# Submitted to The Government Reform Committee's Subcommittee on Technology, Information Policy, Intergovernmental Relations and the Census

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## Summary

Prior to 1989, phosphogypsum was sold for agricultural use in central and north Florida and elsewhere in the United States. The December 1989 National Emission Standards for Hazardous Air Pollutants (NESHAPS) regulation specifically required that phosphogypsum be disposed of in stacks or mines and prohibited alternative uses of phosphogypsum in construction, agriculture or other uses, in effect, converting phosphogypsum from a beneficial by-product to a waste.

Subsequently, in a 1992 rulemaking, the Environmental Protection Agency (EPA) decided to allow the use of phosphogypsum in agriculture provided that the average radium-226 content was less than 10 pCi/g. The 1992 rule also allowed for the use of discrete amounts of phosphogypsum (up to 700 lbs) for specific research applications and for other uses on a case-by-case basis with the prior approval of the EPA. We are not aware that any such alternative uses have been approved to date. Subsequently, a 1999 reconsideration increased the amount of phosphogypsum that could be used for specific research applications to 7000 lbs.

The Florida Institute of Phosphate Research (FIPR) has carried out considerable research in support of a variety of beneficial alternative uses of phosphogypsum. Several of the FIPR evaluations have been supported by risk assessments conducted by SENES Consultants Limited. As is shown in the main body of this submission, none of the risk analyses carried out to date by EPA have specifically considered the factors and conditions that would apply to the beneficial use of phosphogypsum in Florida. Moreover, the risk assessments carried out to date by the EPA for the alternative uses of phosphogypsum use assumptions that are unnecessarily conservative. Several examples are provided in the submission.

When still conservative, but more reasonable, assumptions are used in the risk assessments for alternative uses of phosphogypsum, the risks estimated to a maximally exposed individual (who for example is assumed to build a home on a field where phosphogypsum has been applied for 100 years) are found, with a high degree of confidence, to be below the EPA's range of acceptable lifetime risk from 1 to 3 x $10^{-4}$.

In addition, the doses (and risks) to the maximally exposed individual are predicted to be small with respect to the variation in natural background radiation which is unavoidable. In my opinion, potential radiological risks arising from alternative uses of phosphogypsum as for example, those proposed by FIPR, including in agriculture, in road construction and for daily cover at a municipal landfill are small and should not prevent such suitable beneficial uses of phosphogypsum.

## 1.0 Introduction

Phosphogypsum is a by-product of the production of phosphoric acid for the fertilizer industry. Phosphogypsum contains naturally occurring radioactivity, the same radioactivity that is present in the phosphate ore from which phosphogypsum is derived.

Prior to December 1989, phosphogypsum was considered an item of commerce and sold for agricultural use in central and north Florida and throughout the United States at locations where it was manufactured. The off-site use of phosphogypsum was prohibited by the final National Emissions Standards for Hazardous Air Pollutants (NESHAPS) for radionuclides promulgated in 40 CFR Part 61, Support R, National Emission Standards for Radon Emissions from Phosphogypsum Stacks (54 FR 51654 December 15, 1989). This rule required (as of March 15, 1990) that phosphogypsum be disposed of in stacks or mines and prohibited alternative uses of phosphogypsum in construction, agriculture or research and development. In effect, the December 1989 rule converted phosphogypsum from a useful by-product to a waste.

Subsequently, the Environmental Protection Agency (EPA) reconsidered the portion of Subpart R that required all phosphogypsum to be disposed in stacks or mines. On June 3, 1992, the EPA issued its decision on the reconsideration and adopted a final rule (FR Vol.57 No.107 pp.23305-23320) which:

1. Allowed distribution of phosphogypsum in agriculture, provided the phosphogypsum contains less than 10 pCi/g of radium-226;
2. Allowed, with prior EPA approval, the use of discrete amounts (up to 700 lbs) of phosphogypsum for specific R&D activity; and
3. Permitted other uses of phosphogypsum on a case-by-case basis with prior EPA approval.

In their June 1992 rulemaking, the EPA stated that the 10 pCi/g limit on the average radium-226 (Ra-226) concentration in phosphogypsum is intended to *"assure that the risk from indoor radon and direct gamma radiation exposure in residences constructed on land previously treated with phosphogypsum do not exceed an acceptable level"* (ibid at 23305). In discussing the basis for the limit of 10 pCi/g Ra-226 in phosphogypsum, the EPA indicate that phosphogypsum applied at the upper 95$^{th}$ percentile application rate in the United States, would result in a maximum individual lifetime risk from indoor radon and direct gamma exposure of $3 \times 10^{-4}$ (ibid at 23312) suggesting that EPA considers a maximum individual lifetime risk of $3 \times 10^{-4}$ to be "acceptable".

In essence, the 1992 rule allowed the use of phosphogypsum from north Florida and North Carolina for agriculture and research and development and prohibited all other uses. EPA determined that the use of phosphogypsum in road construction was not acceptable since the maximum individual risk was always greater than the *"outer bound of the presumptively safe level of approximately* $1 \times 10^{-4}$*"* (ibid 23312).

Subsequently, the EPA revised Subpart R in 1999 (64 FR 5574, February 3, 1999) to increase the limit from 700 to 7000 pounds of phosphogypsum used for indoor research and development, eliminated sampling requirements for phosphogypsum used in indoor research and development, and clarified the sampling procedures for removal of phosphogypsum from stacks for other purposes.

The Florida Institute of Phosphate Research (FIPR) has studied a number of potential beneficial uses of phosphogypsum, including among others, its use in agriculture, in road construction and as a daily cover for a sanitary landfill. In support of FIPR's work to develop safe and beneficial alternative uses of phosphogypsum, FIPR retained SENES to carry out independent evaluations of the potential radiological risks associated with various potential alternative uses of phosphogypsum.

In the remainder of this submission, I present overview comments on the evolution of the EPA's regulatory position on phosphogypsum, various aspects of EPA's risk assessments in support of their rulemaking, and selected observations from SENES risk assessments.

## 2.0 Regulatory Evolution

The National Emission Standards for Hazardous Air Pollutants (NESHAPS) were based on the framework outlined in the 1987 "vinyl chloride decision" (as referenced by 57 FR 23305, June 3, 1992). The "vinyl chloride decision" requires the administrator to use judgement under Section 112 of the Clean Air Act for radionuclide emissions in two steps:

1. Determine a "safe" or "acceptable" level of risk considering only health factors; and
2. Provide an "ample margin of safety, where the costs, feasibility, and other relevant factors in addition to health are considered.

The EPA implemented the "vinyl chloride decision" in the 1989 NESHAPS for Benzene (54 FR 38044, September 14, 1989). This NESHAPS established the "Benzene Policy" and set the specific criteria used by EPA for determining the safe level of risk under Section 112 of the Clean Air Act. The "Benzene Policy" includes the requirement that NESHAPS must protect the individual receiving the highest lifetime risk to a level of 1 in 10,000 ($1 \times 10^{-4}$).

The EPA issued the first NESHAPS for radon emissions from phosphogypsum (PG) stacks on December 15, 1989 (54 FR 51654). This NESHAPS required that all PG be disposed of in stacks or in mines with all off-site use of PG prohibited, including PG use in agriculture, road construction or research and development. Additionally, this NESHAPS set a radon flux standard of 20 pCi/m$^2$/s for PG stacks.

After issuing the NESHAPS for radon emissions from PG stacks, EPA received petitions requesting reconsideration of the standards in order to permit alternate methods of PG disposal. Due to the potential impacts of farmers, researchers and other users of PG, EPA issued a Notice of Limited Reconsideration on April 10, 1990 (55 FR 13480) and a limited class waiver that would allow the use of PG for agricultural application during 1990, which was extended until June 1, 1991 (55 FR 40834) and further extended to October 1, 1991 (56 FR 23519). After October 1, 1991, all individuals possessing PG stacks became subject to the work practice requirements in subpart R of the NESHAPS for radon emissions from PG stacks; however, at the time of issuing the Notice of Limited Reconsideration, EPA issued a proposed rule concerning radon from PG stacks (55 FR 13482) with the following 4 options (EPA, May 1992):

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 EPA approval, use of discrete quantities of phosphogypsum for the research and development to 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 PG in stacks or mines; and/or*
4. *Allow, upon 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.*

On June 3, 1992, EPA issued a final rule NESHAPS for 40 CFR Part 61 Subpart R (57 FR 23305) that allowed PG to be used in the following three categories:

1. Outdoor agricultural uses, provided that the certified average Ra-226 concentration in PG doesn't exceed 10 pCi/g (it should be noted that EPA determined the 10 pCi/g limit by assuming a maximum individual risk (MIR) of $3 \times 10^{-4}$);
2. Indoor research and development (R & D) activities, provided facilities don't use more than 700 pounds of PG for a particular R & D activity and warning labels are in place; and
3. Other alternate uses that are approved by the EPA on a case-by-case basis.

Although this NESHAPS states that the *"risks represented by uses of phosphogypsum in which the MIR does not exceed the presumptively safe level of approximately $1 \times 10^{-4}$ are acceptable"* (ibid p. 23311)*,* it is further stated that ***"in the case of phosphogypsum, considering all of the information available on potential exposures and the associated risks, as well as the uncertainties inherent in deriving risk estimates, EPA has concluded that certain uses of phosphogypsum may be considered acceptable so long as those uses are restricted to limit the estimated lifetime risk to any individual to no more than 3 in 10 thousand."*** (ibid p23311-23312). [Emphasis Added]

After issuing the 1992 Final Rule (57 FR 23305), EPA received petitions regarding the revision to Subpart R and issued a further revision on February 3, 1999 (64 FR 5574) with the following three changes (effective April 5, 1999):

1. Increased the limit on PG quantity that can be used for indoor R&D from 700 to 7,000 pounds,
2. Eliminated current sampling requirements for PG used in indoor R&D; and
3. Clarified sampling procedures for removal of PG from stacks for other purposes.

The increased limit on PG quantity used in indoor R&D was revised since the EPA determined that there were calculation errors in the amount of Rn-222 (radon) that would be present in a laboratory with PG used for indoor R&D. Therefore, EPA revised three assumptions in the calculation of the revised limit (7000 pounds of phosphogypsum), which included, decreasing the number of phosphogypsum drums opened at one time from five drums to one drum, decreasing the amount of radon that actually emanates from phosphogypsum into ambient air of laboratory by incorporating ventilation, size of laboratory and effect of moisture, and decreasing the number of hours spent in the laboratory by the researcher from 4000 hours per year to 1000 hours per year (ibid p 5575). Additionally, the sampling requirements were removed since Subpart R doesn't contain a corresponding limit on Ra-226 in PG when it's used for indoor R&D activities. Furthermore, the sampling procedures were clarified to establish the level of statistical uncertainty that is allowed in measurements of Ra-226 in PG.

## 3.0 EPA's Risk Assessments for Alternative Uses of Phosphogypsum

### 3.1 1992 Reconsideration

In support of their 1992 reconsideration, the EPA used the PATHRAE dose assessment model to evaluate the *"incremental increases in the maximum individual risk associated with the use of phosphogypsum in agriculture, road construction, and research and development activities"* (FR Vol.57 No.107, p.22308).

The EPA modeled eight pathways of potential radiation exposure including: groundwater migration to a river, groundwater migration to a well, erosion and transport to a river, food grown on-site, direct gamma radiation, on-site dust inhalation, inhalation of radon in structures, and atmospheric transport of contaminants. Maximum individual lifetime risks from one year of exposure were obtained from the PATHRAE dose assessment results using the risk conversion factors in EPA's Environmental Impact Statement for radionuclide NESHAPS (EPA, May 1992).

In addition, the EPA used a different code, MicroShield, to augment the PATHRAE model in order to assess the potential exposure to gamma radiation from people carrying out experimental analysis.

In total, the EPA assessed twelve exposure scenarios[1]: seven agricultural scenarios, four road construction scenarios and one research scenario. In carrying out their assessment, the EPA calculated individual annual dose and subsequently lifetime risk based on the annual dose and an assumed 70-year exposure period.

Figure 1 of the 1992 rulemaking [FR Vol. 57 No.107, p. 23310] shows a curve that is generated from plotting the combinations of Ra-226 content and phosphogypsum application rate that yield an estimated maximum lifetime individual risk of $3 \times 10^{-4}$. The EPA noted that *"If the point representing a given Ra-226 content in phosphogypsum and a given application rate for phosphogypsum is located within or on this curve, the corresponding lifetime individual risk from exposure to gamma radiation and radon inhalation will not exceed the presumptively safe level."*. (ibid p. 23309)

In deciding on an acceptable level of risk from the use of PG in agriculture, the EPA estimated the upper 95$^{th}$ percentile of the phosphogypsum application rate. This estimate was based on the application rates reported **for various crops in California and for peanut crops in Georgia**. The curve in Figure 1 of the 1992 rulemaking discussed above was then used to identify the Ra-226 concentration in phosphogypsum that, when applied at the upper 95$^{th}$ percentile application rate (approximately 2,700 pounds per acre) would result in a maximum individual risk from indoor radon inhalation and direct gamma exposure of $3 \times 10^{-4}$. By this procedure, the EPA arrived at the limiting Ra-226 value of 10 pCi/g.

For the road construction scenarios analyzed by EPA, the use of phosphogypsum always resulted in a MIR greater than the outer bound of the presumptively safe level of approximately $1 \times 10^{-4}$.

In the risk estimates for the research and development scenario, the EPA determined that limiting the amount of phosphogypsum utilized in any research and development activity to 700 pounds (one 55 gallon drum) would correspond to a maximum individual risk to researchers over the time periods evaluated to $2.1 \times 10^{-4}$. This is within the range of risks that has been determined to be acceptable for other radionuclide NESHAPS categories.

### 3.2 1999 Reconsideration

As noted previously, the 1999 reconsideration increased the limit for use in indoor R&D activities from 700 to 7000 pounds.

[1] The EPA provides greater detail on their risk assessment methodology in the Background Information Document (BID) "Potential Use of Phosphogypsum and Associated Risks, Background Information Document" May 1992 (EPA 402-R92-002).

3.3 Selected Comments on EPA's Risk Assessment

EPA Lifetime Risk of $3 \times 10^{-4}$

As stated in the 1992 Final Rule NESHAPS for radon emissions from phosphogypsum stacks (Section 2.0, Regulatory Evolution), the EPA determined that for certain uses of PG the emissions corresponding to a 70 year lifetime risk with a 100 year biennial application period could be up to $3 \times 10^{-4}$ (slightly higher than the presumptively safe level of $1 \times 10^{-4}$). Furthermore, EPA used the $3 \times 10^{-4}$ risk to calculate the 10 pCi/g Ra-226 concentration limit allowed for the outdoor agricultural use of PG.

Additionally, EPA used the slightly increased lifetime risk for PG ($3 \times 10^{-4}$) to establish the cleanup levels for the CERCLA sites with radioactive contamination in 1997. EPA concluded that an effective dose equivalent of 15 mrem/year (exclusive of radon) calculated from a site-specific dose assessment would be the maximum dose limit, and this dose corresponded to a lifetime risk of approximately $3 \times 10^{-4}$. [EPA, 1997a]

In May 1994, the EPA issued a working draft of radiation site clean-up regulations (EPA 1994). The proposed regulations (which to our knowledge have not been to date finalized or promulgated) set standards for the remediation of soil, groundwater, surface water, and structures at federal facilities contaminated with radioactive material that would allow these sites to be released for public use. The proposed regulations limit the doses received by members of the public to 15 mrem/year in excess of natural background levels for 1000 years after completion of the clean-up. In addition, the proposed 15 mrem/year limit excludes the dose from radon progeny.[2]

Application Rate

The potential risks resulting from the use of PG in agriculture are directly proportional to the assumed application rate.

Based on the risk assessment described in the 1992 Background Information Document (BID, EPA 1992) supporting their ruling on PG uses, the EPA ascertained that a biennial application rate of 900 lbs/acre for 100 years lead to a lifetime risk of approximately $1 \times 10^{-4}$ (or 1 in 10,000). Trovato (1995) notes that the 900 lbs/acre rate is somewhat higher than many of the rates reported in a survey of PG use in agriculture in the southeast U.S.

The EPA derived a nationwide 95$^{th}$ percentile value for the application rate, or 2700 lbs/acre biennially i.e., the actual application rate used across the country in

[2] Doses due to radon were excluded from the draft U.S. EPA clean-up criterion. However, all existing and future buildings on the remediated sites would be required to meet the guidelines of the U.S. EPA radon program i.e., radon levels must be below 4 pCi/L.

95% of the cases would be less than this value. The corresponding lifetime risk of $3 \times 10^{-4}$ was considered by the EPA to be the highest likely risk from the application of PG and was considered acceptable as a limiting risk.

Clearly, the use of more reasonable application rates specific to Florida would result in lower estimated risks. Based on the 1992 BID assessment (and Travato), an upper range biennial application rate of 900 lbs/acre at a Ra-226 concentration of 30 pCi/g, rather than 10 pCi/g, would be consistent with a lifetime risk limit of $3 \times 10^{-4}$.

Years of Fertilizer Application

EPA's risk assessment assumes 100 continual years of application. This seems highly unlikely for any particular site. Furthermore, the chance that the 95$^{th}$ percentile application rate would be used at a particular site for 100 years is vanishingly small.

Exposure Duration

In deriving the limiting concentration of 10 pCi/g radium in PG, the EPA risk assessment assumed a lifetime (70 y) of exposure to a site to which PG had been applied for 100 years at the likely maximum rate. However, very few people ever live at the same location for their entire lifetime.

Based on a review of several surveys and reports on the activities of the American public, the EPA Exposure Factors Handbook (1997b) recommends a value of 30 y, which is the 95$^{th}$ percentile for a family to reside in a single home; the central value is given as 9 y. The central residence time given for a farm residence in the same reference is about 17-18 y. Indeed, the EPA's own assessment of the risks from contaminants (non-radioactive) contained in agricultural fertilizers used this latter value (EPA 1999).

Using 17-18 y rather than 70 y as the duration of exposure would lower the estimated mean lifetime risk by about a factor of 4 (i.e. 70/17.5). Correspondingly, all other factors being equal, a radium concentration as high as 40 pCi/g would result in a lifetime risk of $3 \times 10^{-4}$, the same risk considered acceptable by the EPA in their PG rule making.

## 4.0 FIPR's Risk Assessments

FIPR has been carrying out research on a variety of potential alternative (to disposal in stacks and mines) uses of phosphogypsum, including among others, as an agricultural soil amendment, for use in road construction (as an alternative or complement to traditional borrow material) and as a landfill cover. In support of these research activities, SENES has carried out a number of radiological risk assessments, from which the following comments have been extracted.

## 4.1 Roads and Agriculture

In 1995 FIPR called for more realistic risk assessments (than those carried out by EPA) of the recognized hazards so that industry, the public and the regulators could make informed decisions based on facts.

The objective of a 1998 SENES risk assessment (SENES 1998) was to develop an updated methodology, and to use it to determine the radiological implications of PG use in agriculture and road construction in Florida and, using the updated methodology, to determine if the lifetime risk to a reasonably maximally exposed individual (MEI) is below the regulatory benchmark of $1 \times 10^{-4}$ to $3 \times 10^{-4}$.

With the help of FIPR, available data, especially that relevant to Florida, was identified. Florida-specific data considered in the SENES study included, but was not limited to, information on: radon in homes, local soil types, moisture contents, depth to water table, near-by housing, water usage, agricultural practices and road construction methods.

### (i) Deterministic Screening Analysis

Screening calculations incorporate conservatisms which result in predicted doses and risks exceeding the likely doses and risks to which people might be exposed. Screening calculations of incremental dose and risk attributable to radionuclides in PG from all potentially significant exposure pathways were carried out using simple models and deterministic methods (i.e. a single value for each of the parameters). The models and parameter values were selected to ensure that predicted doses and risk were unlikely to underestimate the doses and risks to which people might be exposed. Those pathways for which conservative screening risk estimates exceeded 10% of the risk criterion of $3 \times 10^{-4}$ for the maximum exposed individual (MEI) were identified for more focussed and detailed evaluation.

The magnitude of the conservatism is illustrated in a qualitative manner by identification of the parameter values that tend to overestimate dose and risk. By comparison of the results of screening calculations to the results of the focussed calculations, the magnitude of the conservatism could be quantified.

For both roads constructed with PG and agricultural land amended with PG, the EPA estimated radiation doses and risks from one year of exposure to workers, and to members of the public on or living near the affected area. The results are reported in the BID (EPA, 1992) as risk from one year of exposure and are multiplied by the number of years of exposure (according to the EPA 70 years) to calculate risk values for a lifetime of exposure.[3]

[3] As a consistency check, SENES were asked to reproduce the EPA's result in the 1992 BID using the same parameter values.

Seven pathways by which on-site residents (residents in a house built on a field to which PG had previously been applied) may be exposed to radiation from and radioactivity in PG were considered in the screening analysis carried out by SENES:

- external gamma radiation - residents living in a house would be exposed to external gamma radiation from the radioactivity in the PG;
- inhalation of radon progeny - two radon pathways were evaluated, 1) some of the radon (Rn-222) gas produced by the Ra-226 in the PG will escape into the atmosphere above the field. The gas will be dispersed by the wind, radon progeny (Po-218 to Po-214) will grow in from the radioactive decay of radon, and residents will be exposed both inside and outside the residence; and 2) some of the radon gas produced by the Ra-226 in the PG under the house will be transported by diffusion and mass flow into the house to expose the residents;
- inhalation of resuspended dust - the wind will resuspend dust containing radionuclides from PG which may be inhaled by the resident;
- ingestion of dust - dust containing radionuclides from PG may become fixed to residents hands and other surfaces from which it may be ingested;
- ingestion of (irrigated) locally grown food - radionuclides in the PG may accumulate on produce and crops due to the deposition of dust from the field. Root uptake by plants may also result in radionuclides in plants. Radionuclides may also be transported by infiltrating rainwater from the field into the groundwater and to a well at the residence. Residents may irrigate a home garden and consume the fruit and vegetables. Residents may also use the well water to irrigate crops fed to livestock and to water the livestock. Soil ingested by animals during grazing is also considered in this pathway. Consumption of these animal products may transfer radionuclides from the PG to the residents;
- ingestion of contaminated well water - residents may consume water from the local well; and
- ingestion of fish - fish from an on-site pond may develop concentrations of radionuclides in their flesh.

The predicted effective doses to the on-site resident from one year of exposure to radionuclides in PG are listed in Table 1. The predicted dose from one year of exposure from all pathways was 53 mrem, and the single largest component was from inhalation of radon progeny (83% at 44 mrem/y). The predicted incremental lifetime risks of fatal cancer to the on-site resident from lifetime exposures are also summarized for each pathway in Table 1. The predicted lifetime risk (from 30 years of exposure) from all pathways was $8 \times 10^{-4}$ (for 70 years of exposure, the risk would be $8 \times 10^{-4} \times \frac{70}{30} = 1.9 \times 10^{-3}$). The predicted risks from external gamma and the inhalation of radon progeny each exceeded the threshold of $3 \times 10^{-4}$. Therefore, both of these pathways were identified for detailed assessments as briefly described below.

**Table 1**
**SCREENING RESULTS FOR DOSE AND RISK TO ON-SITE RESIDENT**

| Pathway | Annual Dose mrem/y | Risk from Lifetime Exposure* |
|---|---|---|
| External gamma radiation | 3.7 | $6 \times 10^{-5}$ |
| Inhalation of radon progeny | 44 | $7 \times 10^{-4}$ |
| Inhalation of resuspended dust | 0.012 | $2 \times 10^{-7}$ |
| Ingestion of dust | 0.07 | $1 \times 10^{-6}$ |
| Ingestion of well water | 1.3 | $2 \times 10^{-5}$ |
| Ingestion of fish | 1.2 | $2 \times 10^{-5}$ |
| Irrigated garden produce | 1.8 | $3 \times 10^{-5}$ |
| Irrigated animals products | 0.52 | $8 \times 10^{-6}$ |
| | | |
| Total | 53 | $8 \times 10^{-4}$ |

* 30 years of exposure

The potentially most exposed individuals were found to be the person who was assumed to live in a home constructed on a field after PG had been regularly added as a soil amendment or fertilizer for a period of time or on a reclaimed road which had been built using PG. The predominant pathways were found to be exposure to external gamma radiation and to indoor radon. The following example of dose (and risk) to a person who lives in a house built on a field treated with PG for 100 years is provided as an example.

(ii) Probabilistic Analysis

For more detailed evaluation, SENES (1998) adopted a probabilistic modelling methodology which takes account of natural variability and uncertainty to provide the most likely result and a probability distribution other possible results. With such a distribution of possible results, the level of confidence in the dose or risk is calculated. This information helps in the formulation of a reasonable decision regarding the acceptable levels of dose and risk. Such approaches, which attempt to account for uncertainty and variability, are widely used for risk assessments.

In the SENES (1998) analysis, the upper 95$^{th}$ percentile from the lifetime risk distribution was used to estimate the lifetime risk to the MEI and therefore, this MEI value was assumed to represent the reasonably maximum lifetime risk from within the exposure groups expected to have the highest lifetime risks.

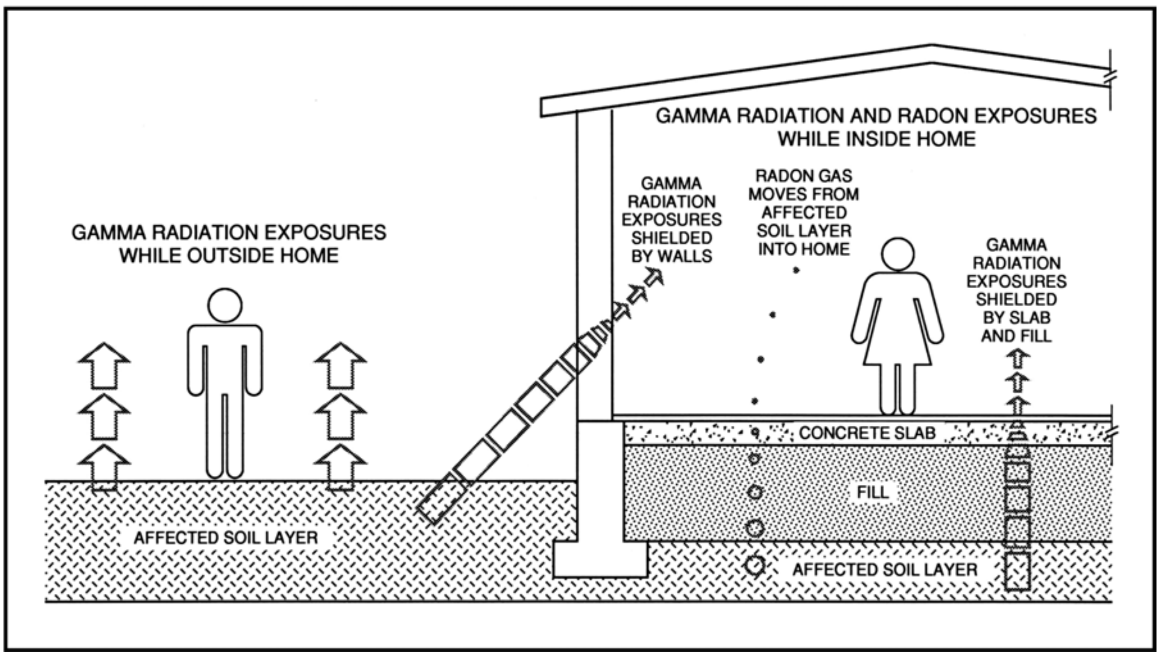
The exposure to residents of homes built on land that was previously used to grow crops and where PG had been applied for its agronomic benefits was assessed in detail. As suggested by Table 1, indoor radon and gamma radiation are the primary dose contributors and doses from other pathways can be considered negligible compared to indoor radon and gamma radiation pathways.

Incremental radium-226 levels in the affected soil layer were calculated using PG radium concentrations and representative application rates for growing peanuts. Application rates for other crops in Florida are generally lower than the application rate for peanuts.

Figure 1 shows a conceptual model of the gamma radiation and indoor radon pathways. Gamma radiation exposures were calculated for indoor and outdoor locations and incorporated the amount of time spent indoors and outdoors. Indoor gamma radiation exposures were modelled to include both geometry effects and shielding of the outdoor gamma radiation by the structure.

Figure 1

**EXPOSURES TO RESIDENT OF HOME ON AFFECTED SOIL**




For the on-site resident, partial excavation of the affected soil layer was modelled prior to construction and the houses were assumed to be slab-on-grade. Incremental indoor radon levels were predicted from the affected soil layer using a two step method. First, soil gas levels are estimated and then an empirically derived transfer factor was used to predict indoor radon levels as a function of soil gas levels.

Annual doses and risks were calculated based on exposure rates estimated for the residents. Lifetime risks are based on a distribution of occupancy that reflects the typical range of time people stay at a residence.

Table 2 and Figure 2 shows summary statistics from the probabilistic assessment. The table shows the mean value, the 95$^{th}$ percentile and other statistics. The 95$^{th}$ percentiles are considered to represent the reasonably maximum exposed individual (MEI) and reflect the upper end of the range of potential risk that may be compared to an acceptable risk level.

**Table 2**
**SUMMARY OF PROBABILISTIC ANALYSES FOR AGRICULTURAL USE SCENARIO**

| | Units | $5^{th}$ Percentile | Median | Mean | $95^{th}$ Percentile |
|---|---|---|---|---|---|
| 100 y of PG application | | | | | |
| Ra-226 Concentration in Soil | pCi $g^{-1}$ | 0.16 | 0.34 | 0.36 | 0.64 |
| Years at Site | Y | 1.0 | 8.9 | 11.4 | 30.0 |
| Gamma Radiation Pathway | | | | | |
| Exp. (Indoor) | µR $hr^{-1}$ | 0.10 | 0.22 | 0.24 | 0.45 |
| Exp. (Combined | µR $hr^{-1}$ | 0.12 | 0.27 | 0.29 | 0.53 |
| Annual Dose | mrem $y^{-1}$ | 0.4 | 1.0 | 1.1 | 2.2 |
| Lifetime Risk from One Year Exposure | | $2.2x10^{-7}$ | $5.2x10^{-7}$ | $5.7x10^{-7}$ | $1.1x10^{-6}$ |
| Lifetime Risk | | $4.4x10^{-7}$ | $4.4x10^{-6}$ | $6.5x10^{-7}$ | $2.0x10^{-5}$ |
| Years at Site x Risk from 1 year | | | | | |
| Radon Pathway | | | | | |
| Radon (Indoor) | pCi $g^{-1}$ | 0.007 | 0.033 | 0.050 | 0.149 |
| RDP Dose (Indoor) | WLM $y^{-1}$ | $9.5x10^{-4}$ | $4.5x10^{-3}$ | $7.0x10^{-3}$ | $2.1x10^{-2}$ |
| Annual Dose | mrem $y^{-1}$ | 0.4 | 1.8 | 2.8 | 8.4 |
| Lifetime Risk from One Year Exposure | | $1.9x10^{-7}$ | $9.1x10^{-7}$ | $1.4x10^{-6}$ | $4.2x10^{-6}$ |
| Lifetime Risk | | $5.5x10^{-7}$ | $7.5x10^{-6}$ | $1.6x10^{-5}$ | $5.8x10^{-5}$ |
| Combined Pathway | | | | | |
| Annual Dose | mrem $y^{-1}$ | 1.00 | 3.00 | 3.90 | 9.90* |
| Lifetime Risk from One Year Exposure | | $5.2x10^{-7}$ | $1.5x10^{-6}$ | $2.0x10^{-6}$ | $4.9x10^{-6}$* |
| Lifetime Risk | | $1.1x10^{-6}$ | $1.3x10^{-5}$ | $2.3x10^{-5}$ | $7.4x10^{-5}$* |

* Please note that the $95^{th}$ percentiles in such an analysis are not additive and the $95^{th}$ percentile values reported under "combined" are the appropriate values to consider.

Selected comments are presented below.

Radium-226 Concentration in Affected Soil Layer

The predicted (incremental) Ra-226 concentrations in the affected soil layer were 0.36 and 0.64 pCi $g^{-1}$ for the mean and $95^{th}$ percentile values, respectively, based on 100 year duration of PG application before the house was built. These incremental values are in the lower range of natural soil Ra-226 concentrations for Florida.

Gamma Radiation Pathway

The mean outdoor gamma radiation exposure above the affected soil was 0.73 µR $h^{-1}$ and the $95^{th}$ percentile value was 1.31 µR $h^{-1}$ (SENES 1998). The primary component of indoor gamma radiation exposures was gamma radiation from affected soil outside the house. The house walls provided some shielding, and most of the gamma radiation emitted by the affected soil located below the slab was attenuated by the fill and concrete slab. Indoor gamma exposure rates were 0.24 and 0.45 μR $h^{-1}$ for the mean and 95$^{th}$ percentile values, respectively. Since a higher proportion of time at a residence is spent indoors rather than outdoors, the average (indoor and outdoor durations) gamma exposure rate was closer to the indoor rate than to the outdoor rate and average values ranged from 0.29 for the mean to 0.53 for the 95$^{th}$ percentile.

Radon Pathway

Indoor radon levels were highly variable. The mean incremental radon level was 0.050 pCi $L^{-1}$ and the 95$^{th}$ percentile value was about three times larger (i.e. 0.149 pCi $L^{-1}$). These incremental increases in indoor radon level are relatively small fractions of the mean indoor radon level, 1.0 pCi $L^{-1}$, measured in Florida slab-on-grade homes (GEOMET 1987).

Dose and Risk

The 95$^{th}$ percentile annual dose rate from the gamma radiation pathway was 2.2 mrem $y^{-1}$ based on a application of PG for 100 years before the home was built. This value is about 25% of the estimated 95$^{th}$ percentile dose, 8.4 mrem $y^{-1}$, from the indoor radon pathway. The 95$^{th}$ percentile combined dose, from gamma radiation and indoor radon, was 9.9 mrem $y^{-1}$, which can be compared to the EPA's 15 mrem/y limit (exclusive of radon).

These dose rates lead to a 95$^{th}$ percentile risk value of 4.9 x $10^{-6}$ from living for one year in the house from the combined pathways. The 95$^{th}$ percentile value for lifetime risk from a lifetime of exposure (30 years) was 7.4 x $10^{-5}$. This value is lower than the EPA's acceptable risk level of 3 x $10^{-4}$.

Radon is the dominant contributor to dose and it must be acknowledged that some uncertainty is present with respect to the radon modelling component. The empirical factor used in the SENES analysis represents Florida slab-on-grade homes in 1986 and where actions were taken to reduce the air exchange rate (closed-room or closed home protocols) during the measurements. The empirical method implies that homes built in the future will have a similar relationship between indoor radon and soil gas radon.

There has been a tendency towards energy efficient homes and newer homes that will potentially have lower air exchange rates than found in the homes surveyed in the GEOMET study. However, there is increased consideration about indoor air quality and construction techniques that reduce transfer of soil gas, including radon into the buildings will potentially be more common in the future. These are counteracting effects. In our opinion, these anticipated developments, in combination with the reduced ventilation protocol implemented during the

GEOMET measurements, should result in the empirical model providing reasonable predictions of indoor radon levels in Florida homes built in the future.

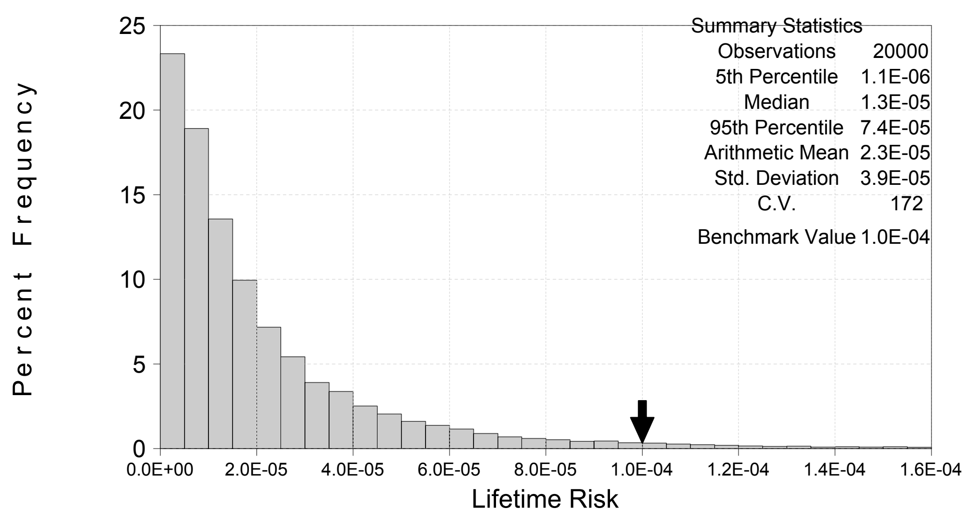
Context

Background terrestrial gamma radiation levels range from 3.2 to 62.4 μR $h^{-1}$ in a state-wide survey of Florida homes (GEOMET 1987). Most locations had gamma radiation levels below 10 μR $h^{-1}$, with 8.2 μR $h^{-1}$ being the $95^{th}$ percentile and 6.1 μR $h^{-1}$ the mean value. Based on this value, the mean annual dose from continuous exposure to terrestrial gamma radiation (assuming equal indoor and outdoor rates) is about 32 mrem $y^{-1}$.

Indoor radon levels showed substantial variability across the State with values ranging from 0.2 to 32.4 pCi $L^{-1}$ as measured in the GEOMET survey. The mean indoor radon level was 1.0 pCi $L^{-1}$; this concentration corresponds approximately to an annual indoor exposure of about 0.16 WLM which converts to an annual dose of about 64 mrem/y.

Thus average annual dose, from natural background terrestrial gamma radiation and indoor radon, is estimated at about 96 mrem $y^{-1}$ or an lifetime risk level due to natural background terrestrial gamma radiation in Florida is approximately 3.4 x $10^{-3}$ (based on 96 mrem $y^{-1}$ times a risk factor of $5x10^{-7}$ per mrem times a 70 year lifetime), more than 10 times larger than the 1.0 to 3.0 x $10^{-4}$ benchmark considered in this study.

**Figure 2**
**TOTAL LIFETIME RISKS TO RESIDENTS FOR AGRICULTURAL SCENARIO**



## 4.2 Landfill Daily Cover

In April 2002, an application for exemption was submitted to the EPA in order to obtain EPAs approval for a specific alternate use of phosphogypsum namely, to use PG as a landfill cover material in a test cell at the Brevard County Landfill, in Cocoa, Florida (SENES 2000). The test cell is proposed to be approximately 60' by 20' and to a depth of 10'. The PG would be used as a daily cover over municipal solid waste. Overall, a total of approximately 25 tons of PG was proposed to be used for the test cell.

Risks were estimated for four categories of receptors: landfill workers, PG researchers investigating the test cell during the experimental period, an on-site resident that could in the distant future live in a house that is located on the land that was previously the landfill site, and a resource recovery worker that digs into the former landfill to recover materials that remain.

Without going into details, the largest potential risks were estimated for the on-site resident who built a home on the test cell in the future. Other potential receptors under this scenario are not expected to result in as high exposures as those for the residential and occupational receptors. Other possible receptors that are reasonably expected to receive a lower dose and risk related to potential land use such as parkland, golf courses, agriculture, industrial/commercial development, etc.

Table 3 shows that all receptors and pathways are below EPA's presumptively safe risk level (which we take to be a lifetime risk of $3 \times 10^{-4}$). For all receptors except the on-site resident, the lifetime risks are several orders of magnitude below any reasonable levels of concern. These low risks result due to in part from the relatively low exposure durations for the receptors and, the design of the landfill, which eliminates several potential pathways through the inclusion of final covers and leachate collection systems. The design, operation and relatively limited access to the PG by the public makes a landfill a good opportunity for an alternate use of PG.

In our view, it is not reasonable to consider that a residence would be constructed on the landfill in the short or medium term time horizons. Other issues, such as methane production and chemical exposure are likely to be a greater immediate hazard. In the long term, while the theoretical potential exists for this scenario to arise, there is no foreseen attraction that would increase the likelihood that a person would choose the location of the test cell over any other location. It seems more probable that, if any historic records were maintained into the future, even with the loss of institutional control, the history of the site being a landfill would deter most people from building in that location.

**Table 3**
**LIFETIME INDIVIDUAL RISK ESTIMATES**
**PG USE IN TEST CELL AT BREVARD COUNTY LANDFILL**
**(Test Cell Constructed Using Phosphogypsum Containing Radium-226 at 26 pCi/g)**

| Receptor - Pathways | Lifetime Risk from a Lifetime of Exposure |
|---|---|
| Landfill Spotter | |
| - gamma (no final cover, no shielding) | $5.2 \times 10^{-8}$ |
| - inhalation of radon/progeny | $2.5 \times 10^{-11}$ |
| - inhalation of dust | $7.2 \times 10^{-10}$ |
| - ingestion of dust | $2.5 \times 10^{-9}$ |
| PG Researcher | |
| - gamma (final cover) | $7.8 \times 10^{-10}$ |
| - inhalation of radon/progeny | $5.8 \times 10^{-10}$ |
| On-Site Resident | |
| - gamma | $4.7 \times 10^{-8}$ |
| - inhalation of radon/progeny | $2.8 \times 10^{-4}$ |
| Resource Recovery Worker | |
| - gamma | $2.2 \times 10^{-7}$ |
| - inhalation of radon/progeny | $1.9 \times 10^{-10}$ |
| - inhalation of dust | $1.1 \times 10^{-9}$ |
| - ingestion of dust | $3.9 \times 10^{-9}$ |

Context

Exposure to radon is unavailable, the county of Brevard, the location of the landfill and proposed test cell, is reported to have an average indoor radon concentration of 0.5 pCi/L with a standard deviation of 0.4 pCi/L (GEOMET 1987). The maximum reading in the 85 homes measured in Bervard county was 3.2 pCi/L. When these values are compared to indoor radon concentration potentially due to the test cell of 0.26 pCi/L it is likely that the radon levels contributed from the PG in this scenario would be indistinguishable from the radon level from natural soils.

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