rock Tunnels**

<table>
<tr><th colspan="6">Kusnetz Sample</th></tr>
<tr><th>Filter Type</th><th>Date</th><th>Time</th><th>Conditions</th><th colspan="2">Result (mWL)</th></tr>
<tr><td>Gelman</td><td>04/07/98</td><td>10:14 AM</td><td>No rock</td><td colspan="2">0.59</td></tr>
<tr><td>0.7 um</td><td>04/07/98</td><td>10:21 AM</td><td>No rock</td><td colspan="2">0.51</td></tr>
<tr><th colspan="6">Working Level Monitor</th></tr>
<tr><th colspan="2">Sample Start</th><th colspan="2">Sample End</th><th colspan="2">Result (mWL)</th></tr>
<tr><td>Date</td><td>Time</td><td>Date</td><td>Time</td><td>Range</td><td>Avg.</td></tr>
<tr><td>04/07/98</td><td>10:27 AM</td><td>04/09/98</td><td>01:27 PM</td><td>1 to 11</td><td>5</td></tr>
<tr><td colspan="4" rowspan="3"></td><td colspan="2">Result (pCi/L)</td></tr>
<tr><td>Range</td><td>Avg.</td></tr>
<tr><td>0.5 to 18</td><td>8.3</td></tr>
<tr><td colspan="6">Note: Conveyor running but no rock emptying in tunnel at time of Kusnetz sampling.</td></tr>
<tr><th colspan="6">Kusnetz Sample</th></tr>
<tr><th>Filter Type</th><th>Date</th><th>Time</th><th>Conditions</th><th colspan="2">Result (mWL)</th></tr>
<tr><td>Gelman</td><td>04/09/98</td><td>01:28 PM</td><td>Rock on line</td><td colspan="2">0.65</td></tr>
<tr><td>0.7 um</td><td>04/09/98</td><td>01:34 PM</td><td>Rock on line</td><td colspan="2">0.94</td></tr>
<tr><td colspan="6">Note: Conveyor operation - Rock emptying onto conveyor - Fan running at tunnel opening</td></tr>
<tr><td colspan="6">Kusnetz samples taken with SAIC Radeco, Mod. H809V-1 Med Vol Sampler, SN 5776</td></tr>
<tr><td colspan="6">Working Level Monitor: EDA Instruments, Inc., Mod. WLM 30, SN A 118.</td></tr>
<tr><td colspan="6">Kusnetz samples counted on NMC proportional counters, Mod. PC-5.</td></tr>
<tr><td colspan="6">Kusnetz filters either 0.7 micron membrane or Gelman A/E glass fiber.</td></tr>
<tr><th colspan="6">Kusnetz Sample</th></tr>
<tr><th>Filter Type</th><th>Date</th><th>Time</th><th>Conditions</th><th colspan="2">Result (mWL)</th></tr>
<tr><td>0.7 um</td><td>04/01/98</td><td>10:59 AM</td><td>No rock</td><td colspan="2">0.51</td></tr>
<tr><td colspan="6">Notes: Conveyor in tunnel not in operation - recently cleaned.</td></tr>
<tr><th colspan="6">Kusnetz Sample</th></tr>
<tr><th>Filter Type</th><th>Date</th><th>Time</th><th>Conditions</th><th colspan="2">Result (mWL)</th></tr>
<tr><td>0.7 um</td><td>04/03/98</td><td>10:26 AM</td><td>No rock</td><td colspan="2">0.39</td></tr>
<tr><td>Gelman</td><td>04/03/98</td><td>10:33 AM</td><td>No rock</td><td colspan="2">0.41</td></tr>
<tr><td colspan="6">Note: Conveyor in rock tunnel remains inactive. No rock on belt in tunnel.</td></tr>
<tr><td colspan="6">Kusnetz samples taken with SAIC Radeco, Mod. H809V-1 Med Vol Sampler, SN 5776</td></tr>
<tr><td colspan="6">Working Level Monitor: EDA Instruments, Inc., Mod. WLM 30, SN A 118.</td></tr>
<tr><td colspan="6">Kusnetz samples counted on NMC proportional counters, Mod. PC-5.</td></tr>
</table>

| Kusnetz filters either 0.7 micron membrane or Gelman A/E glass fiber. | | | | | |
|---|---|---|---|---|---|
| **OFF-SITE BACKGROUND AREA** | | | | | |
| Facility: Polk County Health Dept. Lab (Background) | | | | | |
| Area: Rear lab area | | | | | |
| **Kusnetz Sample** | | | | | |
| **Filter Type** | **Date** | **Time** | **Conditions** | **Result (mWL)** | |
| 0.7 um | 04/06/98 | 10:52 AM | Normal | 0.75 | |
| Gelman | 04/06/98 | 10:59 AM | Normal | 0.73 | |
| **Working Level Monitor** | | | | | |
| **Sample Start** | | **Sample End** | | **Result (mWL)** | |
| Date | Time | Date | Time | Range | Avg. |
| 04/06/98 | 10:44 AM | 04/07/98 | 08:30 AM | 1 to 2 | 1 |
| | | | | Result (pCi/L) | |
| | | | | Range | Avg. |
| | | | | 0.4 to 0.9 | 0.7 |

## TIME/MOTION DESCRIPTIONS

**Table C-10. Condensed Duty Descriptions Followed by Task Durations**

| Job Title | Duty # | Duty Description | Location |
|---|---|---|---|
| **ROCK AREA** | | | |
| Production Supervisor | 1 | communications | office |
| | 2 | inspections | storage |
| | 3 | inspections | open area |
| Ball Mill Chief Operator | 4 | control panel | control room |
| Rock Operator | 5 | sample slurry | open plant |
| | 6 | dust loading | loading area |
| | 7 | cleaning | open plant |
| Rock Services Supervisor | 8 | instruction | office |
| Rock Services Laborer | 9 | clean spillage | open plant |
| | 10 | screen hydroblast | sizers |
| | 11 | dust unloading | hoppers |
| | 12 | rock tunnel spillage | rock tunnels |
| | 13 | shoveling | rock pits |
| | 14 | truck unloading | wet rock tun. |
| Maintenance Supervisor | 15 | supervises mechanics | office |
| Maintenance Mechanic | 16 | repair items, fabrication | shop |
| | 17 | reclaim | stor. reclaimer |
| | 18 | belt work | wet rock tun. |
| | 19 | pipes, hoes | gyp. stack |
| | 20 | ball mill clutch changes | open plant |

| Job Title | Duty # | Work Hrs/yr | | Fraction in Dusty Area |
|---|---|---|---|---|
| | | Minimum | Maximum | |
| **ROCK AREA** | | | | |
| Production Supervisor | 1 | 1925 | 1962.5 | |
| | 2 | 25 | 50 | |
| | 3 | 12.5 | 25 | |
| Ball Mill Chief Operator | 4 | 2800 | 2800 | |
| Rock Operator | 5 | 125 | 125 | |
| | 6 | 500 | 1000 | 1 |
| | 7 | 875 | 2300 | |
| Rock Services Supervisor | 8 | 2000 | 2000 | |
| Rock Services Laborer | 9 | 1400 | 1400 | |
| | 10 | 100 | 300 | |
| | 11 | 100 | 100 | 1 |
| | 12 | 750 | 1000 | |
| | 13 | 250 | 500 | 1 |
| | 14 | 250 | 250 | |
| Maintenance Supervisor | 15 | 2000 | 2000 | |
| Maintenance Mechanic | 16 | 1100 | 1800 | |
| | 17 | 50 | 50 | |
| | 18 | 200 | 400 | |
| | 19 | 0 | 400 | |
| | 20 | 50 | 50 | |

| Job Title | Duty # | Duty Description | Location |
|---|---|---|---|
| **DRY PROD. AREA** | | | |
| AF Production Supervisor | 21 | supervises operators | office |
| AF Process Operator | 22 | inspections, cleaning | open plant |
| | 23 | evaporator cleaning | evaporators |
| | 24 | clean ducts, mills | open plant |
| | | + dryers, coolers | |
| AF Operator Trainee | 25 | blast screens | open plant |
| | 26 | refill cage mills | open plant |
| | 27 | clean up | open plant |
| | 28 | operator training | control room |
| AF Maint. Planner | 29 | scheduling | office |
| AF Maint. Supervisor | 30 | supervises mechanics | office |
| AF Maint. Mechanic | 31 | inspections, repair | open plant |
| | 32 | repair items, fabrication | shop |
| AF Trucker - Services | 33 | drive dump truck, grader | open plant |

| Job Title | Duty # | Work Hrs/yr | | Fraction in Dusty Area |
|---|---|---|---|---|
| | | Minimum | Maximum | |
| **DRY PROD. AREA** | | | | |
| AF Production Supervisor | 21 | 2000 | 2000 | |
| AF Process Operator | 22 | 2182.5 | 2275 | 0.5 |
| | 23 | 17.5 | 17.5 | |
| | 24 | 125 | 200 | 1 |
| AF Operator Trainee | 25 | 125 | 375 | |
| | 26 | 500 | 625 | |
| | 27 | 375 | 375 | |
| | 28 | 750 | 1000 | |
| AF Maint. Planner | 29 | 2000 | 2000 | |
| AF Maint. Supervisor | 30 | 2000 | 2000 | |
| AF Maint. Mechanic | 31 | 1600 | 1750 | 0.25 |
| | 32 | 400 | 450 | |
| AF Trucker - Services | 33 | 2000 | 2000 | 0.2 |

| Job Title | Duty # | Duty Description | Location |
|---|---|---|---|
| **DRY PROD. AREA** | | | |
| Granular Maint. Super. | 34 | supervises mechanics | office |
| Granular Maint. Mech. I | 35 | repair items, fabrication | shop |
| | 36 | retrieve items | open plant |
| Granular Maint. Mech. II | 37 | welding | open plant |
| | 38 | flame cutting | open plant |
| | 39 | replacing belts | open plant |
| | 40 | replacing pumps, motors | open plant |
| | 41 | replacing rubber lined items | open plant |
| Granular Op. Coordinator | 42 | coordinates all areas | office |
| Granular Op. Prod. Super. | 43 | paperwork | office |
| | 44 | oversight touring | open plant |
| Chief Operator | 45 | running process | control room |
| | 46 | sample collection | open plant |
| Reclaim Process Op. | 47 | running process | control room |
| | 48 | operate payloader | open plant |
| Ammonia Operator | 49 | inspect gauges, open valves | open plant |
| Bobcat Operator | 50 | cleaning spills | open plant |
| | 51 | training | control room |
| Operator Trainee | 52 | cleaning spills | open plant |
| | 53 | training | control room |
| MAP Process Operator | 54 | sample collection | open plant |
| | 55 | nozzle change | MAP tower |
| | 56 | inspection | open plant |
| | 57 | running process | control room |
| DAP Process Operator | 58 | running process | control room |
| | 59 | sample collection | open plant |
| | 60 | overseeing granulator | open plant |
| Laborer (Dry Op.) | 61 | shoveling and hammering | open plant |
| Services Supervisor | 62 | super. truckers, laborers | office |
| Tank Farm Operator | 63 | transfer acid, hammer, clean | open plant |
| Wet Op. (Scrubber Man) | 64 | check scrubbers | open plant |
| | 65 | catch samples | open plant |
| | 66 | clean granulator nozzle | open plant |
| | 67 | training | control room |

| Job Title | Duty # | Work Hrs/yr | | Fraction in Dusty Area |
|---|---|---|---|---|
| | | Minimum | Maximum | |
| **DRY PROD. AREA** | | | | |
| Granular Maint. Super. | 34 | 2000 | 2000 | |
| Granular Maint. Mech. I | 35 | 1900 | 1900 | |
| | 36 | 100 | 100 | |
| Granular Maint. Mech. II | 37 | 500 | 500 | |
| | 38 | 250 | 500 | |
| | 39 | 200 | 200 | 1 |
| | 40 | 1000 | 1000 | |
| | 41 | 200 | 200 | |
| Granular Op. Coordinator | 42 | 2000 | 2000 | |
| Granular Op. Prod. Super. | 43 | 1000 | 1000 | |
| | 44 | 1000 | 1000 | |
| Chief Operator | 45 | 1900 | 1900 | |
| | 46 | 100 | 100 | |
| Reclaim Process Op. | 47 | 1850 | 1850 | |
| | 48 | 150 | 150 | 1 |
| Ammonia Operator | 49 | 2000 | 2000 | |
| Bobcat Operator | 50 | 500 | 750 | 1 |
| | 51 | 1650 | 1900 | |
| Operator Trainee | 52 | 500 | 500 | 0.25 |
| | 53 | 1500 | 1500 | |
| MAP Process Operator | 54 | 250 | 350 | |
| | 55 | 250 | 250 | |
| | 56 | 150 | 250 | |
| | 57 | 1350 | 1150 | |
| DAP Process Operator | 58 | 1175 | 2050 | |
| | 59 | 350 | 500 | |
| | 60 | 275 | 350 | |
| Laborer (Dry Op.) | 61 | 2000 | 2500 | 0.75 |
| Services Supervisor | 62 | 2000 | 2000 | |
| Tank Farm Operator | 63 | 2000 | 2250 | |
| Wet Op. (Scrubber Man) | 64 | 100 | 100 | |
| | 65 | 100 | 100 | |
| | 66 | 50 | 325 | |
| | 67 | 1487.5 | 1750 | |

| Job Title | Duty # | Duty Description | Location |
|---|---|---|---|
| **PHOS. ACID AREA** | | | |
| Production Coordinator | 68 | oversees supervisors | office |
| Labor Supervisor | 69 | supervises laborers | filter pans |
| | 70 | supervises laborers | gyp. stack |
| | 71 | supervises laborers | office |
| Product Operator Trainee | 72 | clean filter floors | filter pans |
| | 73 | blast evaporator tubes | evaporators |
| | 74 | sample collection | open plant |
| Maintenance Supervisor | 75 | supervises mechanics | office |
| Maintenance Mechanic | 76 | inspect, repair, evaporators | open plant |
| | 77 | repair items, fabrication | shop |
| | 78 | preventive maint., repair | gyp. stack |
| Maint. Mech. (Clarification) | 79 | clean, repair motors, valves, pumps | acid clar. |
| | 80 | sandblasting | open plant |
| | 81 | forklift and picker operation | open plant |
| Machinist | 82 | repair items, fabrication | shop |
| Machinist Supervisor | 83 | supervises machinists | shop |
| Production Supervisor | 84 | supervises operators | office |
| Production Operator I | 85 | set up evaporators | evaporators |
| | 86 | sample collection | open plant, lab |
| | 87 | running process | control room |
| Production Operator II | 88 | running process | control room |
| | 89 | sample collection | open plant |
| | 90 | patch filter cloths | filter pans |
| | 91 | wash filters | filter pans |
| | 92 | change filter cloths | filter pans |
| | 93 | rod evaporators | evaporators |
| | 94 | hydroblast evaporators | evaporators |
| | 95 | clean fume ducts | open plant |
| Production Laborer | 96 | change filter cloths | filter pans |
| | 97 | air hammer pipes, clean gyp. | open plant |
| | 98 | work on condensers | condensers |
| Utility Super. (Hydroblast) | 99 | supervises operators | office |
| Hydroblaster | 100 | hydroblasting | phos. acid |
| | 101 | hydroblasting | DAP area |

| Job Title | Duty # | Work Hrs/yr | | Fraction in Dusty Area |
|---|---|---|---|---|
| | | Minimum | Maximum | |
| **PHOS. ACID AREA** | | | | |
| Production Coordinator | 68 | 2000 | 2000 | |
| Labor Supervisor | 69 | 400 | 400 | |
| | 70 | 800 | 800 | |
| | 71 | 800 | 1050 | |
| Product Operator Trainee | 72 | 500 | 600 | |
| | 73 | 400 | 400 | |
| | 74 | 1000 | 1100 | |
| Maintenance Supervisor | 75 | 2000 | 2000 | |
| Maintenance Mechanic | 76 | 2000 | 2250 | |
| | 77 | 100 | 125 | |
| | 78 | 100 | 125 | |
| Maint. Mech. (Clarification) | 79 | 1800 | 1800 | |
| | 80 | 100 | 100 | |
| | 81 | 100 | 100 | |
| Machinist | 82 | 2000 | 2000 | |
| Machinist Supervisor | 83 | 2000 | 2000 | |
| Production Supervisor | 84 | 2000 | 2000 | |
| Production Operator I | 85 | 1000 | 1000 | |
| | 86 | 500 | 500 | |
| | 87 | 500 | 500 | |
| Production Operator II | 88 | 925 | 1200 | |
| | 89 | 100 | 100 | |
| | 90 | 75 | 125 | |
| | 91 | 400 | 400 | |
| | 92 | 75 | 75 | |
| | 93 | 100 | 600 | |
| | 94 | 100 | 200 | |
| | 95 | 75 | 75 | |
| Production Laborer | 96 | 300 | 400 | |
| | 97 | 1500 | 1675 | |
| | 98 | 25 | 100 | |
| Utility Super. (Hydroblast) | 99 | 2000 | 2000 | |
| Hydroblaster | 100 | 1900 | 1900 | |
| | 101 | 100 | 100 | 1 |

| Job Title | Duty # | Duty Description | Location |
|---|---|---|---|
| **SHIP./STOR. AREA** | | | |
| Ship. Super. (Dry P.) | 102 | super. operators, rail crew | office |
| Prod. and Ship. Super. | 103 | phone operators and rail crew | office |
| | 104 | in warehouses | warehouses |
| | 105 | checking wells, pH, gates | open plant |
| Chief Operator | 106 | running belt units | control room |
| | 107 | sampling rail cars, check equip. | open plant |
| Reclaim Operator | 108 | load fertilizer rail cars | open plant |
| | 109 | wash rail cars | open plant |
| | 110 | operate front end loader | open plant |
| | 111 | hook-up rail cars | open plant |
| | 112 | cleaning during turnarounds | open plant |
| Payload Operator | 113 | move product | open plant |
| | 114 | cleaning spills in truck loading | open plant |
| Car Loader | 115 | wash rail cars | open plant |
| | 116 | load rail cars | open plant |
| | 117 | beating screens | open plant |
| | 118 | cleaning general area | open plant |
| | 119 | loading trucks | open plant |
| | 120 | shovel in storage on down days | storage |
| Locomotive Engineer | 121 | operating locomotive | cab of loco. |
| | 122 | operate locomotive in dusty areas | cab of loco. |
| Switchman | 123 | switch cars | open plant |
| Granular Services Super. | 124 | supervises laborers | office |
| Laborer | 125 | shoveling, washing, cleaning spills | ship./storage |
| | 126 | shoveling, washing, cleaning spills | DAP area |
| | 127 | shoveling, washing, cleaning spills | GTSP area |
| | 128 | shoveling, washing, cleaning spills | general area |
| AF Services Super. | 129 | supervises laborers | office |
| AF Shipping Super. | 130 | supervises car loaders, operators | office |
| AF Ship. Car Loader/Un. | 131 | load/unload rail cars | open plant |
| | 132 | inspect incoming trucks | open plant |
| | 133 | run bagging machine | open plant |
| | 134 | stack bags | open plant |
| | 135 | wash rail cars | open plant |
| | 136 | unload silica | open plant |
| AF Ship. Payload Op. | 137 | move stored dry product | storage, rail |

| Job Title | Duty # | Work Hrs/yr | | Fraction in Dusty Area |
|---|---|---|---|---|
| | | Minimum | Maximum | |
| **SHIP./STOR. AREA** | | | | |
| Ship. Super. (Dry P.) | 102 | 2000 | 2000 | |
| Prod. and Ship. Super. | 103 | 2000 | 2050 | |
| | 104 | 25 | 50 | 1 |
| | 105 | 25 | 50 | 1 |
| Chief Operator | 106 | 1600 | 1600 | |
| | 107 | 400 | 400 | 1 |
| Reclaim Operator | 108 | 1400 | 1400 | 1 |
| | 109 | 200 | 200 | |
| | 110 | 100 | 200 | |
| | 111 | 200 | 200 | |
| | 112 | 200 | 200 | 1 |
| Payload Operator | 113 | 1400 | 1400 | |
| | 114 | 600 | 600 | 1 |
| Car Loader | 115 | 800 | 800 | |
| | 116 | 800 | 800 | |
| | 117 | 25 | 25 | 1 |
| | 118 | 200 | 200 | |
| | 119 | 150 | 150 | 1 |
| | 120 | 25 | 25 | 1 |
| Locomotive Engineer | 121 | 2375 | 2375 | |
| | 122 | 125 | 125 | 1 |
| Switchman | 123 | 2400 | 2400 | |
| Granular Services Super. | 124 | 2000 | 2000 | |
| Laborer | 125 | 600 | 600 | 1 |
| | 126 | 200 | 200 | 1 |
| | 127 | 200 | 200 | 1 |
| | 128 | 1000 | 1000 | 1 |
| AF Services Super. | 129 | 2000 | 2000 | |
| AF Shipping Super. | 130 | 2000 | 2000 | |
| AF Ship. Car Loader/Un. | 131 | 400 | 800 | 1 |
| | 132 | 200 | 200 | |
| | 133 | 400 | 800 | 1 |
| | 134 | 200 | 200 | |
| | 135 | 150 | 150 | |
| | 136 | 650 | 650 | |
| AF Ship. Payload Op. | 137 | 2000 | 2000 | 1 |

**INTERVIEW RAW RESULTS**
**Phosphate Company #1: Areas Selected and Individuals Interviewed**

**Rock Area (Wet rock and some sulfuric area)**

**Maintenance Supervisor**
Works one shift 40 hrs/wk. Supervises maintenance mechanics who change rollers, pulleys on conveyors; weld - patch chutes, work on back hoes. Generally, items are not caked with materials. There are two supervisors and two crews in the area. One crew has seven workers. The crew also works in the tunnels (vented) about 8 hrs/wk. Occasionally, contractors (a maintenance service company) are hired to change out ball mill liners (alloy steel). The material involved is wet rock with no dust. Some items are taken off site for repair: back hoes go to the manufacturer; back hoe buckets, etc. are repaired locally at a machining service company; and rubber lined pipes are refurbished locally at specialty service company.

**Ball Mill Chief Operator**
Works 56 hrs/wk on average on three shifts with a 7-day rotation (7-3, 3-11, 11-7). Worker operates a panel in the control room running four mills.

**Rock Operator**
Works 56 hrs/wk on average on two shifts with a 7-day rotation. About half that time in dusty areas. Respiratory protection worn occasionally.

1. Worker samples (catches) wet rock slurry samples every two hours.
2. Loads TSP dust into the hopper at a rate of two cars/day. The task takes 4 hrs/day. This is a dusty activity and a dust mask is worn.

**Rock Laborer**
Works 40 hrs/wk in rock and sulfuric, and is currently issued a radiation badge. Mainly performs spill cleaning, with screen cleaning for 2-3 hours once or twice per week. Cleaning involves hydroblasting while wearing dust mask and goggles plus coveralls.

**Rock Services**

**Rock Services Supervisor**
Supervises one shift (7-3:30) of nine male laborers. These workers clean up rock spills, inspect belts, wash equipment (payloaders and bobcats). Outside contractors are used to clean up spills of rock dust with vacuum trucks. All laborers currently wear TLDs. The laborers work 98% in the rock area and 2% in sulfuric. Many pipes are rubber lined and are taken down for cleaning. Rock sifting screens are cleaned about once per week.

**Rock Maintenance Mechanic**
Works 40 hrs/wk. Does not wear a radiation badge. Performs welding and equipment repair.

Only works in dusty areas (dust pit) about one day per year. Works on ball mill clutch changes about 40 hrs/yr. The particular worker interviewed spends about 8 hrs/wk on the gypsum stack.

**Rock Maintenance Mechanic**
Works 40 hrs/wk on average (7:30-4). General duties include replacing gear boxes, conveyor belts, and piping throughout the rock area. The dust pit is the only dusty area (about 8 hrs/yr). Occasionally a dust mask is worn. About 4 hrs/wk are spent in the rock tunnels doing conveyor belt work. Another 8 hrs/wk are spent on the gypsum stack working on back hoes and pipes.

**Rock Services Laborer**
Works an average of 50 hrs/wk. Works in rock mostly (98%) and rarely in sulfuric (2%). General duties include shoveling, hosing, and bobcat operation to clean up rock spillage. And about half that time in dusty areas. Respiratory protection worn occasionally.

1. Dust unloading - very dusty work cleaning up hoppers for about 2 hrs/wk.
2. Rock tunnel - inside about 3-4 hrs/day.
3. #1 and #2 pits (belts) - spends 1-2 hrs/day shoveling in a confined area. Rock is wet so dust is not a problem.
4. Truck unloading - about 1 hr/day in a 50-foot tunnel with wet rock (not dusty).

## Animal Feeds Production

**Animal Feeds Production Supervisor**
Supervises one chief operator, three process operators (one female), and two operator trainees (clean cage mills). No radiation badges are worn. Workers rotate each seven days through three shifts, but the jobs are exactly the same. Most equipment is cleaned in place. Acid tanks, lines, and evaporators are rubber lined. The process operator goes in and cleans out evaporators.

**Animal Feeds Process Operator**
Works an average of 48 hrs/wk. Roams throughout animal feeds, production, and storage. Performs inspections and cleaning. Most (98%) of time spent on foot doing strenuous work, and about half that time in dusty areas. Respiratory protection worn occasionally.

1. Evaporator cleaning (interior) - takes about four hours and done four times per year.
2. Every three weeks is down day used to clean out fume ducts, cage mills, dryer, and cooler (can be dusty).
3. All other time spent on routine inspections and maintenance.

**Operator Trainee**
Worker spends about 40 hrs/wk on the following duties:

1. Blast 6 primary screens - biophos sand blast. Takes 20-30 minutes each time and is

done 2-3 times per day. Use white paper suit, sand blasters hood with supplied air for blasting and de-dusting.

2. Refill sand for five cage mills (an interior job) because product is moist and builds up. Takes 2-2.5 hrs/day.
3. General clean up - lime clean up (upper level) for 30 minutes, and pug mill floor (lower) wash down for one hour, then 3-4 hours in operator training. Wears paper suit and face shield (impact protection) for pug mill work.

**Animal Feeds and Multiphos Shipping**

**Animal Feeds Services Supervisor**
Supervises about 10 men and sometimes temporary labor women. They clean up spills from animal feeds and multiphos products. Each worker has been issued a radiation badge. Workers have 8 hr shifts (up to 12 hrs for unusual times). Only assume different shifts to cover vacations, or changes in position. Acid storage tanks in area are rubber lined.

**Animal Feeds and Multiphos Shipping Supervisor**
Supervises eight car loaders, two payload operators, and two chief operators. All are male and wear no radiation badges. The bulk crew rotates on a 7-day swing shift, and the bag crews rotate every other week.

**Animal Feeds Shipping Car Loader/Unloader**
Worker does not rotate to other shifts, but works two shifts for an average of 40 hrs/wk. Duties are:

1. Load/unload rail cars - 8 to 16 hrs/week working mostly on foot or forklift. Very dusty. Attire is normal work clothing.
2. Inspect incoming trucks
3. Run bagging machine - 8 to 16 hrs/week in dusty area
4. Stack bags
5. Wash rail cars
6. Unload silica - 2 weeks straight every six weeks. Strenuous work and dusty - no respiratory protection used.

**Animal Feeds Payload Operator**
Works one 12-hour shift/day for an average of 40 hrs/wk. 100% of time spent pulling product out of dry storage to rail cars or animal feeds storage. 60-90% of time is spent on the loader.

**Animal Feed and Multiphos Maintenance**

**Maintenance Planner**
Plans maintenance for animal feeds, multiphos, and shipping. Oversees two front-line supervisors who each supervise seven employees. Supervises typically nine contractor

personnel on the site normally, and 25 to 30 on down days. Employees work only in animal feeds and multiphos (occasionally in the tank farm). Equipment is repaired on site (90%), e.g., gear reducers, acid pumps (54% merchant $P_2O_5$). Rubber lined vessels repaired 80% on site and 20% off site (e.g., a spool piece that has a spare is taken off site). Planner reports that solids (deposits on equipment) are only 13% gypsum.

**Maintenance Supervisor**
Works one shift (7:15-3:45) five days/wk. Supervises seven maintenance mechanics (all male). The mechanics rebuild motors and work on pipes from multiphos and shipping; not pipes with scale buildup (pond water). Workers do not wear badges although one was assigned as a representative in the past. Shifts are only split for turnarounds. At night there is a "shift maintenance" for the entire plant. On-site work includes: rebuilding acid pumps (six total) and they repair about 60% of their own pumps; repair of fan housings done by contractors on the site, but if there is a need to strip and re-line (rubber), they are taken off site. Pumps must be taken off site to machine shops from time to time.

**Maintenance Mechanic**
Works 40 hrs/wk on the day shift. Duties include welding, belt repair, piping repair. About 25% of time is spent in dusty conditions, and a regular dust mask is worn most of that time. Usually normal attire is worn except when welding gear or an acid suit is appropriate.

**Maintenance Mechanic**
Works and average of 44 hrs/wk. Duties include: oil, grease, and inspect equipment such as pumps, motors, kiln, elevators, belts, rollers, gearboxes, etc. Work is out in the plant 80% of time and in the shop 20%. Dusty areas include walkways near belts and storage for multiphos and animal feeds. Occasionally a respirator is worn.

**Trucker-Services**
Works 40 hrs/wk in all areas as needed. Currently wears a TLD. Operates "grade-all" and dump truck to haul materials from phos acid area ditches (dig out) to gypsum stack. Also runs bobcat, payloader, farm tractor, and forklift. About 20% of time is spent in dusty conditions. One duty in the last year was inside a clarifier tank for 12 hours wearing respiratory protection. Others from "services" work in phos acid area on down days changing out filter cloths, changing out scrubber packing, and performing scrubber duct work.

**<u>Granular Shipping</u>**

**Shipping Supervisor (MAP, DAP, GTSP, GMAP)**
Supervises one rotating shift involving two chief operators, one reclaim operator, four payload operators, seven car loaders, two local (train) engineers, two switchmen. At this time there are 15 men and three women (all car loaders). Contractors are only involved in on site rail repair: usually C.J. Bridges, and sometimes Central Maintenance. No workers

wear radiation badges. The train crews work plant wide rotating through multiphos, phos acid, etc. In general, duties are:

1. Chief operator - keep the plant running, catch samples on rail cars and trucks.
2. Reclaim operator - run reclaimer and payloader.
3. Payload operator - run payloader and bobcat.
4. Car loader - load rail cars and clean up spills.
5. Train crews (engineers and switchmen) - run trains and spotting in plant.

All areas are dry and there is dust, but oil is used to reduce air suspension. In GTSP workers are required to wear true respirators.

**Chief Operator - Shipping 2 and 3**

Works 40 hrs/wk on a rotating shift. Duties include:

1. Running two belt units. Normally 80% of time is spent in the control room.
2. Collecting samples from rail cars (cup off belt) - end of car load. Typically loading 10 to 20 cars, and it takes a few minutes to sample on a smoothly operating day.
3. Check product fines.
4. Check equipment.
5. Currently installing oil drums. These are cleaned about once per month because they get plugged up (an oily and strenuous job). GTSP can be dusty, but a respirator is worn.

**Payload Operator**

Works 40 hrs/wk on a 7-day rotation. Main duty is to take product to piles and move it to the hoppers. This is done every hour of the day and occupies 70% of working time. Payloader cabs are enclosed and air conditioned, but masks are worn outside in dusty areas. The remaining 30% of the time is spent cleaning up spills in truck loading using a bobcat. There may be differences in the way some loaders are sealed, so the better ones are used on particularly dusty jobs. Masks are used accordingly.

**Car Loader**

Works 40 hrs/wk rotating through 3 shifts. Worker is mainly on foot. Duties include:

1. Washing rail cars.
2. Loading rail cars. Very little dust.
3. Beating screens. Slightly dusty. Requires about 10 minutes every three days.
4. Maintaining clean area.
5. Occasionally loading trucks. In GTSP a mask is worn occasionally. Fans are used and the area is slightly dusty (stirred by trucks).
6. Shoveling in storage areas on down days. Only done once every one to three months (depending on rotation) and takes about two hours per event.

**Granular Services Supervisor**

Works 40 hrs/wk on day shift. Currently supervises three male laborers, but may supervise as many as 15 men and women. Workers under supervision shovel spilled product, and wash down floors in all granular areas (MAP, DAP, GTSP). Specific duties include replacing packing and washing gas scrubbers, and air hammering buildup in chain mills and cyclones (both dusty). Chain mills - chutes are rubber lined. Workers routinely wear TLD badges. Workers normally do not rotate to different plant areas (may go to DAP-2).

**Locomotive Engineer**
Works about 50 hrs/wk on a weekly swing shift. Currently does not wear a TLD badge. Spends 98% of time inside the locomotive. It is dusty inside the cab about 5% of the time, but no respiratory protection is worn (possible location for air sampling). Also, some dust is encountered at AFI shipping occasionally.

**Switchman**
Works an average of 48 hrs/wk on 3 rotating shifts on #1 DAP shipping. Works in all plant areas serviced by rail. Main duty is to switch cars on railroad from track to track. Job is done outside and is not usually dusty depending on wind direction (e.g., AFI shipping area). No respiratory protection is needed. The rock area is described as dusty, but very little time is spent there.

**Laborer**
Works about 40 hrs/wk mostly in shipping, but in GTSP on down days (about one to two times per month), and DAP-2 on down days (all day about twice per month). GTSP storage is dusty and a mask is always worn. DAP-2 is somewhat dusty. Worker spends 4 hrs/day three times/week inside Shipping-1 which is dusty enough to require a mask. Duties include shoveling, washing down equipment, and product spill clean up. Mostly done on foot with some use of bobcats and payloaders. Work is strenuous and mask, paper suit, and gloves are worn.

<u>**Granular Maintenance**</u>

**Granular Maintenance Supervisor**
Supervises seven maintenance mechanics (all male). They typically change out large industrial equipment such as pumps, pipes, motors using cutting and welding tools. Outside contractors are used to repair scales, perform concrete and structural work, do asbestos work, and repair pressure vessels. Workers rarely shift to other areas (99% in granular). Most equipment stays on site (gear boxes, pumps, etc.). Only large valves go off site for repair, and some pumps are sent to Chesterton Pumps for work. Rubber-lined equipment includes acid scrubbers, storage tanks, day tank (phos acid).

**Granular Maintenance Mechanic**
Works 40 hrs/wk in DAP 1&2, MAP, GTSP, rarely shipping. Duties include repair of pumps in all granular areas with 95% of repair time spent in the shop. This involves cleaning, washing, tearing down, and repairing pumps. The only work that is dusty is when

a needle gun is used to chip product from pumps. Gloves, ear plugs, and facial protection are worn, but no respiratory protection is considered needed.

## Granular Operations

**Granular Operations Coordinator**
Works with four shift supervisors to coordinate maintenance activities for GTSP, MAP, DAP, and ammonia storage. He determines outside contractor needs and calls the maintenance planner to schedule (fiberglass repair, metal welding, and rubber liner repair).

**Production Supervisor**
Works one rotating shift. Supervises two chief operators, two process operators, one ammonia operator, one bobcat operator, six operator trainees, 1 MAP operator (= 13 men). Chief operators operate the DAP plant and GTSP plant from the control room. The DAP process operator works out in the plant checking scrubbers, etc. The GTSP process operator does the same. The ammonia operator monitors flow levels (mostly office work). Operator trainees clean floors, etc. The MAP operator is out in the plant. All workers came through services and were badged while there. All equipment is maintained on site, but several service companies are used.

**Chief Operator**
Works 40 hrs/wk on three rotating shifts. Most (95%) of time is spent in the control room (MAP and DAP). The rest (5%) of time is spent in the plant collecting samples.

**Reclaim Process Operator**
Works 40 hrs/wk on three rotating shifts. Duties include:
1. Running DAP operations from the control room (92% of time).
2. Running payloaders (8% of time). DAP storage #1 is a little dusty. GTSP building is very dusty. A dust mask is worn in the GTSP building only. No other respiratory protection or protective clothing is worn.

**Ammonia Operator**
Works 40 hrs/wk. Currently does not wear a TLD badge. Remains in ammonia storage area all the time. No respiratory protection is used. Duties include:
1. Opening valves from pipe line into on site storage.
2. Inspecting gauges.

**Bobcat Operator**
Works about 48 hrs/wk on three rotating shifts. Duties include cleaning spills on DAP, GTSP, and MAP floors. Conditions are usually dry and a dust mask is worn routinely (also gloves). About two to three hours/day spent running a bobcat in these areas, and the rest of the day is spent in the control rooms.

**Operator Trainee**
Works 40 hrs/wk on a weekly rotation. Also, rotates to other plant areas one time per month for one day. Wears normal attire except for coveralls on some jobs. About 50% of jobs require respiratory protection. Duties include cleaning up DAP-1 area, and maintaining cage mills. Conditions are dusty when running GMAP (about 50% of the time). Supplied air or a full face mask is used when inside ducts or granulators.

**MAP Process Operator**
Works 40 hrs/wk on the day shift. Dust mask or full face respirator rarely used. Duties include:

1. Sample collection every two hours for 15 to 20 minutes.
2. Nozzle changing (top of MAP tower) every four hours for 30 minutes for each change.
3. Thorough check of the plant every four hours for 20 to 30 minutes.

**DAP Process Operator**
Works 40 hrs/wk on three rotating shifts. Duties include turning valves on and off and collecting samples. About 3 hrs/day spent out in the plant, and the rest (~ 5 hrs/day) is spent in the control room. Plant conditions are somewhat dusty, and a dust mask and gloves are routinely worn. Acid suit is sometimes used when sampling. When in the granulator, about 4 to five times per month for 10 minutes each time, a full face respirator is used.

**Granular Services**
Works 40 hrs/wk. Interviewee has worn a TLD badge for the last six months. Duties include shoveling, air hammering, cleaning confined spaces, and washing roads. A dust mask is used about 75% of the time. Sometimes a full face respirator is used in confined spaces. An acid suit is worn in DAP-1 and GTSP about 25% of the time.

**Services Supervisor**
Works 40 hrs/wk on the day shift. Supervises two truckers and six laborers (four females). Everyone in services wears a TLD badge. Contractors mow grass, and do some culvert blasting.

**Services Laborer**
Works 40 hrs/wk on the day shift. Currently wears a TLD badge. Main duty is cleaning. Sometimes works down days in phos acid on filter changes. About 5% of time is spent in dusty areas, and sometimes respirators are used.

**<u>Phosphoric Acid</u>**

**Production Coordinator**
Oversees 4 shift supervisors and 12 chief operators for rotating shifts.

**Labor Supervisor**
Works 40 hrs/wk on the day (7:00 - 3:30 PM) shift supervising nine laborers on normal days, and up to 20 workers on down days (extra manpower from "services" dept.). The workers under supervision wash down equipment, shovel debris, change out filter cloths, change packing in scrubbers, and operate air hammers to clean pipes. All workers wear TLD badges. Piping, scrubbers, and all tanks are rubber lined (workers go in scrubbers and tanks). Each reactor tank is cleaned (washed) out annually on average. Outside contractors come in to do hydraulic air hammering on reactors.

**Product Operator Trainee**
Works 40 hrs/wk rotating three shifts for seven days each. Not issued a TLD yet. Most work is under wet conditions, so dust is not a problem. Most work is on foot. Duties include:
1. Clean up on filter floors for about 10-12 hrs/wk.
2. Water blasting evaporator tubes for about 8 hrs/wk.
3. Opening and closing valves, collecting samples, running samples in lab, and other duties in the area take about 20 hrs/wk.

**Maintenance Supervisor**
Works 40 hrs/wk supervising nine mechanics (evaporator maintenance crew). Rubber workers are contracted (2 - 20 persons depending on the job), and all rubber stays on site. All workers (except contractors) are badged. About 20 to 40 pieces of equipment are taken off site each month, and all others are maintained on site. Repair of all rubber-lined equipment is contracted.

**Maintenance Supervisor**
Supervises day shift for Byrd filter maintenance crew consisting of nine mechanics. All workers are badged. Most equipment is maintained on site, but rubber-lined equipment is taken to a specific "burn out yard" when rubber replacement is needed.

**Maintenance Mechanic**
Works an average of 44 hrs/wk on the day shift. Currently issued a TLD badge. Duties include repair of pumps, replacing piping, opening evaporators, and welding. A respirator is only worn when going into tanks or evaporators (rare situation). Work is done on foot with no heavy machinery. Most of the piping is rubber-lined as are evaporators. Workers on the "evaporator crew" spend the majority of time (25-30 hrs/wk) working on evaporators.

**Mechanic**
Works an average of 50 hrs/wk on the day shift. Most work is done on foot with occasional use of heavy machinery. Worker on the "filter pan crew" spends most time (~ 25 hrs/wk) on Byrd filters. The remaining time is spent in the shop area. Duties include repairing tilt arms, welding, and repair of every aspect of the filters. Dry scale is present, but not dusty.

**Production Supervisor**
Works 40 hrs/wk supervising two chief process operators, two process operators, and two operator trainees. All workers are badged. All equipment is cleaned on site, and ~ 99% is repaired on site. Most (~95%) of equipment is rubber-lined.

**Production Operator**
Works an average of 40 hrs/wk on three rotating shifts. Currently issued a TLD badge. Duties include operations from the control room, draining and setting up evaporators, and sample collection. Conditions are wet and not dusty. Protective clothing and respirators are seldom used. Working areas and times are:

1. Evaporator area ~ 4 hrs/day.
2. Filter floor and reactor ~ very little time.
3. Lab ~ 2 hrs/day.
4. Control room: all remaining time (~ 2 hrs/day).

**Process Operator**
Works 40 to 48 hrs/wk on a weekly rotating shift. Currently wears a TLD badge. Time is spent in the control room, except every two hours the operator walks through the plant catching samples for 15-20 minutes each time. There are no dusty areas, and respiratory protection is rarely used. Gloves and occasionally coveralls are the only protective garments worn. No operation of heavy equipment is involved.

**Production Laborer**
Works the day shift (7:00 - 3:30) for 40 hrs/wk. Currently wears a TLD badge. Gloves and paper suit are worn for messy jobs. Duties include:

1. Filter cloth change out: one of 9 persons doing the job. Performed once a week for 6-8 hours per job.
2. Operates air hammer on piping in the phos acid area.
3. Cleans up (washes) gypsum, if lines break.
4. Works on barometric condensers 0.5 to 2 hrs/wk. Sometimes a full face respirator is worn.

**Phosphate Company #2: Areas Selected and Individuals Interviewed**

Each worker (according to shift assignment) attends a training class for four hours per week for three consecutive weeks about every three months.

**Area I (Sulfuric, Machine Shop, 2nd Shift)**

**Maintenance department**

| Area or Shift | Number of Workers |
|---|---|
| A, B, C, & D Sulfuric | 10 |
| Machine Shop | 8 |
| 2nd Shift | 6 |

**Area II (Phos Acid, Daypool/Acid Clar.)**

Production Superintendent (1)
Day Supervisor (1)

**A Phos Acid**

| Area or Shift | Number of Workers |
|---|---|
| A Shift | 5 (1 for each of Stations #1, #2, #3, #4 and one supervisor) |
| B Shift | 5 |
| C Shift | 5 |
| D Shift | 5 |

**B Phos Acid**

| Area or Shift | Number of Workers |
|---|---|
| A Shift | 5 (1 for each of Stations #1, #2, #3, #4 and one supervisor) |
| B Shift | 5 |
| C Shift | 5 |
| D Shift | 5 |

Utility: 1 operator on A, B, and D shifts.

**Acid Clean-up**

| Area or Shift | Number of Workers |
|---|---|
| A Shift | 2 (1 for each of Stations #1 and #2) |
| B Shift | 2 |
| C Shift | 2 |
| D Shift | 2 |

**Hydroblast Day Crew**

| Area or Shift | Number of Workers |
|---|---|
| Supervisor | 1 |
| A Shift | 4 |
| B Shift | 3 |
| C Shift | 4 |
| D Shift | 3 |

Hydroblast crew job assignments:

1. Rodding and pressure checking evaporators in A Plant and B Plant.
2. Rodding evaporator steam jets in A Plant and B Plant.
3. Rodding flash cooler steam jets in A Plant and B Plant
4. Cleaning A, B, and C lamellas in A Plant.
5. Blasting and cleaning filters in A Plant and B Plant.
6. Blasting and cleaning filters at Acid Clean Up.
7. Rodding and cleaning lines in A Plant, B Plant, and Acid Clean Up.
8. Blasting and cleaning splitter boxes in A Plant, B Plant, and Acid Clean Up.
9. Patching filter cloths in A Plant and B Plant.
10. Blasting cold well screens.
11. Blasting fume scrubber packing in A Plant, B Plant, and Acid Clean Up.
12. Cleaning all fume scrubber ducts in A Plant, B Plant, and Acid Clean Up.
13. Cleaning all fume scrubber spray nozzles in A Plant, B Plant, and Acid Clean Up.
14. Blasting and cleaning pond water strainers in A Plant, B Plant, and Acid Clean Up.
15. Blasting and cleaning all ditches in A plant, B Plant, and Acid Clean Up.
16. Blasting and cleaning sumps in A plant, B Plant, and Acid Clean Up.
17. Blasting and cleaning acid coolers in Acid Clean Up.
18. Cleaning cooler tower south of non-process water tank.
19. Maintenance of tools and equipment in the tool room.

20. Inspecting fire extinguishers in A Plant, B Plant, Acid Clean Up, Area 20 and 50.
21. Inspecting safety showers and eye wash stations in A Plant, B Plant, Acid Clean Up, Area 20, and Area 50.
22. Inspecting hand rails and toe boards in A Plant, B Plant, Acid Clean Up, Area 20, and Area 50.
23. Inspecting retrieval devices for A Plant and B Plant.
24. Inspect and log kilowatt readings from MCC rooms A-10-1, A-10-2, A-20, A-50, Coldwell, and Main substations.
25. Inspect and log fume scrubber readings at A Plant, B Plant, and Acid Clean Up.
26. Keep water drained from retaining walls around #15 diesel tank -B Plant, #17 diesel tank -Area 20 MCC, #18 diesel tank for fire water, #52 No. 2 fuel oil tank, extraction pad, and float cell pad Area 20.
27. Down days every three to six weeks in A Plant, B Plant, and Acid Clean Up.
28. Cleaning tanks, rake, and outlets in A Plant, B Plant, and Acid Clean Up.
29. Blasting and cleaning flash coolers in A Plant and B Plant.
30. Coverage for tank car unloading.
31. Coverage for vacation in A Plant, B Plant, and Acid Clean Up.
32. Coverage for supervisors.
33. Rodding culverts under roadway at Area I and blasting sump at XYZ.
34. Turnarounds every 12 to 18 months.

**Maintenance department**

| Area or Shift | Number of Workers |
|---|---|
| A Phos | 9 |
| B Phos | 11 |
| Day Pool | 7 |
| Day Pool/Acid Clarification | 10 |

**Supervisor (A Phos Acid)**
Works an average of 40 hrs/wk on day shift (7:00-3:30 PM). Supervises phos acid mechanics (9 men). The supervised workers maintain pumps, motors, gears, agitators, filter pans, etc. Workers are provided TLD badges that they "wear occasionally." Workers do not rotate to other plant areas. About half of the pumps go out of the plant to contractors (big pumps). Other items may also go out for repair such as pipes, duct work, pans, evaporators, etc. Pipes, evaporators, and tanks are rubber-lined.

**PM Mechanic (A Phos Acid)**
Works an average of 44 hrs/wk. Main duties include preventative maintenance, lube

equipment, etc., and equipment check out. Clothing is normal attire with coveralls sometimes, and use of a cartridge mask on some jobs (5%).

**AM Mechanic (A Phos Acid)**
Works an average of 45 hrs/wk on day shift (7:00-3:30 PM). Worker rotates to different areas of the plant about once per month for eight hours doing weekend maintenance. Works with forklift type equipment and trucks. Spends about 50% of time in the shop area, and 50% of time in phos acid plant around all parts of that area (not dusty - acid fumes). When breaking down large pumps there can be some dust, and a dust mask is worn. Performs filter pan grinding wearing a welding fume mask (more than just dust mask). This is a very small job, i.e., infrequent and taking only 10-15 minutes at most. Equipment is monitored for exposure rates before work is started.

**Main Supervisor (Day Pool Wet Side)**
Works an average of 45 hrs/wk on day shift (6:30-4:00 PM). This worker covers the entire plant.
1. 8 hrs/week around filters.
2. 7 workers below.
3. On stack about 16 hrs/week.
4. Moving lines.
5. Occasionally on tanks.
6. Assigns workers to different areas about 8 hrs/wk.

**Machinist (Machine Shop)**
Works an average of 40 hrs/wk on day shift (7:00-3:30 PM). Works in the machine shop making new items and repairing others. Work rarely involves pipes with scale, and there is no dust. Some work on pumps.

**Machinist Supervisor (Machine Shop)**
Works an average of 40 hrs/wk on day shift (7:00-3:30 PM). Supervises two machinists, one machinist trainee, four mechanics, and one welder. Workers do not wear badges, and contractors are not used. There is no rotation to other plant areas. All equipment from all areas is worked on in the shop. The items must first be cleaned using wire brushes and grinders, so there is some dust created. Usually, respiratory protection is not used, but if it is very dusty, a dust mask or respirator is used. On rare occasions they will machine a rubber-lined pipe.

**Hydroblaster**
Performs hydroblasting for all utility. Spends one to 8 hrs/wk in phos acid tanks (28, 54%). Also, works turnarounds in DAP.

**A Operator (B Phos Acid)**
Works 48 hrs/wk on 12 hour shifts. Currently wears a TLD badge and has for four years.

Worker does not rotate to other areas. Worker spends 50% of time in the control room, and 50% of time taking samples and making adjustments out in the plant. There is not much dust in these activities, but respiratory protection is used with some systems that produce fumes, inside containers, etc. An acid suit is used for some jobs on average about twice per month.

**A Operator (Phos Acid)**
Works 44 hrs/wk on 12 hour shifts. Currently wears a TLD badge. Worker does not rotate to other areas. Respiratory protection is used when needed; mainly in sulfuric for fumes. Duties include:

1. Catch sample once per hour: "A" Plant filtrate on bottom floor (takes ~ 10-15 minutes).
2. Patch filter cloths during down times (~ 6 hrs/month).
3. Changing filter cloths: once per month during turnaround (~ 6 hrs/month).
4. On filter about 12 hrs/month.
5. Evaporator work: empty out and bring back up.
6. Generally around all phos acid areas: evaporators, attack tank, filters, etc.
7. Reactors (2) cleaned about once per year (not more than two hours at a time). Not dusty, but fumes.

**A Operator (Phos Acid)**
Works 40 hrs/wk on 12 hour shifts and 16 to 20 hrs/wk overtime. Currently wears a TLD badge (clipped to back of hard hat). Worker does not rotate to other areas. Worker is usually in A Phos Acid, but sometimes works in B Phos Acid. Also, this worker is on shift 6 months, and on crew (hydroblast) for six months. Duties include:

1. On hydroblast crew cleaning tanks, Acid Clean Up, and filters.
2. Tool room: maintenance and issue (check out) up to 8 hrs/day.
3. Filter patching: get supplies and show workers what to do (~ 2 hrs/wk).
4. Overtime work: removing hose, running payloader, riding evaporator (16-20 hrs/wk).

**A Operator (Phos Acid)**
Works 50 hrs/wk six months on day crew and six months on shift. Currently wears a TLD badge. Worker does not rotate to other areas. A half mask respirator is used on special jobs and turnarounds with hydroblasting. Duties include:

1. Working four stations in A Plant, and two stations in B Plant.
2. Hydroblasting evaporators (2 days/wk).
3. Wash down filters (one day/wk).
4. Cleaning fume ducts occasionally (every two weeks).

**A Operator (Phos Acid)**
Works 40 hrs/wk on day shift with up to 32 hrs/wk additional overtime. Currently wears a TLD badge on back of hard hat. Worker does not rotate to other areas. Worker is currently on the hydroblast day crew (6 months on crew, then six months on shift). Covers four stations in B Plant, two stations in A Plant, and two URC stations). Duties include:

1. Work on fume scrubber in B Plant (3 hrs).
2. Patch filter cloths in two sessions: first for 20 minutes, second for 30 minutes for three days per week.
3. In house hydroblast crew changes filter cloths every 3 weeks (used to change every six weeks with better rock).
4. Wash filter system with hot water about 2 times per week.
5. Rod evaporators (one evaporator per day). This is an 8-hour task in A Plant, and a 12-hour task in B Plant (larger unit) that requires a team of two workers. Usually evaporators are caked with muds and solids, but not scale.
6. Wash under filters on floor.
7. Clean fume ducts (carry fumes to scrubber).
8. Clean splitter boxes.
9. Clean attack tanks once per year.
10. Clean all other tanks.
11. Most of these jobs are done every three weeks on down days (12 hour shift).

**Production Supervisor**
Works 12 hour shifts. Supervises A Operators. Station #1 Operator runs attack filtration system. Station #2 Operator runs evaporators. Station #3 Operator runs samplers for Station #1. Station #4 Operator runs samplers for Station #2. There are 10 total A Operators and 2 Acid Clean Up workers. TLD badges are worn by 1 Operator on Station #3, and 1 Training Operator on Station #1 (B Plant). Workers change from day to night shift every six weeks. Contractors are not used.

**Utility Supervisor (Hydroblast)**
Works the day shift supervising A, B, C, D Operators and new employees. Currently supervises 1 C Operator in training for B, and 14 A Operators (all male). Employees clean equipment, change filter cloths, and perform water blasting. Some employees on each shift wear TLD badges. Most workers (95%) rotate through phos acid areas A, B, and Acid Clean Up, and about 5% may also work in sulfuric or Areas III and IV when needed. Pipes, evaporators, and tanks are rubber-lined.

**Maintenance Mechanic (Phos Acid)**
Works 40 hrs/wk on the day shift. Occasionally (3-4 times/yr) works in other areas. Worker spends over 90% of time out in the phos acid area, and a minimal amount of time in the shop. Worker is not currently badged. Duties include:
1. Reinstallation of motors, and pipeline repair.
2. Occasional grinding prior to welding, and welding type respiratory protection is worn.
3. Evaporator change out: changes valves and piping (rubber-lined). Generally works on evaporators daily, and is inside the evaporators about once a year.

**Maintenance Mechanic (Acid Clarification)**
Works 40 hrs/wk on the day shift and 6-8 hours overtime. Worker does not currently wear a TLD badge (last used one 10 years ago). Worker only works in acid clarification. Duties include:

1. Remove buildup on and repair pumps, and remove pipes, etc.
2. Cleaning on sandblasting crew.

**Maintenance Mechanic (Phos Acid)**
Works 48 hrs/wk on the day shift. Worker does not currently wear a TLD badge, but has when working on filter pans. Works only in phos acid (90% of time) and the gyp stack area. A respirator is only worn for fumes (air purifier cartridge), not dust. Duties include:

1. Maintain and repair pumps and lines.
2. Repair other items, especially evaporators.
3. Grinding and welding in dry conditions: welding mask is worn, but this is rarely done (<5% of time).

**Maintenance Mechanic (Acid Clarification)**
Works 40 hrs/wk on the day shift. Worker does not currently wear a TLD badge. Worker spends 90% of time in acid clarification area. Duties include:

1. Working on pumps, motors, valves, filter belts, and repairing and replacing lines. Involves rubber-lined pipes and tanks, but no evaporators. Conditions are wet, not dusty.
2. About once per week in XYZ area (dusty): working around granulator where fertilizer is made which is dusty, but dust mask is not worn often.
3. Forklift and picker operation to help move pumps and piping.

**Maintenance Mechanic (Wet Side)**
Works 40 hrs/wk on the day shift. Worker does not currently wear a TLD badge. Worker wears coveralls occasionally, but is not around dusty areas. Sometimes wears a cartridge mask. Mainly works on equipment, pipes, and valves.

**<u>Area III (Shipping & Wet Rock)</u>**

**Shipping & Wet Rock Production**

| Area or Shift | Number of Workers |
|---|---|
| Supervisors - Area III | 4 (1 per shift) |
| Wet Rock - Panel Board | 16 (4 per shifts A, B, C, D) |
| A Shipping | 12 (3 per shifts A, B, C, D) |
| B Shipping | 12 (3 per shifts A, B, C, D) |
| Rail - Track Man | 8 (2 per shifts A, B, C, D) |
| Locomotive | 8 (2 per shifts A, B, C, D) |

**Maintenance department**

| Area or Shift | Number of Workers |
|---|---|
| Shipping & Wet Rock | 8 |
| $NH_3$ Unloading and Dist.<br>A DAP and Prim. Rock | 4 |

**Maintenance Mechanic (Area III)**
Works 40 to 48 hrs/wk on day shift (7:00-3:30 PM). Worker rotates to other plant areas about once a year, and does not wear a TLD badge. Interviewee is a safety observer and must cover the entire plant daily. Worker occasionally wears coveralls and a dust mask (~5% of the time).

**Maintenance Mechanic (Area III - Shipping)**
Works 40 hrs/wk on day shift (7:00-3:30 PM). Worker does not wear a TLD badge. Duties include:

1. Repair all items.
2. Fabrication of new items, and preventive maintenance.
3. On down days works about half the day at the storage reclaimer.
4. Works for a couple of hours in the wet rock tunnels on rare occasions. Others working preventive maintenance spend more time in the tunnels.
5. Down time for repairs once per week.
6. Remainder of time spent in shop and wet rock.

**A Operator (Area III - Wet Rock and Shipping)**
Works an average of 40 hrs/wk. Worker does not rotate to other plant areas. Worker does not wear a TLD badge. Mainly performs utility work (cleaning). Worker operates a front end loader 5-10% of the time. A dust mask is used about 5% of the time.

**A Operator (Area III - Shipping)**
Works an average of 42 hrs/wk on rotating 12 hour shifts. Worker does not rotate to other plant areas. Worker does not wear a TLD badge. Working attire is normal except when conditions occasionally require coveralls, rubber boots, or dust mask. Duties include:

1. Load fertilizer rail cars (a little dusty) ~ 66% of time.
2. Wash incoming rail cars.
3. Operate payloader.
4. Hook up rail cars.
5. Cleaning during turnarounds (some dusty).
6. Load trucks.
7. Wet rock unit ~ little work here.

**Production Supervisor**
Works 12 hour shifts switching from day to night every six weeks. Worker does not wear a TLD badge, and has worked the same location for 10 years. Duties include:

1. Call shipping and control room.
2. Check on wet rock.
3. Talk to locomotive engineers.
4. In warehouses 5-10 minutes/day.
5. In field checking water in pans, pH, wells, gates.

**<u>Area IV (A, X, Y. Z-DAP Trains)</u>**

Area IV has 4 DAP "trains" working under four shifts (two day, two night). Shifts have train operators, wet side operators, and dry side operators. Other operators work in the lab, tank farm area, ammonia area, and utilities. "A" Train is an old plant and is not running. "Y" Train produces MAP.

**Maintenance department**

| Area or Shift | Number of Workers |
|---|---|
| X, Y, Z | 15 |

**A Operator (Area IV Granular Production)**
Works an average of 42 hrs/wk on rotating 12 hour shifts. Currently does not wear a TLD badge. Does not rotate to other plant areas.
1. Spends 85% of time in the control room.
2. Spends 15% of time overseeing granulator (not real dusty in this area).
3. On down days (~ one per week): clean buildup in granulator (30-40 minutes), and may work in phos acid up to several hours cleaning up.

**A Operator (Area IV Granular Production)**
Works an average of 40 hrs/wk. Currently does not wear a TLD badge. Does not rotate to other plant areas. Operates granulation and cleans up spills and buildup. Works in very dusty areas about 10% of the time, and wears respirators (cartridge and full face) as appropriate.

**Supervisor (Area IV)**
Works an average of 40 hrs/wk on day shift (7:00-3:30 PM). Supervises A, B, C, D Operators and day shift utility crew (12-18 workers). All equipment is maintained on site. Vessels and tanks are rubber-lined.

**Shift Supervisor (Area IV)**
Works an average of 36 hrs/wk three days at a time for three consecutive weeks (7:00-7:00 PM). Supervisor does not rotate to other areas. Supervises 14 employees (all A Operators) consisting of three panel board operators, three wet side operators (scrubbers), three dry side operators, one lab man, one tank farm operator, one ammonia operator, and two extra on shift. Contractors provide sand blasting of beams, tanks, and stairs (Bradshaw), and install insulation around the steam line (Stalcon). Supervisors duties include:

1. Paperwork in office ~ 4 hrs/day.
2. Overseeing operations by walking the production floors (4 levels) on a touring route to the control room (little dust on route).

**Tank Farm Operator (Area IV)**
Works 40 to 45 hrs/wk on 12 hour day and night shifts (six week rotation). Worker does not rotate to other plant areas. Duties include:

1. Transfer acid (28% and 54% phos acid), and open and close valves.
2. Air hammer mills and sulfuric scrubbers to remove buildup.
3. Once every week there is a full 24 hrs down time (XYZ Train) to recycle buildup in the system.
4. Cleaning the system.

**A Operator (Area IV - MAP/DAP)**
Works 40 to 48 hrs/wk on day shift (7:00 - 3:30 P.M.). Worker does not currently wear a TLD badge. Worker sometimes wears rain suit, acid gloves, face shield, boots, etc. Occasional use of a respirator is required, but usually only a dust mask is needed. Duties include:

1. DAP/MAP - running different product at different times. Currently, two plants are running DAP and one plant is running MAP. DAP is the major product, and there is no GTSP.
2. Worker is on the bottom floor 90% of the time (not too dusty), and 10% of time is spent out in the plant and in the control room. When running MAP, it is dusty, and when running DAP it is not dusty.
3. Shut downs occur about once a month for 24 hours to open up tanks, etc. and clean them out. This work can be either wet or dry.

**Wet Side Operator (Scrubber Man)**
Works both day and night 12 hour shifts for three days on and three days off for an average of 40 hrs/wk (some eight hour shifts worked in). Worker does not currently wear a TLD badge. Duties include:

1. Check scrubbers every 45 minutes for 10-15 minutes (checking to see if they are warm to the touch).
2. Catch samples - 2 cups: scrubber liquid (28% acid) and dust (reuse 28% and 54% for slurry). Takes 15-20 minutes per hour. 1550 - 1560 gravity - slurry; 1280 -1320 gravity in scrubber. Workers wears gloves, acid jacket (coat drapes over knees, and

hood for areas where water is falling), and face shield.

3. Cleans nozzle in granulator wearing a dust mask (assisting A Operator when on vacation), but only takes 10-15 minutes. Also, takes 15-20 minutes to unplug if needed. If header is bad, takes 30-45 minutes to clean header.
4. If a chute plugs in another plant, they will move over to get it running quickly.

**Laborer (Dry Side Operator)**
Works an average of 44 hrs/wk on 12 hour shifts for three consecutive days. Worker does not rotate to other plant areas. Duties include:

1. Maintain dry side: shoveling and jack hammering (strenuous) under very dusty conditions. A dust mask is used and replaced about every 20 minutes. Runs bobcat rarely for large spills. This work takes 8-10 hrs/day.
2. Overtime work: (about 16 hrs/month) hydroblasting, air hammering, sledge hammer use on fume scrubbers.

**Maintenance Mechanic (Area IV Granulation)**
Works 40 hrs/wk on day shift and up to 10 hrs/wk overtime. Worker does not wear a TLD badge, but works all over the plant on weekends (overtime). Duties include:

1. Welding: pipes with and without scale including some still in place with scale (~ 2 hrs/day). Some pipes are fibercast, but they do not work on many rubber-lined pipes.
2. Flame cutting: on same items (~ 1-2 hrs/day).
3. Replacing dry belts and conveyor belts: fertilizer - some real dusty and a dust mask is used. (This worker used to work in ammonia area six months ago and wore a cartridge mask).
4. Replace pumps, motors, etc. out in the plant and not in the shop (~ 4 hrs/day). Occasionally replaces rubber-lined panels. A few contractors work in that area.

**Maintenance Mechanic (Area IV Granulation)**
Works 40 hrs/wk on day shift and up to 5 hrs/wk overtime. Worker does not wear a TLD badge. Work involves a lot of welding (hot welding) and burning. Most work is with structural steel. Worker is very rarely in storage. A lot of work around granulators changing pumps, and acid lines on pre-neutralizers. Works on pond water lines, and acid lines which have scales. Worker also works on conveyor belts that are in a dusty area requiring a dust mask. One day per week for about half the day is spent in the 54 area or on filter pans.

**Maintenance Mechanic (Area IV Granulation)**
Works an average of 44 hrs/wk. Worker does not wear a TLD badge. Worker covers the entire plant on weekends. Duties include replacing pumps and gear boxes, and placing lines and valves throughout the plant. Occasionally wears coveralls, and rarely wears a cartridge mask.

**Area V (Paint and Labor, Gyp Stacking)**

**Maintenance department**

| Area or Shift | Number of Workers |
|---|---|
| Paint and Labor | 9 |

**Maintenance Supervisor (Paint and Labor Crew, Utilities - Entire Plant)**
Works straight days and some turnarounds. Supervises painters, plumbers, gardeners, road repair crew, tours, training programs, in-plant cleaning service, in-plant fueling, forklift service, and painting done by contractors. All of these jobs are done by nine men. Of those, two blasting/painting, one fueling, one plumbing, and two gardening have been working at the site from seven to 20 years. A contractor handles wood repair, screening, and concrete. A plumbing company handles jobs that are not routine, e.g., routing and rooting sewer lines, bowl and urinal replacements, etc. Workers are not currently badged. Workers may shift to nights on turnarounds, but are still all over the plant. Workers only paint new rubber-lined pipes.

**Maintenance Mechanic (Utility)**
Works 45-55 hrs/wk all over the plant. Spends 90% of time sand-blasting in maintenance yard and painting. Spends 10% of time sand-blasting on turnarounds. Wears coveralls during painting and blasting, and uses supplied air respiratory protection for blasting and painting.

**Maintenance (Utility)**
Works 40 to 44 hrs/wk on day shift (7:00-3:30 PM). Worker does not wear a radiation badge or rotate to different areas. Duties include:

1. Plumbing ~ six to 8 hrs/day (bathrooms).
2. Cutting grass up to 4 hrs/day.
3. Painting ~ 2 hrs/wk.

**Area VI (Instrument, Electric, & Heavy Equipment)**

**Maintenance department**

| Area or Shift | Number of |
|---|---|
| Instrument | 9 |
| Mechanics | 4 |
| Electric | 12 |
| Heavy | 8 |

**Maintenance Mechanic (Complex Machine Shop)**
Works an average of 40 hrs/wk.  Works 2nd shift sometimes on weekends.  Spends all time in the machine shop which is not normally dusty and requires no respiratory protection.

**Instrument Supervisor (Instrument Shop)**
Works an average of 45 hrs/wk.  This worker is currently badged with a TLD.  Supervises nine instrument technicians.  Spends 75% of time in the office, and 25% out in the plant.

**Instrumentation Technician**
Works an average of 40 hrs/wk on day shift (7:00-3:30 PM).  Interviewee has worn a TLD when working with cesium gauges.  Job involves coverage of entire plant.  Duties are to repair flow meter level indicators, pressure switches, sulfur dioxide monitors, etc.  Worker is rarely around filters and never in the storage areas.

**Service Companies:  Companies Selected and Individuals Interviewed**

**<u>Service Company #1</u>**

**Shipper/Receiver**
Works an average of 42 hrs/wk.  Worker has never worn a TLD badge.  This worker does not have much exposure to NORM.  Duties include:
1. Receiving new parts (~ 2 hrs/day).
2. Build crates and package new parts (~ 6 hrs/day).
3. Occasional help with castor assemblies.

**Mechanic/Inspector**
Works an average of 42 hrs/wk.  Worker has never worn a TLD badge.  This worker does not have much exposure to NORM.  Duties include:
1. Disassembly of components, inspection of pans (sandblasted at plant), and repair as needed (~ 5 hrs/day).
2. Inspect new parts (~3 hrs/day).

**<u>Service Company #2</u>**

**Welder**
Works an average of 50 hrs/wk.  Primary duties are welding, shearing, and plasma cutting filter pans, timing ground, distributor manifolds, lift arms, and castor brackets.  Also, some grinding and polishing.  All of this work is sporadic, i.e., there may be none for months to a peak of 10 hrs/day.

**Pressure Brake and Roll Operator**
Works an average of 55 hrs/wk.  Duties include:
1. Forming pump bases for Bainey pumps (~ 10 hrs/month).

2. Bending cones for fertilizer industry (~ 10 hrs/wk).
3. Repairing sides and ends of filter pans (takes a full day and is done 2-3 times per month).
4. Shearing and breaking parts (~ 2-3 hrs/day).

**Shop Foreman**
Works an average of 50 to 80 hrs/wk (lots of overtime). Duties include:
1. Master fitter (75% of time). Fitting is a variety; not necessarily phosphate industry items.
2. Welding (5% of time).
3. Supervising and coordinating (20% of time).

**Materials Worker**
Works an average of 60 to 65 hrs/wk. Duties include:
1. Unload incoming materials: most from citrus industry, not phosphate (25-30% of time).
2. Load outgoing materials (25-30% of time).
3. Move materials from area to area (40-50% of time).

**Painter/Sandblaster**
Works an average of 60 hrs/wk. Works primarily in the rear of the facility (paint yard), and occasionally in front. Duties include:
1. Paints with atomizing spray gun: wears a charcoal cartridge respirator. Wears Tyvex, hat, no gloves, and forced air helmet.
2. Sandblasting with forced air: always wearing a respirator.
3. Has not yet dealt with phosphate related equipment.

**<u>Service Company #3</u>**

**Pump Technician**
Works an average of 40 hrs/wk. Duties include:
1. Rebuilding pumps: most are from the phosphate industry mines and chemical plants. Gloves are the only protective clothing worn. Occasionally a dust mask is used, but usually not.

**Radiation Safety Officer**
Works an average of 40 hrs/wk. Duties include:
1. Monitoring jobs and checking radiation areas. RSO tours through the entire complex 7-8 times per day, but never does hands-on work.
2. Spends ~ 2 hrs/day in office doing paperwork.

**Welder/Fitter JAT**
Works an average of 40 hrs/wk. Duties include:

1. Working on filter pans: welding, fitting, grinding (~ 90-95% of time).
2. Removing gypsum from pans with air hammer wearing a dust mask or respirator (~5% of time).
3. Working in fabricating shop (< 5% of time).
4. Driving trucks, etc. (~ 1% of time).

**Pan Shop Lead Man**

Works an average of 40 hrs/wk. This worker currently wears a TLD and has for nearly 3 years. Duties include:

1. Repairing pumps and filter pans. Sometimes a dust mask is worn while "chipping" on filter pans.

**Machinist**

Works an average of 42 hrs/wk. This worker wears a TLD badge "two or three times a week." Duties include:

1. Parts fabrication and machining. No respiratory protection is needed.

**Sandblaster**

Works an average of 40 hrs/wk. Currently wears a TLD badge. Duties include:

1. Sandblasting pans (~5 hrs/day when pans are in). After blasting, they put the sand in drums and ship it to the customer.
2. Fabrication shop - grinding (~ 3 hrs/day).
3. Driving trucks.
4. Sets large objects into lathe in machine shop (~ 3 hrs/day).
5. Painting.

**EXAMPLE OF TIME/MOTION OBSERVATIONS**

**Phos Acid Turnaround**

November 3, 1997

11:03 Medium volume air sample begun at the SW side on a small platform at the outside edge of the filter assembly in the vicinity of chipping and cleaning of the buildup in the space below where the filter pans were mounted on the # 3 Filter. The loose material is being put in wheel barrows and dumped in the gypsum dump area. This work is being done by 5 Contractor A temporary workers. Two Contractor B workers are in the vicinity using water pressure to erode the material.

11:19 A survey is performed using the Ludlum 12S (S.N. 4633). Measurements are made on the inside edge of the space below where the filter pans were mounted. This is about a meter above the floor of this area. See attached survey results.

11:30 A survey is performed using the Ludlum 12S (S.N. 4633). Measurements are made on the outside edge of the filter assembly at about one meter above the floor. See attached survey results.

11:36 A measurement is made from the platform extending over the filter assembly at the NE side. This platform extends almost to the inside edge. The level at the floor of the platform is 132 micro-R/hr (approx. 8 ft. above the floor of the space below the filter pans). An Contractor A worker waits in this area to receive a full wheelbarrow for dumping.

11:49 A survey is performed on the platform in the center of the filter assembly around the main valve. There is evidence that workers have been working in this area but are not presently here. A survey is also performed for the platform on the inside circumference of the filter pans. These measurements are made at the level of the floor of this platform. An Contractor B worker is on this platform seated on a bucket at the SE side performing work on the rollers as he moves around the platform. See attached survey results.

11:58 Workers on the # 3 Filter take a lunch break.

12:04 All workers are off the top of the reactor except for two workers setting up a hose to pump out the oil from one of the agitators.

12:32 Back at the # 3 Filter, one Contractor B worker reenters space normally occupied by the filter pans and begins hosing down material.

12:40 Contractor A workers begin to reenter work area.

12:43 All Contractor A workers are back on the job.

12:44 Medium volume air sample begun on the platform at the NE side. The sampler is placed at the end of this platform which almost extends to the inside edge of the pan area.

14:39 5 Contractor A workers and 2 Contractor B workers continue task of removing built-up material from the sub-filter pan space.

November 4, 1997

13:50 On the platform in the center of the filter assembly, three Contractor B workers are working on the main valve. A measurement is made in the area of their work with the Ludlum 12S (S.N. 4633). The level is 132 micro-R/hr. A phosphate company employee is working in the area of the hydraulic motor which is at this level and is in the vicinity of the tank where a previous survey indicated an exposure level of 1110 micro-R/hr. The level at his location is about 1000 micro-R/hr. He is wearing both TLD and X9 badges. An Contractor B employee continues to work his way around the inner circle of the pan assembly.

On the second level of this facility below the platform in the middle of the pan assembly, a large-diameter pipe is surveyed. This pipe comes out of the bottom of the small tank which surveys indicate to have the higher exposure levels. A measurement at a 90-degree turn indicates a level of 1650 micro-R/hr at the surface. This pipe has been opened at a clean-out in this area. A measurement at this opening indicates a level of 220 micro-R/hr. A buildup of material is evident inside the pipe.

13:56 A survey is performed around the # 3 Filter Pan assembly. Measurements are made on the inside of the outside edge at about one meter above the floor of the sub-filter pan space and on the outside of the assembly at about one meter above the floor. See attached survey results.

14:14 Contractor B workers are cleaning the roller mounting pads from inside the sub-filter pan space, one on the inside circle and one on the outside circle. This is first done with water and finally with compressed air blowing the material away from the worker. One Contractor B worker is in this space hosing down the area.

14:19 Scale-type material from cleanup on the outside of the filter pan assembly is being dumped down a chute from the third level to a small dump truck, which is a commercial rental truck.

14:22 Two Contractor B employees are working on the main valve from the platform in the center of the pan assembly.

15:36 On top of the reactor a survey is done around opening to compartment 6. These measurements are at one meter using the Ludlum 12S (S.N. 4633). Levels are 121-132 micro-R/hr.

15:39 A survey is performed around the opening for compartment 7. The four measurements are: 308, 330, 220, and 132 micro-R/hr. Four people are working here at this time.

15:44 Measurement on the debris in the side opening of compartment 2-88 micro-R/hr. Measurement in the side opening for compartment 3-77 micro-R/hr. Measurement in the side opening for compartment 4-414 micro-R/hr.

15:52 In the filter pan lay down area (# 3 filter pans), Contractor B workers are removing bushings from each end of the pans. A survey is performed with measurements taken at the end of the pans where the workers are removing the bushings. The following measurements were made on a sampling of 5 pans with the Ludlum 12S (S.N. 4633): 132 micro-R/hr, 242, 99, 121, 88, 231, 231, 275, 468, 306. In general the higher exposure is at the narrower end of the pan.

16:41 Survey of pipe just east of the phos acid facility. Only one pipe found to have elevated levels. Inside of one end-132 micro-R/hr. Inside opposite end-33 micro-R/hr. Measurements with Ludlum 12S (S.N. 4633)

17:10 Robot is being used in compartment 2 to chip away scale. Access is through the side opening. Lights are being set up. There are 4 workers present including the robot operator.

17:14 Contractor B workers have left the pan lay down area. The phosphate company employees are still at the filter pan scale chipping site. They are sitting on the pans taking a break. Of the five pans present, one and one half remain to be cleaned.

Material from the reactor is being transported out to a location just east of the pan chipping site. It is then loaded onto a Contractor C truck with a front end loader.

17:17 Contractor D has set up at ground level to supply Black Beauty for four blasters in the # 3 Filter area. All blasters are using supplied air. Entry to the area is restricted.

17:33 Medium volume air sample begun adjacent to the entrance to the #3 Filter level.

17:41 On top of the reactor, hydroblasting continues in compartments 5, 7, and 8. Four persons are working near the opening of each compartment. One person is at the outside rail communicating with workers below and a second person is sitting on a bucket operating a water valve. A third person is sitting on the ramp in the middle of the reactor.

17:47 In front of the side opening to compartment two, three workers are near the opening, four workers are watching from behind. The robot is inside the compartment chipping the scale buildup.

17:51 Three phosphate company employees are chipping on what appears to be the last pan in the area. A sixth pan is being transported in for further cleanup.

18:08 Hydroblasting continues in the same three compartments. Lights are being set up for greater visibility. Twelve workers are on the roof of the reactor.

18:17 A survey is performed around the openings for the compartments. Measurements are in micro-R/hr and are made at one meter using the Ludlum 12S (S.N. 4633). Compartment 8: 66, 66, 66, 77. Compartment 7: 297, 242, 242, 330. Compartment 5: 55, 55, 66.

18:45 At the side opening to compartment 2, material is being pulled out using the robot. The operator is standing on this debris. A measurement at this location using the Ludlum 12S (S.N. 4633) indicated 66 micro-R/hr.

18:50 Filter pan chipping operation has ended. The last pan brought in has been taken away. Still some chipping necessary on the last of the five which were present. A survey is performed on the pans present in this area. All are upside down. Measurements are made with the Ludlum 12S (S.N. 4633) at about 2 feet above the pan, which appears to be a good approximation of the worker location during chipping operations. The results are in micro-R/hr. Six measurements were made per pan. 319, 341, 198, 242, 330, 330; 330, 330, 308, 242, 198, 330; 264, 330, 286, 308, 330, 330; 521, 1005, 1005, 683, 629, 629; 468, 468, 575, 360, 360, 306.

A survey was also performed for the surrounding area at approximately six feet from the pans. 44, 72, 66, 66, 77, 88, 66, 44, 44, 44, 44, 33, 44.

19:03 Measurement in the side opening for compartment 3: 88 micro-R/hr. Measurement in the side opening for compartment 4: 360 micro-R/hr. (Ludlum 12S/4633)

19:05 Measurements on top of the pile of debris from compartment 2: 66 micro-R/hr, 66 micro-R/hr, and 77 micro-R/hr. (Ludlum 12S/4633)

19:08 Hydroblasting continues in the same three compartments: 5, 7, and 8. Twelve persons are on top of the reactor.

November 5, 1997

16:00 The side opening to compartment 1 appears the same as last evening. A plywood barricade has been established around the area in front of the side openings for compartments 2, 3, and 4. This is due to hydroblasting in compartment 3. The debris in front of compartment 2 which was noted last evening has been removed. Debris from the hydroblasting of compartment 3 is being blasted out the door and is periodically removed using a bobcat. Otherwise, there are no workers in the vicinity of these openings.

16:05 A survey is performed around the openings on top of the reactor. Measurements are made at one meter using the Ludlum 12S/4633 and are reported in micro-R/hr. Compartment 3: 66, 66, 55, 55. Compartment 5: 66, 55, 66, 88. Compartment 6: 88, 88, 154, 132. Compartment 7: 143, 143, 154, 99. Compartment 8: 44, 44.

A basket is in place in compartment 8 with a hydroblaster working at about 8 feet below the surface of the reactor roof.

16:12 Fourteen personnel are involved in hydroblasting on top of the reactor. Two hydroblasters are noted wearing a badge.

16:20 In the #3 Filter area, the primary chore for the day has been the cleanup after the abrasive blasting which was performed during the night. One temporary worker reported working inside the sub-filter pan space since 7:00 AM. The material is scraped into piles with a shovel and placed in a wheelbarrow for dumping in the gypsum dump area. Three phosphate company employees were working on the cleanup of the area outside the filter assembly. Basically the same procedure was used; however the material is dumped down a the chute at the outside edge of the building. There was no sweeping of this material.

A survey is performed at the outside edge of the filter assembly. Measurements are made inside at about one meter above the floor of the sub-filter pan area and outside at about one meter above the floor. The Ludlum 12S/4633 is used. See attached survey results.

A survey is performed on the outside of the concrete pad for the filter assembly. See attached survey results. Measurements are made at one meter from the floor which is the primary floor for the third level of this facility. The Ludlum 12S/4633 is used.

An area at the SW corner is being used to store flexible pipe which connects the filter pans to the main valve. Measurements in the walkway beside the pipes are: 132, 132, 132, 99.

16:40 On the level below the # 3 Filter assembly, measurements are made with the Ludlum 12S/4633 in the vicinity of the large-diameter pipe which has apparently been opened up for cleaning. Levels are about 242 micro-R/hr in the vicinity of this work area. Levels in the end of the pipe are 319-330 micro-R/hr.

A survey of the circular platform in the central area of the filter assembly below the main gear is performed. The measurements are taken from the lower platform at a point level with the floor of the upper platform (as done in a previous survey). See attached survey results.

16:55 There are 16 workers on top of the reactor plus one worker down inside compartment 8 hydroblasting.

16:58 In the filter pan chipping area, same 5 pans are in place with the same work to be done as last evening. There does not appear to have been any work done in this area today.

17:06 A survey of the agitators is performed in a lay down yard east of the contractors' trailers. There is some scale buildup but no elevated levels were detected.

The duct to the flash coolers is also present in this area and is surveyed. One spot where there was a junction shows scale buildup and a level of 154-165 micro-R/hr at the surface of the scale on the interior of the duct (Ludlum 12S/4633). From the exterior, the level measures 44 micro-R/hr. There is also some scale buildup at the other end of this duct with levels of 33-44 micro-R/hr at a meter from the surface on the interior of the duct, with no appreciable increase noticed from the exterior.

17:36 No change in the setup at ground level next to the reactor in the vicinity of compartments 2, 3, and 4. Hydroblasting continues in compartment 3.

17:49 Contractor D workers are on the scene setting up for some additional blasting prior to painting. Two workers will be blasting for about 1 and a half hours. Three to four workers will perform the spray painting with the goal of completing this by 2:00 AM.

18:03 On the ground level by the reactor, hydroblasting has stopped in compartment 3 while a worker on a bobcat removes debris from in front of the side opening.

18:14 A survey is performed at the temporary dump site for the sludge and pieces of debris from the reactor. Sludge-306, 306, 468, 468, 360. Debris (compartment 3): 77, 110, 110, 121. Measurements are in micro-R/hr and are made at one meter at the edge of the material with the Ludlum 12S/4633.

18:28 There are 15 workers on top of the reactor. Hydroblasting is going on in compartments 3, 6, and 7. Lights are being set up on compartment 5. No tripod is being used for compartment 3 since vacuuming is not required with the side opening. The hydroblaster for this compartment is about 6 feet from the opening. There are 7 or 8 workers crowded around the opening to compartment 7. There are 2 workers at the compartment 6 opening. Three workers are sitting on buckets operating water valves.

18:32 Contractor D workers are still preparing to begin blasting.

18:40 Two workers begin blasting from a position inside the filter assembly.

18:45 On top of the reactor the following is noted: Compartment 3-one person hydroblasting from a position about 4 ft. from the opening; a second person sitting about 6 ft. from the opening operating the valve. Compartment 5-one person sitting next to the opening with no activities at this time. Compartment 6-hydroblaster and two other workers around the opening; a fourth person about four feet from the opening. Compartment 7: 5 workers around the opening; one worker about 6 feet away. Compartment 8: hydroblaster inside the compartment in a basket; one worker at the top at the edge of the opening. Two workers are at the outside rail communicating with workers operating the vacuum trucks on the ground.

18:51 Black Beauty blasting of the #3 Filter assembly is in full force.

19:05 No changes in hydroblasting activities at the reactor.

<u>November 6, 1997</u>

11:55 From the ground level next to the reactor, hydroblasting is noted to be continuing in compartment 3.

12:00 From above the reactor, the following is noted: Hydroblasting is ongoing in compartments 3 and 7. Preparations are being made to begin blasting in compartment 9. The basket has been removed from compartment 8 and sits between compartments 5 and 6. There are 13 workers on top of the reactor at this time.

12:13 Contractor B and Contractor A workers are presently taking a lunch break in the #3 Filter area. It appears that the painting has been completed.

12:22 In the filter pan chipping area, workers are chipping on the five pans which are there.

There are two workers standing on top of the pans to perform the chipping. One is wearing a dust mask, the other is not.

12:38 Contractor B workers have gone back to work on the #3 Filter. They are reinstalling the pan supports on the inner and outer circle of the assembly. The main filter in the center of the assembly has been lifted from its position and is in transit to the outside for lowering to the ground. It is presently suspended from the hoist in a stopped position. One Contractor B worker is performing cutting and welding on the outside of the assembly in the vicinity of the gypsum dump area.

12:46 Hydroblasting has begun in compartment 9. It continues in compartments 7 and 3. Vacuuming is going on in compartment 6 with no blasting at the present time. There are 13 workers on top of the reactor: 2 at compartment 6, 1 at compartment 5, 4 at compartment 7, 2 at compartment 9, and 4 workers at least 6 feet from the openings at various points around the reactor roof.

There is a lot of back-spray coming out of the compartment 9 opening. It is brownish and is covering the hydroblaster's face shield and protective clothing.

Hydroblasting has stopped in compartment 3 while debris is removed at the ground level.

12:56 At ground level, the bobcat is being maneuvered into the doorway of compartment 3 to remove the loose debris.

13:31 Two workers continue to chip on the bottom of the pans in the filter pan chipping area. An air sampler is in operation in the area.

13:38 On the roof of the reactor, workers are relocating the hydroblast position for compartment 3. There are 4 workers in the vicinity of this opening. Two workers continue hydroblasting and vacuuming in compartment 9. Four workers around the opening to compartment 7. No activities for compartments 5 and 6 at this time. There are 16 workers on the roof of the reactor.

13:58 At the filter pan chipping operation, one worker is taking a break at the location, the other worker is not there presently. The air sample at this site is completed.

14:11 An air sample is started in the #3 Filter area.

14:18 A survey is made of the main valve which has now been lowered to the ground: 143, 154, 360, 209, 187, 88, 88, 55 micro-R/hr (Ludlum 12S/4633). Two Contractor B workers are removing fittings from this valve at the present time.

15:40 One phosphate company worker is hosing down the pan chipping area. The chipping operation appears to be complete.

15:42 A new main valve has been delivered. Four Contractor B workers are now working on the old valve.

15:51 Air sample is stopped in the filter pan area. This sample was taken at the end of the platform on the NE side which extends almost to the inside circle of the filter assembly. A measurement with the Ludlum 12S/4633 indicates a level of 66 micro-R/hr at this location.

Three Contractor B workers are in the sub-filter pan area preparing new rollers for installation. One Contractor A worker is assisting. Four Contractor B workers are on the outside of the assembly in the vicinity of the gypsum dump cutting and refitting of metal parts.

16:05 A survey is performed of the pipes below where the main valve was removed in the center of the filter pan assembly. Measurements are made from the platform around these pipes at one meter with the Ludlum 12S/4633: 132, 165, 154, 132, 209, 264, 330, 575, 264, 187 micro-R/hr. The higher levels are in the vicinity of the small tank, which is at the NW corner of this platform.

16:10 Three phosphate company workers and an employee of Contractor E are working on the reinstallation of the hydraulic motor, which is the primary drive for the main gear for the filter assembly. This is just NW of the tank with elevated measurements. A measurement with the Ludlum 12S/4633 near where one of the phosphate company workers is sitting on the platform indicates a level of 1865 micro-R/hr. These workers were noted in this area at 15:51 when the air sample was completed. Two of the phosphate company workers are badged as part of the 3-month program with TLD’s and X9’s. A measurement in the middle of where these workers are standing indicates a level of 220 micro-R/hr.

16:24 On top of the reactor, there are two workers at the compartment 3 opening, and two workers hydroblasting and vacuuming in compartment 9. The tripod has been removed from the compartment 7 opening. No activities in compartments 5 and 6 at the present time. There are 12 workers on the reactor roof.

There is a ladder lowered into compartment 5. One worker is preparing to descend.

16:27 The worker descends into compartment 5. Another worker is stationed at the top next to the opening.

16:31 A survey is performed of general-use areas on the roof of the reactor away from the compartment openings. These measurements are made at one meter, begin at the entrance to the roof and are performed using the Ludlum 12S/4633: 44, 33, 33, 28, 50, 33, 33, 44, 39, 44, 33, 22, 28, 28, 39, 44, 22, 22, 33 micro-R/hr.

A survey of compartment 7 opening at one meter around the edge: 143, 154, 132, 110 micro-R/hr. Compartment 9 opening: 110, 110, 110, 132 micro-R/hr.

16:50 14 Contractor B workers are present in the # 3 Filter area as well as 2 Contractor A workers. The foreman states that they will work until 7:00 PM and then stop for the night. Five Contractor B workers are on the ground attaching fittings from the old valve to the new valve. There are no workers in the center area in the vicinity of the hydraulic motor. Bushings are being installed in the filter pan supports around both the inner and outer circle of the assembly. Rollers are being installed as other workers prepare them and deliver them to the appropriate location. The rebuilding operation in the gypsum dump area continues. One worker is painting new numbers on the various newly painted parts of the filter assembly.

16:56 On top of the reactor the basket is being placed inside compartment 7.

17:33 The filter pans have been removed from the pan chipping area and one employee continues to hose down the area.

17:40 Contractor B workers continue tasks on the #3 Filter.

17:43 Three Contractor B workers at ground level continue to remove fittings from the old valve and attach them to the new valve.

17:46 Two Contractor E workers reenter the center area in the vicinity of the hydraulic motor which they have been reinstalling. Measurements in the area where they are working indicate levels of 165-220 micro-R/hr (Ludlum 12S/4633).

17:55 Hydroblasting has begun in compartment 2. Hydroblasting continues in compartment 3. Hydroblasting is set up for compartment 9 but is not going on at the present time. An air sampler has been set up at about 5 feet above the reactor at a central point to these compartment openings.

18:34 Three workers are in compartment 5. They are standing on the bottom. Water is provided using a hose and vacuuming is being performed with a smaller diameter hose than the ones used for vacuuming from the top. They appear to be trying to do some final cleanup. One of these workers is now leaving the compartment.

18:36 A second worker is exiting compartment 5 leaving one worker inside.

18:40 Two workers continue to work on the hydraulic motor. Contractor B workers are preparing to leave.

18:45 A worker is reentering compartment 5 of the reactor.

19:00 Contractor B and Contractor A workers have left the # 3 Filter area. The two workers continue in the vicinity of the hydraulic motor.

19:15 The Contractor E workers have completed the reinstallation of the hydraulic motor and are out of the area.

Survey results for #3 filtration assembly taken November 3, 1997 (11:19 A.M.) in µR/hr using Ludlum 12S (s.n. 4633) corrected to PIC.

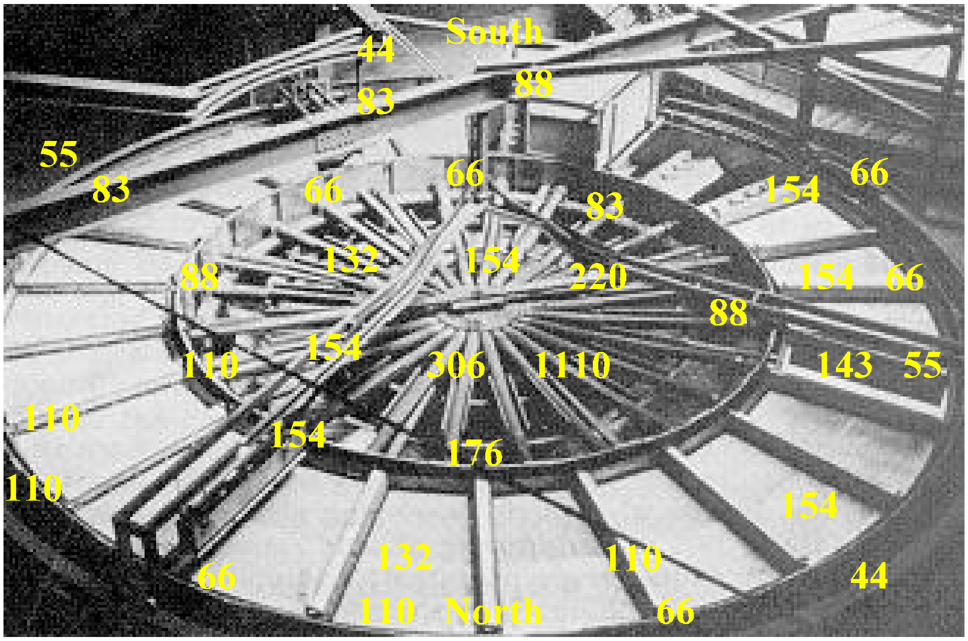


**Figure C-1. Turnaround Filter Exposure Rates # 1**

Survey results for #3 filtration assembly taken November 4, 1997 (1:56 P.M.) in μR/hr using Ludlum 12S (s.n. 4633) corrected to PIC.

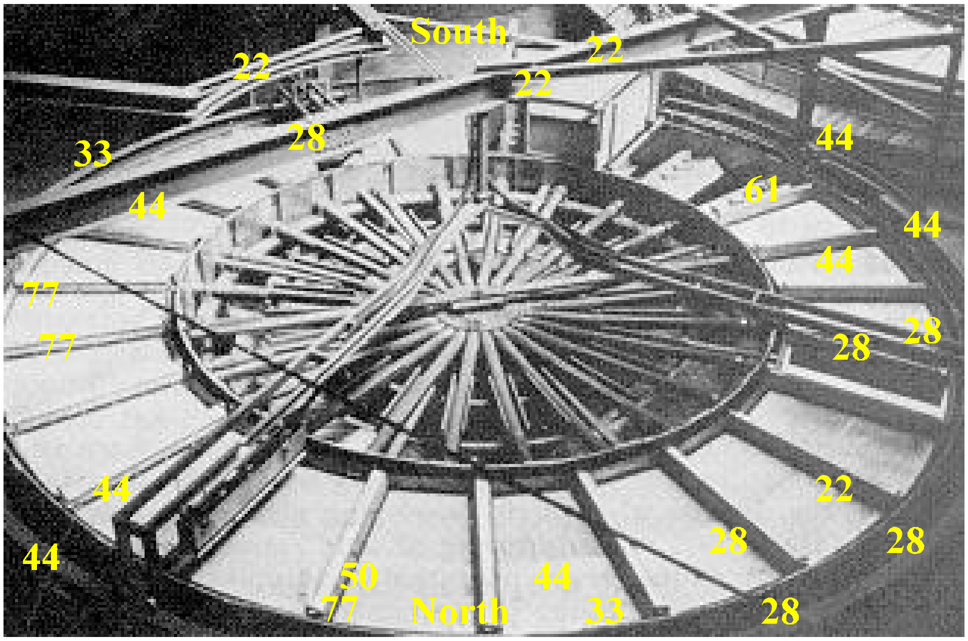


**Figure C-2. Turnaround Filter Exposure Rates # 2**

Survey results for #3 filtration assembly taken November 5, 1997 (4:20 P.M.) in μR/hr using Ludlum 12S (s.n. 4633) corrected to PIC.

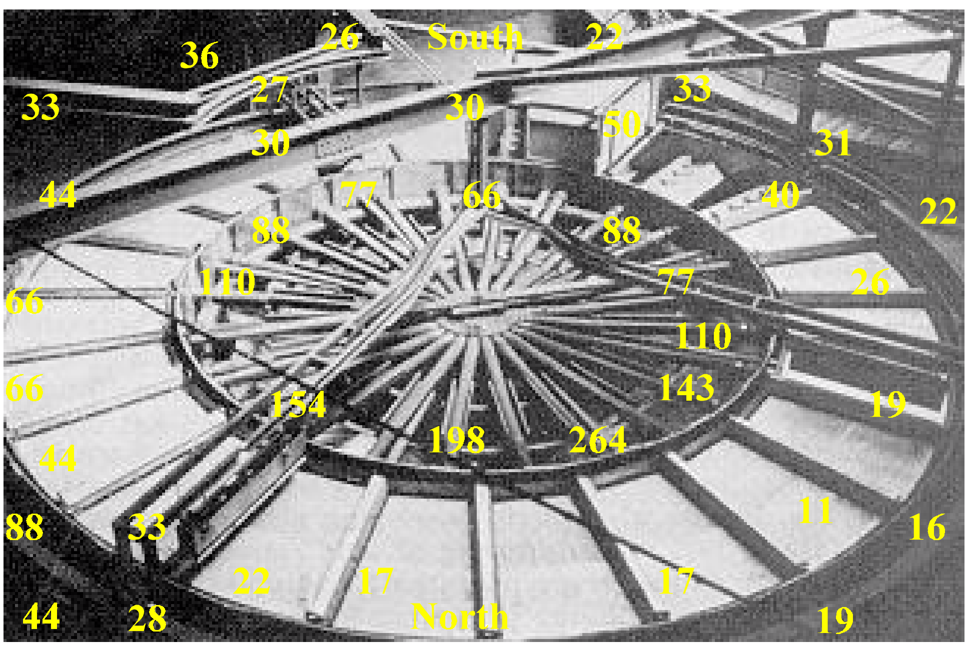


**Figure C-3. Turnaround Filter Exposure Rates # 3**