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RISK ESTIMATES
FOR USES OF PHOSPHOGYPSUM

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FINAL REPORT

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DISCLAIMER

PERSPECTIVE

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Phosphogypsum is the name given to hydrated calcium sulfate that is generated as a by-product by the phosphate industry during the wet-process manufacture of phosphoric acid. Although small amounts have found use in the past, the great majority of the material produced in Florida has been stockpiled on the ground. Some 700 million tons of the material are stored currently in nearly two dozen stacks, some of which can occupy several hundred acres of ground surface and reach as much as 200 feet in height. Typically an additional 30 million tons of phosphogypsum are added annually. A major research goal of the Institute since virtually its inception, and certainly a goal of the industry, has been to find uses for the material that are technologically practical, economical, and environmentally safe and protective of public health. Past research has been focused in three areas: (1) Recovery of sulfur from the gypsum, (2) Use in construction, mainly in roads, and (3) Use in agriculture as a soil conditioner and to supply calcium and sulfur nutrients. The major hindrance to its use has been an elevated level of natural radionuclides. Phosphate ore contains higher levels of uranium and its decay products than do most soils and rocks. As the ore is processed, the majority of radium, and the daughter products polonium and lead, tend to locate in the gypsum.

In June of 1992 the U. S. Environmental Protection Agency issued a final rule under the "National Emission Standards for Hazardous Air Pollutants" (40 CFR, Part 61) that, in addition to establishing rules for storage, severely restricted both use and research involving phosphogypsum. The ruling banned the use of the material in agriculture unless the radium content was minimal, banned its use in road construction, and limited the amount that could be used in research. The material was simply to be stockpiled on the ground or placed into mine cuts. In a Background Information Document (1992) the EPA explained that their goal was to achieve a maximum lifetime risk of 1 in 10,000. They determined that, while risks to current users and exposed population groups generally would be acceptable, future risks to persons who might live in homes eventually built on abandoned agricultural or road-bed lands would be unacceptable. Indoors, inhalation of radon gas and its progeny, plus direct exposure to gamma radiation, would present too great a risk.

A number of interested parties, including industry, trade associations, consulting firms, and the Institute felt the agency had overestimated the risk to future home dwellers on affected lands, that the true risk would fall within EPA's usual criteria for acceptability. As one aspect of its phosphogypsum program, the Institute engaged the services of Battelle Pacific Northwest Laboratories (PNL) to review and critique the EPA background document. Battelle's findings are presented in this report. Also PNL conducted an independent evaluation of risks, using dose factors from several Federal Guidance Reports and reports issued by the International Council on Radiation Protection. A tabular comparison of risks from the two approaches is included herein.

A. Introduction

This report describes work done by PNL to review and critique the EPA background information document (BID) (EPA 1992). In addition, a re-evaluation of the "Maximum Individual Risks" (MIR) were carried out for the following exposure scenarios:

(a) home built on reclaimed road constructed with phosphogypsum (PG)

(b) the application of PG as a soil conditioner or fertilizer

(c) the use of PG in research and development laboratories

The BID also gave the calculated exposures that would occur during road construction: that scenario is reviewed here, but MIR's are not re-evaluated.

Three issues have been addressed for each scenario reviewed:

(1) appropriateness of methodology used in the BID

(2) appropriateness of model parameters used in the BID

(3) what are the best available models and parameters to do the calculations

The review of the data and parameters, and the exposure scenarios are given in Section B.1 and B.2 respectively, and the re-evaluation MIR's are given in Section C

Calculated doses for external gamma exposures, inhalation of PG dust, and ingestion of water and food contaminated with PG are reported in the BID. These doses were converted to lifetime risks per year of exposure and compared to the risk from exposure to radon. The reason that doses were not calculated for radon exposure in the BID is not stated.

The PNL evaluation is done using the dose factors from Federal Guidance Reports FGR-11 and FGR-12 and dose and risk factors from ICRP Publications 60, 65, 66, and 68. Risks from inhalation and ingestion are calculated using ICRP Publication 60 risk factors and the dose data in ICRP Publication 68. Risks from radon exposure are taken from ICRP Publication 65.

B. Review of EPA 520/1-91-029

B.1 Input Data and parameters

B.1.1 Phosphogypsum

The relative (to ^{226}Ra) concentrations of radionuclides in phosphogypsum used in BID are given in the Table 1. The Natural Th chain radionuclide concentrations were based on a ratio of 0.133 for ^{228}Ra to ^{226}Ra. However, the Th chain radionuclide will not remain with the radium, and these concentrations are probably too high. The BID is the only place found that gives Th chain radionuclides in PG above that in soil.

Annex A, para 159 of the 1993 UNSCEAR Report (UNSCEAR 1993) states that ^{232}Th in phosphate rock is 'similar to that observed normally in soil', and Table 7 of that Annex gives the concentration ratio of Ra to Th in phosphogypsum of 30. Recommended revised values based on the UNSCEAR report are included in Table 1.

B.1.2 Direct Gamma

The main contributing radionuclides to the external gamma dose are ^{226}Ra, ^{228}Ra and ^{228}Th (see BID Table 4-4). Since ^{228}Ra and ^{228}Th are members of the thorium chain, the external gamma doses will be over estimated if the thorium chain radionuclides are over estimated. If the PNL concentrations (Table 1) are applied to PG the sum of the direct gamma dose conversion factors (DCF) in Table 4-4 of the BID the doses and the corresponding risks are reduced by 47%.

The direct gamma doses from contaminated surfaces given in Table 4-4 of the BID have been compared with the values given in Table III.3 of FGR-12 (Eckerman and Ryman, 1993). The dose from the short lived progeny of ^{222}Rn and ^{220}Rn are included in the DCF taken from the FGR with the assumption that they stay with the parents (^{226}Ra and ^{228}Th) as reasonable agreement between the BID and FGR values can not be achieved unless this is assumed. The results of this comparison are shown in Table 2. The ratio of the DCF from the two documents are close to unity except for ^{210}Pb, ^{235}U and ^{238}U. The reason that the DCF for ^{210}Pb in the BID being zero is not known, but the DCF's for ^{235}U and ^{238}U are exchanged in Table 4-4 of the BID.

B.1.3 Radon

The lifetime risk per year of exposure to radon is assumed to be 4.4 x 10^{-8} and 4.4 x 10^{-9} per pCi m^{-3} for indoor and outdoor exposure respectively in the BID. These values are converted to the units used in the ICRP publications by converting pCi to Bq (0.037 pCi Bq^{-1}) and using the potential alpha energy 5.6 x 10^{-9} (J Bq^{-1}) for radon at equilibrium. An exposure to one pCi m^{-3} for one hour is equivalent to 5.3 x 10^{-6} (J h m^{-3}). If this unit is used the BID values for the lifetime risk per year of exposure become 2.1 x 10^{3} and 2.1 x 10^{2} per (J m^{-3}) for indoor and outdoor exposure respectively.

In contrast, ICRP Pub 65 gives a risk factor of 8.0 x 10^{-5} per (mJ h m^{-3}) for workers and members of the public. Factors recommended to convert from dose to fatal cancer risk are 1.1 and 1.4

Sv per (J h m^{-3}) for exposures in the home and at work respectively. The difference between home and work is caused entirely by the different coefficients (to convert dose to risk) for workers and members of the public given in ICRP Publication 60. The risk factor of 8.0 x 10^{-5} per (mJ h m^{-3}) results in a lifetime risk of 700 for a 8760 hour year. Hence the ICRP value is midway between the indoor and outdoor factors assumed in the BID.

B.1.4 inhalation and ingestion

The risks from inhalation of PG contaminated dust and the ingestion of PG contaminated food and water are reproduced in Table 3 from the BID along with values calculated from the most recent recommended of the ICRP. The ICRP values are calculated from the effective dose (Sv) per Bq intake from ICRP Publication 68 and the risk per Sv given in ICRP Publication 60.

The Type used by the ICRP refers to the transportability of compounds from the respiratory tract to blood; Type F, M and S refer to fast, medium and slow respectively (ICRP Publication 66). These classifications are also used for ingestion in Publication 68, but DCF for ingestion are not given for all the Types for which inhalation values are given as they do not occur in food or water.

The BID values are compared to the ICRP derived value (Table 3) using the ICRP Type with the largest DCF for inhalation and the most soluble factor for ingestion. The ICRP derived values are smaller than, or approximately equal to, the BID values, except for those for ingestion of the long lived isotopes of thorium, for which the ICRP values are greaterthan the BID values by about a factor of two.

8.2 Summary of the scenarios and results of the' BID

B.2.1 Road construction with PG

Two type of roads were considered; one of asphalt covering a road base constructed with a PG:soil= 1:2 mixture, and the second with a PG:Concrete=0.15:1 mixture replacing the asphalt.

Risks per year of exposure were evaluated and reported in Tables 4-15 to 4-18 for construction workers, commuters using the road, members of the critical population group (CPG) and people living on land reclaimed from deserted road beds. Only the risks to construction workers are evaluated in this section.,

The results reported for external gamma for construction workers with no shielding is 1.5(-5) per year, and 9.0(-6) per year with shielding. A year is taken as 2000 hours and the shielding factor as 0.6. The time factor used (2000 hours) is a maximum as the worker is assumed to spend the total time on the road surface. The shielding factor (0.6) is a minimum that would be expected if the worker was in the cab of heavy construction equipment. The risks given in the BID are therefore maxima for the PG concentration to risk conversion factors used.

The results reported for dust inhalation are 8.4(-8) and 2.2(-7) per year for a humid and a dry site respectively. The increased risk at dry sites is reasonable, but exposures to dust would be highly variable and depend on the suspendability of the PG in the construction material and a workers job assignments. Since that information is not given in the BID, the suitability of the risk factors given cannot be evaluated.

B.2.2 Application of PG as a soil conditioner or fertilizer

PG is assumed to be applied to soil every two years for 100 years after an initial application of twice the biennial application rate. PG concentrations in soil were evaluated for six scenarios and the were reported in Tables 4-6 to 4-11. These scenarios are the average (Scenario 1 and 2), and maximum (Scenario 3 and 4) use of PG as a source of calcium and sulfur. Scenarios 5 and 6 were for the application of PG for sediment control. The two scenarios for each PG application rate are for sand and clay soils.

Scenarios 1 and 2 had an application rate of 664 kg of PG per acre with a tillage depth of 22 cm. Scenarios 3 and 4 had an application rate of 2032 kg of PG per acre with a tillage depth of 46 cm. The ^{226}Ra concentrations in soil after 100 years of application of PG with a ^{226}Ra concentration of 30 pCi g^{-1} was calculated to be 0.69 for scenarios 1 and 2 (average site) and 1.02 pCi g^{-1} for scenarios 3 and 4 (maximum site). Scenarios 5 and 6 had an application rate of 4000 kg of PG per acre with a tillage depth of 30 cm. The corresponding ^{226}Ra concentrations in soil after 100 years of application of PG with a ^{226}Ra concentration of 30 pCi g^{-1} was calculated to be 3.12.

. The risks from direct gamma to an agricultural worker for the application of PG with a radon concentration of 26 pCi g^{-1} range from 1.4(-6) to 6.4(-6) for scenario 1 and 5 respectively. The risk from dust inhalation is 5.8(-9) for scenarios 1, 2 and 5, and 9.0(-9) for scenarios 3, 4 and 6.

B.2.3 Home built on land reclaimed from road constructed with PG and on land contaminated by PG for agricultural purposes.

These two situations are treated separately in the BID. The results were reported in Tables 4-6 to 4-11 (scenarios 1 to 6) for agricultural land and in Tables 4-15 to 4-18 (scenarios 8-11) for the reclaimed road bed. Since they are similar, they are reviewed together in this evaluation. Different concentrations of ^{226}Ra (26, 10, 7, 5 and 3 pCi g^{-1}) were assumed. Since these risks are proportional to the ^{226}Ra concentration assumed, only the risks corresponding to 26 pCi g^{-1} of ^{226}Ra are summarized in Table 4.

Risks to the occupant of a home built on the reclaimed road bed (the term 'reclaimer' is used for the occupant) and of a home built on agricultural land (the term 'on-site individual' is used for the occupant) have been calculated. A member of the CPG is a adult living in the nearest residence, but the risks to the CPG were calculated separately from those for reclaimers and on-site individuals. In addition to these residents, the risk to individuals who drink river water contaminated by surface runoff are given for scenarios 8-10. For simplification, only the highest risk for any scenario is given in Table 4 and are therefore not additive.

The annual risk from direct gamma exposure ranges from a low of 3.0(-6) for an on-site individual (scenarios 1 and 2) to a high of 5.1(-5) for a reclaimer (scenarios 10 and 11). The time spent in the houses is not stated but the assumption that the occupants reside and work at home will result in 8760 hours exposure in a year and the highest risk for the photon fields used.

The annual risk from indoor radon ranges from a low of 2.6(-5) for an on-site individual (scenarios 1 and 2) to a high of 8.1(-5) for a reclaimer at a dry site (scenarios 10 and 11).

The annual risk from ingestion to people occupying a home on the reclaimed road bed obtain their water from a well drilled at the site and one half of their vegetables from a home garden. The risk is 4.2(-10) and 1.5(-8) from drinking water and eating food respectively. People occupying a home on the contaminated agricultural land do not eat food or drink water from the site. The risk to a member of the CPG from eating food grown on the contaminated soil ranges from a low of 5.2(-9) for scenarios 1 and 2 to a high of 2.3(-8) for scenarios 5 and 6 respectively:

The risk from inhaling dust is not given for on-site individuals or reclaimers, but has been for the CPG from contaminated agricultural land. The values range from a low of 3.6(-12) for scenario 3 to a high of 3.7(-8) for scenario 6.

B.2.4 The use of PG in research and development laboratories

Doses were evaluated for a researcher exposed to an open 55-gallon drum containing PG and reported in Table 4-17.

The researcher is assumed to spend 1000 hour per year at an average distance of one meter from the drum, and be exposed to an air concentration of 100 µg m^{-3} of PG contaminated dust and radon from the drum. The BID results are summarized in Table 5. Subsequent to the BID publication, the EPA reported (Decision Concerning Petition for Reconsideration, 3/7/94) that the calculations were done for five drums, rather than one. Hence the values reproduced from the BID in Table 5 are too large by a factor of five, and results reduced by this factor are included.

It is difficult to estimate the average distance that a researcher would be from a PG drum. The use of an average distance of 1 meter from a drum for 4 hours per day as assumed in the BID will result in an estimate that is likely a maximum. A more reasonable working situation that would result the researcher spending a few hours per week at this distance and the remainder a much greater distance. A dust air concentration of 100 µg m^{-3} also is a maximum as this concentration would only be expected during times when the PG was being sampled or otherwise disturbed.

The room is ventilated with clean air at an average rate of 2 air changes (162 m^3) per hour. The number of air changes in laboratories range from 1 to 10 and are typically at the high end of this range (Traub, R. J. and G. A. Jensen. 1995). Since the radon and dust concentrations will decrease as the ventilation is increased, the choice of 2 air changes per hour is conservative.

C. Re-evaluation of risks

C.1 Living in a home built on land contaminated with PG.

As was done in Section B.2.3, the two scenarios for houses are treated together in this re-evaluation. The model house used in the re-evaluation is based on the one described by Revzan et el (1995); a 'slab-on-grade' house typical of those built in Florida. The soil beneath the slab and the fill around the footings and trenches is assumed to be homogeneously contaminated with PG. The dimension used are those used by Revzan et al. The radionuclide concentration ratios (relative to ^{226}Ra) used are those in Table 1.

Individuals are assumed to spend 50% of their time indoors and 50% of their time out-of-doors. The individual is exposed to radiation from four major sources:

1. 'Direct Gamma' external radiation from radioactive material in the soil
2. Radon and its progeny that is released from the soil
3. Inhalation of radioactive dust in the air
4. Ingestion of food and water.

These four sources are treated separately below.

C.1.2 Direct Gamma

The radionuclides are assumed to have the relative concentrations given in Table 1, with the short lived progeny in equilibrium, for the computation of the radiation doses from radioactive ground contamination. The dose factors used are those for ground contaminated to an infinite depth given in Table III.7 of FGR.12 (Eckerman and Ryman; 1993). The calculated dose rate to an individual standing on the contaminated soil is 0.0013 mrem h^{-1}. Dose reduction factors from house construction materials, specifically the concrete floor slab and non-radioactive fill material under the slab, were computed using Microshield Version 3.13, and are given in Table 6. The range in the annual dose for individuals who spends one half of their time outdoors ranges from 11.4 to 5.88 mrem, for no shielding and maximum shielding from the house materials, respectively.

C.1.3 Radon

The emanation of radon from soil will depend on the emanation of radon from the PG particles in the soil (emanation coefficient) and the transport of 'free' radon through soil gas (radon exhalation) (Rutherford et al, 1995). The emanation fractions will depend on the size fractions of the PG in the fill around the house. An example for central Florida PG were recently reported by Rutherford et al (1995) and are reproduced in Table 7.

The concentration in. the house was calculated under the assumptions that the interior of the house was 3 meters tall. The house was built on contaminated soil but there was a 30 cm layer of clean, fill overlying the contaminated soil and over the fill material was a 10 cm thick concrete slab. The flux was computed using the Rn3D code (Holford, 1994) and the radon transport characteristics for the soil, fill and concrete were taken from the Rn3D users documentation. To maximize the radon flux, the calculations assumed that the soil was dry.

Equilibrium radon concentration were calculated for a soil contamination of one pCi g^{-1} of ^{226}Ra and the other radionuclides in the relative concentrations given in Table 1. Two limiting assumptions about radon emanating into the air in the house that are thought to represent a likely range were made. If the floor has no cracks the concentrations is 221 pCi m^{-3}; this value increases to 367 pCi m^{-3} if a 0.3 cm wide crack every 40 cm is assumed.

C.1.4 Inhalation of Dust

The dose rates due to the inhalation of dust was calculated using the dose conversion factors published in FGR-11 (Eckerman et al 1988). These dose factors are for the dose received in the 50 years following the intake of the radioactive material. As a conservative measure, the largest published conversion factor was used. While out-of-doors, the individual was assumed to breath at the ICRP-23 (ICRP 1975) “light activity” rate of 1.2 m^3 per hour.

The inhaled quantities will depend on the resuspendability of the PG in soil and have not been re-evaluated. The outdoor dust loading assumed in the BID was 500 $\mu g/m^3$ (this is an extremely heavy dust loading), and the indoor dust loading is assumed to be zero. With these assumptions about dust loading and the assumptions outlined above, the annual mass of dust inhaled is 2.6 grams, and the annual risk due to inhalation of radioactive dust is 9.2 x 10^{-7} for soil contaminated at one pCi g^{-1} of ^{226}Ra.

C.1.5 Ingestion of PG in Food and Water

The most soluble lung retention Type is used to re-evaluate the BID results. The ingested quantities will depend on the solubility of the PG, and the subsequent transport through soil to well water or uptake by roots. The concentrations in drinking water and vegetation have not been re-evaluated. The risk results (Table 3) are multiplied by the relative concentrations from Table 1. The annual risk per Bq of ^{226}Ra ingested is 7.6(-8).

C.2 Use of PG in research and development laboratories

The scenario for the re-evaluated is that the researcher spends all 1000 hours per year in a room that contains one barrel of PG (^{226}Ra concentration=26 pCi g^{-1}) contaminated soil. The room is assumed to be 3 meters square with a ceiling height of 3 meters (air volume=27 m^3). The barrel is situated in a corner of the room and the average distance from the surface of the drum to a worker is 1 meter for 250 hours and 2 meters for 750 hours. The barrel is covered and PG contaminated dust is not generated unless the researcher is taking a sample from the barrel. A dust concentration of 100µg m^{-3} is assumed for 10 minutes 12 times per year. The room is ventilated with clean air at an average rate of 2 air changes (162 m^3) per hour, as was done in the BID.

Radon that is produced in the soil in the barrel will be emanate into the air in the room but all progeny produced in the barrel will be trapped and decay there.

The research activities are as follows. The worker is assumed to spend 4 hours per day, 250 days per year in a laboratory that contains one 55-gallon drum of phosphogypsum. The worker is exposed via direct gamma irradiation from both the material in the drum and from gamma emitting materials in the air, dust inhalation, and radon inhalation pathways.

The parent radionuclide concentrations used for these calculations are shown in Table 1. The short lived progeny of these basis radionuclides are assumed to be in equilibrium with their parent radionuclides. All calculations were based on the Ra-226 concentration of 26 pCi g^{-1} phosphogypsum, the radiation doses due to other Ra-226 concentrations can be obtained by scaling. The phosphogypsum material was assumed to have a bulk density of 1.5 g/cm^3 which is a midrange value of those provided by Chang and Mantell (1990, p10). The research facility was assumed to have a volume of 81 m^3 and an air turnover rate of 2 h^{-1}. When calculating doses due to inhalation, the worker was assumed to be breathing at the ICRP-23 (ICRP 1975) "light activity" breathing rate of 1.2 m^3 per hour.

C.2.1. Direct Gamma

External gamma dose rates from the drum of phosphogypsum were calculated using Version 3.13 of the Microshield shielding code. This code calculates. exposure rates to a point in space and these exposures were conservatively taken as dose rates. Doses for 1 and 2 meters from the drum were calculated and are included in the calculations in Table 5. The external doses due to the airborne dust were calculated from the 100 $\mu g/m^3$ dust loading by using the dose conversion factors published in FGR-12 (Eckerman and Ryman, 1993, Table III.1), and are included in Table 5.

C.2.2 Radon

The Rn-3D code has been used to calculate radon concentrations in the room. The air concentration in the laboratory was calculated based on the flux of radon emanating from the drum of phosphogypsum as calculated by the Rn3D computer code (Holford 1994). The equilibrium air concentration of radon is given in Table 5. This air concentration is based on a radon flux from the drum of 0.23 pCi s^{-1}. This computed flux is much less than the rate at which radon is generated in the drum (0.71 pCi s^{-1}).

There is a large divergence between this, report and the BID document when considering the radon air concentrations and the consequent risk. The difference is due to the extent of "holdup" of radon in the drum. The, authors of the BID document apparently assumed that all radon generated in the drum was immediately released to the air whereas in this document the retention of radon by the soil in the drum was taken into account. The risk values published in the BID document can be obtained by assuming that the radon is released immediately upon generation.

C.2.3 Dust

The amount of air inhaled by the researcher while taking samples from the barrel is 2.4 m^3 y^{-1} and the intake of PG contaminated dust is 240 µg. The resulting intake of ^{226}Ra is 2.3(-3) Bq in a year, and the risk is 2.1(-9).

The inhalation dose rates due to the airborne dust was calculated using the dose conversion factors published in FGR-11 (Eckerman et al, 1988). As a conservative measure, the largest published conversion factor was used. Doses due to inhalation of radioactive dust are shown in table 5.

D Summary

Since the major concern addressed in this report is the use of land contaminated with PG, only the findings related to that potential use are summarized here. These results are consistent with those presented by James (1995). The risks given by James are for 70 years (lifetime) of exposure whereas the risks in the BID are the lifetime risks for per year of exposure.

D.1 'Direct Gamma' external radiation from radioactive material in the soil

The calculated dose rate to an individual standing on the contaminated soil is 0.0013 mrem h^{-1} and for an individual in a house is 2.5 x 10^{-5} mrem h^{-1}. Therefore the range in the annual dose for individuals who spends one half to all of their time outdoors ranges from 5.8 to 11.4 mrem. These doses result in annual risks from a low of 2.4 x 10^{-6} to a high of 4.6 x 10^{-6}. This can be compared to the range in. risk values from a low of 3.0 x 10^{-6} (scenarios 1 and 2) to a high of 5.1 x 10^{-5} (scenarios 10 and 11) given in the BID.

D.2 **Radon and its progeny that are released from the soil**

The annual risk from radon exposures range from a low of 2.9 x 10^{-6} to a high of 4.9 x 10^{-6}. This can be compared to a low of 2.6 x 10^{-6} (scenarios 1 and 2) to a high of 8.1 x 10^{-6} (scenarios 10 and 11) given in the BID.

D.3 Inhalation of radioactive dust in the air

The annual risk due to inhalation of radioactive dust is 2.0 x 10^{-6}. A range of risks has not been calculated. By comparison, the BID results range from a low of 3.6 x 10^{-12} (scenario 3) to a high of 3.7 x 10^{-8} (scenario 6). Dust exposures have not been evaluated for reclaimers (scenarios 7 to 11) in the BID.

D.4 Ingestion of food and water.

The annual risk per Bq of ^{226}Ra ingested is 7.6(-8). As with inhaled dust, a range has not been calculated. This value can be compared to a low of 5.9 x 10^{-9} (scenarios 1 and 2) to a high of 3.6 x 10^{-8} (scenarios 10 and 11) given in the BID.

Table 8 summarizes the range of result calculated in this report and those given in the BID. The only major difference is for the risk from exposure to direct gamma.

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Table 1. Phosphogypsum radionuclide concentrations assumed in the BID and estimated by PNL.

Radionuclide	BID	PNL	Source
^{226}Ra	1.000	1.000	Natural U
^{210}Po	1.040	1.040	Natural U
^{210}Pb	1.400	1.400	Natural U
^{228}Th	0.133	0.033	Natural Th
^{228}Ra	0.133	0.033	Natural Th
^{230}Th	0.187	0.187	Natural U
^{232}Th	0.123	0.033	Natural Th
^{234}U	0.120	0.120	Natural U
^{235}U	0.005	0.005	Natural U
^{238}U	0.110	0.110	Natural U

Table 2. Dose conversion factors (DCF) from direct gamma exposures for the radionuclides in Table 1 for a surface concentration of one pCi m^{-2}. The BID values are from Table 4-4 of BID and the FGR are calculated data given in Table III.3 in FGR-12.

Radionuclide	BID	FGR	BID/FGR
^{226}Ra	1.67(-04)	1.94(-4)[a)]	0.86
^{210}Po	8.55(-10)	9.68(-10)	0.88
^{210}Pb	0	2.90(-7)	0
^{228}Th	3.37(-4)	1.64(-4)[b)]	2.05
^{228}Ra	9.04(-5)	1.09(-4)[c)]	0.83
^{230}Th	8.88(-8)	8.76(-8)	1.01
^{232}Th	6.56(-8)	6.44(-8)	1.02
^{234}U	8.00(-8)	8.74(-8)	0.92
^{235}U	6.41(-8)	1.73(-5)	0.0037
^{238}U	1.67(-5)	6.44(-8)	259

a) Includes the contributions from the short lived progeny (^{222}Rn, ^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po) in equilibrium.
b) Includes the contributions from ^{224}Ra and its short lived progeny (^{220}Rn, ^{216}Po, ^{212}Pb, ^{212}Bi, ^{212}Po, ^{208}Tl) in equilibrium.
c) Includes the contribution from ^{228}Ac in equilibrium.

Table 3. Comparison of risks from inhalation of dust and ingestion for the radionuclides in Table 1 between those from Table 4-4 of BID and those calculated using dose factors from ICRP Pub 68 and risk factors from ICRP Pub. 60. Risks are for fatal cancers per Bq intake.

	Inhalation				Ingestion			
Radionuclide	BID	Type F	Type M	Type S	BID	Type F	Type M	Type S
^{226}Ra	7.6(-7)	-	6.0(-7)	-	2.5(-8)	-	1.4(-8)	-
^{210}Po	6.5(-7)	3.6(-8)	1.1(-7)	-	3.8(-8)	1.2(-8)	-	-
^{210}Pb	3.8(-7)	5.5(-8)	-	-	1.5(-7)	3.4(-8)	-	-
^{228}Th	1.9(-5)	-	1.2(-6)	1.6(-7)	3.5(-9)	-	3.5(-9)	1.6(-7)
^{228}Ra	1.6(-7)	-	1.3(-7)	-	1.9(-8)	-	3.4(-8)	-
^{230}Th	7.8(-6)	-	1.4(-6)	3.6(-8)	6.2(-9)	-	1.1(-8)	4.4(-9)
^{232}Th	7.8(-6)	-	1.5(-6)	6.0(-8)	5.7(-9)	-	1.1(-8)	4.6(-9)
^{234}U	6.8(-6)	3.2(-8)	1.1(-7)	3.4(-7)	2.0(-8)	2.5(-9)	4.2(-10)	-
^{235}U	6.2(-6)	3.0(-8)	9.0(-8)	3.1(-7)	2.0(-8)	2.3(-9)	4.2(-10)	-
^{238}U	5.9(-6)	2.9(-8)	8.0(-8)	2.9(-7)	2.0(-8)	2.2(-9)	3.8(-10)	-

Table 4. Risk data from the BID from a house built on soil contaminated with the PG at a ^{226}Ra concentration of 26 pCi g^{-1}. The highest risk from any scenario is given. Hence the risks, are not additive.

BID Table No.	Scen. No.	Gamma	Radon		Dust Inhalation	Ingestion	
						Food	Water
4-6	1	3.0-6)	2.6(-6)		5.7(-11)	5.2(-9)	7.4(-10)
4-7	2	3.0-6)	2.6(-6)		3.3(-9)	5.2(-9)	7.4(-10)
4-8	3	4.6(-6)	6.8(-6)		3.6(-12)	9.1(-9)	7.8(-9)
4-9	4	4.6(-6)	6.8(-6)		5.0(-9)	9.1(-9)	7.8(-9)
4-10	5	1.4(-5)	1.2(-5)		5.4(-10)	2.3(-8)	1.3(-8)
4-11	6	1.4(-5)	1.2(-5)		3.7(-8)	2.3(-8)	1.3(-8)
			Radon; Dry Site	Radon; Humid Site			
4-15	8	2.6(-5)	6.2(-5)	5.9(-5)	-	1.5(-8)	1.5(-9)
4-16	9	2.6(-5)	6.2(-5)	5.9(-5)	-	1.5(-8)	1.5(-9)
4-17	10	5.1(-5)	8.1(-5)	6.8(-5)	-	1.5(-8)	1.5(-9)
4-18	11	5.1(-5)	8.1(-5)	6.8(-5)	-	1.5(-8)	1.5(-9)

Table 5. Risks in a research and development laboratories reported in the BID and calculated at PNL. The BID results were reported for one drum containing PG at 26 pCi g^{-1}, but are for five drums. The PNL gamma results are for workers who spend 250 hours/year at one meter and 750 hours/year at two meters from one drum.

Risk from one 55 gallon drum								
Gamma			Radon			Dust		
BID	BID/5	PNL	BID	BID/5	PNL	BID	BID/5	PNL
9.1(-7)	1.8(-7)	2.3(-7)	2.1(-5)	4.2(-6)	7.5(-7)	8.3(-8)	1.7(-8)	2.1(-9)

Table 6. Dose reduction factors for an individual in a house built on reclaimed land contaminated to an infinite depth with PG at one pCi g^{-1}, and other radionuclides in the concentration ratios given in Table 1. The dose with no shielding is 0.0013 mrem h^{-1}.

Shielding	Dose Reduction Factor
None	1
10 cm concrete slab	0.23
30 cm clean fill material	0.071
10 cm concrete slab and 30 cm clean fill material	0.019

Table 7. The size fractions in samples of central Florida PG reported by Rutherford et al (1995).

Size	Mass Fraction	^{226}Ra Bq/kg^{-1}	% of ^{226}Ra	Emanation Fraction
Bulk PG	1.00	690	100	13
>53 μm	0.59	550	48	11
20-53 μm	0.39	710	41	13
<20 μm	0.02	3460	10	51

Table 8. Summary of range of results for the risk calculated in this report and those given in the BID.

Source	Low	High	BID low	BID high
Gamma	2.4×10^{-6}	4.6×10^{-6}	3.0×10^{-6}	5.1×10^{-5}
Radon	2.9×10^{-6}	4.9×10^{-6}	2.6×10^{-6}	8.1×10^{-6}
Inhaled Dust	9.2×10^{-7}		3.6×10^{-12}	3.7×10^{-8}
Ingestion	7.8×10^{-8}		5.9×10^{-9}	3.6×10^{-8}