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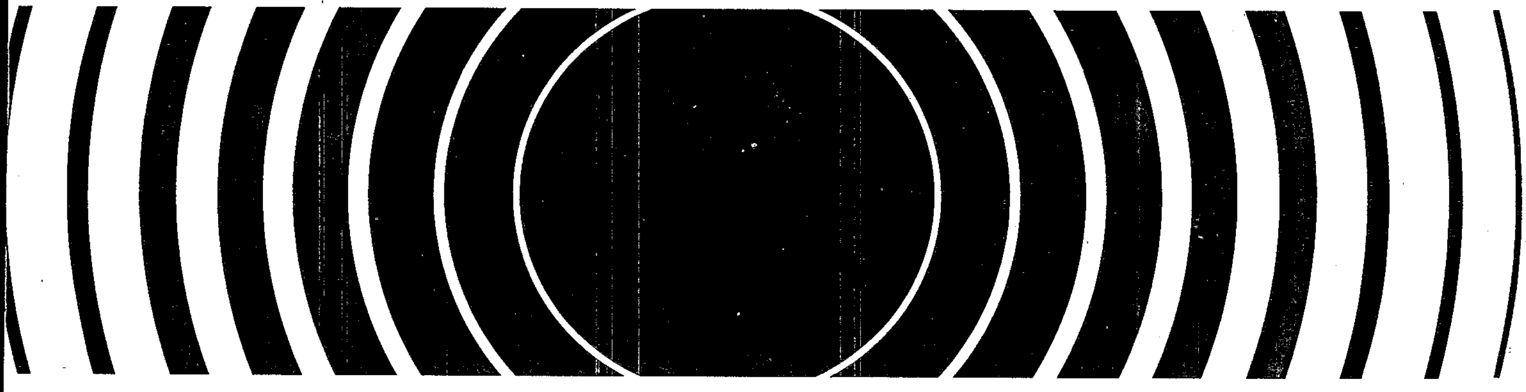
Potential Uses Of Phosphogypsum And Associated Risks

Background Information Document



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40 CFR 61 Subpart R
National Emission Standards for
Radon Emissions from
Phosphogypsum Stacks

402-R-92-002

POTENTIAL USES OF PHOSPHOGYPSUM AND ASSOCIATED RISKS

BACKGROUND INFORMATION DOCUMENT

for

40 CFR 61 Subpart R
National Emission Standards for
Radon Emissions from
Phosphogypsum Stacks

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Prepared Under
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Prepared for
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DISCLAIMER

PREFACE

The Environmental Protection Agency (EPA) is promulgating revisions to 40 CFR Part 61, Subpart R, National Emission Standards for Radon Emissions From Phosphogypsum Stacks. This Background Information Document (BID) has been prepared in support of the rulemaking. This BID contains an introduction, a general description of the fertilizer industry, a discussion of the physical and radiological characteristics of phosphogypsum, a discussion of the uses of phosphogypsum, analyses of the radiological risks associated with various uses of phosphogypsum, and an analysis of the availability and costs of substitute materials.

Copies of this BID, in whole or in part, are available to all interested persons. For additional information, contact Craig Conklin at (703) 308-8755 or write to:

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1. INTRODUCTION

1.1 FEDERAL REGULATORY BACKGROUND

The off-site use of phosphogypsum was prohibited by the final National Emission Standards for Hazardous Air Pollutants (NESHAPs) for radionuclides promulgated at 40 CFR Part 61, Subpart R, National Emission Standards for Radon Emissions from Phosphogypsum Stacks (54 FR 51654, December 15, 1989). This rule requires that as of the effective date of the rule (March 15, 1990), phosphogypsum be disposed of in stacks or in mines, prohibiting uses of phosphogypsum in construction, agriculture, or research and development.

Because of concerns about the potential impact on farmers, researchers, and other users of phosphogypsum, a Notice of Limited Reconsideration was published in the Federal Register on April 10, 1990 (55 FR 13480). Simultaneously EPA issued a limited class waiver allowing the continued use of phosphogypsum for agricultural application during the 1990 growing season. This waiver had an expiration date of October 1, 1990. However, the waiver was extended on September 28, 1990 with an expiration date of June 1, 1991 (55 FR 40834), and again on May 16, 1991 with an expiration date of October 1, 1991 (56 FR 23519). When the waiver expired on October 1, 1991, all persons holding stacks of phosphogypsum became subject to the work practice requirements in subpart R.

In conjunction with the Notice of Limited Reconsideration, EPA issued a notice of proposed rulemaking at 55 FR 13482 which contains the following options:

1) Retain Subpart R as promulgated on December 15, 1989;

2) Establish a threshold level of radium-226 which would further define the term "phosphogypsum";

3) Allow, upon prior EPA approval, the use of discrete quantities of phosphogypsum for the research and development of processes to remove radium-226 from phosphogypsum, to the extent that such use is at least as protective of public health as is disposal of phosphogypsum in stacks or mines; and/or

4) Allow, upon prior EPA approval, other alternative use(s) of phosphogypsum to the extent that such use(s) is at least as protective of public health as is disposal of phosphogypsum in stacks or mines.

1.2 PURPOSE AND SCOPE OF THE BID

This Background Information Document (BID) provides information relative to the management, disposal and potential uses of phosphogypsum. It also contains an assessment of the radiological risks associated with agricultural, construction, and research and development applications of phosphogypsum.

The BID contains a detailed description of the Agency's procedures and methods for estimating the radiological risks associated with the potential uses of phosphogypsum. The material is arranged as shown in the following descriptions of the chapters and appendices.

- Chapter 2 - A general description of the phosphoric acid industry, including phosphate rock, fertilizer, and phosphogypsum production rates and the nature and composition of phosphogypsum.
- Chapter 3 - A description of the potential uses of phosphogypsum, including the quantity of material utilized for each use, and the scope of ongoing research activities.
- Chapter 4 - A detailed description of the risk assessment performed and the results obtained.
- Chapter 5 - A discussion of the availability of nonradioactive materials that could compete with phosphogypsum and the costs associated with their use.
- Chapter 6 - References.
- Appendix A - A description of the PATHRAE pathway equations used in the assessments.
- Appendix B - A description of the Ra-226 soil concentration calculations used in the assessments.
- Appendix C - The risk assessment for the ingestion of soil treated with phosphogypsum based on different application rates and exposure periods.

2. GENERAL DESCRIPTION OF THE FERTILIZER INDUSTRY

2.1 FERTILIZER PRODUCTION

Modern agricultural practice uses large amounts of chemical fertilizers to replenish and supplement the nutrients that growing plants take up from the soil. A number of chemical elements are required to support vigorous plant growth. Most soils contain adequate trace amounts of the minor chemicals required, but to maintain the long-term fertility of the soil, quantities of nitrogenous material, phosphates, and compounds of potassium and sulfur must be replaced.

Phosphorus fertilizer requirements can be met by the application of chemicals derived from natural deposits of what is known as phosphate rock. Phosphate rock does not have a definite chemical composition, and the composition varies in different mining areas. The major phosphorus materials in the rock are geologically in the apatite group, which in high grade ores is about seventy percent calcium phosphate and is mixed with a large number of impurities, such as calcium fluoride, chlorides, chromium, rare earths, and radionuclides.

Extensive deposits of phosphate rock are found in Florida, Tennessee, and North Carolina. Workable deposits are also found in Idaho. The phosphate rock is recovered by open pit mining. Phosphate rock is transported to a washing plant where it is separated from accompanying soil, stones, etc. Particles less than 200 mesh size are called slimes and are separated from the ore at the washing plant creating a slurry of up to one third the total mined tonnage. The slurry is discharged to slime ponds. The material larger than 200 mesh size is treated in an amine flotation circuit to remove the silica sand from the ore, dried, and ground into particle sizes of 150 micrometers or less. The calcium phosphate is nearly insoluble in water and, to be useful as fertilizer, must be converted into a soluble form. This is most commonly done by converting the phosphate content of the rock into phosphoric acid. There are wet and dry processes for doing the conversion. United States production facilities utilize a wet process where the prepared material is digested with sulfuric acid to produce the phosphoric acid. Phosphoric acid is water soluble and can be concentrated, as desired, by evaporating water from the mixture. The byproduct remaining after the acid conversion is largely calcium sulfate and has been given the name phosphogypsum. Gypsum is the common tradename for calcium sulfate, a common building material.

The phosphogypsum product appears as the dihydrate or the hemihydrate form (water molecules attached to the calcium sulfate molecule), depending on the specific processing details. This byproduct material, filtered from the phosphoric acid, is transferred as a water slurry to open air storage areas known as stacks. A stack can be created by filling a previously mined area or constructed directly on the land surface.

2.1.1 Phosphate Rock

Phosphate rock, mined in open-pit mines, consists of about one-third quartz sand, one-third clay minerals, and one-third phosphate particles. After mining, the ore is processed by beneficiation (washing and flotation processes), followed by drying of the marketable rock. The production of phosphate rock in the United States during 1988 was estimated to be 38 million metric tons (MT)[a] (TFI89). Production in the United States peaked in 1980 when 54 million MT were produced (TVA86), and has since declined at a rate of about 3 percent per year (TVA86, TFI89, BOM88). Phosphate rock inventories have also decreased, from 15 to 7.5 million MT in 1985 and 1988, respectively (TFI89).

Phosphate ores mined in the United States contain uranium concentrations ranging from about 7 to 67 pCi/g (20-200 ppm)[b] (SCA91). This is 10 to 100 times higher than the uranium concentration in typical rocks (1 to 2 ppm). Uranium decay products, such as radium-226, exist with the uranium at near secular equilibrium levels. Actual radium-226 concentrations in central Florida phosphate ore range from 18-84 pCi/g, with an average value of 38 pCi/g (Ro87a). Thorium-232 occurs in the ore at much lower concentrations, ranging between 0.1 to 0.6 pCi/g (SCA91).

2.1.2 The Wet Process

In general, the wet process for manufacturing phosphoric acid involves four primary operations: raw material feed preparation, phosphate rock digestion, filtration, and concentration. The phosphate rock is generally dried in direct-fired rotary kilns, ground to a fineness of less than 150 μm for improved reactivity, and digested in a reaction vessel with sulfuric acid to produce the product, phosphoric acid, and the byproduct, phosphogypsum.

Specific wet-acid processes used include the classic Prayon and Nissan-H processes which generate a dihydrate form of phosphogypsum ($CaSO_4 \bullet 2H_2O$), and the Central-Prayon and Nissan-C processes which generate a hemihydrate form of phosphogypsum ($CaSO_4 \bullet \frac{1}{2}H_2O$) (EPA90). The processes that generate the hemihydrate form result in phosphoric acid concentrations of 40 to 50 percent without evaporation, as opposed to the 30 to 35 percent normally produced by the dihydrate processes. It is uncertain which of the above processes are used by each of the phosphoric acid facilities; however, indications are that only two or three facilities use one of the processes which generate the hemihydrate phosphogypsum while the large majority of the facilities use one of the processes which generate the dihydrate phosphogypsum (EPA90). All four processes generate two special wastes: process wastewater and phosphogypsum.

The phosphogypsum is transferred as a slurry to onsite disposal areas referred to as phosphogypsum stacks. These stacks are generally constructed directly on unused or mined-out land with little or no prior preparation of the land surface. The gypsum slurry is pumped

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[a] One metric ton (MT) is approximately 1.1 tons.

[b] 1 ppm U-238 = 0.33 pCi/g or 0.67 pCi/g total uranium, U-238 + U-234.

to the top of the stack where it forms a small impoundment, commonly referred to as a gypsum pond. Gypsum is dredged from the pond on top of the stack and used to increase the height of the dike surrounding the pond. The phosphogypsum stacks become an integral part of the overall wet process. Because the process requires large quantities of water, the water impounded on the stack is used as a reservoir that supplies and balances the water needs of the process. Thus, the stack is not only important as a byproduct storage site, but also contributes to the production process.

As of September 1989, the phosphoric acid production industry consisted of 21 active facilities that use the wet-acid production process (EPA90). Two additional facilities, Agrico's Fort Madison, IA and Hahnville, LA facilities, were on standby at that time. The locations of these facilities are shown in Table 2-1. The majority of the 21 facilities are located in the southeast, with 12 in Florida, three in Louisiana, and one in North Carolina. The combined annual production capacity of 19 reporting facilities is over 11 million MT. In 1988, the aggregate production of nearly 8.5 million MT yielded a capacity utilization rate of about 77 percent (EPA90). Several facilities, however, operated at low utilization rates, e.g., three facilities reported rates of 15.8, 30.1, and 37.5 percent. The generation of 8.5 million MT of P_2O_5(c) would produce an estimated 38 million MT of phosphogypsum, based on 4.5 MT of phosphogypsum per MT P_2O_5 (Gu75).

In 1985, 51 million MT of marketable phosphate rock were produced, of which 41 million MT (80 percent) were used to produce 12 million MT of P_2O_5 by the wet acid process (EPA89a). By 1988, these production figures had dropped to 38 million MT of marketable phosphate rock producing 8.5 million MT of P_2O_5. The main cause for this reduced production, nearly 30 percent, was the poor financial condition of the fertilizer industry during much of the 1980s. These conditions were the result of low domestic demand and reduced foreign purchases (EPA90). About 95 percent of the commercial phosphoric acid produced by the wet process is used in the production of fertilizers and animal feed, with a small portion used as a feedstock in chemical processing operations (BOM87). The data shown in Table 2.2 reflect the use of phosphate fertilizers on major crops, such as coarse grain, wheat, soybeans, and cotton and, as can be seen, the demand for fertilizer closely parallels the acreage of major agricultural crop production. However, the domestic demand for phosphoric acid is expected to increase as a result of the 1988 recovery of the farm economy, and should continue to grow as crop prices and planted acreage increases (EPA90). Non-fertilizer uses of phosphoric acid also declined during the 1980s, due to strict regulations governing the use of phosphates in household products, such as detergents, and a decline in industrial demand (SP88).

(c)By convention, the phosphate industry relates the production of phosphoric acid to P_2O_5 rather than H_3PO_4.

Table 2-1. Wet process phosphoric acid plants (EPA90).

Operator	Location	Parent Company
Agrico	Donaldsonville,LA	Freeport-McMoRan
Agrico	Mulberry (Pierce), FL	Freeport-McMoRan
Agrico	Uncle Sam, LA	Freeport-McMoRan
Arcadian	Geismar, LA	Arcadian
Central Phos.	Plant City, FL	CF Industries
CF Chemicals	Bartow (Bonnie), FL	CF Industries
Chevron Chemical	Rock Springs, WY	Chevron Corp.
Conserv	Nichols, FL	Conserv
Farmland, Inc.	Bartow (Pierce), FL	Farmland Ind.
Fort Mead Chemical	Fort Meade, FL	US Agric Chem/WR Grace
Gardinier	Riverview (Tampa), FL	Gardinier
IMC Fertilizer	New Wales (Mulberry), FL	IMC Fertilizer
Mobil Mining	Pasadena, TX	Mobil Corp.
Nu-South Ind.	Pascagoula, MS	Nu-West Industries
Nu-West	Soda Springs, ID	Nu-West Industries
Occidental Chem.	White Springs, FL	Occidental Petroleum
Royster	Mulberry, FL	Cedar Holding Co.
Royster	Palmetto (Piney Pt), FL	Cedar Holding Co.
Seminole Fert.	Bartow, FL	Seminole Fertilizer
J.R. Simplot	Pocatello, ID	J.R. Simplot
Texasgulf	Aurora, NC	Texasgulf
Argico(a)	Ft. Madison, IA	Freeport - McMoRan
Agrico(a)	Hahnville, LA	Freeport - McMoRan

(a) On standby in 1989.

Table 2-2. Trends in phosphate fertilizer demand and application (BOM88).

-- Year -- Actual/Projected	Fertilizer Demand (million MT)	Major Crop[a] Harvested Areas (million acres)	Application Rates (Kg/acres)
1980	5.5	331	16.6
1981	5.6	351	15.8
1982	5.0	336	15.0
1983	4.4	297	15.0
1984	5.2	324	16.2
1985	4.9	331	15.0
1986	4.5	311	14.2
1987	4.2	289	14.2
1988	4.2	296	14.2
1990	4.4	309	14.2
1995	5.0	333	15.0
Average[b]	4.8	319	15.0

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[a] Major crops include coarse grain, wheat, soybeans, and cotton.

[b] Does not include 1990 or 1995 projections.

2.2 PHOSPHOGYPSUM

2.2.1 Composition of Phosphogypsum

Phosphogypsum, which has an average particle diameter of less than 0.2 mm, is primarily calcium sulfate dihydrate, $CaSO_4 \bullet 2H_2O$, in association with varying amounts of silicon, phosphate and fluoride. Phosphogypsum is only slightly soluble in water, about 2g per liter (EPA89a). Phosphogypsum contains appreciable quantities of radium-226, uranium, and other uranium decay products. This is due to the high uranium concentration in phosphate rock which was discussed in Section 2.1.1. The radionuclides of significance are: uranium-238, uranium-234, thorium-230, radium-226, radon-222, lead-210, and polonium-210. When the phosphate rock is processed through the wet process, there is a selective separation and concentration of radionuclides. Most of the radium-226, about 80 percent, follows the phosphogypsum, while about 86 percent of the uranium and 70 percent of the thorium are found in the phosphoric acid (Gu75).

Table 2-3 shows the average radionuclide concentrations measured in 50 phosphogypsum samples collected in 1985 by EPA from five stacks in central Florida (Ho88). For comparison, the radionuclide concentrations normally observed in uncontaminated rock and soil are also presented. The concentrations measured in the phosphogypsum samples are similar to those previously reported (Gu75) and exceed those in background soil by factors of 10 (uranium) to 60 (radium-226). These radionuclides and radon-222 are possible sources of airborne radioactivity. Radon-222, a decay product of radium-226, is a gaseous element which may diffuse into the air. Also, these radionuclides in particulate form may be resuspended into the air by wind and vehicular traffic. Wind and vehicular traffic are the two principal mechanisms for airborne releases of radioactivity from phosphogypsum stacks.

Table 2-3. Average radionuclide concentrations in phosphogypsum, pCi/g dry weight (Ho88).

Material	Ra-226	U-234	U-238	Th-230	Po-210	Pb-210
Phosphogypsum	31	3.3	3.2	5.1	27	36
Background Soil	0.5	0.3	0.3	0.3	0.5	0.7

The radium-226 concentration in phosphogypsum varies significantly at different sampling locations on a single stack and also in phosphogypsum from different stacks within the same geographical area. This variation is illustrated by the data in Table 2-4. All stacks were active except Estech, which was inactive (closed). The ranges of radium-226 concentrations measured in phosphogypsum collected from stacks in six states are presented

Table 2-4. Radium-226 concentrations in Florida phosphogypsum samples (Ho88).

Phosphogypsum Stack	Mean Concentration (pCi/g dry)[a]	Concentration Range (pCi/g dry)
Gardinier	33±2	31-37
W.R. Grace	30±9	19-48
Royster	30±11	16-49
Conserv	34±18	23-81
Estech	25±4	19-31

(a). Mean concentration with the standard deviation of samples from 10 locations on each stack.

Table 2-5. Radium-226 concentrations in phosphogypsum, listed by state (EPA90).

State	Phosphogypsum Generated in 1988 (MT)	Ra-226 Concentration in Phosphogypsum (pCi/g)
Florida	29,777,000	5.9-36
Idaho	2,646,000	7.9-23
Louisiana	7,280,000	1.4-26
Mississippi	474,000	5.9-36
North Carolina	5,425,000	4.3-46
Texas	1,157,000	13-15

in Table 2-5. The radium-226 concentrations observed in phosphogypsum from Louisiana and Mississippi are similar to those observed in Florida, as might be expected since Florida phosphate rock is processed in those states.

The average activity ratios of the major radionuclides in the composite phosphogypsum samples from the central Florida study are shown in Table 2-6. For example, the activity ratio of Ra-226/U-238 is the average radium-226 concentration in phosphogypsum divided by the average uranium-238 concentration in phosphogypsum. These activity ratios indicate that concentrations of uranium and thorium isotopes are depleted in phosphogypsum relative to their concentrations in phosphate rock. However, the concentration of Ra-226 in phosphogypsum is similar to that in phosphate rock. Thus, most of the radium-226 follows the phosphogypsum in the wet process, while most of the uranium and thorium are in the phosphoric acid product.

In addition to radionuclides, phosphogypsum contains some trace metals in concentrations which the EPA believes may pose a potential hazard to human health and the environment (EPA90). Two contaminants, chromium and arsenic, were identified in phosphogypsum from some facilities at concentrations that may pose significant health risks. The concentrations of these contaminants vary greatly in phosphogypsum from different facilities, ranging over three orders of magnitude. Trace metals may also be leached from phosphogypsum, as are radionuclides, and migrate to nearby surface and groundwater resources. The EPA has identified a number of potential constituents in phosphogypsum from some facilities that could, under the appropriate conditions, cause adverse health effects or the restriction of potential uses of nearby surface or groundwater resources. Elements identified include arsenic, lead, cadmium, chromium, fluoride, zinc, antimony, and copper (EPA90). The presence of these trace metals in phosphogypsum is mentioned here in order to provide a more complete description of phosphogypsum, but they will not be addressed in the risk assessment.

2.2.2 Phosphogypsum Stacks

A total of 63 phosphogypsum stacks were identified nationwide in 1989 (EPA89a). Table 2-7 gives the location, size, and status, as of 1989, for each stack. Phosphogypsum stacks were present in 12 different states, with two-thirds located in just four states, Florida, Texas, Illinois and Louisiana. Of the stacks identified, 26 were operating, 24 were inactive, and 13 were considered idle. An operating or active stack is one that is currently receiving gypsum, and an inactive stack is one that is permanently closed. A stack was classified as idle if there were definite plans to reactivate it and it has the characteristics of an active stack, e.g., water may be maintained on the stack top surface and utilized in the water balance for the facility. The phosphogypsum stacks ranged in area from approximately 5 to almost 741 acres, and heights of the stacks ranged from 3 to about 60 meters.

The number of phosphogypsum stacks in each state is given in Table 2-8. The information in this table relates the phosphogypsum stacks to individual states and gives the

Table 2-6. Average activity ratios of major radionuclides in composite phosphogypsum samples (Ho88).

Radionuclides	Activity Ratio
Ra-226 / U-238	9.1
Th-230 / U-238	1.7
Pb-210 / U-238	13.0
Pb-210 / Ra-226	1.4
Po-210 / Pb-210	0.74
U-234 / U-238	1.1

distribution of stack and stack areas within each category (operating, idle, and inactive). Over half of the operating stacks are in Florida, which accounts for 57 percent of the total base area of all operating stacks. In 1989, the total base area of all phosphogypsum stacks in the United States was approximately 8,490 acres, of which 69 percent was associated with operating stacks, 14 percent with idle stacks, and 17 percent with inactive stacks. From Table 2-8, it is apparent that older inactive stacks are generally much smaller than the newer operating stacks. For example, the average base area of an operating stack was 224 acres, while the average base area of an inactive stack was only 60 acres.

In addition to their large sizes, operating phosphogypsum stacks are characterized by other physical features. Large areas of the stack top are covered by ponds of water, ditches, or beaches (saturated land masses that protrude into the ponds). These surface features may cover up to 75 percent of the top of the stack. Other surface features include areas of loose, dry materials, access roads, and thinly-crusted stack sides. Inactive stacks are characterized by a hard, thick-crusted top and dry, thinly-crusted sides.

2.2.3 Production Rate of Phosphogypsum

The production of phosphogypsum can be estimated by applying the rule of thumb of 4.5 MT of phosphogypsum per Mt of P_2O_5 (Gu75). For illustrative purposes, the annual phosphate rock, phosphoric acid, and phosphogypsum production rates are provided in Table 2-9 for selected years since 1965 (TFI89, TVA86).

Table 2-7. The location and characteristics of phosphogypsum stacks in the United States (EPA89a).

Facility Name		Location	Stack Status	Stack Height(m)	Base Area(acres)
Districhem Inc.(a)		Helena, AR	Inactive	23(a)	22
Agrico Fertilizer Co.		Bartow, FL	Operating	21	346(a)
Royster Phosphate,Inc(a)		Palmetto, FL	Operating	21	299
Brewster Phosphates		Bradley, FL	Inactive	9	124
CF Industries, Inc.		Plant City, FL	Operating	28	400
CF Industries, Inc.		Bartow, FL	Idle(a)	40	361
Conserv, Inc.	1(b)	Nichols, FL	Operating	10	79
	2		Operating	27	77
Estech, Inc.		Bartow, FL	Inactive	9	27(a)
Farmland Industries,Inc.		Bartow, FL	Operating	20	227
Gardinier, Inc.		Tampa, FL	Operating	54	341
Seminole Fertilizer Corp.	1	Bartow, FL	Operating	6	158
	2		Operating	27	561
IMC Corp.		Mulberry, FL	Operating	24(c)	388(c)
Occidental Chem.Co. (Suwanne River)	1	White Spgs, FL	Operating	22	99
	2		Operating	20	99
Occidental Chemical Co. (Swift Creek)		White Spgs, FL	Operating	18	131
Royster Co.	1	Mulberry, FL	Operating	18	74
	2		Operating	24	44
USS Agri-Chemicals,Inc.		Bartow, FL	Inactive	18	49
USS Agri-Chemicals,Inc.		Ft. Meade, FL	Operating	23	151
Nu-West Ind.,Inc.(a)		Conda, ID	Operating	24	89
J.R. Simplot Co.	1	Pocatello, ID	Idle	12(d)	42(d)
	2		Operating	20(d)	200
Bunker Hill Co. 1		Kellogg, ID	Inactive	8(e)	5(e)
	2		Inactive	8(e)	12(e)
	3		Inactive	8(e)	49(e)
General Chemical Corp.		E.St.Louis, IL	Inactive	9	21

Table 2-7. The location and characteristics of phosphogypsum stacks in the United States (EPA89a) (continued).

Facility Name		Location	Stack Status	Stack Height(m)	Base Area(acres)
F&W Flying Service, Inc.		Marseilles, IL	Inactive	6	65
Mobil Mining & Minerals Co.		Depue, IL	Inactive	13	135
Northern Petrochem. Co.		Morris, IL	Inactive	4	69
Olin Corp.	1	Joliet, IL	Idle(a)	27	210(a)
	2		Inactive	5	20(a)
Smith Douglas/Borden		Streator, IL	Inactive	18	25(a)
Quantum Chemical Corp.		Tuscola, IL	Inactive	16	79
Agrico Fert. Co.	1	Ft. Madison,IA	Inactive	30	49
	2		Inactive	9	49
	3		Inactive	5	59
Agrico Fertilizer Co.		Donaldsonville, LA	Operating	12	502(f)
Arcadian Corp.	1	Geismar, LA	Idle	20(a)	94(a)
	2		Idle	12(a)	35(a)
	3		Idle	12(a)	27(a)
	4		Operating	6(a)	22(a)
Agrico Fert. Co.(a)		Hahnville, LA	Operating	4	22
Agrico Fert. Co.(a)		Uncle Sam, LA	Operating	20	702(g)
Nu-South Ind., Inc.(a)		Pascagoula, MS	Operating	20	250
Farmers Chemical Co.		Joplin, MO	Inactive	15	69
W.R. Grace and Co.	1	Joplin, MO	Inactive	10(a)	25
	2		Inactive	10(a)	25
Texasgulf Chem. Co.	1	Aurora, NC	Idle(a)	26(a)	40(a)
	2		Idle(a)	18(a)	74(a)
	3		Idle(a)	38(a)	126(a)
	4		Idle(a)	19(a)	126(a)
	5		Operating(a)	20(a)	126(a)
Amoco Oil Co.	1	Texas City, TX	Idle	11	35
	2		Idle	3	5

Table 2-7. The location and characteristics of phosphogypsum stacks in the United States (EPA89a) (continued).

Facility Name		Location	Stack Status	Stack Height(m)	Base Area(acres)
Kerley Agricultural Chem. of TX Inc.		Pasadena, TX	Inactive	11	27
Mobil Mining and	1	Pasadena, TX	Inactive	27	59
Minerals Div.	2		Inactive[(a)]	27	89
	3		Operating	30	151
Phillips Chemical Co.		Pasadena, TX	Idle	27	35
Four Court Incorporated		Magna, UT	Inactive[(h)]	5	299
Chevron Chemical Co.		Rock Sp., WY	Operating	10[(i)]	450

(a) Jo88b.

(b) Numbers 1,2,3, etc. refer to different stacks at a facility.

(c) Ba88; (d) Si88; (e) Ap88; (f) Wa88b; (g) Wa88a; (h) Co88; (i) Default value.

Note: Information in this table is from PEI85, except for that identified by footnotes (a), and (c) to (i), and relates to 1988-1989 conditions.

These production figures reflect the capacity of the phosphate mining industry for the last 20 years. It is evident from Table 2-9 that the yearly phosphogypsum production has averaged nearly 40 million MT since 1984. However, this estimate may be low, as the estimated quantity of phosphogypsum produced in 1988, 41.9 million MT, is less than the total reported by the EPA for the same year for six of the larger production states, 46.8 million MT (see Table 2-5). The total phosphate waste volume generated in the U.S. from 1910 to 1981 has been estimated at 7.7 billion MT (EPA85). In Central Florida, the phosphoric acid industry produces about 32 million MT of phosphogypsum each year, with a current stockpile of nearly 400 million MT (SCA91).

The amount of phosphogypsum that will be produced in future years is uncertain. Predictions of the amount of phosphogypsum that will be produced during the next 20 years are reported to range from 310 to 910 million MT (SCA91). Thus, although the amount of phosphogypsum that must be managed in future years will certainly be large, it is not possible to predict with a reasonable degree of certainty the growth of the total phosphogypsum inventory in the U.S.

Table 2-8. Summary of the phosphogypsum stacks in each state-1989 (EPA89a).

State	Number of Stacks	Total Base Areas, acres[a]		
		Operating	Idle	Inactive
Arkansas	1	0	0	22 (1)
Florida	20	3319 (16)	361 (1)	200 (3)
Idaho	6	289 (2)	42 (1)	67 (3)
Illinois	8	0	210 (1)	410 (7)
Iowa	3	0	0	158 (3)
Louisiana	7	1248 (4)	156 (3)	0
Mississippi	1	250 (1)	0	0
Missouri	3	0	0	119 (3)
N. Carolina	5	126 (1)	366 (4)	0
Texas	7	151 (1)	74 (3)	175 (3)
Utah	1	0	0	299 (1)
Wyoming	1	450 (1)	0	0
Total	63	5833 (26)	1209 (13)	1450 (24)
Average Stack Area		224	93	60

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[a] Number of stacks is shown in parentheses.

Table 2-9. Annual phosphate fertilizer production rates.

Year	Phosphate Rock (million MT)	Phosphoric Acid (million MT)	Phosphogypsum (million MT)
1965	26.8	3.5	15.8
1970	35.1	5.2	23.4
1975	44.3	7.0	31.5
1980	54.4	9.8	44.1
1984	49.2	9.9	44.6
1985	44.8	8.9	40.1
1986	32.8	7.4	33.3
1987	35.7	8.1	36.5
1988	38.3	9.3	41.9

3. USES OF PHOSPHOGYPSUM

3.1 INTRODUCTION

Phosphogypsum is currently being used in several commercial applications with additional research being conducted, primarily by the Florida Institute of Phosphate Research (FIPR), in order to identify new applications and expand existing ones. Currently, applications include (SCA91):

1) fertilizer and conditioner for soils where peanuts and a variety of other crops are grown;

2) backfill and road-base material in roadway and parking lot construction;

3) additive to concrete and concrete blocks;

4) mine reclamation; and

5) recovery of sulfur.

Each application is discussed below. Agriculture, and to a lesser extent mine reclamation, presently utilizes the largest quantities of phosphogypsum. Other uses have not moved past the development stage of field testing in the U.S. However, this could change in the future if present restrictions on the disposal of phosphogypsum are removed. Research is continuing on additional uses of phosphogypsum as a soil conditioner, as well as other uses, e.g., sulfur recovery, in ceramic products, as anti-skid aggregate, and as a concrete aggregate (SCA91).

Due to the absence of low-cost natural gypsum and the lack of long-term storage space, the use of phosphogypsum in Europe and Japan has been much more widespread than in the U.S. These countries have used phosphogypsum extensively in cement, wallboard, and other building materials (SCA91).

Because of the elevated levels of radionuclides, primarily radium-226, in phosphogypsum, building construction materials containing phosphogypsum could result in elevated radiation exposures to building occupants. Phosphogypsum was used by a New Jersey based company in the manufacture of wallboard, partition blocks, and plaster for distribution in the northeastern United States between 1935 and 1946 (Fi78). No wallboard containing phosphogypsum is currently manufactured for commercial use in the United States. Therefore, the use of phosphogypsum in wallboard and the associated risk will not be addressed in this assessment.

Radon measurements conducted in a room constructed of Japanese phosphogypsum wallboard at EPA's National Air and Radiation Environmental Laboratory did not detect any increase in indoor radon concentrations (Se88). The emanation fraction was estimated to be less than 2 percent. However, a modular structure constructed of ferrocement panels containing 50 percent phosphogypsum, 25 percent cement, and 25 percent fine aggregate resulted in radon levels, measured under worst-case ventilation conditions (i.e., the structure was made as air-tight as possible) that averaged 4 to 5 pCi/L (Ch87). The upper end of this range is above the level at which the EPA recommends that homeowners take action to determine the long-term average radon concentration in their home (EPA86).

The amount of phosphogypsum currently being used in the U.S. for the above purposes is small compared to the total amount being produced. It has been estimated that only about 5 percent of the U.S. phosphogypsum output is utilized in some way (An88). The quantities of phosphogypsum sold each year are compared in Table 3-1 to the annual production rates at eight facilities (Va89). The phosphogypsum sold at these facilities was primarily for agriculture. Although this survey does not include all facilities, it does indicate the small scale use of phosphogypsum in the United States.

3.2 AGRICULTURAL APPLICATIONS

For more than 30 years, phosphogypsum has been used in the United States as a conditioner for clayey and sodic(a) soils because of its moisture retaining and salt leaching properties. Its use is considered critical to maintaining soil productivity in the southeastern states where highly weathered soils have poor physical properties and high erodability (TFI90a). In addition, phosphogypsum provides needed nutrients, such as calcium and sulfur, to deficient soils. The phosphogypsum in the southeast is used primarily by peanut growers in Georgia, North Carolina, Virginia, and Alabama. Studies have also indicated that phosphogypsum may be beneficial to southeastern soils used to grow tobacco, corn, small grain, and sugar cane. Currently, the state of Georgia is the largest consumer of phosphogypsum, applying 120,000 to 180,000 MT annually to its peanut fields. Application rates vary depending on the crop, soil type, and purpose of the amendment. Phosphogypsum is a source of calcium for peanuts and is added at rates of 0.2-0.4 MT/acre per year. It is applied at higher rates, 0.8-1.2 MT/acre per year, on acidic, crusting soils to improve physical properties and mitigate subsoil acidity (Mi91).

There is also a large demand (estimated 500,000 to 750,000 MT/yr (TFI90a, Va89) for agricultural use of gypsum in California to amend sodic soils growing such crops as citrus, almonds, vegetables, and tomatoes. In 1985, more than 270,000 MT of phosphogypsum were applied to fields in California. The sales of phosphogypsum for agriculture declined sharply to about 84,500 MT in 1988, due primarily to the depletion of phosphogypsum stacks in that state. As a result, phosphogypsum is currently being shipped into California from Utah.

(a)Soils containing elevated levels of sodium.

Table 3-1. Quantities of phosphogypsum sold at eight facilities-1988 (Va89).

Facility Name	Location	Tons Sold Per Year	Percent of Annual Facility Production
Arcadian Corp.	Geismer, LA	5,000	0.7
Farmland Industries, Inc.	Bartow, FL	0-5,000	0 - <0.2
Four Court, Inc.	Magna, UT	200,000(a)	(b)
Mobil Mining & Minerals Div.	Pasadena, TX	(c)	10 - 15
Occidental Chemical Co.	White Springs, FL	100,000	<1
Royster Co.	Mulberry, FL	(c)	<1
J.R. Simplot Co.	Pocatello, ID	40,000-50,000	3-4
Texasgulf Chemicals Co.	Aurora, NC	100,000-150,000	2-3

(a) Shipped to San Joaquin Valley, CA.
(b) Facility is inactive, but has about 8 million tons stockpiled.
(c) Information not provided.

The Fertilizer Institute (TFI) circulated a questionnaire to which eight farmers in California and 30 farmers in Georgia who regularly apply phosphogypsum to their fields responded (TFI90a, Appendix 38). The crops grown in the amended soils in California were almonds and walnuts (69 acres), peaches (40 acres), grapes (20 acres), alfalfa, corn, beans, and oats (1080 acres), and trees (75 acres). The farms in Georgia were used exclusively for growing peanuts, a total of about 4,200 acres. The following results were obtained from this survey.

	Georgia	California
Application, tons/acre	0.06 - 1.0 (0.44)[a]	1.0-2.0 (1.3)
Acres Amended per Farm	5-700 (139)	7-1,000 (183)
Years of Application	3-40 (17.3)	2-15 (10.5)
Average Tillage Depth, inches	1-15 (8.3)	0-18 (7.4)[b]

[a] Average values are given in parenthesis.
[b] Depended significantly on crop.

This is a small sampling of the total farmers that apply phosphogypsum to their fields; however, it probably presents a representative cross-section of this practice, particularly for the peanut farmers in the southeastern United States.

3.3 ROAD CONSTRUCTION

Phosphogypsum, mixed with fly ash, sand, gravel, or cement, has been successfully used in the United States as a base for roads, parking lots, and storage areas. The use of phosphogypsum for road bed construction has been most extensive in the Houston, Texas area (L185, Kr88), with some application in Florida (FIPR88). The quantities of phosphogypsum sold for roadbed construction in Texas and Florida in 1988 was estimated to be about 140,000 MT per year (Kr88). The quantities of phosphogypsum used in North Carolina are not available. However, considering the large amount of phosphogypsum in Florida and the strong demand for aggregate in that state, the use of phosphogypsum in road construction could significantly increase. Some applications of phosphogypsum in roadway and parking lot construction are described below (EPA90, TFI90a).

1) Phosphogypsum from Mobil's facility in Pasadena, Texas was mixed with fly ash or cement and used as road base on five sections of city streets in La Porte, Texas, near Houston.

2) In Polk County, Florida, 2.4 km of road base was constructed of a compacted mixture of phosphogypsum and granular sand, and surfaced with one to two inches of asphalt.

3) In Columbia County, Florida, a 2-mile stretch of road base was constructed using both 100 percent dihydrated phosphogypsum and mixtures of phosphogypsum and sand in ratios of 1:2, 1:1 and 2:1. The road base was then surfaced with one to two inches of asphalt.

4) Phosphogypsum has been used commercially in North Carolina as a fill and sub-base in roads crossing swampy areas.

5) A mixture of phosphogypsum (13 percent) and concrete was used to pave 1,670 m^2 (2,000 yd^2) of driveways and parking areas at the Florida Institute of Phosphate Research in Bartow, Florida.

Several investigators have studied direct radiation exposures from gamma-rays and radon-222 resulting from the use of phosphogypsum in roadbed construction. Roessler reports external gamma-ray exposures ranging as high as 20 μR/hr over a roadbed constructed on a 100 percent phosphogypsum base, to 10-11 μR/hr over roadways constructed of a 25 percent phosphogypsum/gravel or sand base and paved with asphalt (Ro87b). Radon flux measurements over the roadways generally ranged between 1 to 2 pCi/m^2-s. When the roadbed was sealed with asphalt, the radon flux was less than 1 pCi/m^2-s. Exposures along the sides of the roadways were near the background gamma-ray and flux levels of 8-10 μR/hr and less than 0.1 pCi/m^2-s, respectively. Another source cites similar exposure levels (An88).

3.4 CONCRETE AND CEMENT BLOCKS

Phosphogypsum has been used on a very limited basis in the manufacture of building materials, e.g., concrete and cement blocks. Phosphogypsum is not currently being used in the United States in the manufacture of building materials. It is widely used for this purpose in Europe and Japan. It is believed that the utilization of phosphogypsum as a raw material for building materials will require further evaluation and probably the establishment of standards for final construction materials. The potential demand for phosphogypsum for this purpose is not known, but would probably not be great. An exception may be in Florida where there are large quantities of phosphogypsum and a high demand for cement. Currently, natural gypsum is used extensively in cement; about 19 percent of the natural gypsum used in the United States is used as an additive to cement (EPA90).

3.5 SULFUR RECOVERY

Extensive research has been conducted to develop a technology to recover sulfur from phosphogypsum. The development stage appears to be complete and the process could become commercially available should the price of sulfur, currently at $110.00/long ton, increase significantly (Ll91). In general, sulfate is converted to sulfur dioxide (SO_2) by a high temperature decomposition of calcium sulfate ($CaSO_4$) in the phosphogypsum. The sulfur dioxide is scrubbed from the gaseous emissions and sent to the facility's chemical plant where it is converted to sulfuric acid (H_2SO_4) which is utilized in the wet-acid process.

A pilot project to produce sulfuric acid and aggregate has operated successfully at the Agrico plant near Uncle Sam, LA (Ll91). Using the circular grate process, the plant utilized about 35 tons of phosphogypsum and other materials to produce about 30 tons of sulfuric acid and 25 tons of aggregate per day. The plant began operation in 1988 but is presently mothballed, a result of the low price of sulfur.

Consolidated Minerals, Inc. proposes to construct on a 17,100 acre site in DeSoto County, Florida, a multi-production facility that will include a sulfur recovery process. The sulfur dioxide recovered will be converted to sulfuric acid and used in the phosphate fertilizer production unit to precipitate calcium sulfate. In addition to the usual phosphate fertilizer products, the process will also produce calcium oxide for use in Portland cement. The waste products from the plant will include a more pure phosphogypsum (dihydrate with some hemihydrate and anhydrate forms) containing lower radium-226 concentrations (reported to be less than 5 pCi/g) and the insoluble impurities that contain most of the radium-226. It is planned to return the latter to the mine site as part of the reclamation process. The plant is presently scheduled to begin operation in late 1994.

3.6 MINE RECLAMATION

An alternative to the disposal of phosphogypsum directly in stacks has been developed in which the phosphogypsum is mixed with a phosphatic clay suspension (a waste from the beneficiation of phosphate rock) in the approximate ratio of 3 parts phosphogypsum to 1 part clay. The suspension is then pumped to the disposal site. The mixture will dewater and become consolidated in about one year, after which the surface can be revegetated with grass and trees.

There are two factors that must be considered in determining if a phosphogypsum facility can utilize this disposal method. First, the facility must be located near the disposal site (mine) to keep transportation costs to a minimum. Second, the phosphatic clay suspension must contain sufficient base (e.g. calcium carbonate) to neutralize the acids remaining in the phosphogypsum.

Currently, only Texasgulf's facility near Aurora, North Carolina is using this disposal process. At this facility, phosphogypsum is disposed in a mine adjacent to the plant at about the same rate as it is produced (EPA90). Facilities in Florida and Idaho are close enough to mines to make this disposal process feasible. In 1988, mine reclamation could have utilized more than 32 million MT. However, this use is not viable for facilities in Louisiana, Mississippi, and Texas because their phosphate rock is shipped from Florida, nor at the facility in Rock Springs, Wyoming that receives phosphate rock mined in Utah. In 1988, the combined total phosphogypsum generated at these facilities was nearly 10 million MT (EPA90).

Mine reclamation as a means of phosphogypsum disposal is a viable option that may become more prevalent in the future. Two distinct advantages of mine reclamation over the current practice of placing the material in large stacks are the aesthetic advantage of revegetating the mined-out area, and the greatly reduced potential for the waste to be released to surface water by erosion and to the atmosphere by the wind.

3.7 RESEARCH ACTIVITIES

Extensive research is being conducted under the sponsorship of the Florida Institute of Phosphate Research (FIPR) and other organizations to develop commercial uses for phosphogypsum (FIPR87, FIPR89a, FIPR89b, FIPR90a, FIPR90b). Some current and potential uses for phosphogypsum were listed in Section 3.1 and briefly discussed in Sections 3.2 to 3.6. Research and development projects were being actively pursued in all of these applications until the prohibition on its use was enacted on December 15, 1989 (54 FR 51654).

Numerous research efforts have been directed at expanding and developing beneficial uses for phosphogypsum. The major goals of FIPR, an agency of the State of Florida supported financially by the state severance tax on phosphate, are the prevention of further accumulation of phosphogypsum and the reduction of current inventories. FIPR is engaged in research directed toward the recovery of sulfur and other valuable by-products from phosphogypsum; the possible production of building materials such as aggregate, lime, and cement; the use of phosphogypsum as a road-base material; and its use as an agricultural amendment to enhance calcium and sulfur values in the soil.

FIPR and the phosphate industry are not alone in conducting research on possible uses for phosphogypsum. Louisiana State University has established an Institute for Recyclable Materials, one objective of which is the study of beneficial uses of phosphogypsum. Other southeastern universities, including the University of Florida, the University of Miami, and the University of Georgia are also involved in phosphogypsum research.

Research activities related to a few specific potential uses of phosphogypsum are discussed below. This is not intended as a complete listing of current or planned research projects. It is included here only to provide a perspective of the effort being made to identify beneficial uses of phosphogypsum and to point out the diversity of the uses being considered.

3.7.1 Agricultural Uses

AGRO Services International, Inc., under a grant sponsored by FIPR, researched the use of phosphogypsum as a fertilizer on several Florida crops (AGRO89). As part of this study, field trials were conducted using various rates and placement of phosphogypsum (holding constant the addition of other fertilizer containing nutrients not found in gypsum) in order to determine the yield response of several crops to phosphogypsum. The study demonstrated that the application of phosphogypsum on crops, other than cowpeas, is very likely to result in strong economic returns.

Other research studies indicate that phosphogypsum can be an important source of calcium and sulfur for soils that are deficient in these elements (FIPR89b, FIPR90a, Da____). In a study of phosphogypsum as a source of sulfur to improve the yield of wheat grown for forage on sandy loams in Florida and Alabama, phosphogypsum was added at annual rates varying between 12 and 121 kg/acre (FIPR90a). Significant increases in yield were observed at an annual application rate of about 40 Kg/acre. Various studies have also indicated the usefulness of phosphogypsum on crops such as tobacco, corn, wheat, and sugar cane grown in Alabama, Louisiana, and North Carolina (Ba80, Go83).

Phosphogypsum has been found useful in controlling soil erosion and maintaining soil productivity on agricultural fields in the southeastern states where highly weathered soils have poor physical properties and are highly erodable (Mi89, Su80, Oa85). Experimental data indicate that phosphogypsum maintains a higher rate of water infiltration for soils compared with mined gypsum. Higher dissolution of the smaller phosphogypsum crystals provides a relatively high electrolyte concentration in the surface soil, sufficient to prevent crust formation. The improvement in water infiltration rates by phosphogypsum application has resulted in significant reductions in surface water runoff which leads to a reduction in soil erosion. Reductions in soil erosion approaching 60 percent have been observed (Wa89).

3.7.2 Construction Materials

Phosphogypsum use in road construction has been tested in the United States. Several research studies have demonstrated that phosphogypsum is suitable for use as a construction aggregate for various applications, including road construction, road embankments, and railroad beds (Ch89, Ch90). Phosphogypsum has been used on an experimental basis for paving and highway construction in both Texas and Florida (see Section 3.3). The addition of gypsum to cement appears to retard the setting times, counteracts shrinkage, increases the strength of the cement product, and provides resistance to sulfate etching.

Phosphogypsum has the same basic properties as natural gypsum and may be used as a substitute for natural gypsum in the manufacture of commercial construction products such as plasterboard and plaster of Paris. Phosphogypsum has been used extensively in the manufacture of construction materials in Japan, Australia, and Europe. Currently, however, there are no major uses of phosphogypsum in commercial construction materials in the United States due to the low-cost availability of other suitable materials and to the ban on the utilization of phosphogypsum under 40 CFR Part 61, Subpart R. If the ban on the use of phosphogypsum is lifted, research might well lead to the development of building materials that are suitable for the U.S. market.

3.7.3 Purification of Phosphogypsum

The major disadvantage to the commercial use of phosphogypsum is the presence of potentially hazardous concentrations of radium-226. Research is being conducted in the United States and in other countries to reduce or remove the radium from raw phosphogypsum to ensure its safe use in the agriculture and construction industries. Methods for the removal of radium include hydrocycloning, a physical separation process, and calcining raw phosphogypsum into the hemihydrate form which eliminates most of the radium.

The physical process involves the use of a hydrocyclone to separate the smaller phosphogypsum crystals (less than 30 μm) which contain the greatest portion of the radionuclides from the rest of the phosphogypsum (Pe85). Although this process has proven effective in reducing radium concentrations by factors of 2 to 5, it does not remove all of the radium from the phosphogypsum. A new process, which shows promise of producing phosphogypsum of a much lower radioactive content, involves calcining the raw phosphogypsum into the hemihydrate form ($CaSO_4 \bullet 1/2H_2O$) and dissolving the hemihydrate in water (Mo90). The solution is quickly filtered and the radium salts are collected on the filter media.

Although the hemihydrate process generates a relatively low volume of waste, it is concentrated in radium-226, up to 600 pCi/g, and may pose disposal problems that are equal to or even greater than those associated with the original phosphogypsum (EPA90). No information is available on the volume or radium-226 concentration of the waste resulting from the physical separation method, but it too would probably produce wastes with relatively high concentrations of radium-226. This waste disposal problem will need to be resolved if the purification of phosphogypsum is to become viable.

3.8 SUMMARY OF PHOSPHOGYPSUM UTILIZATION

Probably less than 500,000 MT per year of phosphogypsum are being used in the United States today. The majority is for agricultural applications in California and the peanut producing states in the southeast (approximately 220,000 MT/year). The remaining quantity is for road construction in Texas and Florida (approximately 140,000 MT/yr). Quantities used for mine reclamation are not presently available, but could be substantial in the future if it were decided to dispose of the phosphogypsum by this process. The quantities of phosphogypsum used for building materials and research are very small.

The historic usage of phosphogypsum from 1984 through 1987 shows a general decline, primarily due to the closing of the California facilities and the depletion of the phosphogypsum generated in that state. This decline is demonstrated in Table 3-2 (Jo88a, EPA89a).

Table 3-2. Estimated quantities of phosphogypsum used per year (EPA89a).

Year	Total Estimated MT(a)
1984	660,000
1985	460,000
1986	540,000
1987	360,000

(a) These totals are based on the results of a mail survey (Jo88a). Since some of the companies failed to respond to the survey, it does not represent a total response for the industry; however, it is believed that the survey gives an approximate total usage rate.

4. RADIOLOGICAL ASSESSMENTS OF PHOSPHOGYPSUM USE

4.1 INTRODUCTION

The purpose of this assessment is to analyze the radiological risk associated with various uses of phosphogypsum. The PATHRAE dose assessment model is employed to evaluate potential doses and risks for plausible exposure scenarios involving the commercial use of phosphogypsum. Section 4.3 provides a discussion of the methodology for this risk assessment, including a brief description of the PATHRAE dose assessment model, the exposure scenarios evaluated, and the input parameter values used in the PATHRAE analysis. The results of the risk assessment are summarized in Section 4.4. Risks to workers, to individuals in the critical population group (CPG), and to reclaimers are evaluated for agricultural, road construction, and research and development (R&D) uses of phosphogypsum.

There is some concern that crops grown in soils amended with phosphogypsum may contain elevated concentrations of radionuclides, primarily radium-226, polonium-210, and lead-210 (see Table 2-3). To better understand the significance of this pathway, both long- and short-term uptake studies were conducted at the University of Georgia for the EPA (Mi91). As part of the study, the leachability of radionuclides in amended soils was investigated. The results of the University of Georgia study are presented in Section 4.2.

4.2 RADIOLOGICAL EFFECT OF AMENDING SOILS WITH PHOSPHOGYPSUM

Both long- and short-term studies were conducted by the Agronomy Department at the University of Georgia to determine the significance of the uptake of radionuclides by plants grown in soils treated with phosphogypsum (Mi91). Locations having two different soil types were selected for study: one at Athens, GA where there is a sandy loam topsoil (25-30 cm) overlying a clayey subsoil, and at Tifton, GA where there is a very sandy topsoil (50 cm) over a sandy clay loam subsoil.

4.2.1 Long-Term Study

In 1985, 2 m by 5 m plots were established at both locations and treated with an equivalent of 4 MT/acre (simulating 5 to 10 years of field treatment) of phosphogypsum from Bartow, FL. The phosphogypsum was mixed with the top 15 cm of soil and planted with alfalfa. Similar untreated plots were used as controls. All plots were treated with commercial nitrogen, phosphorus, and potassium fertilizers. Plant tissues were randomly harvested from each plot in 1990, after which five core samples, 5 cm in diameter and 90 cm deep, were obtained from each plot, divided into three sections (0-15 cm, 15-30 cm, and 75-90 cm depths), and combined with respect to the depth increment.

4.2.2 Short-Term Study

This study was conducted in 1990 at the Athens, GA farm. Plots of 4 m by 5 m were treated with an equivalent of 4 MT/acre of the same phosphogypsum that was used in the long-term study. The phosphogypsum was lightly raked into the soil surface immediately after soybeans had been planted in June. Untreated plots were used as controls. The soybeans were harvested in the fall and separated into leaves (including stems) and seeds.

Prior to analysis, the plant samples were dried at 60°C and ground in a Wiley mill. The soil samples were air-dried and sieved to <2 mm. All samples, including samples of the phosphogypsum used in the studies, were analyzed for isotopic uranium and thorium, radium-226, lead-210, and polonium-210.

Of the pertinent radionuclides, only Ra-226 was consistently present above the detection limit in the soil samples; however, concentrations in samples from the treated plots were no higher than those from the control plots, about 2 pCi/g. The analysis of core samples from fields treated five years earlier with phosphogypsum showed no detectable elevated levels of radionuclides at any depth. These results were attributed to the small quantities of radionuclides added in the phosphogypsum relative to the amounts naturally present in the soil.

Radium-226 was the only radionuclide associated with phosphogypsum that was detected in either alfalfa or soybeans. There were no statistical differences in the concentration of Ra-226 measured in plant tissues grown in the treated and control plots. Although the uptake of Ra-226 was measurably higher in alfalfa grown in Tifton soil than in alfalfa grown in Athens soil (2 pCi/g dry weight vs less than 1 pCi/g dry weight), it was not statistically significantly greater in plants from treated soils than in the controls at the two sites. The dominant radionuclide was potassium-40 in both plant types, ranging from about 7 to 20 pCi/g dry weight.

4.2.3 Leaching Studies

A series of leaching studies was performed as part of the uptake studies (Mi91). Intact soil columns, 10 cm diameter and 30 cm deep, were taken of both Tifton and Athens soils using a truck-mounted hydraulic ram. Two columns of each soil type were treated with an equivalent of 4 MT/acre of the phosphogypsum used in the uptake studies. The phosphogypsum was applied as a powder to the soil surface. Two columns of each soil type were untreated and used as controls. Deionized water was ponded on the surface at a constant 2-cm depth and allowed to perculate through the column until a total of 8 liters of leachate in 1-liter increments had been collected from the column base. This is equivalent to about one year of precipitation.

The leachate was filtered to remove suspended clay particles prior to analysis. The columns were cut into 5-cm sections, and the soil in each section analyzed separately for the same radionuclides as listed above for the soil samples.

Only Ra-226 was consistently detected in the leachate of the soil columns. The amount of Ra-226 leached from the treated and untreated Athens soil columns was about the same, totaling 2.2 pCi in the 8 liters collected. However, the Ra-226 concentrations in the leachate of Tifton soil treated with phosphogypsum was 3 to 5 times higher than in the control leachate. The Ra-226 concentration in the leachate peaked at 3 liters (0.8 pCi/L), and then decreased to near the control level after 8 liters were collected. The total amount of Ra-226 collected in the Tifton soil leachate was 6.5 pCi, equivalent to about 5 percent of the Ra-226 initially added in the phosphogypsum. The higher leachability of Ra-226 in the Tifton soil was attributed to the sandy nature of the soil allowing rapid percolation of water with limited adsorption capacity of the soil. No discernable trend was observed in the Ra-226 concentration with soil depth.

Considering the relative immobility of the principal radionuclides associated with phosphogypsum in soil and the small quantities added in the phosphogypsum relative to the amounts naturally present in the soil, 0.7 pCi/g and 1.9 pCi/g of radium-226 in Tifton and Athens soils, respectively, University of Georgia investigators concluded that short-term treatments (5-10 years) of farm lands with phosphogypsum does not pose an acute environmental hazard.

Studies conducted earlier to characterize the radiological hazards associated with soils amended with phosphogypsum produced similar results and conclusions. A University of Florida study of radionuclide uptake by foods grown in soil receiving one ton of phosphogypsum per acre every four years concluded that there would be no significant radiation problems for up to at least 50 years (Ro88). Another study measured the radon flux on three fields that had been amended with varying amounts of phosphogypsum for different periods of time (Po90). The mean of 13 flux measurements, using charcoal canisters, made on each field ranged from 0.4 to 1 pCi/m^2-s. The background flux, measured on areas receiving no application, was 0.4 pCi/m^2-s. It was difficult to correlate the radon flux measurements with the amount of phosphogypsum applied.

4.3 RISK ASSESSMENT METHODOLOGY

The methodology employed in evaluating individual and population risks from commercial uses of phosphogypsum is described in this section. Dose calculations were performed using the PATHRAE dose assessment model (EPA87). Calculations were performed for exposure scenarios which included the use of phosphogypsum in agriculture, road construction, and R&D activities. Where PATHRAE does not model the exposure scenario (e.g., a person performing experimental analyses on phosphogypsum contained in metal drums), the MICROSHIELD computer code (GRO85) was used to augment the results of the PATHRAE analyses. Lifetime risks from one year of exposure were obtained from the PATHRAE dose assessment results using the risk conversion factors in the EPA's Environmental Impact Statement for NESHAPS radionuclides (EPA89b).

4.3.1 The PATHRAE Dose Assessment Model

The PATHRAE performance assessment model (EPA87) was initially developed as an analytical tool to assist EPA in developing standards for low-level radioactive waste and below regulatory concern waste disposal. The PATHRAE model estimates health effects which could potentially occur if radioactive wastes were disposed of in a near surface facility, sanitary landfill, or other geological setting. PATHRAE can be used to calculate effective dose equivalents[a] to members of a critical population group from the disposal of radioactive material at sites located in diverse hydrogeologic, climatic, and demographic settings. An important PATHRAE model feature is its simplicity in analyzing a comprehensive set of radionuclides, disposal settings, and exposure pathways. The effects of changes in disposal site and facility characteristics can be readily investigated with relatively few parameters needed to define the problem.

PATHRAE models both off-site and on-site pathways through which persons may come in contact with radioactivity from disposed material. The off-site pathways include groundwater transport to a well and a river, surface water runoff to a river, and atmospheric transport of radioactive particulates. On-site pathways include direct gamma exposure, dust inhalation, exposure from foodstuffs grown on-site, and inhalation of radon gas and radon daughters. See Appendix A for a detailed description of the PATHRAE pathway equations.

For this risk assessment, the phosphogypsum is assumed to be mixed with soil in an agricultural field or mixed with other construction materials to construct roadbeds and concrete highways. Exposure scenarios and values for some important input parameters used in modeling these scenarios are described later in this section.

4.3.2 The MICROSHIELD Computer Code

Where the exposure geometry is not readily modeled by PATHRAE (e.g., person exposed to the radioactivity in phosphogypsum contained in metal drums), MICROSHIELD was used to estimate the external gamma dose. MICROSHIELD (GRO85) is a microcomputer adaptation of the ISOSHLD II (Eng66) mainframe code for analyzing gamma radiation shielding. MICROSHIELD has solution algorithms for 14 different geometries which include point, line, sphere, disk, cylinder, plane, and rectangular volume sources; and slab, cylindrical, and spherical shield configurations. MICROSHIELD sorts individual gamma energies from each isotope in the source term into 21 energy groups. Dose rate calculations are performed by one of three geometry-based calculational routines which include analytical expressions, Simpson's rule integration, and point-kernel integration. Execution of the program proceeds by repeating the solution algorithm for each energy group that has any activity until all 21 energy groups have been evaluated.

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[a] Throughout this report the term "dose" refers to the effective whole body dose equivalent.

The MICROSHIELD code user supplies input information describing the characteristics of the exposure scenario to be evaluated. This input information includes: distance between the source and the exposed individual; source inventory; dimensions of the source region; the dimensions, locations, and orientations of intervening shields; and the material (including air) used for these intervening shields.

4.3.3 Exposure Scenarios

The exposure scenarios evaluated for this phosphogypsum risk assessment include potential exposures to individuals from the use of phosphogypsum in agriculture, road construction, and R&D activities.

4.3.3.1 Phosphogypsum in Agriculture

Seven scenarios involving the agricultural use of phosphogypsum are evaluated. Scenarios 1, 3, and 5 assume a clay soil base type, with the exposed individual being greater than 100 m from the site edge. Scenarios 2, 4, and 6 consider similar pathways, using a sand soil base type, and exposed individuals 100 m from the site boundary. Scenarios 1 through 4 involve the use of phosphogypsum as a source of calcium and sulfur for soils deficient in these elements. Scenarios 5 and 6 involve its use in sediment control for soils that have been eroded and leached. Scenario 7 evaluates the effect of using phosphogypsum containing a range of Ra-226 concentrations with different application rates.

Scenarios 1 through 4: Phosphogypsum as a source of calcium and sulfur for soils deficient in these elements. Parameters which characterize the four scenarios involving phosphogypsum as a source of calcium and sulfur on agricultural fields are shown in Table 4-1. Four scenarios are evaluated: two involving an average phosphogypsum application rate on a moderate size clay or sand field, and another for a maximum application rate on a large clay or sand field. The parameter values in Table 4-1 are based on responses by agricultural users of phosphogypsum to a survey by The Fertilizer Institute (TFI). The reference agricultural fields for Scenarios 1 through 4 are postulated to be located in the southeastern United States. Values of environmental and climatological parameters used in the risk assessment are representative of a humid permeable site.

The dose calculations for Scenarios 1 through 4 assume biennial applications of phosphogypsum to the reference site for a period of 100 years. Phosphogypsum is spread over a field and diluted by mixing with the soil. Hence the incremental radionuclide concentrations in the soil are much lower than the concentrations in the phosphogypsum itself. Over time, as phosphogypsum continues to be applied, the radionuclide concentrations in the soil are expected to increase until equilibrium is reached with competing mechanisms that remove the gypsum, and its radioactive constituents, from the soil. These removal mechanisms include plant uptake, leaching by infiltration of surface water, and wind and water erosion. The radionuclide content in the soil is also reduced as a result of radioactive decay. A simple mass balance equation is used to estimate radionuclide concentrations in the

Table 4-1. Phosphogypsum use parameters for Scenarios 1 through 4.

	Average Site (Scenario 1&2)	Maximum Site (Scenario 3&4)
Kilograms of phosphogypsum per acre	664	2,032
Acres per farm	138	1,000
Tillage depth (cm)	22	46
Application rate	Biennially	Biennially
Distance to nearest residence (m)	890 & 100	6,440 & 100
Soil Type	Clay, Sand	Clay, Sand

reference soil as a result of biennial applications of phosphogypsum for a period of 100 years. For a Ra-226 concentration of 30 pCi/g in phosphogypsum, the increase in the Ra-226 concentration in the soil after 100 years of biennial application is calculated to be 0.69 pCi/g for Scenarios 1 and 2 and 1.02 pCi/g for Scenarios 3 and 4. A detailed description of the Ra-226 soil concentration calculation method is presented in Appendix B.

Scenarios 5 and 6: Phosphogypsum as sediment control for soils that have been eroded and leached. Parameters which characterize Scenarios 5 and 6 are shown in Table 4-2. The reference agricultural site for this scenario is assumed to be located in south-central California. The phosphogypsum is initially applied at the rate of 8 MT per acre, followed by biennial applications of 4 MT per acre. As in Scenarios 1 through 4, an application period of 100 years is postulated. For a Ra-226 concentration of 30 pCi/g in phosphogypsum, the increase in the Ra-226 concentration in the soil after 100 years of biennial application is calculated to be 3.12 pCi/g for Scenarios 5 and 6.

For Scenarios 1 through 6 the following exposure pathways are evaluated:

- <u>Agricultural Worker</u>
    - Direct gamma exposure
    - Dust inhalation

- <u>On-site Individual</u>
    - Direct gamma exposure
    - Indoor radon inhalation
    - Use of contaminated well water

- Member of CPG
  - Inhalation of contaminated dust
  - Ingestion of drinking water from a contaminated well
  - Ingestion of foodstuffs contaminated by well water
  - Ingestion of foodstuffs grown on fertilized soil
- Off-Site Individual
  - Ingestion of river water contaminated via the groundwater pathway
  - Ingestion of river water contaminated by surface runoff.

Table 4-2. Phosphogypsum use parameters for Scenarios 5 and 6.

Kilograms of phosphogypsum per acre	
- Initial application	8,000
- Subsequent applications	4,000
Acres per farm	556
Tillage depth (cm)	30
Application rate	biennially
Distance to nearest residence (m)	1,000 & 100
Soil Type	Clay, Sand

The agricultural worker is assumed to spend 2,000 hours per year at the agricultural site, performing activities such as plowing, fertilizing, harvesting, etc. The worker would probably use machinery for most of these activities which would provide some shielding from direct gamma radiation (as in the construction scenarios plowing equipment on average provide a shielding factor of 0.6). However, to ensure conservatism in the results of this risk analysis, no credit for shielding is taken in calculating the dose from direct exposure to gamma radiation.

The on-site individual is assumed to live in a house in a development constructed on a site which was previously used for agriculture. For conservatism, this individual is also assumed to work at this same site.

The CPG is defined to include individuals who might be exposed to the highest doses as a result of normal daily activities. For this phosphogypsum risk assessment, the member of the CPG is assumed to be an adult at the nearest residence as defined in Tables 4-1 and 4-2. The person obtains all water from a well adjacent to the house. Fifty percent of foodstuffs are assumed to be grown on-site.

Scenario 7: Use of phosphogypsum as a soil amendment based on the application rate and Ra-226 concentration. The purpose of this scenario is to determine if the phosphogypsum containing various concentrations of Ra-226 can be applied for agricultural purposes based on various application rates. To evaluate the feasibility of this approach, risk estimates are performed for the two limiting exposure pathways identified from Scenarios 1-6, direct gamma and indoor radon exposures to the on-site individual. The risks for these exposure pathways are estimated using the following combinations of phosphogypsum application rates and Ra-226 concentrations:

Application Rate (lbs/acre)	Ra-226 Concentration (pCi/g)
500	3, 7, 15, 20, 30, 45, 60
1,000	3, 7, 15, 20, 30, 45
1,500	3, 7, 15, 20, 30
2,500	3, 7, 15, 20
5,000	3, 7, 15
10,000	3, 7, 15

A nine-inch tillage depth is assumed. All other parameters remain constant and are those given above for the average site in the southeastern United States.

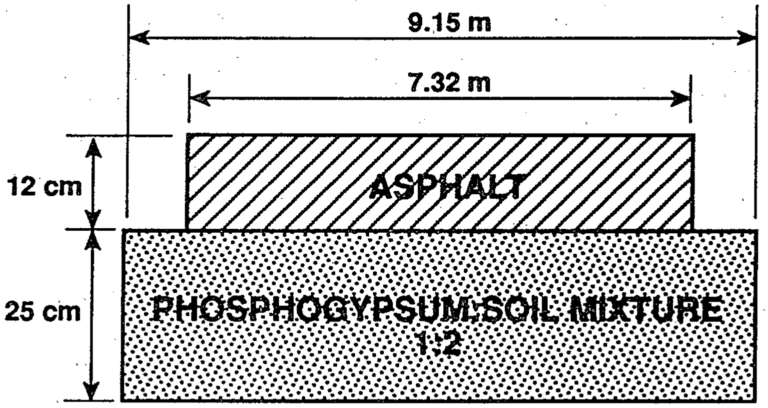
4.3.3.2 Phosphogypsum in Road Construction

Four scenarios involving phosphogypsum in road construction are evaluated. Scenarios 8 and 9 involve the use of phosphogypsum in a road base for a secondary road. Scenarios 10 and 11 involve phosphogypsum as an additive to increase the strength of a concrete road surface. These scenarios are shown schematically in Figure 4-1.

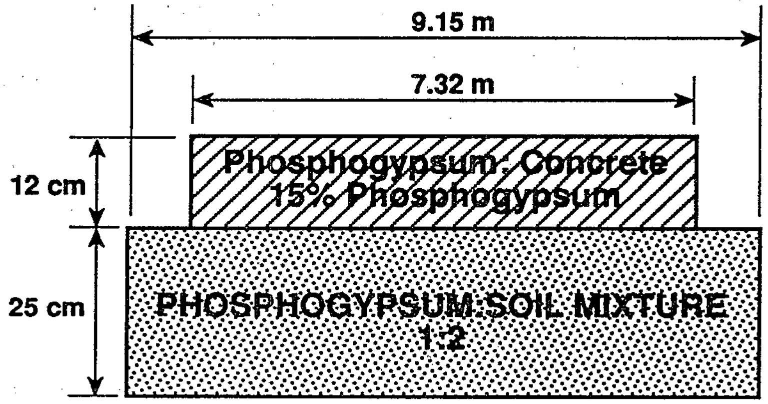
Scenarios 8 and 9: Phosphogypsum in a road base for a secondary road. The road base consists of a 1:2 phosphogypsum:soil mixture with a density of 2.25 g/cm^3 (2.25 MT/m^3). Assuming a Ra-226 concentration of 30 pCi/g in phosphogypsum, the Ra-226 concentration in the road base is 10 pCi/g. The road base is 9.15 m (30 ft) wide and 0.25 m (10 inches) thick and is covered by a 0.12 m (5 inch) thickness of asphalt.

Scenarios 10 and 11: Phosphogypsum in a concrete road surface. The concrete road surface incorporates 15 weight percent phosphogypsum. Assuming a Ra-226 concentration of 30 pCi/g in phosphogypsum, the Ra-226 concentration in the road surface is 4.5 pCi/g. The road surface is 7.32 m (24 ft) wide and 0.12 m (5 inches) thick. The road base under the concrete surface is the same as for Scenarios 8 and 9.

For Scenarios 8 through 11 the following exposure pathways are evaluated:



SCENARIOS 8 AND 9
USE OF PHOSPHOGYPSUM IN A ROAD BASE



SCENARIOS 10 AND 11
USE OF PHOSPHOGYPSUM IN A
CONCRETE ROAD SURFACE

RAE-103855

Figure 4-1. Scenarios involving the use of phosphogypsum in road construction.

- <u>Construction Worker</u>
  - Direct gamma exposure
  - Dust inhalation

- <u>Person Driving on Road</u>
  - Direct gamma exposure

- <u>Member of CPG</u>
  - Direct gamma exposure
  - Ingestion of drinking water from a contaminated well
  - Ingestion of foodstuffs contaminated by well water

- <u>Reclaimer</u>
  - Direct gamma exposure
  - Indoor radon inhalation
  - Use of contaminated well water
  - Ingestion of foodstuffs grown on-site

- <u>Off-Site Individual</u>
  - Ingestion of river water contaminated via the groundwater pathway
  - Ingestion of river water contaminated by surface runoff.

The construction worker is assumed to be engaged eight hours per day for 250 days per year in constructing a 16-km (10-mile) section of road. Gamma exposures are calculated for a worker who is employed directly on the road surface and a worker who uses equipment such as a bulldozer or road grader which provides some shielding from gamma radiation. The shielding coefficient is 0.6.

The person driving on the road is assumed to use the road from home to work, and return. This person travels the road one hour per day for 250 trips per year. The automobile in which this person rides provides some shielding from direct gamma radiation. The shielding coefficient is 0.6.

The reclaimer is assumed to build a house on the roadbed at some future time after the road is closed and the road surface has crumbled and been removed. In addition to living in a house at the site, the reclaimer drills a well for water and plants a vegetable garden in the contaminated soil. The vegetable garden provides 50 percent of the reclaimer's foodstuffs.

The member of the CPG is assumed to live in a house located 100 or 1,000 meters from the road. Potential doses to a member of the CPG could result from direct gamma exposure or from the use of contaminated well water.

4.3.3.3 Phosphogypsum in Research & Development Activities

One scenario (Scenario 12) is evaluated in which phosphogypsum is used in research and development to evaluate the properties of this material for commercial applications. In this scenario, exposures are estimated for a worker who spends four hours per day, 250 days per year in a laboratory containing one open 55-gallon drum of phosphogypsum. The worker is exposed via direct gamma radiation, dust inhalation, and radon inhalation pathways. MICROSHIELD is used to estimate the external gamma dose; the worker is assumed to be positioned at an average distance of one meter from the drum of phosphogypsum. To estimate the exposure from dust inhalation, a dust loading of 100 micrograms/m^3 is postulated. This value is derived from 40 CFR 50.6(b), which specifies a level of 50 μg/m^3 as the arithmetic mean level of primary and secondary standards for airborne particulate matter. The value is doubled to provide a conservative estimate. To estimate the indoor radon exposure, two air changes per hour are assumed.

4.3.4 <u>Input Parameters</u>

Values of input parameters used in PATHRAE to evaluate potential doses to individuals and the attendant risks from the commercial use of phosphogypsum are presented in this section. These input parameters include radionuclide concentrations, dose and risk conversion factors, and parameters used to characterize the exposure scenarios described in Section 4.3.3.

4.3.4.1 Radionuclide Concentrations

The relative radionuclide concentrations in phosphogypsum providing the basis for the risk assessment are shown in Table 4-3. The concentrations in Table 4-3 are based on a radium-226 concentration of 1 pCi/g. The risk estimates presented in Section 4 are given as a function of Ra-226 concentration.

The relative concentrations of Pb-210, Po-210, Th-230, U-234, and U-238 are based on average activity ratios of these radionuclides to Ra-226 in phosphogypsum reported in Ho88. The relative concentration of Ra-228 is derived from the activity ratio of Ra-228 to Ra-226 in phosphate fertilizer, reported in SCA91. Activity ratios for Th-228 and Th-232 relative to Ra-226 are also those for phosphate fertilizer, reported in SCA91. Because concentrations of thorium in phosphogypsum are depleted relative to concentrations in phosphoric acid, the use of thorium to radium-226 activity ratios for phosphate fertilizer may tend to overestimate these thorium concentrations. The activity of U-235 in phosphogypsum is assumed to be about 5 percent of the U-238 activity.

4.3.4.2 Dose and Risk Conversion Factors

The dose and risk conversion factors used in this analysis are shown in Table 4-4. Dose conversion factors for ingestion and inhalation are from the EPA's Federal Guidance

Table 4-3. Phosphogypsum reference radionuclide concentrations.[a]

Radionuclide	Concentration (pCi/g)
Ra-226	1.000
Po-210	1.040
Pb-210	1.400
Th-228	0.133
Ra-228	0.133
Th-230	0.187
Th-232	0.123
U-234	0.120
U-235	0.005
U-238	0.110

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[a] Based on a Ra-226 concentration of 1 pCi/g. See text for explanation of activity ratios of other radionuclides relative to Ra-226.

Report No. 11, which provides guidance for control of occupational exposures to radiation (EPA88).

Dose conversion factors for inhalation, ingestion and direct exposure to gamma radiation are from guidance for modifying PRESTO-EPA-CPG to reflect major recent changes in EPA's dose calculation methodology. The inhalation and ingestion conversion factors represent the effective whole body dose equivalents resulting from a unit curie of intake, and the conversion factors for the direct gamma represent the effective whole body dose rates resulting from the exposure to a unit concentration of a curie per square meter on the ground surface. Risk conversion factors in Table 4-4, except those for radon, are based on the radiation risk factors in Table 6-27 of Volume I of EPA's "Environmental Impact Statement for NESHAPS Radionuclides" (EPA89b). As a result of a recommendation by EPA's Science Advisory Board, EPA reduced the radon risk conversion factors by about 37 percent to 4.4×10^{-8} and 4.4×10^{-9} for indoor and outdoor exposures, respectively (Co92). The risk conversion factors represent average lifetime (i.e., 70-year) risks of fatal cancer per unit

Table 4-4. Dose and risk conversion factors.

I. DOSE CONVERSION FACTORS

Nuclide	Inhalation DCF (mrem/pCi)[a]	Ingestion DCF (mrem/pCi)[a]	Direct Gamma DCF (mrem/yr per pCi/m^2)
Ra-226	8.6E-03	1.3E-03	1.67E-04
Po-210	9.4E-03	1.9E-03	8.55E-10
Pb-210	1.4E-02	5.4E-03	0
Th-228	3.4E-01	4.0E-04	3.37E-04
Ra-228	4.8E-03	1.4E-03	9.04E-05
Th-230	3.3E-01	5.5E-04	8.88E-08
Th-232	1.6E+00	2.7E-03	6.56E-08
U-234	1.3E-01	2.8E-04	8.00E-08
U-235	1.2E-01	2.5E-04	6.41E-08
U-238	1.2E-01	2.7E-04	1.67E-05

(a) 50-year committed dose equivalent from one year of intake (uptake).

II. RISK CONVERSION FACTORS[b]

Nuclide	Inhalation Risk per pCi Inhaled	Ingestion Risk per pCi Ingested	Direct Gamma Risk per pCi/m^2
Ra-226	2.8E-09	9.4E-11	5.7E-11
Po-210	2.4E-09	1.4E-10	2.9E-16
Pb-210	1.4E-09	5.5E-10	0
Th-228	7.2E-08	1.3E-11	4.8E-11
Ra-228	5.8E-10	7.0E-11	3.1E-11
Th-230	2.9E-08	2.3E-11	2.7E-14
Th-232	2.9E-08	2.1E-11	2.0E-14
U-234	2.5E-08	7.5E-11	2.4E-14
U-235	2.3E-08	7.3E-11	5.5E-12
U-238	2.2E-08	7.4E-11	7.23E-13

(b) 70-year lifetime risk of fatal cancer from one year of exposure.

III. RADON RISK CONVERSION FACTORS[c]

Exposure Scenario	Inhalation Risk per pCi/m^3
Indoor Exposure	4.4E-08
Outdoor Exposure	4.4E-09

(c) 70-year lifetime risk of fatal cancer from one year of exposure to Rn-220 and Rn-222 daughters.

of intake or exposure. A quality factor of 1 has been used to convert from rads to rems for low-LET (i.e., gamma) radiation, and a relative biological effectiveness of 8 has been used to convert from rads to rems for the induction of cancer by high-LET (i.e., alpha) radiation.

4.3.4.3 Site-Specific Input Parameters

Values of all important site-specific input parameters used by PATHRAE in the risk assessments are shown in Table 4-5.

4.4 RESULTS

The results of the phosphogypsum risk assessment are given in this section. Results are presented for the commercial use of phosphogypsum in agriculture, road construction, and research and development. Exposure scenarios used for this risk assessment are described in Section 4.3.

4.4.1 Phosphogypsum in Agriculture

The results of the risk assessment for the use of phosphogypsum in agriculture are summarized in Tables 4-6 through 4-14. Estimated doses and risks for Scenarios 1 and 2, involving an average phosphogypsum application rate on a moderate size clay or sand field used to grow peanuts, are shown in Tables 4-6 and 4-7. Estimated doses and risks for Scenarios 3 and 4, involving a maximum phosphogypsum application rate on a large clay or sand field, are shown in Tables 4-8 and 4-9. Estimated doses and risks for Scenarios 5 and 6, involving the use of phosphogypsum for sediment control, are shown in Tables 4-10 and 4-11. Estimated risks for Scenario 7, based on various phosphogypsum application rates and Ra-226 concentrations, for radon and gamma exposures to the on-site individual are shown in Tables 4-12 and 4-13, respectively; the total risks from both pathways are shown in Table 4-14. The risks shown in the tables are estimated lifetime (70-year) risks from one year of exposure.

As explained in Section 4.3, phosphogypsum applications to agricultural fields are assumed to occur biennially. Equilibrium is reached with competing mechanisms that remove gypsum and its radioactive constituents at 1100 yrs for Ra-226 and 1600 yrs for uranium and thorium. Doses and risks are evaluated for fields that have been repeatedly fertilized on a biennial basis over a 100-year period. Results of Scenarios 1 through 6 are shown for Ra-226 concentrations in phosphogypsum ranging from 26 pCi/g to 3 pCi/g. The actual Ra-226 concentrations in the agricultural fields are lower due to dilution of the phosphogypsum with the soil and depletion mechanisms such as plant uptake and leaching which tend to remove radionuclides.

Table 4-5. Site-specific input parameters for PATHRAE risk assessments.

Parameter	Units	Clay Value, Sand Value
Phosphogypsum application rate--agricultural scenarios		
Fertilizer--average	MT/acre/yr	0.66
Fertilizer--maximum	MT/acre/yr	2.03
Soil conditioner	MT/acre/yr	4.05
Phosphogypsum application interval--agricultural scenarios	--	biennially
Total years of application--agricultural scenarios	yrs	100
Agricultural field size		
Fertilizer--average	acre	138
Fertilizer--maximum	acre	1,000
Soil conditioner	acre	556
Tillage depth--agricultural scenarios		
Fertilizer--average	m	0.22
Fertilizer-maximum	m	0.46
Soil conditioner	m	0.30
Agricultural field soil density	kg/m^3	1.50E+03
Roadbed material density	kg/m^3	2.25E+03
Distance to nearest residence		
Fertilizer--average	m	890, 100
Fertilizer--maximum	m	6,440, 100
Soil conditioner	m	1,000, 100
Road construction scenarios	m	1,000, 100
Distance to river	m	5.00E+03
River flow rate	m^3/yr	1.00E+08
Density of aquifer	kg/m^3	1.80E+03
Porosity of aquifer	--	0.33
Horizontal velocity of aquifer	m/yr	20

Table 4-5. Site-specific input parameters for PATHRAE risk assessments (continued).

Parameter	Units	Clay Value, Sand Value
Vertical distance to aquifer		
Fertilizer scenarios	m	3.0
Soil conditioner scenario	m	10.0
Construction scenarios--humid site	m	3.0
Construction scenarios--dry site	m	10.0
Water infiltration rate		
Fertilizer scenarios	m/yr	0.40
Soil conditioner scenario	m/yr	0.25
Construction scenarios--humid site	m/yr	0.40
Construction scenarios--dry site	m/yr	0.25
Fraction of food eaten grown on-site	--	0.50
Adult breathing rate	m^3/yr	8.00E+03
Average dust loading in outside air	kg/m^3	5.00E-07
Average dust loading in R&D lab	kg/m^3	1.00E-07
Atmospheric stability class	--	4
Fraction of time wind blows toward receptor	--	0.093
Average wind speed	m/sec	4.5
Dust resuspension rate for off-site transport	m^3/sec	5.0E-07
Dust deposition velocity	m/sec	1.0E-03
Radon emanating power	--	0.30
Radon diffusion coefficient		
Soil--humid site	m^2/yr	2.2E+01
Soil--dry site	m^2/yr	6.3E+01
Concrete	m^2/yr	1.6E+01
Air change rate in reclaimer house	changes/hr	2
Exposure fraction for indoor exposure	--	0.75
Equivalent exposure fraction for outdoor exposure	--	0.50
Surface erosion rate	m/yr	2.0E-04

Table 4-5. Site-specific input parameters for PATHRAE risk assessments (continued).

Parameter	**Units**	**Clay Value, Sand Value**
Distribution coefficients (K_d)		
Ra-226	m^3/kg	0.45, 0.07
Po-210	m^3/kg	0.50, 0.50
Pb-210	m^3/kg	0.90, 0.90
Th-228	m^3/kg	150.0, 150.0
Ra-228	m^3/kg	0.45, 0.07
Th-230	m^3/kg	150.0, 150.0
Th-232	m^3/kg	150.0, 150.0
U-234	m^3/kg	0.45, 0.07
U-235	m^3/kg	0.45, 0.07
U-238	m^3/kg	0.45, 0.07
Volume of drinking water consumed annually by an individual	m^3/yr	0.37
Length of road perpendicular to aquifer	mile	10
Aquifer thickness	m	10

It is observed that the doses from the groundwater pathways are all zero. As an added sensitivity analysis, scenarios 2, 4, 6, 9 and 11 were created as replicates of 1, 3, 5, 8 and 10, modifying the distance to the offsite individual (100 m). Additionally, the k_d for uranium and radium was reduced to 70 ml/g. Using these modifications, PATHRAE projected a peak risk at year 4200 of $1.5x10^{-8}$. These changes also caused, as illustrated in the summary tables, an increase in the risk to members of the CPG from dust inhalation. For a well placed onsite, and a k_d of 70 ml/g for uranium and radium, a risk of $6.7x10^{-9}$ occurred by the year 1000, for scenario 4. A peak risk of $2x10^{-8}$ occurred in year 3100 for the same scenario.

For Scenarios 1 and 2, a Ra-226 concentration of 26 pCi/g in phosphogypsum is estimated to correspond to an increase in the soil Ra-226 concentration of 0.60 pCi/g at the end of the 100-year period. For Scenarios 3 and 4, a Ra-226 concentration of 26 pCi/g in phosphogypsum is estimated to correspond to an increase in the soil Ra-226 concentration of 0.88 pCi/g at the end of the 100-year period. For Scenarios 5 and 6, a Ra-226 concentration of 26 pCi/g in phosphogypsum is estimated to correspond to an increase in the soil Ra-226 concentration of 2.70 pCi/g at the end of the 100-year period. As shown in the tables, for each scenario, the doses and risks are directly proportional to the Ra-226 concentration in the original phosphogypsum.

Table 4-6. Risk assessment results for Scenario 1 - use as fertilizer - average site (clay).

	Ra-226 Concentrations in Phosphogypsum									
	26 pCi/g		10 pCi/g		7 pCi/g		5 pCi/g		3 pCi/g	
	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]
Agricultural Worker Direct Gamma	3.5E+00	1.4E-06	1.4E+00	5.3E-07	9.5E-01	3.7E-07	6.8E-01	2.7E-07	4.1E-01	1.6E-07
Agricultural Worker Dust Inhalation	7.1E-02	5.8E-09	2.7E-02	2.2E-09	1.9E-02	1.6E-09	1.4E-02	1.1E-09	8.2E-03	6.7E-10
On-Site Individual Direct Gamma	7.6E+00	3.0E-06	2.9E+00	1.2E-06	2.0E+00	8.0E-07	1.4E+00	5.7E-07	8.7E-01	3.4E-07
On-Site Individual Indoor Radon	---	2.6E-06	---[c]	1.0E-06	---	6.8E-07	---	5.0E-07	---	3.0E-07
On-Site Individual Well Water Use	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Inhalation of contaminated dust	7.0E-04	5.7E-11	2.7E-04	2.2E-11	1.9E-04	1.6E-11	1.4E-04	1.1E-11	8.1E-05	6.7E-12
Member of CPG - Ingestion of drinking water from contaminated well	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of foodstuff contaminated by well water	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of foodstuff grown on fertilized soil	4.9E-02	5.2E-09	1.9E-02	2.0E-09	1.3E-02	1.4E-09	9.5E-03	1.5E-09	5.7E-03	3.0E-10
Individual - Ingestion of river water contaminated by groundwater	---[c]	---[c]	---	---	---	---	---	---	---	---
Individual - Ingestion of river water contaminated by surface runoff	8.3E-03	7.4E-10	3.2E-03	2.9E-10	2.2E-03	2.0E-10	1.6E-03	1.4E-10	9.6E-04	8.6E-11

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a. Dose or dose commitment from one year of exposure.

b. Lifetime risk from one year of exposure.

c. No radionuclides are calculated to reach the on-site well via the groundwater pathway for almost 10,000 years, or the off-site river or well for at least 100,000 years because of groundwater velocities and retardation factors.

Table 4-7. Risk assessment results for Scenario 2 - use as fertilizer - average site (sand).

	Ra-226 Concentrations in Phosphogypsum									
	26 pCi/g		10 pCi/g		7 pCi/g		5 pCi/g		3 pCi/g	
	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]
Agricultural Worker Direct Gamma	3.5E+00	1.4E-06	1.4E+00	5.3E-07	9.5E-01	3.7E-07	6.8E-01	2.7E-07	4.1E-01	1.6E-07
Agricultural Worker Dust Inhalation	7.1E-02	5.8E-09	2.7E-02	2.2E-09	1.9E-02	1.6E-09	1.4E-02	1.1E-09	8.2E-03	6.7E-10
On-Site Individual Direct Gamma	7.6E+00	3.0E-06	2.9E+00	1.2E-06	2.0E+00	8.0E-07	1.4E+00	5.7E-07	8.7E-01	3.4E-07
On-Site Individual Indoor Radon	---	2.6E-06	---[c]	1.0E-06	---	6.8E-07	---	5.0E-07	---	3.0E-07
On-Site Individual Well Water Use	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Inhalation of contaminated dust	4.0E-02	3.3E-09	1.5E-02	1.3E-09	1.1E-02	8.8E-10	7.7E-03	6.3E-10	4.6E-03	3.8E-10
Member of CPG - Ingestion of drinking water from contaminated well	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of foodstuff contaminated by well water	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of foodstuff grown on fertilized soil	4.9E-02	5.2E-09	1.9E-02	2.0E-09	1.3E-02	1.4E-09	9.5E-03	1.5E-09	5.7E-03	3.0E-10
Individual - Ingestion of river water contaminated by groundwater	---[c]	---[c]	---	---	---	---	---	---	---	---
Individual - Ingestion of river water contaminated by surface runoff	8.3E-03	7.4E-10	3.2E-03	2.9E-10	2.2E-03	2.0E-10	1.6E-03	1.4E-10	9.6E-04	8.6E-11

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a. Dose or dose commitment from one year of exposure.

b. Lifetime risk from one year of exposure.

c. No radionuclides are calculated to reach the on-site well via the groundwater pathway for about 4,000 years, or the off-site river or well for at least 100,000 years because of groundwater velocities and retardation factors.

Table 4-8. Risk assessment results for Scenario 3 - use as fertilizer - maximum site (clay).

	Ra-226 Concentrations in Phosphogypsum									
	26 pCi/g		10 pCi/g		7 pCi/g		5 pCi/g		3 pCi/g	
	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]
Agricultural Worker Direct Gamma	5.4E+00	2.2E-06	2.1E+00	8.1E-07	1.5E+00	5.7E-07	1.0E+00	4.1E-07	6.2E-01	2.5E-07
Agricultural Worker Dust Inhalation	1.1E-01	9.0E-09	4.2E-02	3.5E-09	3.0E-02	2.4E-09	2.1E-02	1.7E-09	1.3E-02	1.0E-09
On-Site Individual Direct Gamma	1.2E+01	4.6E-06	4.4E+00	1.8E-06	3.1E+00	1.3E-06	2.2E+00	8.7E-07	1.3E+00	5.2E-07
On-Site Individual Indoor Radon	---	6.8E-06	---[c]	2.6E-06	---	1.8E-06	---	1.3E-06	---	7.5E-07
On-Site Individual Well Water Use	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Inhalation of contaminated dust	4.4E-05	3.6E-12	1.7E-05	1.4E-12	1.2E-05	9.6E-13	8.5E-06	6.9E-13	5.1E-06	4.1E-13
Member of CPG - Ingestion of drinking water from contaminated well	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of foodstuff contaminated by well water	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of foodstuff grown on fertilized soil	8.6E-02	9.1E-09	3.3E-02	3.5E-09	2.3E-02	2.5E-09	1.6E-02	1.8E-09	9.9E-03	1.1E-09
Individual - Ingestion of river water contaminated by groundwater	---[c]	---[c]	---	---	---	---	---	---	---	---
Individual - Ingestion of river water contaminated by surface runoff	8.8E-02	7.8E-09	3.4E-02	3.0E-09	2.4E-02	2.1E-09	1.7E-02	1.5E-09	1.0E-02	9.1E-10

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a. Dose or dose commitment from one year of exposure.

b. Lifetime risk from one year of exposure.

c. No radionuclides are calculated to reach the on-site well via the groundwater pathway for almost 10,000 years, or the off-site river or well for more than 100,000 years because of groundwater velocities and retardation factors.

Table 4-9. Risk assessment results for Scenario 4 - use as fertilizer - maximum site (sand).

	Ra-226 Concentrations in Phosphogypsum									
	26 pCi/g		10 pCi/g		7 pCi/g		5 pCi/g		3 pCi/g	
	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]
Agricultural Worker Direct Gamma	5.4E+00	2.2E-06	2.1E+00	8.1E-07	1.5E+00	5.7E-07	1.0E+00	4.1E-07	6.2E-01	2.5E-07
Agricultural Worker Dust Inhalation	1.1E-01	9.0E-09	4.2E-02	3.5E-09	3.0E-02	2.4E-09	2.1E-02	1.7E-09	1.3E-02	1.0E-09
On-Site Individual Direct Gamma	1.2E+01	4.6E-06	4.4E+00	1.8E-06	3.1E+00	1.3E-06	2.2E+00	8.7E-07	1.3E+00	5.2E-07
On-Site Individual Indoor Radon	---	6.8E-06	---[c]	2.6E-06	---	1.8E-06	---	1.3E-06	---	7.5E-07
On-Site Individual Well Water Use	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Inhalation of contaminated dust	6.1E-02	5.0E-09	2.3E-02	1.9E-09	1.4E-02	1.4E-09	1.2E-02	9.7E-10	7.0E-03	5.8E-10
Member of CPG - Ingestion of drinking water from contaminated well	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of foodstuff contaminated by well water	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of foodstuff grown on fertilized soil	8.6E-02	9.1E-09	3.3E-02	3.5E-09	2.3E-02	2.5E-09	1.6E-02	1.8E-09	9.9E-03	1.1E-09
Individual - Ingestion of river water contaminated by groundwater	---[c]	---[c]	---	---	---	---	---	---	---	---
Individual - Ingestion of river water contaminated by surface runoff	8.8E-02	7.8E-09	3.4E-02	3.0E-09	2.4E-02	2.1E-09	1.7E-02	1.5E-09	1.0E-02	9.1E-10

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a. Dose or dose commitment from one year of exposure.

b. Lifetime risk from one year of exposure.

c. No radionuclides are calculated to reach the on-site well via the groundwater pathway for about 4,000 years, or the off-site river or well for more than 100,000 years because of groundwater velocities and retardation factors.

Table 4-10. Risk assessment results for Scenario 5 - use as sediment control (clay).

	Ra-226 Concentrations in Phosphogypsum									
	26 pCi/g		10 pCi/g		7 pCi/g		5 pCi/g		3 pCi/g	
	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]
Agricultural Worker Direct Gamma	1.6E+01	6.4E-06	6.3E+00	2.5E-06	4.4E+00	1.8E-06	3.2E+00	1.3E-06	1.9E+00	7.3E-07
Agricultural Worker Dust Inhalation	8.1E-01	6.6E-08	3.1E-01	2.5E-08	2.2E-01	1.8E-08	1.6E-01	1.3E-08	9.3E-02	7.6E-09
On-Site Individual Direct Gamma	3.5E+01	1.4E-05	1.3E+01	5.3E-06	9.4E+00	3.8E-06	6.7E+00	2.7E-06	4.0E+00	1.6E-06
On-Site Individual Indoor Radon	---	1.2E-05	---[c]	4.7E-06	---	3.3E-06	---	2.4E-06	---	1.4E-06
On-Site Individual Well Water Use	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Inhalation of contaminated dust	6.6E-03	5.4E-10	2.5E-03	2.1E-10	1.8E-03	1.5E-10	1.3E-03	1.0E-10	7.6E-04	6.2E-11
Member of CPG - Ingestion of drinking water from contaminated well	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of foodstuff contaminated by well water	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of foodstuff grown on fertilized soil	2.2E-01	2.3E-08	8.4E-02	9.0E-09	5.9E-02	6.3E-09	4.2E-02	4.5E-09	2.5E-02	2.7E-09
Individual - Ingestion of river water contaminated by groundwater	---[c]	---[c]	---	---	---	---	---	---	---	---
Individual - Ingestion of river water contaminated by surface runoff	1.5E-01	1.3E-08	5.8E-02	5.1E-09	4.1E-02	3.6E-09	2.9E-02	2.6E-09	1.8E-02	1.5E-09

---

a. Dose or dose commitment from one year of exposure.
b. Lifetime risk from one year of exposure.
c. No radionuclides are calculated to reach the on-site well via the groundwater pathway for almost 10,000 years, or the off-site river or well for more than 100,000 years because of groundwater velocities and retardation factors.

Table 4-11. Risk assessment results for Scenario 6 - use as sediment control (sand).

	Ra-226 Concentrations in Phosphogypsum									
	26 pCi/g		10 pCi/g		7 pCi/g		5 pCi/g		3 pCi/g	
	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]
Agricultural Worker Direct Gamma	1.6E+01	6.4E-06	6.3E+00	2.5E-06	4.4E+00	1.8E-06	3.2E+00	1.3E-06	1.9E+00	7.3E-07
Agricultural Worker Dust Inhalation	8.1E-01	6.6E-08	3.1E-01	2.5E-08	2.2E-01	1.8E-08	1.6E-01	1.3E-08	9.3E-02	7.6E-09
On-Site Individual Direct Gamma	3.5E+01	1.4E-05	1.3E+01	5.3E-06	9.4E+00	3.8E-06	6.7E+00	2.7E-06	4.0E+00	1.6E-06
On-Site Individual Indoor Radon	---	1.2E-05	---[c]	4.7E-06	---	3.3E-06	---	2.4E-06	---	1.4E-06
On-Site Individual Well Water Use	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Inhalation of contaminated dust	4.5E-01	3.7E-08	1.7E-01	1.4E-08	1.2E-01	9.9E-09	8.7E-02	7.1E-09	5.2E-02	4.3E-09
Member of CPG - Ingestion of drinking water from contaminated well	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of foodstuff contaminated by well water	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of foodstuff grown on fertilized soil	2.2E-01	2.3E-08	8.4E-02	9.0E-09	5.9E-02	6.3E-09	4.2E-02	4.5E-09	2.5E-02	2.7E-09
Individual - Ingestion of river water contaminated by groundwater	---[c]	---[c]	---	---	---	---	---	---	---	---
Individual - Ingestion of river water contaminated by surface runoff	1.5E-01	1.3E-08	5.8E-02	5.1E-09	4.1E-02	3.6E-09	2.9E-02	2.6E-09	1.8E-02	1.5E-09

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a. Dose or dose commitment from one year of exposure.

b. Lifetime risk from one year of exposure.

c. No radionuclides are calculated to reach the on-site well via the groundwater pathway for about 4,000 years, or the off-site river or well for more than 100,000 years because of groundwater velocities and retardation factors.

Table 4-12. Risk assessment results for Scenario 7 - radon exposure risks to the on-site individual as a function of phosphogypsum application rate and Ra-226 concentration.[a]

Application Rate (lbs/Acre)	Ra-226 Concentration in Phosphogypsum (pCi/g)						
	3	7	15	20	30	45	60
500	1.0E-07	2.4E-07	5.1E-07	6.8E-07	1.0E-06	1.6E-06	2.1E-06
1,000	2.1E-07	4.8E-07	1.0E-06	1.4E-06	2.1E-06	3.1E-06	--
1,500	3.1E-07	7.5E-07	1.6E-06	2.1E-06	3.1E-06	--	--
2,500	5.1E-07	1.2E-06	2.6E-06	3.4E-06	--	--	--
5,000	1.0E-06	2.4E-06	5.1E-06	--	--	--	--
10,000	2.1E-06	4.8E-06	1.0E-05	--	--	--	--

[a] Lifetime risk from one year of exposure.

Table 4-13. Risk assessment results for Scenario 7 - external gamma risks to the on-site individual as a function of phosphogypsum application rate and Ra-226 concentration.[a]

Application Rate (lbs/Acre)	Ra-226 Concentration in Phosphogypsum (pCi/g)						
	3	7	15	20	30	45	60
500	1.1E-07	2.6E-07	5.7E-07	7.5E-07	1.1E-06	1.7E-06	2.3E-06
1,000	2.3E-07	5.3E-07	1.1E-06	1.5E-06	2.3E-06	3.4E-06	--
1,500	3.4E-07	7.9E-07	1.7E-06	2.3E-06	3.4E-06	--	--
2,500	5.7E-07	1.3E-06	2.8E-06	3.8E-06	--	--	--
5,000	1.1E-06	2.6E-06	5.7E-06	--	--	--	--
10,000	2.3E-06	5.3E-06	1.1E-05	--	--	--	--

[a] Lifetime risk from one year of exposure.

Table 4-14. Risk assessment results for Scenario 7 - Total risks to the on-site individual as a function of phosphogypsum application rate and Ra-226 concentration.[a,b]

Application Rate (lbs/Acre)	Ra-226 Concentration in Phosphogypsum (pCi/g)						
	3	7	15	20	30	45	60
500	2.2E-07	5.1E-07	1.1E-06	1.4E-06	2.2E-06	3.3E-06	4.4E-06
1,000	4.4E-07	1.0E-06	2.2E-06	2.9E-06	4.4E-06	6.5E-06	--
1,500	6.5E-07	1.4E-06	3.3E-06	4.4E-06	6.5E-06	--	--
2,500	1.1E-06	2.5E-06	5.4E-06	7.2E-06	--	--	--
5,000	2.2E-06	5.1E-06	1.1E-05	--	--	--	--
10,000	4.4E-06	1.0E-05	2.2E-05	--	--	--	--

[a] Lifetime risk from one year of exposure.

[b] The sum of the risks from Tables 4-12 and 4-13.

For each of the agricultural scenarios, the highest doses and risks result from external gamma exposure and from indoor radon inhalation to the on-site individual. For Scenario 1, the lifetime risk to the on-site individual from one year of external gamma exposure is estimated to range from 3.0×10^{-6} for 26 pCi/g phosphogypsum to 3.4×10^{-7} for 3 pCi/g phosphogypsum. The lifetime risk from one year of indoor radon inhalation is estimated to range from 2.6×10^{-6} for 26 pCi/g phosphogypsum to 3.0×10^{-7} for 3 pCi/g phosphogypsum.

For Scenario 3, the lifetime risk to the on-site individual from one year of external gamma exposure is estimated to range from 4.6×10^{-6} for 26 pCi/g phosphogypsum to 5.2×10^{-7} for 3 pCi/g phosphogypsum. The lifetime risk from one year of indoor radon inhalation is estimated to range from 6.8×10^{-6} for 26 pCi/g phosphogypsum to 7.5×10^{-7} for 3 pCi/g phosphogypsum.

For Scenario 5, the lifetime risk to the on-site individual from one year of external gamma exposure is estimated to range from 1.4×10^{-5} for 26 pCi/g phosphogypsum to 1.6×10^{-6} for 3 pCi/g phosphogypsum. The lifetime risk from one year of indoor radon inhalation is estimated to range from 1.2×10^{-5} for 26 pCi/g phosphogypsum to 1.4×10^{-6} for 3 pCi/g phosphogypsum.

The results of the first four scenarios prompted Scenario 7; an evaluation of the risks associated with the two principal exposure pathways, radon and direct gamma exposures, with varying phosphogypsum application rates and Ra-226 concentrations. Combinations of application rates and Ra-226 concentrations varied from 500 to 10,000 lbs/acre and 3 to 60 pCi/g, respectively. The affect of these two variables on the estimated risk is best illustrated by the family of curves represented in Figures 4-2 to 4-4, which illustrate the increase in risk as the Ra-226 concentrations increase with each application rate. The risks presented in the figures are those listed in Tables 4-12 to 4-14 multiplied by a 70-year exposure period. Thus, they represent the estimated lifetime risk resulting from a 70-year exposure. The total lifetime risk to the on-site individual from 70 years of external gamma and radon exposures is estimated to range from 1.5×10^{-5} for 3 pCi/g phosphogypsum applied at a rate of 500 lbs/acre to 1.5×10^{-3} for 15 pCi/g phosphogypsum applied at a rate of 10,000 lbs/acre. Using Scenario 7, the combinations of phosphogypsum application rates and Ra-226 concentrations that yield an estimated lifetime risk of 3×10^{-4} is plotted in Figure 4-5. For example, a lifetime risk of 3×10^{-4} will result when phosphogypsum, containing 1 pCi/g of Ra-226, is applied at a rate of 25,000 lbs/acre; whereas, to produce the same risk when the application rate is 1,000 lbs/acre will require a Ra-226 concentration of 30 pCi/g.

4.4.2 Phosphogypsum in Road Construction

The road construction scenarios evaluated in this risk assessment are shown schematically in Figure 4-1. The results of the risk assessment of the use of phosphogypsum in road construction are summarized in Tables 4-15 to 4-18. Estimated doses and risks for Scenarios 8 and 9, involving the use of phosphogypsum in a road base, are shown in Tables

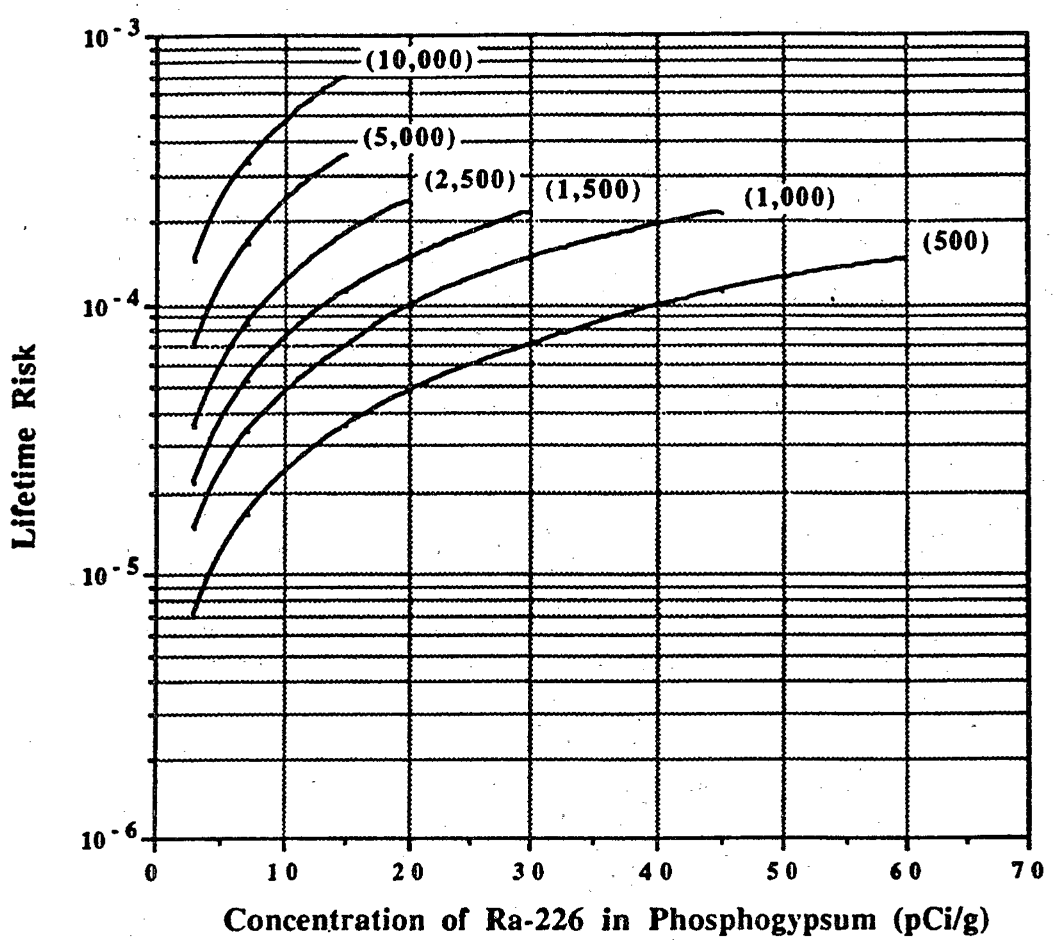

Figure 4-2. Risk assessment results for Scenario 7 - radon exposure risks to the on-site individual as a function of the Ra-226 content of phosphogypsum for the six application rates (lbs/acre) shown in parenthesis

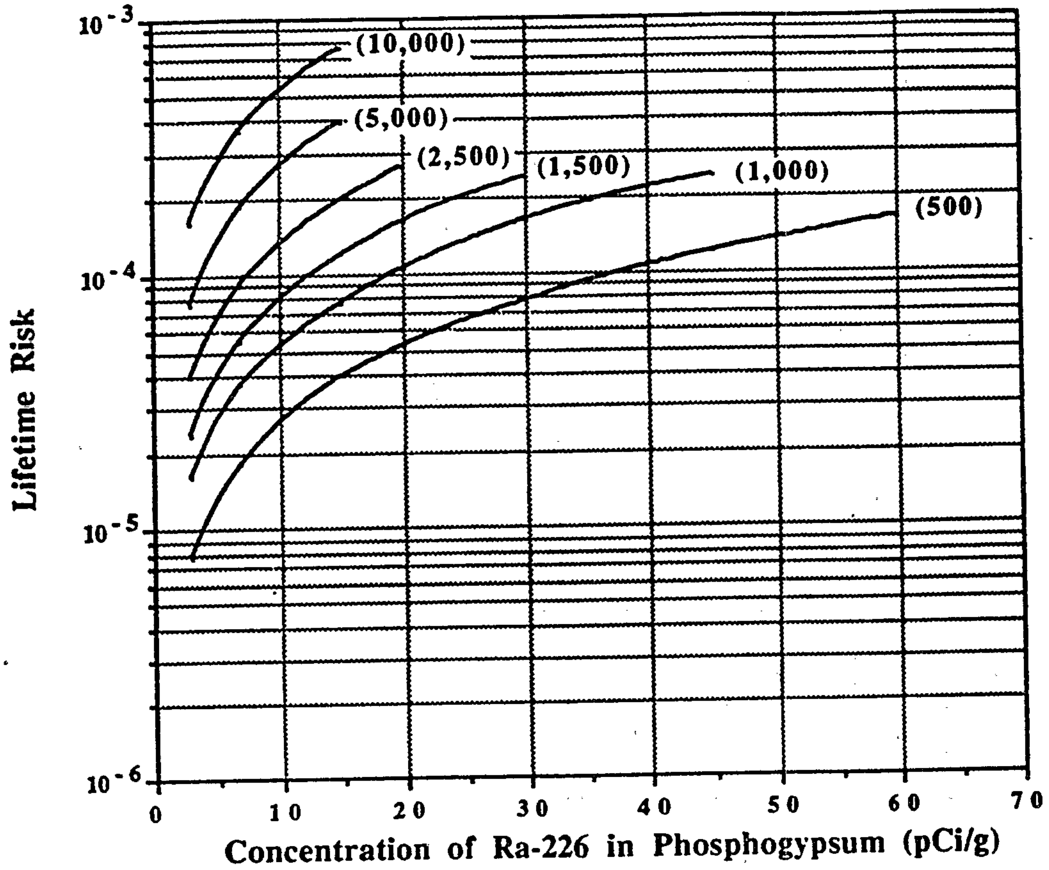

Figure 4-3. Risk assessment results for Scenario 7 - external gamma exposure risks to the on-site individual as a function of the Ra-226 content of phosphogypsum for the six application rates (lbs/acre) shown in parenthesis

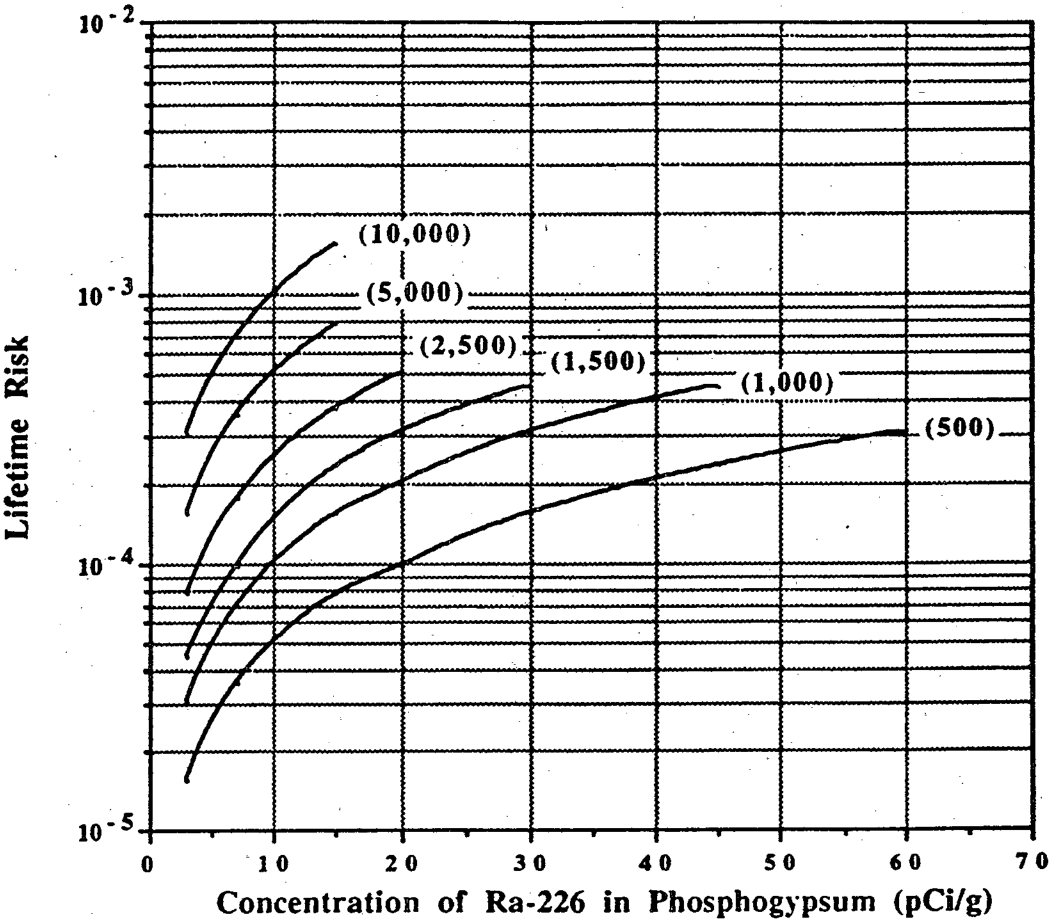

Figure 4-4. Risk assessment results for Scenario 7 - total radon and gamma exposure risks to the on-site individual as a function of the Ra-226 content of phosphogypsum for the six application rates (lbs/acre) shown in paraenthesis

Figure 4-5. Application rate of phosphogypsum as a function of Ra-226 concentration for a lifetime risk of 3×10^{-4}.

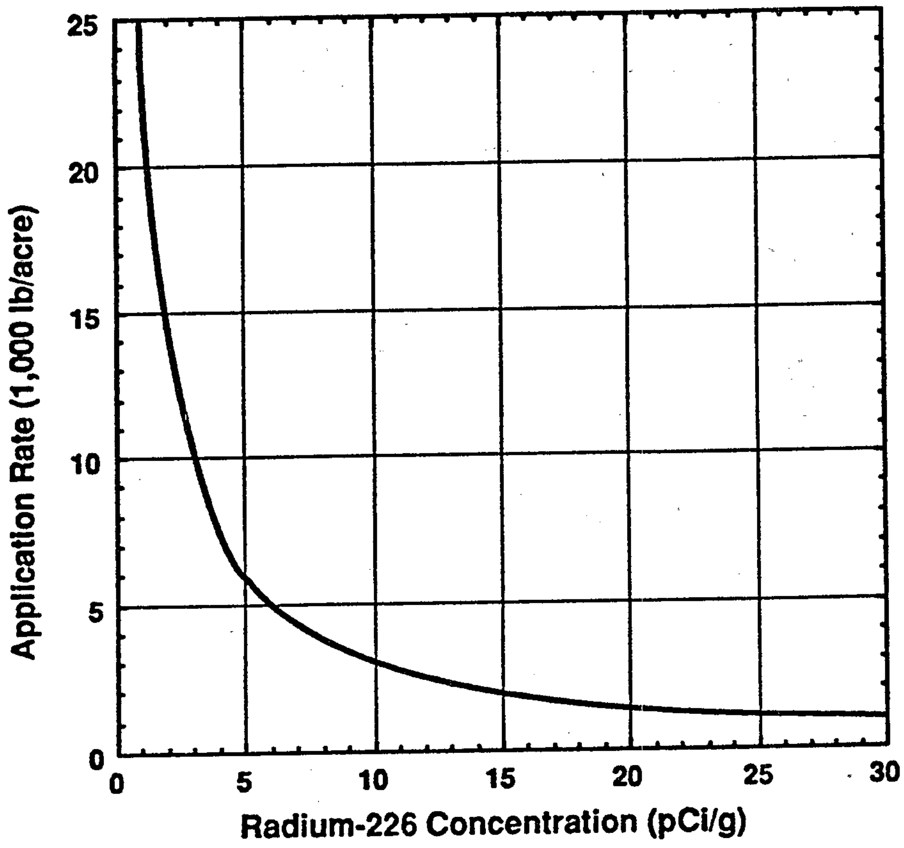

Table 4-15. Risk assessment results for Scenario 8 - use of phosphogypsum in road base for secondary road (clay).

	Ra-226 Concentrations in Phosphogypsum									
	26 pCi/g		10 pCi/g		7 pCi/g		5 pCi/g		3 pCi/g	
	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]
Construction Worker -No Shielding- Direct Gamma	4.1E+01	1.5E-05	1.6E+01	5.9E-06	1.1E+01	4.1E-06	7.9E+00	3.0E-06	4.7E+00	1.8E-06
Construction Worker -With Shielding- Direct Gamma	2.5E+01	9.0E-06	9.4E+00	3.5E-06	6.6E+00	2.5E-06	4.7E+00	1.8E-06	2.8E+00	1.1E-06
Construction Worker -Humid Site- Dust Inhalation	1.0E+00	8.4E-08	3.8E-01	3.1E-08	2.7E-01	2.2E-08	1.9E-01	1.6E-08	1.2E-01	9.4E-09
Construction Worker -Dry Site- Dust Inhalation	2.5E+00	2.2E-07	9.6E-01	8.3E-08	6.7E-01	5.8E-08	4.8E-01	4.2E-08	2.9E-01	2.5E-08
Person Driving on Road Direct Gamma	2.2E-01	8.2E-08	8.4E-02	3.1E-08	5.8E-02	2.2E-08	4.2E-02	1.5E-08	2.5E-02	9.6E-09
Member of CPG Direct Gamma	4.3E-02	1.6E-08	1.6E-02	6.2E-09	1.2E-02	4.4E-09	8.2E-03	3.2E-09	4.9E-03	1.9E-09
Member of CPG - Ingestion of Drinking Water From Contaminated Well	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of Foodstuff Contaminated by Well Water	---[c]	---[c]	---	---	---	---	---	---	---	---
Reclaimer Direct Gamma	7.1E+01	2.6E-05	2.7E+01	1.0E-05	1.9E+01	7.2E-06	1.4E+01	5.3E-06	8.2E+00	3.2E-06
Reclaimer -Humid Site- Indoor Radon Inhalation	---	5.9E-05	---	2.2E-05	---	1.6E-05	---	1.1E-05	---	6.8E-06
Reclaimer -Dry Site- Indoor Radon Inhalation	---	6.2E-05	---	2.4E-05	---	1.7E-05	---	1.2E-05	---	7.5E-06
Reclaimer Well Water Use	---[c]	---[c]	---	---	---	---	---	---	---	---
Reclaimer - Ingestion of Foodstuff Grown On-Site	2.6E-01	1.5E-08	1.0E-01	5.9E-09	6.8E-02	4.2E-09	4.7E-02	3.0E-09	2.9E-02	1.8E-09
Individual - Ingestion of River Water Contaminated by Groundwater	---[c]	---[c]	---	---	---	---	---	---	---	---
Individual - Ingestion of River Water Contaminated by Surface Runoff	2.0E-02	1.5E-09	7.6E-03	5.6E-10	5.3E-03	4.0E-10	3.8E-03	2.7E-10	2.3E-03	1.7E-10

---

a. Dose or dose commitment from one year of exposure.

b. Lifetime risk from one year of exposure.

c. No radionuclides are calculated to reach the on-site well via the groundwater pathway for almost 10,000 years, or the off-site river or well for more than 100,000 years because of groundwater velocities and retardation factors.

Table 4-16. Risk assessment results for Scenario 9 - use of phosphogypsum in road base for secondary road (sand).

	Ra-226 Concentrations in Phosphogypsum									
	26 pCi/g		10 pCi/g		7 pCi/g		5 pCi/g		3 pCi/g	
	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]
Construction Worker -No Shielding- Direct Gamma	4.1E+01	1.5E-05	1.6E+01	5.9E-06	1.1E+01	4.1E-06	7.9E+00	3.0E-06	4.7E+00	1.8E-06
Construction Worker -With Shielding- Direct Gamma	2.5E+01	9.0E-06	9.4E+00	3.5E-06	6.6E+00	2.5E-06	4.7E+00	1.8E-06	2.8E+00	1.1E-06
Construction Worker -Humid Site- Dust Inhalation	1.0E+00	8.4E-08	3.8E-01	3.1E-08	2.7E-01	2.2E-08	1.9E-01	1.6E-08	1.2E-01	9.4E-09
Construction Worker -Dry Site- Dust Inhalation	2.5E+00	2.2E-07	9.6E-01	8.3E-08	6.7E-01	5.8E-08	4.8E-01	4.2E-08	2.9E-01	2.5E-08
Person Driving on Road Direct Gamma	2.2E-01	8.2E-08	8.4E-02	3.1E-08	5.8E-02	2.2E-08	4.2E-02	1.5E-08	2.5E-02	9.6E-09
Member of CPG Direct Gamma	4.3E-02	1.6E-08	1.6E-02	6.2E-09	1.2E-02	4.4E-09	8.2E-03	3.2E-09	4.9E-03	1.9E-09
Member of CPG - Ingestion of Drinking Water From Contaminated Well	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of Foodstuff Contaminated by Well Water	---[c]	---[c]	---	---	---	---	---	---	---	---
Reclaimer Direct Gamma	7.1E+01	2.6E-05	2.7E+01	1.0E-05	1.9E+01	7.2E-06	1.4E+01	5.3E-06	8.2E+00	3.2E-06
Reclaimer -Humid Site- Indoor Radon Inhalation	---	5.9E-05	---	2.2E-05	---	1.6E-05	---	1.1E-05	---	6.8E-06
Reclaimer -Dry Site- Indoor Radon Inhalation	---	6.2E-05	---	2.4E-05	---	1.7E-05	---	1.2E-05	---	7.5E-06
Reclaimer Well Water Use	4.2E-03	4.2E-10	1.6E-03	1.6E-10	1.1E-03	1.1E-10	8.1E-04	8.0E-11	4.8E-04	4.8E-11
Reclaimer - Ingestion of Foodstuff Grown On-Site	2.6E-01	1.5E-08	1.0E-01	5.9E-09	6.8E-02	4.2E-09	4.7E-02	3.0E-09	2.9E-02	1.8E-09
Individual - Ingestion of River Water Contaminated by Groundwater	---[c]	---[c]	---	---	---	---	---	---	---	---
Individual - Ingestion of River Water Contaminated by Surface Runoff	2.0E-02	1.5E-09	7.6E-03	5.6E-10	5.3E-03	4.0E-10	3.8E-03	2.7E-10	2.3E-03	1.7E-10

---

a. Dose or dose commitment from one year of exposure.

b. Lifetime risk from one year of exposure.

c. No radionuclides are calculated to reach the off-site river or well via the groundwater pathway for more than 10,000 years because of groundwater velocities and retardation factors.

Table 4-17. Risk assessment results for Scenario 10 - use of phosphogypsum in a concrete road surface (clay).

	Ra-226 Concentrations in Phosphogypsum									
	26 pCi/g		10 pCi/g		7 pCi/g		5 pCi/g		3 pCi/g	
	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]
Construction Worker -No Shielding- Direct Gamma	4.1E+01	1.5E-05	1.6E+01	5.9E-06	9.1E+00	4.1E-06	7.9E+00	3.0E-06	4.7E+00	1.8E-06
Construction Worker -With Shielding- Direct Gamma	2.5E+01	9.0E-06	9.4E+00	3.5E-06	5.5E+00	2.5E-06	4.7E+00	1.8E-06	2.8E+00	1.1E-06
Construction Worker -Humid Site- Dust Inhalation	1.0E+00	8.4E-08	3.8E-01	3.1E-08	2.7E-01	2.2E-08	1.9E-01	1.6E-08	1.2E-01	9.4E-09
Construction Worker -Dry Site- Dust Inhalation	2.5E+00	2.2E-07	9.6E-01	8.3E-08	6.7E-01	5.8E-08	4.8E-01	4.2E-08	2.9E-01	2.5E-08
Person Driving on Road Direct Gamma	2.6E+00	9.6E-07	9.8E-01	3.7E-07	6.9E-01	2.6E-07	4.9E-01	1.8E-07	2.9E-01	1.1E-07
Member of CPG Direct Gamma	5.0E-01	1.8E-07	1.9E-01	7.3E-08	1.3E-01	5.1E-08	9.7E-02	3.6E-08	5.8E-02	2.2E-08
Member of CPG - Ingestion of Drinking Water From Contaminated Well	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of Foodstuff Contaminated by Well Water	---[c]	---[c]	---	---	---	---	---	---	---	---
Reclaimer Direct Gamma	1.4E+02	5.1E-05	5.2E+01	1.9E-05	3.7E+01	1.4E-05	2.6E+01	1.0E-05	1.6E+01	5.9E-06
Reclaimer -Humid Site- Indoor Radon Inhalation	---	6.8E-05	---	2.7E-05	---	1.9E-05	---	1.4E-05	---	8.1E-06
Reclaimer -Dry Site- Indoor Radon Inhalation	---	8.1E-05	---	3.1E-05	---	2.2E-05	---	1.6E-05	---	9.3E-06
Reclaimer Well Water Use	---[c]	---[c]	---	---	---	---	---	---	---	---
Reclaimer -Ingestion of Foodstuff Grown on-Site	2.6E-01	1.5E-08	1.0E-01	5.9E-09	6.8E-02	4.2E-09	4.7E-02	3.0E-09	2.9E-02	1.8E-09
Individual -Ingestion of River Water Contaminated by Groundwater	---[c]	---[c]	---	---	---	---	---	---	---	---
Individual -Ingestion of River Water Contaminated by Surface Runoff	2.0E-02	1.5E-09	7.6E-03	5.6E-10	5.3E-03	4.0E-10	3.8E-03	2.7E-10	2.3E-03	1.7E-10

---

a. Dose or dose commitment from one year of exposure.

b. Lifetime risk from one year of exposure.

c. No radionuclides are calculated to reach the on-site well via the groundwater pathway for almost 10,000 years, or the off-site river or well for more than 100,000 years because of groundwater velocities and retardation factors.

Table 4-18. Risk assessment results for Scenario 11 - use of phosphogypsum in a concrete road surface (sand).

	Ra-226 Concentrations in Phosphogypsum									
	26 pCi/g		10 pCi/g		7 pCi/g		5 pCi/g		3 pCi/g	
	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]
Construction Worker -No Shielding- Direct Gamma	4.1E+01	1.5E-05	1.6E+01	5.9E-06	9.1E+00	4.1E-06	7.9E+00	3.0E-06	4.7E+00	1.8E-06
Construction Worker -With Shielding- Direct Gamma	2.5E+01	9.0E-06	9.4E+00	3.5E-06	5.5E+00	2.5E-06	4.7E+00	1.8E-06	2.8E+00	1.1E-06
Construction Worker -Humid Site- Dust Inhalation	1.0E+00	8.4E-08	3.8E-01	3.1E-08	2.7E-01	2.2E-08	1.9E-01	1.6E-08	1.2E-01	9.4E-09
Construction Worker -Dry Site- Dust Inhalation	2.5E+00	2.2E-07	9.6E-01	8.3E-08	6.7E-01	5.8E-08	4.8E-01	4.2E-08	2.9E-01	2.5E-08
Person Driving on Road Direct Gamma	2.6E+00	9.6E-07	9.8E-01	3.7E-07	6.9E-01	2.6E-07	4.9E-01	1.8E-07	2.9E-01	1.1E-07
Member of CPG Direct Gamma	5.0E-01	1.8E-07	1.9E-01	7.3E-08	1.3E-01	5.1E-08	9.7E-02	3.6E-08	5.8E-02	2.2E-08
Member of CPG - Ingestion of Drinking Water From Contaminated Well	---[c]	---[c]	---	---	---	---	---	---	---	---
Member of CPG - Ingestion of Foodstuff Contaminated by Well Water	---[c]	---[c]	---	---	---	---	---	---	---	---
Reclaimer Direct Gamma	1.4E+02	5.1E-05	5.2E+01	1.9E-05	3.7E+01	1.4E-05	2.6E+01	1.0E-05	1.6E+01	5.9E-06
Reclaimer -Humid Site- Indoor Radon Inhalation	---	6.8E-05	---	2.7E-05	---	1.9E-05	---	1.4E-05	---	8.1E-06
Reclaimer -Dry Site- Indoor Radon Inhalation	---	8.1E-05	---	3.1E-05	---	2.2E-05	---	1.6E-05	---	9.3E-06
Reclaimer Well Water Use	4.2E-03	4.2E-10	1.6E-03	1.6E-10	1.1E-03	1.1E-10	8.1E-04	8.0E-11	4.8E-04	4.8E-11
Reclaimer -Ingestion of Foodstuff Grown on-Site	2.6E-01	1.5E-08	1.0E-01	5.9E-09	6.8E-02	4.2E-09	4.7E-02	3.0E-09	2.9E-02	1.8E-09
Individual -Ingestion of River Water Contaminated by Groundwater	---[c]	---[c]	---	---	---	---	---	---	---	---
Individual -Ingestion of River Water Contaminated by Surface Runoff	2.0E-02	1.5E-09	7.6E-03	5.6E-10	5.3E-03	4.0E-10	3.8E-03	2.7E-10	2.3E-03	1.7E-10

---

a. Dose or dose commitment from one year of exposure.

b. Lifetime risk from one year of exposure.

c. No radionuclides are calculated to reach the off-site river or well via the groundwater pathway for more than 10,000 years because of groundwater velocities and retardation factors.

4-15 and 4-16. Estimated doses and risks for Scenarios 10 and 11, involving the use of phosphogypsum in both a concrete road surface and a road base, are shown in Tables 4-17 and 4-18.

In evaluating the risk to the construction worker from external gamma radiation, four cases were analyzed -- two in which the worker stands directly on the roadbed for the entire work day (no shielding), and two in which the worker uses equipment, such as a road grader, which provides some protection from external gamma radiation (with shielding). These four cases are considered to bracket the worker doses which could be received from external gamma radiation. Worker doses for Scenarios 8 and 9 were evaluated for the case of no asphalt cover over the roadbed to maximize the results of the dose calculations. Worker doses from dust inhalation were evaluated for a humid site (with characteristics typical of a southeastern site) and a dry site (with characteristics typical of a southwestern site).

Reclaimer doses were evaluated for a time (presumed to be 50 years after road construction) when the road is closed and the road surface has crumbled and been removed. The reclaimer is assumed to live in a house constructed on the site and to obtain 50 percent of his food from a garden grown on the site. Indoor radon doses to the reclaimer were evaluated for both a humid site and a dry site.

For the road construction scenarios, the highest doses and risks result from external gamma exposure and indoor radon inhalation to the reclaimer. For Scenarios 8 and 9, the lifetime risk to the reclaimer from one year of external gamma exposure is estimated to range from 2.6×10^{-5} for 26 pCi/g phosphogypsum to 3.2×10^{-6} for 3 pCi/g phosphogypsum. The lifetime risk from one year of indoor radon inhalation is estimated to range from 6.2×10^{-5} for 26 pCi/g phosphogypsum to 7.5×10^{-6} for 3 pCi/g phosphogypsum.

For Scenarios 10 and 11, the lifetime risk to the reclaimer from one year of external gamma exposure is estimated to range from 5.1×10^{-5} for 26 pCi/g phosphogypsum to 5.9×10^{-6} for 3 pCi/g phosphogypsum. The lifetime risk from one year of indoor radon inhalation is estimated to range from 8.1×10^{-5} for 26 pCi/g phosphogypsum to 9.3×10^{-6} for 3 pCi/g phosphogypsum.

4.4.3 Phosphogypsum in Research & Development Activities

The results of the risk assessment of the use of phosphogypsum in Research & Development activities are summarized in Table 4-19. For the Research & Development scenario (Scenario 12), a researcher is postulated to work in a laboratory and be exposed to an open 55-gallon drum of phosphogypsum. Doses to the researcher from external gamma radiation, dust inhalation, and indoor radon inhalation are evaluated.

The doses and risks to the researcher from external gamma radiation and dust inhalation are estimated to be comparable to worker doses from the agricultural and road

Table 4-19. Risk assessment results for Scenario 12 - use of phosphogypsum in R&D activities.

	Ra-226 Concentrations in Phosphogypsum									
	26 pCi/g		10 pCi/g		7 pCi/g		5 pCi/g		3 pCi/g	
	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]	Dose[a] (mrem)	Risk[b]
Researcher Direct Gamma	2.5E+00	9.1E-07	9.6E-01	3.5E-07	6.7E-01	2.5E-07	4.8E-01	1.8E-07	2.9E-01	1.1E-07
Researcher Dust Inhalation	9.1E-01	8.3E-08	3.5E-01	3.2E-08	2.5E-01	2.2E-08	1.8E-01	1.6E-08	1.1E-01	9.6E-09
Researcher Indoor Radon Inhalation	---	2.1E-05	---	8.1E-06	---	5.6E-06	---	4.0E-06	---	2.4E-06

---

a. Dose or dose commitment from one year of exposure.
b. Lifetime risk from one year of exposure.

construction scenarios. The greatest risk to the researcher is estimated to be from indoor radon inhalation. The indoor radon inhalation risk is estimated to range from 2.1×10^{-5} for 26 pCi/g phosphogypsum to 2.4×10^{-6} for 3 pCi/g phosphogypsum.

4.4.4 Ingestion of Treated Soil

A final risk assessment was conducted of ingesting soil that had been treated with phosphogypsum. Two scenarios are considered: Scenario 13, which assumes a biennial application rate for 100 years of 664 kg/acre of phosphogypsum containing 10 pCi/g Ra-226, and scenario 14, which assumes an initial application of 8,000 kg/acre of phosphogypsum containing 26 pCi/g Ra-226 followed by biennial applications of 4,000 kg/acre for 100 years. These application rates are the same as those used for scenarios 1/2 and 5/6, respectively (see Section 4.3.3.1). The detailed calculations and the results of this risk assessment are provided in Appendix C. The exposure periods and soil ingestion rates selected for this assessment are also listed in Appendix C.

The total estimated risks for each scenario are given in Table 4-20. The estimated risks from ingesting treated soil are small in comparison to those estimated earlier in this section for exposure to either direct gamma radiation or indoor radon-222. As might be expected, the highest estimated lifetime risk, 7.4E-6, is for a 70-year exposure period combined with using the phosphogypsum containing the highest Ra-226 concentration, 26 pCi/g. This risk is similar to that estimated for exposure to either direct gamma radiation or indoor radon when phosphogypsum containing only 3 pCi/g Ra-226 is applied at a rate of 227 kg (500 lbs) per acre (see Tables 4-12 and 4-13). Over 85 percent of the total risk is due to the presence of Pb-210 and Po-210, while the Ra-226 present contributes only about 10 percent of the risk.

Table 4-20. The estimated total risks due to the ingestion of soil treated with phosphogypsum[(a)].

Condition	Exposure Period[(b)]		
	70 year	30 year	9 year
Scenario 13	1.9E-6	8.8E-7	3.7E-7
Scenario 14	7.4E-6	3.5E-6	1.5E-6

(a) Results from Appendix C.
(b) Lifetime risk for the specified exposure period.

5. AVAILABILITY AND COSTS OF COMPETING MATERIALS

5.1 PEANUT FARMING IN GEORGIA

5.1.1 Availability

Georgia grows almost half of the peanuts produced in the United States. Of the more than 600,000 acres of peanuts grown in Georgia, approximately a third require some form of gypsum. Traditionally, 60-70% of that demand has been supplied by phosphogypsum (GDA90). But since the ban on phosphogypsum, there have been numerous entrants into the Georgia market for gypsum materials, even though there have been waivers for the agricultural use of phosphogypsum. New products in the Georgia area include: Nutcracker--a by-product of sulfuric acid neutralization distributed out of Tampa, Florida; Kemira--an industrial acid neutralization product distributed out of Savannah, Georgia; and Fluorolite--another acid neutralization product distributed out of Louisiana and Alabama. According to Agrobusiness, one of the largest distributors of gypsum materials in Georgia, these new products, as well as pure gypsum products, are abundant and available in the Georgia peanut growing area (JA91).

5.1.2 Cost

Dr. Carley, an agricultural economist at the University of Georgia, presented cost and effectiveness data for different types of gypsum fertilizers, including phosphogypsum, during public testimony on the limited reconsideration and proposed rule NESHAP for radionuclide emissions from phosphogypsum stacks in May 1990. He compared the four phosphate fertilizers in Table 5-1 with a control (no gypsum material added) to determine the economic return when using the four different types of gypsum materials. Carley found that phosphogypsum gave the highest return at $1218 per acre. U.S.G. 500, a gypsum product still available on the Georgia market today, provided a slightly lower return of $1212 per acre. The other two products analyzed, granular and pelleted substances, gave significantly lower returns.

By analyzing Dr. Carley's information, it is possible to compare the cost of increasing peanut yield from the control level for each of the gypsum materials. This comparison is shown in Table 5-2. Phosphogypsum provides the lowest cost per pound of peanuts when increasing yield. Gypsum costs are 1 cent for every pound of increased peanut yield if phosphogypsum is used as the source of gypsum. It costs four times as much, 4 cents per pound, to increase crop yield using U.S.G. 500. The two other materials, granular and pelleted substances, have considerably higher costs per pound to provide an increased yield.

Further analysis of phosphogypsum cost compared to substitutes is presented in Table 5-3. The analysis makes no assumption about comparative yield when using one gypsum fertilizer or another. It presents cost indices for gypsum materials competitive with phosphogypsum. Only two products, Fluorolite and Nutcracker have indices less than 1.

Table 5-1. Pod yields per acre of peanuts for various gypsum materials, estimated cost of various materials and estimated net return, Georgia.

Gypsum Material[a]	Experimental Yields (pds/acre)[a]	Gross Return ($/acre)[b]	Cost of Gypsum Material ($/acre)[c]	Return Minus Gypsum Cost ($/acre)
Control (no gypsum material)	2708	854	0	854
Phosphogypsum - Occiwet.	3917	1236	17.5	1218
Crystalline - U.S.G. 500	4000	1262	50	1212
Granular - Abssgram	3091	975	45	930
Pelleted - Abpellet	2768	873	37.5	835

(a) From reference A189.

(b) Priced at 1990 quota support price of $631 per ton, no adjustment made for grade.

(c) Based on Carley's personal communication with Coastal Plain Experimental Station research personnel; 1990 price quotations. Costs include transportation costs to Tift County Georgia.

Kemira is identically priced to phosphogypsum, with a cost index of 1. All of the other gypsum products are at least two and one-half times as expensive as phosphogypsum, with cost indices of 2.69 or greater. These cost indices are misleading, however, because they do not include transportation costs in the cost of the fertilizer. The two products which seem most competitive with phosphogypsum are both produced great distances from the Georgia peanut growing district -- in Tampa, Florida and Geismar, Louisiana. The Table 5-3 cost indices were revised by including estimated transportation costs from the point of sale to Tifton, Georgia for each of the fertilizers. The new cost indices are shown in Table 5-4. Tifton, Georgia was chosen as the final destination for determining transportation costs because it is in the center of the Georgia peanut growing area. The revised fertilizer cost indices show that no gypsum treatments are less expensive than phosphogypsum. Only Kemira, with a cost index of 1.28 approaches phosphogypsum. All other applications cost at least twice as much as phosphogypsum, with the exception of A.C.G.2000 and Nutcracker which cost 1.86 and 1.95 times as much as phosphogypsum, respectively.

As different soil amendments are not applied at the same rate, the application rate should be considered in the comparative pricing of different products. For example, the University of Georgia Cooperative Extension Service recommends a minimum application

Table 5-2. Gypsum material cost per pound of peanuts for competing gypsum materials.

Gypsum Material	Cost of Material ($/acre)	Experimental Yield (pds/acre)	Change in Cost From Control ($)	Change in Yield From Control (pds)	Change in Cost/Change in Yield ($/pd)
None (Control)	0	2708			
Phosphogypsum - Occiwet.	17.5	3917	17.5	1209	0.01
Crystalline - U.S.G. 500	50	4000	50	1292	0.04
Granular - Abssgram	45	3091	45	383	0.12
Pelleted - Abpellet	37.5	2768	37.5	60	0.63

Source: Table 5.1

Table 5-3. Fertilizer cost indices for competing materials relative to phosphogypsum at point of sale.

Fertilizer		Point of Sale[a]	Price at Point of Sale ($/ton)[b]	Fertilizer Cost Index
Phosphogypsum		White Springs, FL	13	1.00
U.S.G. 500		Brunswick, GA	38	2.92
Gold Bond Bag	(bagged)	Savannah, GA	41.5	3.19
	(bulk)	Savannah, GA	35	2.69
Domtar	(bagged)	Savannah, GA	47	3.62
	(bulk)	Savannah, GA	35	2.69
A.C.G. 2000		Cordele, GA	40	3.08
Nutcracker		Tampa, FL	10	0.77
Kemira		Savannah, GA	13	1.00
Fluorolite		Geismar, LA	7.5	0.58
		Columbia, AL	47	3.62
Granular (made from Kemira by Florida Favorites)		Moultrie, GA	63	4.85
		Macon, GA	63	4.85

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[a] Prices obtained from a phone conversation with Jim Arnold of Agrobusiness in Albany, Georgia on August 13, 1991.

[b] The fertilizer cost does not include equipment and labor cost for applying the fertilizer or transportation costs to the farm. Equipment costs can be considered the same for all fertilizers, but labor costs are higher for the two dry gypsums, Gold Bond Bag and Domtar, than for the damp gypsums.

Table 5-4. Fertilizer cost indices for competing materials relative to phosphogypsum incorporating transportation costs into the fertilizer cost.

Fertilizer		Point of Sale	Miles From Point of Sale to Tifton, GA[a]	Transportation Cost ($/ton)[b]	Total Fertilizer Cost (Transportation & Sale) ($/ton)	Fertilizer Cost Index
Phosphogypsum		White Springs, FL	107	10.7	23.7	1.00
U.S.G. 500		Brunswick, GA	111	11.1	49.1	2.07
Gold Bond Bag	(bagged)	Savannah, GA	174	17.4	58.9	2.49
	(bulk)	Savannah, GA	174	17.4	52.4	2.21
Domtar	(bagged)	Savannah, GA	174	17.4	64.4	2.72
	(bulk)	Savannah, GA	174	17.4	52.4	2.21
A.C.G. 2000		Cordele, GA	40	4	44	1.86
Nutcracker		Tampa, FL	363	36.3	46.3	1.95
Kemira		Savannah, GA	174	17.4	30.4	1.28
Fluorolite		Geismar, LA	400	40	47.5	2.00
		Columbia, AL	107	10.7	57.7	2.43
Granular (made from Kemira by Florida Favorites)		Moultrie, GA	29	2.9	65.9	2.78
		Macon, GA	104	10.4	73.4	3.10

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[a] Miles determined from a 1989 Rand McNally Road Atlas.

[b] Transportation Costs determined based on an estimated truck freight rate of $.10/ton/mile. The estimate is derived from the truck freight rate of Exhibit 2.6 of "Transportation Benefits of The Proposed Wabash Waterway," completed by Jack Faucett Associates in December of 1986. The figure was revised to account for inflation.

rate (broadcasting) for phosphogypsum and USG 500 of 1000 lbs/acre and 750 lbs/acre, respectively (USG90). Thus, a complete comparative pricing for phosphogypsum and substitute products will include their respective application rates. Table 5-5 presents the results of such an analysis for phosphogypsum and three substitute materials. It is estimated that USG 500 will cost $6.56 (about 55 percent) more per acre than phosphogypsum. Gold Bond and Kemira are 132 and 150 percent more costly per acre, respectively, than phosphogypsum.

Table 5-5. The comparison of material costs per acre.

Material	Costs (dollars/ton)		Application Rates (lbs/acre) (USG90)	Cost ($/acre)	Cost/Acre Differential ($)
	Product (Table 5-3)	Transportation (Table 5-4)			
Phosphogypsum	13	10.70	1000	11.85	0
USG500	38	11.10	750	18.41	6.56
Gold Bond	35	17.40	1050	27.51	15.66
Kemira	63	2.90	900	29.66	17.81

5.2 PEANUT FARMING IN NORTH CAROLINA

The North Carolina Agricultural Extension Service recommends that gypsum be applied to all peanuts regardless of soil type or soil nutrient levels. Although soil calcium is usually sufficient for good plant growth, it is inadequate for pod development and good quality peanuts. Application rates are balanced with the calcium content of the gypsum. Table 5-6 provides the application rates recommended by the North Carolina Agricultural Extension Service for four forms of gypsum (NC90).

According to the Department of Agriculture of the State of North Carolina, approximately two-thirds of peanut growers used phosphogypsum on crops in 1990. They estimate that the banning of phosphogypsum for agriculture use on peanuts would cost North Carolina peanut farmers approximately $2 million per year in producing 160,000 acres of peanuts (Gr90). In March 1991, the North Carolina Peanut Growers Association wrote that other gypsum sources may be available in North Carolina, but that "Phosphogypsum is less expensive, easier to handle, and convenient (Su91)." The Plant Food Association of North Carolina, which includes fertilizer manufacturers and dealers, materials suppliers, NC State University Research and Extension, and NC Department of Agriculture, wrote in April 1990, "Phosphogypsum provides a readily available and economical source of nutrients for our

Table 5-6. Gypsum sources and application rates for peanuts in North Carolina.

Source	Percent Calcium	Application Rate (lbs/acre) 16-18 in. Band	 Broadcast
Bagged (finely ground)	25	600-800	--
420 Granular	25	600-800	1,200-1,600
By-Product Wet Bulk	17	--	1,800-2,300
Granular By-Product	20	750-1,000	1,500-2,000

Eastern North Carolina peanut crop. There are other sources available, but excessively expensive (Yo90)."

5.3 PEANUT FARMING IN VIRGINIA

According to S. Mason Carbaugh, Commissioner of the Commonwealth of Virginia's Department of Agriculture and Consumer Services, and his staff, "an adequate supply of gypsum is available in Virginia to meet the needs of Virginia farmers (Ca90)." Carbaugh investigated prices for substitutes and found a price of $24.30 an acre for gypsum from U.S. Gypsum and $15.75 an acre for gypsum from Materials Byproducts, Inc. Phosphogypsum, available in Virginia from Texasgulf, was comparatively priced at $15.75 an acre. All prices are FOB at a dealer warehouse. The Virginia Farm Bureau Association estimates that banning the use of phosphogypsum would cost southeast Virginia peanut farmers, who currently use phosphogypsum, $20 more an acre for an alternative. The Association estimates that this increased cost would translate into a cost of several million dollars a year for the farmers of the approximately 100,000 acres of peanuts in Virginia (As90).

5.4 AGRICULTURE IN FLORIDA

AGRO Services International, Inc., under a grant sponsored by the Florida Institute of Phosphate Research, researched the use of phosphogypsum as a fertilizer on several Florida crops (AGRO89). As part of this study, AGRO Services completed field trials using various rates and placement of phosphogypsum (holding constant the addition of other fertilizers containing nutrients not in gypsum) in order to determine the yield response of several crops to phosphogypsum. As well as determining yield response for each crop tested, AGRO determined the economic returns due to the use of phosphogypsum on the crops. By assigning a cost to phosphogypsum and its application, assigning a selling price to the tested crops, and by using the percentage yield increases of the experiment, AGRO found that only cowpeas present a real risk in obtaining an economic return on investment in phosphogypsum among the crops tested. See Table 5-7 for a summary of the AGRO study. Application of phosphogypsum on the crops, other than cowpeas, is highly likely to result in strong economic returns, because the percentage increases in the last column of Table 5-7 are substantially higher than the break-even levels.

5.5 AGRICULTURE IN IDAHO

Simplot operates a plant in Pocatello, Idaho. In 1988 Simplot sold approximately 40,000 to 50,000 tons of phosphogypsum for use on alfalfa, onion, and potato crops in Idaho. In 1991, Simplot only sold approximately 4,500 tons of phosphogypsum for use on a ranch which produces corn, potatoes, and wheat. Due to the regulatory uncertainty surrounding the use and sale of phosphogypsum, they no longer promote sales (Mc91).

5.6 AGRICULTURE IN CALIFORNIA

According to The Fertilizer Institute, phosphogypsum is used on a variety of crops in California including citrus, almonds, vegetables, and tomatoes. The 1988 sales of phosphogypsum in California were 84,507 tons. The Fertilizer Institute estimates, however, that 1990 demand for gypsum for agricultural use in California is at 500,000-750,000 tons per year (TFI90b). Four Court, Inc., whose 1990 sales of phosphogypsum to California sources were 50,000 tons, questions the use of alternative mined gypsum from Utah. They suggest that mined gypsum from one Utah source contains high levels of uranium and thorium (Se90).

5.7 ROAD BUILDING IN FLORIDA

5.7.1 Availability

In a study considering the use of phosphogypsum for secondary road construction, the University of Miami writes, "Traditional road building materials, such as limerock, shellrock, shell, and clay are in short supply in many parts of Florida. Significant tonnages of aggregates used in road construction are now imported from foreign countries. The U.S. Bureau of Mines has forecasted that Florida will have to import all its aggregate by the year 2000 (UoM89)." The study suggests phosphogypsum as an alternative. According to the Florida Department of Transportation, however, limestone - the primary material used as a roadbase in the state of Florida - is plentiful from local sources throughout the state of Florida with a few exceptions. Natural sand-clay material and natural shellrock are also available in limited supply in some areas (He91). Thus, there appears to be differing opinions on the availability of roadbase materials in Florida, and the need for phosphogypsum in road construction is unclear.

Table 5-7. Economic returns using phosphogypsum on selected Florida crops.

Crop	Selling Price of Produce (Dollars)	Average Yield of Crop Without Phosphogypsum (pounds)	Cost of Phosphogypsum ($/acre)	Percentage Increase Needed to Break Even Using 1000 lbs/acre	Percentage Increase Needed to Break Even Using 2000 lbs/acre	Percentage Increase Found
Cantaloupe	0.10	36000	90	2.5	5	37
Sweet Corn	0.12	24000	90	3.1	6.2	55
Cow Peas	0.06	(a)	90	12.5	25	20
Bell Peppers	0.25	12000	90	1	2	40
Potatoes	0.08	60000	90	1.9	3.8	22
Tomatoes	0.14	36000	90	1.8	3.6	6
Watermelon	0.05	(a)	90	4.5	9	49

(a) Value missing from the source document.

Source: "Uses of Phosphogypsum Fortified With Other Selected Essential Elements as a Soil Amendment on Low Cation Exchange Soils." Prepared by Agro Service Intl., Inc. under a grant sponsored by the Florida Institute of Phosphate Research, Bartow, Florida, November 1989.

5.7.2 Cost

The University of Miami in conjunction with the Florida Institute of Phosphate Research constructed one and one-half miles of secondary road (Parrish Road) utilizing phosphogypsum(UoM89). They then compared the costs of building the road to the costs encountered in building two similar roads. The roads used for comparative purposes, Tanner Road and Windy Hill Road, were built in Polk County about the same time as Parrish Road, but were built with clay. The building of Parrish road was broken down into 9 tasks for which economic data (labor, capital, and energy expense) were collected. The tasks included: setting stakes and grading, hauling gypsum, spreading gypsum, boxing out and shaping up, mixing subgrade and gypsum, watering, final blade, compaction, and foreman's work. According to the analysis, the total cost for building Tanner Road and Windy Hill Road were $98,339 per mile and $129,320 per mile, respectively. In comparison, the cost of building Parrish Road was $23,485 per mile. Figure 5-1 breaks these costs down by vehicle, material, and labor costs. The road built with phosphogypsum materials has no material costs as the road was built close to the source of the phosphogypsum and the phosphogypsum was donated to the project. In order for the cost of building Parrish Road to equal the cost of Tanner Road and Windy Hill Road, the amount of phosphogypsum necessary to build one mile of road and the transportation of that amount of material would have to cost $74,854 and $105,835, respectively.

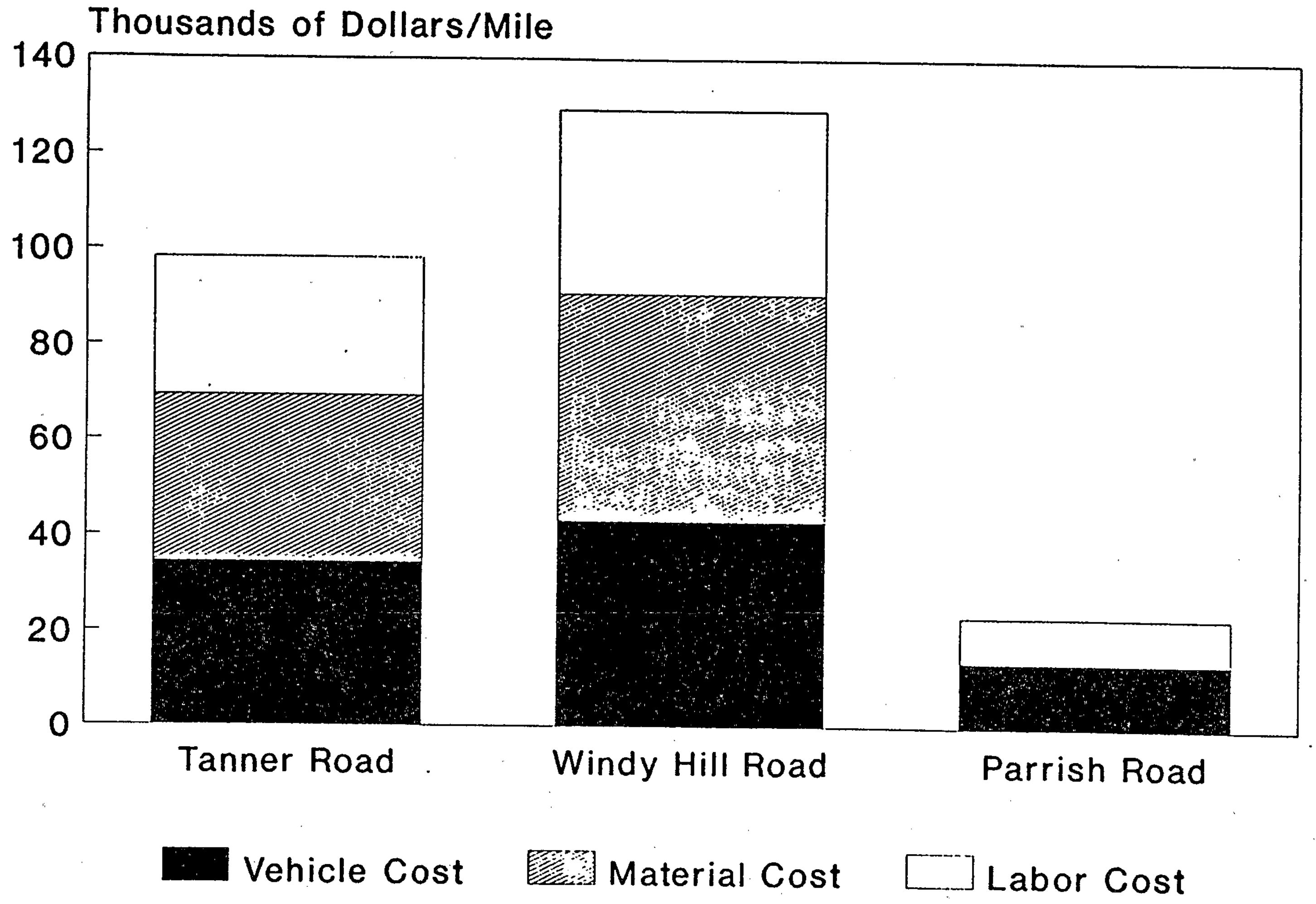
It is possible to estimate the cost of phosphogypsum to construct one mile of roadway using information provided in the BID; however, it is difficult to estimate the transportation costs. Because the transportation cost is a function of the haulage distance, it is possible, however, to estimate the distance phosphogypsum can be transported and not exceed the cost of using conventional materials ($74,854 and $105,835). The following information was provided earlier in this document.

- Roadbed Dimensions (Figure 4-1) - 0.25 m thick x 9.15 m wide x 1613 m long
- Roadbed Material Density (Table 4-5) - 2250 kg/m^3
- Cost of Phosphogypsum (Table 5-3) - $13.00/ton
- Transportation Cost (Table 5-4) - $0.10/ton-mile

Using this information, one mile of roadbed will contain 3690 m^3 of material weighing 9,151 tons. Phosphogypsum is usually mixed in various ratios with soil (clay/sand) in roadbed preparation. The amounts of phosphogypsum required and its cost for three commonly used mixtures are:

Phosphogypsum: Soil Mixture	Amount (tons)	Cost ($)
1:2	3,050	39,650
1:1	4,576	59,488
2:1	6,101	79,313

Fig. 5-1. Road building cost comparison-traditional material vs. phosphogypsum.



Source: UoM89

Thus, the amount of money for transportation costs not to exceed the cost of Tanner ($74,854) and Windy Hill ($105,835) roads will be:

Phosphogypsum: Soil Mixture	Tanner Road ($)	Windy Hill Road ($)
1:2	35,204	66,185
1:1	15,366	46,347
2:1	-4,459	26,522

The distance phosphogypsum could be shipped and not exceed the cost of using conventional materials is presented in Table 5-8.

Table 5-8. Estimated maximum distances phosphogypsum can be hauled for road use and remain competitive with conventional materials.

Phosphogypsum: Soil Mixture	Tanner Road (miles)[a]	Windy Hill Road(miles)[a]
1:2	115	217
1:1	34	101
2:1	0	43

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[a] miles = Trans. dollars available ÷ tons required x $ 0.10/ton-mile.

From this analysis, the economical advantage of using phosphogypsum in roadbed construction is not conclusive, but will depend in great part on the transportation costs. Therefore, the viability of using phosphogypsum in road construction will be dependent upon the location of the phosphogypsum in relation to the road construction site and the availability, cost, and location of competing materials.

5.8 RECLAIMING MINED LAND

5.8.1 Availability

Texasgulf produces phosphogypsum as a by-product at its wet phosphoric acid producing plant in Aurora, North Carolina (Pe91). The company's chemical processing facility is adjacent to their phosphate rock mine. In light of the proximity of the two sites, the company spent time and energy developing a method to mix clay, separated from the mined phosphate rock, and by-product phosphogypsum to reclaim mined land. This process, although economical for Texasgulf, may not be economical for other companies because the mines and the chemical processing plants of the other companies may not be close enough together to make the blending process economical, and the clay recovered from the phosphate rock in other locations may not be suitable for this type of process.

5.8.2 Cost

Quantitative figures on the savings Texasgulf achieves by reclaiming mined land were not available. However, obvious savings include the cost of building and maintaining phosphogypsum stacks and clay settling ponds. Additionally, land reclaimed with the phosphogypsum/clay blend is available for use sooner than when it is reclaimed with only clay. Texasgulf estimates that land reclaimed with the phosphogypsum/clay mixture is suitable for revegetation approximately 9 months after reclamation. Alternatively, land reclaimed with only clay may take 20 plus years before it is suitable for revegetation.

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APPENDIX A

PATHRAE PATHWAY EQUATIONS

APPENDIX A
PATHRAE Pathway Equations

A.1 PROGRAM DESCRIPTION

The PATHRAE methodology models both offsite and onsite pathways through which man can come in contact with the waste. For each of the pathways, the dose from each nuclide is calculated as a function of time. These doses are then summed to give the total dose for the pathway. The dose to the CPG from all pathways is then computed, assuming the entire nuclide inventory is accessible through each pathway.

In this assessment, the PATHRAE code considered eight pathways by which radioactivity may reach humans. These pathways were:

1. Groundwater migration with discharge to a river.
2. Groundwater migration with discharge to a well.
3. Surface erosion of the cover material and subsequent contamination of surface water.
4. Food grown on the site.
5. Direct gamma exposure.
6. Inhalation of radioactive dust on site.
7. Inhalation of radon gas and radon daughters on site.
8. Inhalation of radioactive particulates offsite (dust resuspension).

A.2 PATHWAY EQUATIONS

The equations used to calculate the doses, D, for each of the eight pathways are presented in this section. References are given to aid the reader in understanding the assumptions on which the equations are based and, where appropriate, some discussion is given of the important features of the equations. In general, the equations can be grouped into three components representing the waste form or release rate, the transport pathway, and environmental uptake. For simplicity, the results of the environmental foodchain analysis are represented in the equations by the symbol, U, called the equivalent uptake factor.

A.2.1 Pathway One - Groundwater to a River

Groundwater migration with discharge to a river is calculated from the following equation:

$$D = \frac{Q\lambda_L f_o U_1 (DF)}{q_w} \qquad \textbf{(A-1)}$$

where

Q = inventory of the isotope available in a given year (pCi)

q_w = flow rate of the river (m^3/yr)

f_o = fraction of inventory arriving at the river from transport through the aquifer

λ_L = fraction of each nuclide leached from the inventory in a year (l/yr)

U_1 = annual equivalent uptake by an individual (m^3/yr)

DF = dose conversion factor (mrem/pCi)

The components of the equation are:

Release Rate = $Q\ \lambda_L$
Transport Pathway = f_o
Environmental Uptake = $U_1\ /\ q_w$ (DF)

The term f_o can be calculated for dispersive groundwater transport using two methods. For the first case, a constant fraction leach model is used to obtain a non-dispersion solution, which is modified by the Hung Correction Factor[(4)] to obtain a dispersion solution form for f_o given by:

$$f_o = 0 \qquad \text{for } t \leq t_1 - t_0$$

$$f_o = \frac{v_a F_h}{LR\lambda_L}\left[1-\exp[-\lambda_L(t-(t_1-t_0))]\right] \text{ for } t_1 - t_0 < t < t_1\,. \qquad \textbf{(A-2)}$$

$$f_o = \frac{v_a F_h}{LR\lambda_L}\exp\left[-\lambda_L(t-t_1)\right]\left[1-\exp(-\lambda_L t_0)\right] \text{ for } t_1 \leq t$$

where

t = time (yr)

t_0 = RL/v_a

t_1 = $R(L+x_w)/v_a$

R = retardation factor = $1 + (\rho/p)k_d$

k_d = sorption coefficient in the aquifer (m^3/kg)

ρ = aquifer density (kg/m^3)

F_h = correction factor for dispersion

λ_L = length of waste site in direction parallel to aquifer flow (m)

v_a = interstitial horizontal aquifer velocity (m/yr)

x_w = distance of groundwater flow for nearest edge of burial pits to the river (m)

p = aquifer porosity.

The term F_h is strictly applicable to a time integration of the release and is given by:(4)

$$F_h = \exp\left[\frac{(L+0.5x_w)}{2D_a}\left(v_a + 2u - \sqrt{4uv_a + v_a2}\right)\right] \quad , \qquad \textbf{(A-3)}$$

where

D_a = longitudinal dispersivity (m)

u = $R\lambda D_a$

For dispersive groundwater transport a band release leaching model is used and f_o is given by:(5)

$$f_o = \frac{1}{N}\sum_{j=1}^{N}\left[\, F_j(t) - F_j(t-1/\lambda_L)\right] \qquad \textbf{(A-4)}$$

where

$F_j(t)$ = 0.5 U(t) [erfc (z-) + exp(d_j) erfc (z+)]

U(t) = unit step function

$z\pm$ = $\dfrac{\sqrt{d_j}\left[1+t/(Rt_{wj})\right]}{2\sqrt{t/(Rt_{wj})}}$

d_j = distance from sector center to access location, divided by the dispersity

t_{wj} = water travel time from sector center to access location (yr)

N = number of mesh points in numerical integration.

The numerical integration referred to above is a means by which the point source analytical solution for dispersive transport can be extended to approximate an area source. The disposal facility of length L is divided into N sectors of equal length. A point source of the appropriate magnitude is placed at the center of each sector. The distance, d_{jh}, is proportional to the distance from the center of sector j to the access location. The point source analytical solutions are then summed over all sectors to approximate an area source.

A.2.2 Pathway Two - Groundwater to a Well

Groundwater migration with discharge to a well is calculated from:

$$D = \frac{Q\lambda_L f_o U_2 (DF)}{q_w} \quad \textbf{(A-5)}$$

The aquifer dilution water flow rate q_w is given, in this case, by:

$$Q_w = \begin{cases} WLP \text{ for } H_w > L_p \\ WL_p V_a p \text{ for } H_w < L_p \end{cases} \quad \textbf{(A-6)}$$

where

W = width of waste pit perpendicular to aquifer flow (m)

L = length of waste pit parallel to aquifer flow (m)

P = water percolation rate (m^3/m^2-yr)

L_p = length of well casing in aquifer (m)

H_w = vertical dimension of contaminated zone in aquifer (m)

v_a = horizontal velocity of aquifer (m/yr)

p = aquifer porosity

U_2 = annual equivalent total uptake of well water by an individual (m^3/yr).

The vertical dimension of the contaminated zone, H_w, is related to the other parameters as follows:

$$H_w = \frac{P\,L}{p\,v_a}$$

A well that intercepts the contaminated zone of the aquifer may also draw in uncontaminated water if the length of the well casing, L_p, exceeds H_w. This is why Equation A-6 gives two forms for the dilution rate based on the relative magnitudes of H_w and L_p. In the general use of PATHRAE, the factor U_2 differs from U_1 in that contaminated seafood is not included.

In addition to modeling the effects of longitudinal dispersion in the aquifer, the well pathway can account for any transverse dispersion that may occur. This reduces the conservatism when calculating nuclide doses for the well pathway. When modeling transverse dispersion, the term f_o in Equation 2-5 is modified by an additional multiplicative term, f_t, given by:

$$F_t = \frac{1}{2} \operatorname{erf} \frac{(y_w + W/2)R}{2\sqrt{D_y\ t}} - \frac{1}{2} \operatorname{erf} \frac{(Y_w - W/2)R}{2\sqrt{D_y\ t}} \qquad \textbf{(A-7)}$$

where

y_w = distance to well from center of water area in the direction perpendicular to the aquifer flow (m)

D_y = transverse dispersion coefficient (m^2/yr).

For the limiting case in which D_y goes to zero, f_t, becomes equal to one. Therefore, the effects of transverse dispersion can be ignored by choosing D_y equal to zero.

The groundwater pathways to the (river and the well) can also accommodate transport in the vertical unsaturated zone between the waste and the aquifer. This is accomplished in the same manner as in the PRESTO codes.(2,4) The vertical water velocity and retardation are given by:

$$V = P/(pS)$$

$$R = 1 + \frac{\rho}{p * s} k_d \qquad \textbf{(A-8)}$$

where

S = fraction of saturation.

The term S can either be input or calculated from the expression:

$$S = S_r + (1 - S_r) \left[\frac{P}{K_h} \right]^{SNO} \qquad \textbf{(A-9)}$$

where

S_r = residual saturation

SNO = soil index

K_h = vertical zone saturated hydraulic conductivity (m/yr).

A.2.3 Pathway Three - Erosion and Transport to a River

The dose for sheet erosion of cover material and waste and its subsequent deposition in a nearby river is given by:

$$D = \frac{Q f_e f_{dil} U_1 (DF)}{q_w} \tag{A-10}$$

where

f_{dil} = fraction of solids entering river that originated in waste trenches (calculated internally in the code)

f_e = fraction of waste eroded each year

q_w = river flow rate (m^3/yr).

The parameter f_e is calculated from the surface erosion rate, E_r, which is an input variable, according to the relation $f_e = E_r/t_w$, where t_w is the waste thickness (m) and E_r is expressed in m/yr.

A.2.4 Pathway Four - Food Grown Onsite

The equation for D for food grown over the disposal site is:

$$D = \frac{Q f_d f_g (DF) U_3}{V \quad s} \tag{A-11}$$

where

V = volume of waste (m^3)

ρ_s = soil density (kg/m^3)

f_d = dilution factor representing the dilution of waste in the soil

f_g = fraction of individual's diet consisting of food grown over the disposal site

U_3 = total equivalent uptake factor for food (kg/yr).

Equation A-11 assumes that at some future time a reclaimer moves onto the waste disposal site and builds a house. By excavating a basement for the house and by drilling a well on the property, some of the waste material is brought to the surface and is mixed with the surface soil to some depth (t_g). Using these assumptions, the factor f_d representing the dilution of waste in the surface soil is given by:

$$f_d = f_m \left[\frac{t_m - t_c}{t_g \left[\frac{A_l}{A_h} - 1 \right]} + \frac{t_w}{t_g \left[\frac{A_l}{A_w} - 1 \right]} \right] \qquad \textbf{(A-12)}$$

where

t_w = thickness of the waste (m)

f_m = dilution of waste in the trench before reclaimer activities occur

t_c = thickness of cover (m)

t_m = depth of maximum mechanical disturbance (m)

t_g = depth to which contaminants are mixed with surface soil (m)

A_l = lot area (m^2)

A_h = house area (m^2)

A_w = cross sectional area of wells drilled (m^2).

The first term in the brackets of Equation A-12 is the component due to the excavation of a basement. The second term is the well drilling component. A complete derivation of Equation A-12 is given in Reference 6.

A.2.5 Pathway Five - Direct Gamma

The dose from direct gamma exposure to an intruder is calculated from:

$$D = \frac{Q}{A\mu_w t_w} B(\mu_c t_c) \left[1 + \frac{3\sqrt{\pi}}{4E_\gamma} - B(\mu_{wt_w}) \exp(-\mu_{wt_w}) \right] f_{exp} \, (8760)(DFG) \qquad \textbf{(A-13)}$$

where

$B(\mu t)$ = $1 + (\mu t)^{1.5}/e_\gamma$

μ_w = gamma attenuation constant of the waste (1/m)

μ_c = gamma attenuation constant of the cover (1/m)

t_w = thickness of the waste (m)

t_c = thickness of the cover (m)

$f_{(exp)}$ = fraction of the year the individual is exposed

A = plane area of the waste, the waste is assumed to be a circular horizontal plane with the exposed individual standing at the center (m^2)

E_γ = weighted average gamma energy emitted by nuclide (MeV)

DFG = infinite ground plane dose conversion factor (mrem/hr per pCi/m^2).

The function, B, in Equation A-13 is the gamma buildup factor which is used to account for the effects of gamma-ray scattering in the waste and in the cover. It is an empirical relation based on gamma scattering data at energies from 0.25 MeV to 1.0 MeV.(7)

The term in brackets in Equation A-13 accounts for self-shielding and buildup in the waste.

The weighted average gamma energy is computed by taking the average of all gamma energies emitted by a particular nuclide, each energy being weighted by its probability of occurrence.

There are three alternatives available when calculating direct gamma doses using PATHRAE. The first alternative allows the calculation of the gamma dose from the undisturbed buried waste. The second alternative assumes that plant roots penetrate the waste and transport some nuclides to the surface. Each year the plants die and deposit their absorbed nuclides on the ground surface, so there is continual transport of nuclides and deposition on the ground surface. The gamma dose is calculated from the nuclides deposited on the surface, as well as the nuclides remaining in the original burial trenches. The third alternative assumes that a reclaimer builds a house and digs a well on the site, as is described under Pathway Five. This brings some of the waste material to the surface where it is mixed with the existing soil. The gamma dose is calculated from the waste on the surface and from the waste that remains underground.

The three options in Pathway Five are selected by the value of the PATHRAE variable IGAMMA which can have the value 0, 1, or 2.

A.2.6 Pathway Six - Onsite Dust Inhalation

The dose, D, for the inhalation of resuspended dust by an inadvertent intruder is given by:

$$D = \frac{Q f_d \rho_d U_i f_{exp} (DF)}{V \rho_w} \qquad \textbf{(A-14)}$$

where

ρ_w = waste density (kg/m^3)

ρ_d = dust loading in the air breathed (kg/m^3)

f_{exp} = fraction of the year the individual is exposed to dust

U_i = volume of air breathed in a year (m^3/yr)

V = total volume of waste (m^3)

f_d = dilution factor representing the dilution of waste in the soil.

The assumptions for this pathway are similar to those for Pathway Four. That is, a reclaimer builds a house and drills a well over the waste site. The dose arises as a result of inhalation of contaminated dust during the excavation of the house's basement and the drilling of the well. As in Pathway Four, the dilution factor, f_d, is calculated using Equation A-12.

A.2.7 Pathway Seven - Inhalation of Radon in Structures

The dose from inhalation of radon and radon daughters in a structure built over the waste is calculated from:

$$D = \frac{Q}{h \lambda_r V F} E \sqrt{\lambda D_w} \tanh(100 b_w t_w) \exp(-100 b_1 t_1 - b_2 t_2) U_i (df) \qquad \textbf{(A-15)}$$

where

Q = inventory of Ra-226 (pCi)

E = fraction of radon which can emanate upward from the waste

h = height of rooms in structure built over the waste (cm)

r = air ventilation rate of the structure (air changes/sec)

V = volume of waste (m^3)

λ = decay constant of radon (1/sec)

t_w = waste thickness (m)

t_1 = thickness of earthen cover (m)

t_2 = thickness of concrete floor in reclaimer house (cm)

D_w = radon diffusion coefficient of the waste (cm^2/sec)

D_1 = radon diffusion coefficient of the cover (cm^2/sec)

D_2 = radon diffusion coefficient of concrete floor (cm^2/sec)

b_i = $\sqrt{\lambda/D_i}$ $(i = w, 1, 2)$

$$F = \frac{1}{2}\left[1 + \sqrt{a_w/a_c}\ \tanh(b_w t_w)\right] + \frac{1}{2}\left[1 - \sqrt{a_w/a_c}\ \tanh(b_w t_w)\right] \exp(-2(100\ b_1 t_1 + b_2 t_2))$$

a_i = $p_i^2\ D_i\left[1 - (1-k)m_i\right]^2$

m = $0.01\ M\rho/p$

M = moisture content (dry weight percent)

k = 0.26 pCi/m^3 in water per pCi/m^3 in air

p = porosity

U_i = total volume of air breathed in a year (m^3/yr).

A.2.8 Pathway Eight - Atmospheric Transport of Contaminants

The dose from the inhalation of airborne contaminants from dust resuspension (also valid for incinerator or trench fire) is given by:

$$D = \frac{Q}{V}\ r\ f_f\ f_v\left[\frac{X}{Q'}\right] U_i\ (df) \qquad \textbf{(A-16)}$$

where

r = dust resuspension rate or burn rate of incinerator or trench fire (m^3 waste/sec)

f_f = deposition velocity for dust resuspension (m/sec) or fraction of the year the burning occurs for incinerator and trench fire

f_v = nuclide-specific volatility factor for incineration or trench fire (fraction of nuclide released to atmosphere)

X = downwind atmospheric concentration (pCi/m^3)

Q´ = atmosphere source release rate (pCi/sec).

PATHRAE uses Gaussian plume(9) expressions for X/Q´:

$$\frac{X}{Q'} = \sqrt{\frac{2}{\pi}}\ \frac{f_w}{\sigma_z u}\ \frac{n}{2\pi x}\ \exp\ (-h^2/2\sigma_z^2 \tag{A-17}$$

where

f_w = fraction of time wind blows in direction of interest

σ_w = standard deviation of plume concentration in vertical direction (m)

u = average wind speed (m/sec)

n = number of sectors or wind directions (usually 16)

x = distance from source to receptor (m)

h = effective release height including momentum and thermal plume rise effects (m).

Plume depletion effects from deposition are represented by a reduced source release rate calculated internally to the code.(9)

The actual release height is modified to account for momentum and thermal plume rise effects by the following equations:(9)

$$h = h_s + \frac{1.5\ v_s\ d_s}{u} + \frac{1.6(3.7E-5\ x^2\ Q_H)^{0.333}}{u} \tag{A-18}$$

where

h_s = actual release height (m)

v_s = stack gas velocity (m/sec)

d_s = stack inside diameter (m)

Q_H = heat emission rate from stack (cal/sec).

Equation A-18 is valid as long as the distance to the receptor location is less than ten times the stack height. For greater distances the receptor distance, x, is replaced with 10 h_s.

If some parameters are unknown or poorly characterized, a default option, based on the location of the maximum plume concentration, is used. In this case:

$$\frac{X}{Q'} = \frac{2}{\pi h^2 e u} \qquad \textbf{(A-19)}$$

where

e = Euler's number (2.71828).

Equations A-17 and A-19 are from Reference 10 and are expressions for point sources. For the trench fire scenario it is assumed that the fire involves a relatively small amount of waste (for example, the amount received by the facility in one day). For an incinerator the only source is a single incinerator stack. Since the extent of the source is small in these cases, the use of the point source expression is justified.

If an area source is desired it can be represented by the virtual point source approximation, where x is replaced by x´, given by(1)

$$x' = x + 1.5137\ y$$

where

y = width of the facility (m)

The σ_z in Equation A-17 is calculated in PATHRAE using Briggs' approximations.(9) This necessitates specifying one of the six Pasquill atmospheric stability classes. If no stability class is specified in the input data set, the moderately stable Class D is used. The stability class should be chosen to represent an annual average stability. The wind speed, u, is the annual average wind speed in the direction from source to receptor.

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APPENDIX B

RA-226 SOIL CONCENTRATION CALCULATIONS

APPENDIX B
Ra-226 Soil Concentration Calculations

Radium-226 soil concentrations, resulting from periodic applications of phosphogypsum, can be calculated by solving a standard mass balance equation:

$$\frac{dC}{dt} = K - kC \qquad \textbf{(B-1)}$$

The solution to equation B-1 is obtained through standard differential equation solution techniques, and is found to be:

$$C = \frac{K}{k}\,(1 - e^{-kt}) \qquad \textbf{(B-2)}$$

Using the boundary condition of C=0 at t=0, the arbitrary constants can be solved for. The resulting solution then becomes:

$$Cs = \frac{k_i\ C_{pG}}{W} * \frac{1}{k_2 + k_3 + k_4 + k_5)} * (1 - e^{-(k_2 + k_3 + k_4 + k_5)t}) \qquad \textbf{(B-3)}$$

where

Cs = Ra-226 concentration in soil (pCi/g)

C_{pG} = Ra-226 concentration in phosphogypsum (pCi/g)

k_i = application rate of phosphogypsum (g/yr)

W = mass of soil (g)

k_2 = Ra-226 decay rate (4.3×10^{-4} yr^{-1})

k_3 = rate loss of Ra-226 due to uptake by plants (2.6×10^{-6} yr^{-1})

k_4 = rate loss of Ra-226 by leaching (2.8×10^{-5} yr^{-1})

k_5 = rate loss of Ra-226 by wind erosion (8.9×10^{-4} yr^{-1})

Using the data in the table presented below, the Ra-226 soil concentration can be calculated after 100 years of biennial phosphogypsum application.

Table B-1. Ra-226 soil concentration calculation parameters.

Parameter	Scenario 1 & 2	Scenario 3 & 4	Scenario 5 & 6
k_2 (yr^{-1})	4.3E-04	4.3E-04	4.3E-04
k_3 (yr^{-1})	2.6E-06	2.6E-06	2.6E-06
k_4 (yr^{-1})	2.8E-05	2.8E-05	2.8E-05
k_5 (yr^{-1})	8.9E-04	8.9E-04	8.9E-04
k_i (g/yr)	4.6E+07	1.0E+09	1.1E+09
t (yrs)	100	100	100
W (g)	1.9E+11	2.8E+12	1.0E+12
CpL (pCi/g)	30	30	30

A summary of the Ra-226 soil concentrations calculated for scenarios 1-6 is presented in Table B-2.

Table B-2. Ra-226 soil concentrations.

Scenario	Ra-226 Concentration (pCi/g)
1 & 2 (Agriculture: Average Case	0.69
3 & 4 (Agriculture: Maximum Case)	1.02
5 & 6 (Soil Amendment)	3.12

APPENDIX C

RISK ASSESSMENT FOR THE INGESTION OF TREATED SOIL

APPENDIX C
Risk Assessment for the Ingestion of Treated Soil

The risks that result from the direct ingestion of treated soil has been estimated using the following information:

1. Exhibit 6-14 of the Superfund Risk Assessment Guidance handbook
   a. Ingestion Rate
      - 200 mg/d 1-6 yrs of age
      - 100 mg/d 6-70 yrs of age
      - 365 days/yr

   b. Exposure Periods
      - 70 yrs - lifetime
      - 30 yrs - 90 percentile residency
      - 9 yrs - national average residency

   c. Total Uptake

9 Year Exposure

(200 mg/d)(365 d/y)(6 y)+(100 mg/d)(365 d/y)(3 y)= x mg
438,000 mg + 109,500 mg = x mg
547,500 mg = x mg
547.5 g

30 Year Exposure

(200 mg/d)(365 d/y)(6 y)+(100 mg/d)(365 d/y)(24 y)= x mg
438,000 mg + 876,000 mg = x mg
1,314,000 mg = x mg
1,314 g

70 Year Exposure

(200 mg/d)(365 d/y)(6 y)+(100 mg/d)(365 d/y)(64 y)= x mg
438,000 mg + 2,336,000 mg = x mg
2,774,000 mg = x mg
2,774 g

Table C.1. Scenario 13 - Based on 10 pCi Ra-226/g of phosphogypsum applied at the rate of 664 kg/acre biennially for 100 years.

Nuclide	Relative[1] Concentration (pCi/g soil)	RF[2] (Risk/uCi)	70 YR Risk	30 YR Risk	9 YR Risk
Ra-226	0.69	9.4 E-5	1.8 E-7	8.5 E-8	3.6 E-8
Po-210	0.66	1.4 E-4	2.6 E-7	1.2 E-7	5.1 E-8
Pb-210	0.89	5.5 E-4	1.4 E-6	6.4 E-7	2.7 E-7
Th-228	0.09	1.3 E-5	3.3 E-9	1.5 E-9	6.4E-10
Ra-228	0.09	7.0 E-5	1.8 E-8	8.3 E-9	3.5 E-9
Th-230	0.12	2.3 E-5	7.7 E-9	3.6 E-9	1.5 E-9
Th-232	0.08	2.1 E-5	4.7 E-9	2.2 E-9	9.2E-10
U-234	0.08	7.5 E-5	1.7 E-8	7.9 E-9	3.3 E-9
U-235	0.003	7.3 E-5	6.1E-10	2.9E-10	1.2 E-10
U-238	0.07	7.4 E-5	1.4 E-8	6.8 E-9	2.8 E-9
TOTAL RISK			1.9 E-6	8.8 E-7	3.7 E-7

1 Soil concentrations after 100 years of application taking into consideration removal mechanisms.

2 Risk factors from Table A-5 of EPA89b.

Table C.2. Scenario 14 - Based on 26 pCi Ra-226/g of phosphogypsum applied at the rate of 8,000 Kg/acre initial application followed by biennial applications of 4,000 Kg/acre for 100 years.

Nuclide	Relative[1] Concentration (pCi/g soil)	RF[2] (Risk/uCi)	70 YR Risk	30 YR Risk	9 YR Risk
Ra-226	2.74	9.4 E-5	7.1 E-7	3.4 E-7	1.4 E-7
Po-210	2.64	1.4 E-4	1.0 E-6	4.8 E-7	2.0 E-7
Pb-210	3.55	5.5 E-4	5.4 E-6	2.6 E-6	1.1 E-6
Th-228	0.34	1.3 E-5	1.2 E-8	5.8 E-9	2.4 E-9
Ra-228	0.34	7.0 E-5	6.6 E-8	3.1 E-8	1.3 E-8
Th-230	0.47	2.3 E-5	3.0 E-8	1.4 E-8	6.0 E-9
Th-232	0.31	2.1 E-5	1.8 E-8	8.8 E-9	3.6 E-9
U-234	0.30	7.5 E-5	6.3 E-8	3.0 E-8	1.2 E-8
U-235	0.013	7.3 E-5	2.6 E-9	1.2 E-9	5.0 E-10
U-238	0.28	7.4 E-5	5.7 E-8	2.7 E-8	1.1 E-8
TOTAL RISK			7.4 E-6	3.5 E-6	1.5 E-6

[1] Soil concentrations after 100 years of application taking into consideration removal mechanisms.

[2] Risk factors from Table A-5 of EPA89b.