TECHNICAL REVIEW OF THE FERTILIZER INSTITUTE RISK ASSESSMENT FOR ADDITIONAL USE OF PHOSPHOGYPSUM IN ROAD BASE

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FINAL

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LIST OF ABBREVIATIONS AND ACRONYMS

ASSHTO	American Association of State Highway and Transportation Officials
At	astatine
BEIR	Biological Effects of Ionizing Radiation
Bi	bismuth
BID	background information document
Bq	becquerel
Bq/m^3	becquerel per cubic meter
cm	centimeter
DCF	dose conversion factor
DM	depth of soil mixing layer
EFH	Exposures Factors Handbook
EPA	U.S. Environmental Protection Agency
FA2	area factor
FDOT	Florida Department of Transportation
FGR	Federal Guidance Report
FHWA	Federal Highway Administration
FIPR	Florida Institute of Phosphate Research
FOTD	fraction of time spent outdoors
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiation Protection
ISCORS	Interagency Steering Committee on Radiation Standards
K_d	distribution coefficient
kg	kilogram
L	liter
LCF	latent cancer fatality
LET	linear energy transfer
m	meter
mBq	megabecquerel
mR	milliroentgen
mR/hr	milliroentgen per hour
mrem	millirem

NRC	U.S. Nuclear Regulatory Commission
OSWER	Office of Solid Waste and Emergency Response
Pa	protactinium
pCi	picocurie
pCi/g	picocuries per gram
PG	phosphogypsum
Pb	lead
Po	polonium
Ra	radium
RCW	road construction worker
RESRAD	residual radiation
RG	Regulatory Guide
Rn	radon
SPG	stabilized phosphogypsum
Sr	strontium
Sv/s	Sievert per second
SZNE	saturated zone
TCLP	toxicity characteristic leaching procedure
TFI	The Fertilizer Institute
Th	thorium
Tl	thallium
U	uranium
USZN	unsaturated zone
V&V	verification and validation
WLM	working level month

EXECUTIVE SUMMARY

Phosphogypsum (PG) is the byproduct of phosphoric acid fertilizer production via the wet acid process and is regulated by the U.S. Environmental Protection Agency (EPA) at 40 CFR Part 61, Subpart R. In 1993, the EPA amended Subpart R to allow the Assistant Administrator for Air and Radiation to approve alternate uses of PG following a written request, provided that a risk assessment showed that the proposed use posed no greater risk than managing the PG in engineered stacks. The EPA later published a guidance and workbook for entities seeking to perform and submit a risk assessment under Subpart R.

In 2018, The Fertilizer Institute (TFI or Institute), which represents the phosphate industry, approached the EPA to discuss the submission of a generic risk assessment that could be used to support specific use applications. The EPA has now received a petition, including a risk assessment, for approval of additional use of PG that includes a risk assessment, performed by consultants to TFI, for the use of PG in road base for paved roads. EPA asked SC&A to perform a thorough technical review of TFI's risk assessment. This report presents the results of that review, which was divided into four parts: 1) Computer Model Confirmatory Analysis, 2) Phosphogypsum Radionuclide Concentrations, 3) TFI Analyzed Exposure Scenarios, and 4) Potential Exposure Pathways Not Analyzed by TFI.

Below are presented the most significant findings of SC&A's review, there are numerous secondary findings throughout the report that may change the numerical value of the result, but are not expected to change the overall conclusion. For example, if the U.S. Environmental Protection Agency's "Exposure Factors Handbook" (EFH, EPA 2011) heavy activity inhalation rate is used instead of the RESRAD industrial worker default, the inhalation dose would increase by about a factor of 3.7. However, since the inhalation pathway is a negligible contributor to the overall RCW dose, this increase would be insignificant to the overall conclusion regarding the acceptability of the RCW's total dose. Nonetheless, it is recommended TFI review the entire report and incorporate the alternative parameter values and exposure scenarios presented therein into their risk assessment, as appropriate.

Computer Model Confirmatory Analysis

The review began by SC&A successfully verifying that TFI's computer analyses were performed correctly. The hand calculations did reveal a couple of interesting points. First, for both Road Construction Worker-Road Base_Surface Shield (RCW-RB_SS) scenarios the RESRAD models used to calculate the inhalation and ingestion doses are not consistent with the ground shine model. That is, for the ground shine model RESRAD assumes that the PG road base is shielded by a 12 cm thick surface layer of solid cement. However, for the inhalation and ingestion models RESRAD assumes that the surface layer is a 15 cm thick mixing layer of 80% cement and 20% PG. This inconsistency results in a slightly (i.e., <10%) higher total dose, and is conservative.

Second, for both the RCW-Road Surface (RCW-RS) scenarios the RESRAD model assumes a mixing depth of 15 cm, which results in 3 cm of clean soil from beneath the PG road surface "somehow" being mixed with the 12 cm of PG road surface, and reduces the doses from these two scenarios by 80%. TFI should have reduced the RESRAD mixing depth to 12 cm, so that the doses would result from the PG road surface, rather than be diluted by clean soil from below the road surface.

Phosphogypsum Radionuclide Concentrations

TFI assumed a 50/50 mixture of PG and soil and preformed their risk assessment based upon that assumption. That means that any conclusions based on the TFI risk assessment presented in this report by SC&A, or elsewhere by the EPA, are applicable to no more than a 50/50 mixture of PG. For perspective, in the late 1980s 11 test road beds containing various amounts of PG were constructed in the Houston, TX vicinity. The amount of PG in those 11 test road beds ranged from 18.8% to 94%. One of the forms of PG used in the tests was referred to as stabilized phosphogypsum (SPG), a mixture of 94% PG and 6% portland cement. Also in the late 1980s SPG was tested as a base in State Highway 146 in La Porte, TX. Two variations of SPG were tested, the first with 94% PG and 6% cement and the second with 91% PG and 9% cement. These are examples where road bases were constructed using larger amounts of PG than assumed in the TFI risk assessment, and as such, they would not have been covered by the TFI risk assessment.

Additionally, the following concerns and observations concerning the use of SPG as a road base have been identified by other researchers:

1) early cracking of the base top and asphaltic concrete pavement;
2) dissolution of the phosphogypsum;
3) possible false moisture readings from the nuclear gauge; and
4) significant percentage of nuclear density readings not meeting specified minimum compaction.

> … if phosphogypsum is to be used in highway construction as base material, it must be blended with other aggregates in order to increase its strength. Also, fly ash or other stabilizing agents should be considered to reduce cracking due to shrinkage. (Wong and Ho 1988)

SC&A is unaware whether these concerns are still valid, or if they have been resolved.

TFI Analyzed Exposure Scenarios

Road Width: The road cross-section modeled for the TFI risk assessment does not include a shoulder. On the other hand, the Federal Highway Administration states that road bases "are typically extended 3 to 4 feet beyond the edge of pavement". Increasing the road base's width would have the greatest impact on the Road Construction Worker – Road Base with Surface Shield at the road's Edge (RCW-RB_SS_Edge) ground shine dose rate, since the RCW would now be exposed uncovered PG containing road base material.

Road Model: TFI's risk assessment identified the following three road construction uses for PG:

- PG in road base during construction with no surface material present.
- PG in road base (mixed with soil and compacted) and PG in the concrete paving on the road surface.
- Road base without PG and PG in the concrete paving on the road surface.

However, the Nearest Resident scenario that was analyzed in the risk assessment, namely PG in the road base with uncontaminated paving, does not comply with any of the three identified uses of PG. Rather, TFI's risk assessment model accounts for the shielding the road surface provides to the PG in the road base, but fails to account for the dose contribution from the unshielded PG in the road paving.

Mixing Depth: When a contaminated area is covered with noncontaminated material, such as a road surface (in the two RCW–RB_SS scenarios, i.e., Center and Edge), RESRAD assumes that the contamination is uniformly distributed in a mixing layer of user-specified thickness. It is believed that an asphalt or cement road surface would not mix with the road base material, and that a mixing depth of 0.0 m would be appropriate for the two Road Base with Surface Shield scenarios. However, TFI's use of a 0.15 m mixing depth is conservative, i.e., it tends to overestimate the inhalation and ingestion doses, and therefore, no change is necessary.

Nearest Resident, Shielded Dose: To estimate the dose rate at the Nearest Resident from the PG road base covered with a concrete road surface, TFI simply reduced the unshielded dose rate by a factor of 3.5 to account for the five- to six-inch thick road surface. This approach does not account for the angle between the road surface and the Nearest Resident located 20-feet from the edge of the road. Due to this angle, gamma rays must travel through much more than five- or six-inches of concrete, with the subsequent reduction in their flux. The SC&A analysis found that the shine dose at the Nearest Resident due to a PG road base covered with a non-PG road surface would be negligible—TFI's reported dose rate of 0.33 μR/hr is indeterminately conservative.

Utility Worker: TFI assumed that the Utility Worker spent 160 hr/yr within the contaminated trench. If a Utility Worker's only job involved trench work and all those trenches were in roads with PG bases, then his/her annual dose would increase by a factor of 12.5.

Radon Dose: TFI's risk assessment gives the home Rn-222 concentration as 0.013 pCi/L (13 pCi/m^3), while SC&A's radon buildup in the home calculation gives the concentration as 169 pCi/m^3. Almost all the difference in the home Rn-222 concentration is due to the difference in the calculated radon flux through the foundation. This is due to TFI's use of a radon diffusion coefficient of 4×10^{-4} cm^2/s for intact concrete, whereas SC&A used a diffusion coefficient of 0.003 cm^2/s to account for possible cracks and other penetrations that may develop in the foundation. TFI's risk assessment goes on to give the reclaimer's inhalation dose as 1.8 mrem/yr, while SC&A calculated the reclaimer's dose as 63.3 mrem/yr. This difference in the reclaimer's inhalation dose is mainly the result of differences in the calculated foundation radon fluxes, but also the assumed inhalation rates and radon daughter equilibrium factor.

Potential Exposure Pathways Not Analyzed by TFI

In addition to reviewing the analyses performed by TFI, SC&A performed analyses for four additional potential exposure pathways: 1) Phosphogypsum Stacks – Backhoe Operator, 2) Road Users – Occupational Drivers, 3) Groundwater, and 4) Ingestion of Crayfish. The first two of these scoping analyses were simply variations of exposure pathways analyzed by TFI. That is, PG stacks-backhoe operators are similar to Road Construction Workers, except that they are exposed to undiluted PG; while occupational drivers are the same as Road Users, except they spend more time on the road. SC&A found that if the backhoe operator were to perform this task for 8.7 years, his/her LCF risk would be at EPA's reference risk of 3 in 10,000, and that the occupational driver would require 83 years of driving to be at EPA's reference risk of 3 in 10,000, well beyond an individual's working lifetime.

For the groundwater and crayfish ingestion potential exposure pathways, SC&A developed the scoping analysis methodologies. Rather than attempt to localize the groundwater analysis to Florida, or any other specific location, SC&A utilized the RESRAD-OFFSITE computer program and most of the RESRAD default parameter values for the groundwater pathway. We believe that this is appropriate for a scoping analysis. Because Florida soils are primarily sandy, the scoping analysis did utilize the RESRAD provided distribution coefficients (K_ds) for sand. Based on the results of this scoping analysis, which were all below the 3 in 10,000 EPA reference risk, at this time SC&A does not recommend any further study of the groundwater potential exposure pathway.

For the crayfish ingestion potential exposure pathway, SC&A assumed that the pond water (where the crayfish were living) radionuclide concentrations were in equilibrium with the PG stack concentrations. Based on this scoping analysis, SC&A found that primarily due to the concentration of Po-210 in crayfish (i.e., crustacea) the conservative, upper bound crayfish ingestion annual dose is unacceptably large, and would greatly exceed EPA's 3 in 10,000 reference risk. Based on the results of this scoping analysis, SC&A recommends that further study of the crayfish ingestion potential exposure pathway be performed. Among other things, these further studies would determine: 1) is this a viable exposure pathway (e.g., do crayfish live in the vicinity of PG stacks?; if so, do people regularly harvest the crayfish?) and 2) is it appropriate to utilize equilibrium K_ds to calculate the pond water radionuclide concentrations.

1.0 INTRODUCTION AND BACKGROUND

Phosphogypsum (PG) is the byproduct of phosphoric acid fertilizer production via the wet acid process and is regulated by the U.S. Environmental Protection Agency (EPA) at 40 CFR Part 61, Subpart R. In 1993, the EPA amended Subpart R to allow the Assistant Administrator for Air and Radiation to approve alternate uses of PG following a written request, provided that a risk assessment showed that the proposed use posed no greater risk than managing the PG in engineered stacks. The EPA later published a guidance and workbook for entities seeking to perform and submit a risk assessment under Subpart R.

In 2018, The Fertilizer Institute (TFI or Institute), which represents the phosphate industry, approached the EPA to discuss the submission of a generic risk assessment that could be used to support specific use applications. The EPA has now received a petition for approval of additional use of PG that includes a risk assessment, performed by consultants to TFI, for the use of PG in road base for paved roads. The petition does not apply to unpaved roadways. TFI's petition consists of five parts: 1) the petition itself, 2) Appendix 1, *Summary of the Risk Analysis of the Use of PG for Road Construction*, 3) Appendix 2, *Radiological Risk Assessment in Support of Petition for Beneficial Use of Phosphogypsum*, 4) Appendix 3, *Human Health Risk Screening for Metals and Metalloids: Phosphogypsum in Road Construction*, and 5) Appendix 4, *Documents Cited in the Petition*.

The focus of this report is a thorough technical review of TFI's radiological risk assessment (i.e., Appendix 2, Arcadis 2019).

TFI's risk assessment must demonstrate that the proposed use of PG in road base for paved roads is no more hazardous than leaving it in stacks (i.e., a latent cancer fatality [LCF] risk of less than 3 in 10,000). This risk level was established by the EPA in 1992:

> 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. (Federal Register, Vol. 57, No. 107, pp. 23311–23312, June 3, 1992)

TFI's risk assessment demonstrated that the proposed use of PG in road bases for paved roads would limit the estimated lifetime risk to any individual to no more than 3 in 10,000. In this report, SC&A reviews TFI's risk assessment and supporting appendices to determine their accuracy and robustness. The SC&A review presented in the following sections begins by verifying that TFI's computer analyses were performed correctly, and then focuses on the scenario designs, conceptual models, parameter input values, assumptions, and results. The review makes a general evaluation of whether they are reasonable and durable (i.e., are the assumptions used going to persist, or are they subject to change over a reasonable time frame with respect to roads, ownership and possession?), and identifies the parameters and assumptions most likely to influence the results of the risk assessment and performs a sensitivity analysts of those most pertinent parameters. The SC&A review ends with an evaluation of several potential exposure pathways that were not analyzed by TFI's risk assessment.

1.1 Report Organization

Following this *Introduction and Background* section are four technical review sections. In Section 2.0, *Computer Model Confirmatory Analysis*, the results of the MicroShield® (Grove 2009) and RESRAD (ANL 2016b, ANL 2018) computer runs performed by TFI are confirmed, including a hand calculation check of the RESRAD results. Section 3.0 examines the PG radionuclide concentrations utilized by TFI and compares them to concentrations used in previous similar analyses and elsewhere in the publicly available literature. The analytical approach and assumptions used in each of the six TFI-analyzed exposure scenarios are examined in Section 4.0, including a determination if it is reasonable to use more conservative assumptions or an alternative analytical approach. When such a determination is made, Section 4.0 includes the results of an SC&A analysis that uses the more conservative assumptions and/or alternative analytical approach. Finally, Section 5.0 analyzes potential exposure pathways not analyzed by TFI. These four technical sections are followed by Section 6.0, *Summary of Results*, and Section 7.0, *References*.

2.0 COMPUTER MODEL CONFIRMATORY ANALYSIS

The review began by SC&A successfully verifying that TFI's computer analyses were performed correctly. As part of their submittal, TFI provided EPA with the input files for each of the RESRAD computer program runs documented in Appendix B[1] of TFI's risk assessment. SC&A used those input files to verify TFI's results. In addition to RESRAD, TFI used the MicroShield® computer program to analyze the direct shine dose for some of the exposure scenarios. Although the input files were not provided, TFI did provide the MicroShield® results in Appendix B of their risk assessment. SC&A utilized the Appendix B MicroShield® results to develop input files to verify TFI's MicroShield® runs. In addition to the RESRAD and MicroShield® computer programs, TFI utilized a spreadsheet to calculate the radon flux and dose within a home built on the abandoned PG road base (i.e., the Reclaimer exposure scenario). Because the spreadsheet was used for a single scenario, it has been critiqued in Section 4.6, *Reclaimer*.

2.1 Confirmation of TFI MicroShield® Results

As shown in Table 2-1, using the input assumptions from TFI, SC&A was able to confirm the MicroShield® results presented in Arcadis (2019, Appendix D). However, we did identify the following inconsistency in the Appendix D MicroShield® Nearby Resident case.

Table 2-1 Comparison of TFI MicroShield® Model Results to SC&A Confirmatory Results

MicroShield® Models	Results (mR/hr)	
	TFI	SC&A
Nearby Resident – Dose Point # 1	1.135e-03	1.136e-03
Nearby Resident – Dose Point # 4	3.237e-04	3.237e-04
Truck Driver	1.857e-02	1.857e-02
Utility Worker	2.081e-03	2.081e-03

[1] TFI's submittal (TFI 2019) contains Appendices 1, 2, 3, and 4, while the risk assessment (Arcadis 2019, or TFI 2019, Appendix 2) contains Appendices A, B, and C.

According to Arcadis (2019, p. 3-2), the MicroShield® dose receptors were supposed to be at distances of 20 and 50 feet (ft) from the source (i.e., road). The Appendix D Nearby Resident MicroShield® results show that the source is 49 ft-2.6 inches (in) (i.e., 15 m) wide, and dose rates were calculated at distances of 69 ft-2.7 in, 79 ft-10.8 in, 89 ft-10.8 in, 99 ft-10.8 in, 109 ft-10.8 in, and 119 ft-10.8 in. These dimensions result in source-to-dose receptor distances of 20 ft-0.1 in, 30 ft-8.2 in, 40 ft-8.2 in, 50 ft-8.2 in, 60 ft-8.2 in, and 70 ft-8.2 in. While the first dose receptor distance is essentially 20 feet from the source, the fourth dose receptor distance used differs from 50 feet by over half a foot. Additionally, Arcadis (2019) indicates that a resident was assumed to be 1 meter (m) above the road surface. When including a 25 centimeter (cm) road base and a 12 cm road surface, that corresponds to a modeling height of 137 cm. SC&A notes that a height of only 125 cm was modeled, which fails to include the height of a road surface. SC&A has re-run the Nearest Resident MicroShield® case, with dose receptor-to-source distances of exactly 20, 30, 40, 50, 60, and 70 feet. At all distances the SC&A results, shown in Table 2-2, agree with TFI's results to within 8%. Notably, this dose only represents dose from the PG base layer and assumes no shielding or dose contribution from the road surface. It is reasonable to assume doses of this magnitude would only be observed during road construction. Further discussion is included in Section 4.2.

Table 2-2 Nearby Resident MicroShield® Results with Adjusted Dose Receptor-to-Source Distance

Location	TFI		SC&A		TFI to SC&A Ratio
	Distance	Dose Rate (mR/hr)	Distance	Dose Rate (mR/hr)	
1	20 ft-0.1 in	1.135e-03	20 ft	1.230e-03	92.3%
2	30 ft-8.2 in	6.569e-04	30 ft	7.105e-04	92.5%
3	40 ft-8.2 in	4.454e-04	40 ft	4.806e-04	92.7%
4	50 ft-8.2 in	3.237e-04	50 ft	3.484e-04	92.9%
5	60 ft-8.2 in	2.462e-04	60 ft	2.643e-04	93.2%
6	70 ft-8.2 in	1.934e-04	70 ft	2.072e-04	93.3%

Additionally, Arcadis (2019, p. 3-2) describes two MicroShield® models, one "from the side face during construction and the surface of the road following construction." However, results (i.e., 1.14 µR/hr at 20 ft) and MicroShield® files have been provided only for the "surface" model. Since the results from the "side face" model have not been provided, they have not been verified. SC&A performed independent modeling investigating this issue, which is discussed in Section 4.2.

2.2 Confirmation of TFI RESRAD Results

As shown in Table 2-3 for the risk assessment, TFI made nine (9) RESRAD runs for various combinations of dose receptors (i.e., Road Construction Worker, Nearest Resident, Utility Worker, and Reclaimer Resident), PG sources (i.e., either the road base or surface), whether the PG source is shielded or not, and where on the road the receptor is located (i.e., at the Center or on the Edge).

Table 2-3 TFI RESRAD Runs

Dose Receptor	Source	Shield	Location	TFI Acronym
Road Construction Worker	Road Base	No Cover	Center	RCW-RB_NC_Center
			Edge	RCW-RB_NC_Edge
		Surface Shield	Center	RCW-RB_SS_Center
			Edge	RCW-RB_SS_Edge
	Road Surface	—	Center	RCW-RS_Center
		—	Edge	RCW-RS_Edge
Nearest Resident	Road Base	—	—	NR_PG in RB
Utility Worker	Road Base	—	—	UW_PG in RB
Reclaimer Resident	Road Base	—	Center	RR_PG in RB_Center

Table 2-4 compares the results of the SC&A and TFI RESRAD runs and shows that there is good agreement.

Table 2-4 Comparison of TFI RESRAD Model Results to SC&A Confirmatory Results

RESRAD Model / TFI Acronym	Results (mrem/yr)	
	TFI	SC&A
RCW-RB_NC_Center	2.817E+01	2.817E+01
RCW-RB_NC_Edge	1.576E+01	1.576E+01
RCW-RB_SS_Center	3.519E+00	3.519E+00
RCW-RB_SS_Edge	1.966E+00	1.966E+00
RCW-RS_Center	1.016E+00	1.016E+00
RCW-RS_Edge	5.724E-01	5.724E-01
NR_PG in RB – Inhalation	1.026E-01	1.026E-01
NR_PG in RB – Soil	2.767E+00	2.767E+00
UW_PG in RB – Inhalation	1.501E-01	1.501E-01
UW_PG in RB – Soil	1.114E-02	1.114E-02
RR_PG in RB_Center	1.228E+00	1.228E+00

2.2.1 Hand Calculation Confirmation of Road Construction Worker – Road Base No Cover_Center

For the Road Construction Worker – Road Base No Cover_Center scenario TFI analyzed three (3) exposure pathways: ground shine, inhalation, and soil ingestion. The hand calculations that were performed to verify the dose from each exposure pathway are described in this section.

Ground Shine Dose — SC&A used Eq 2-1 to calculate the ground shine dose to the road construction worker (RCW) from a PG road base with no cover. For consistency, whenever possible, the RESRAD parameter names have been used in the right side of Eq 2-1. Thus, the values used for these parameters can be easily obtained in Appendix C of the risk assessment.

$$D_S = SHF1 \times FOTD \times \sum_{i=1}^{N} S1_i \times DCF1_i \qquad \text{Eq 2-1}$$

Where: D_S = Worker dose due to ground shine (mrem/yr)
$SHF1$ = Shielding factor, external gamma
= 0.7
$FOTD$ = Fraction of time spent outdoors (on site)
= 0.23
$S1_i$ = PG radionuclide concentration (pCi/g) (see Table 2-5)
$DCF1_i$ = Dose conversion factors for external ground radiation (mrem/yr)/(pCi/g) (see Table 2-5)
N = Number of radionuclides

The results of this calculation are shown in Table 2-5, and compared to the RESRAD results from Appendix C, RCW_RB_CENTER070319, p. 12[2].

Table 2-5 Ground Shine Pathway Hand Calculation Comparison

Nuclide	DCF (mrem/yr)/(pCi/g)	Concentration (pCi/g)	Calculated (mrem/yr)	RESRAD (mrem/yr)	Ratio
Bi-210	5.476E-03	13.5	1.190E-02	3.596E-04	33.1
Pb-210	1.981E-03	13.5	4.306E-03	1.864E-02	0.23
Po-210	4.934E-05	13.5	1.072E-04	6.047E-05	1.77
Ra-226	2.915E-02	13.5	6.336E-02	2.581E+01	0.002
Rn-222+D	1.057E+01	13.5	2.298E+01	6.296E-01	36.5
Th-230	1.071E-03	2.5	4.311E-04	1.592E-03	0.27
Th-234+D	1.374E-01	1.5	3.318E-02	4.563E-03	7.27
U-234	3.439E-04	1.6	8.859E-05	1.155E-04	0.77
U-238	7.961E-05	1.5	1.923E-05	4.300E-02	0.000
Total	—	—	2.310E+01	2.651E+01	0.87

Notice that there is fairly good agreement between the hand and RESRAD calculated total dose, but almost no agreement between the individual radionuclide doses. This is due to the manner in which decay and buildup was addressed in each calculation. For the hand calculation, it was implicitly assumed that all the radionuclides are at equilibrium and remain that way throughout the 1-year dose period (i.e., the concentrations do not change throughout the 1-year dose period). RESRAD assumes that the entered concentrations are at time zero, and then uses the Bateman equation[3] to decay and buildup the individual radionuclides over the 1-year dose period. When

[2] TFI utilized the results from page 13 (t = 1.000E+00 years) of the RESRAD outputs, rather than page 12 (t = 0.000E+00 years). Because RESRAD integrates the dose, the year 0 annual dose is actually the 0 to 1 year integrated dose, while the year 1 annual dose is the 1 to 2 year integrated dose. Since the radionuclides of concern for this analysis (i.e., Ra-226 and U-238) have long half-lives (i.e., 1,600 years and 4.468 billion years, respectively), the choice of page 12 or page 13 results makes little difference.

[3] To explain their experiments with radioactive substances, Ernest Rutherford and Frederick Soddy formulated the exponential laws that govern the decay and growth of radioactive substances in 1902. In 1910, a useful mathematical generalization of the Rutherford and Soddy radioactive decay and in-growth laws was made by mathematician Harry Bateman; thereafter, referred to as the Bateman equation, although they are actually a series of equations.

presenting the individual radionuclide's contribution to the dose, RESRAD includes any contribution from built-up daughter radionuclides with the parent radionuclide. For example, in Table 2-5 under the hand calculation, the Rn-222+D contribution to the dose includes the contribution from the initial amount of Rn-222+D, as well as any Rn-222+D that builds up from the decay of Ra-226. On the other hand, the Rn-222+D Table 2-5 RESRAD entry only includes the contribution from the initial amount of Rn-222, and any contribution to the dose from the buildup of Rn-222+D from the decay of Ra-226 is included under the Ra-226 entry.

Regarding RESRAD's use of Rn-222+D, as well as Th-234+D, the "+D" indicates that the dose factors from the short-lived daughter radionuclides have been added to the parent radionuclide's (i.e., Rn-222 or Th-234) dose factor. Before the daughter's dose factors are added, they are multiplied by the parent-to-daughter's branching fraction. SC&A utilized the data in Table 2-6 to calculate the Rn-222+D and TH-234+D ground shine dose conversion factors shown in Table 2-5.

Table 2-6 Rn-222 and Th-234 Dose Factors, Including Short-Lived Daughters

Nuclide	Individual DCF (mrem/yr)/(pCi/g)	Half-Life	Branching Fraction	Combined DCF (mrem/yr)/(pCi/g)
	Rn-222 Plus Short-Lived Daughters			
Rn-222	2.186E-03	3.82 days	100%	2.186E-03
Po-218	5.326E-05	3.10 min	100%	5.326E-05
Pb-214	1.243E+00	27.1 min	100%	1.243E+00
Bi-214	9.325E+00	19.9 min	100%	9.325E+00
Po-214	4.840E-04	164. µsec	99.98%	4.840E-04
Tl-210	1.661E+01	1.30 min	0.02%	3.322E-03
Rn-222+D	—	3.82 days	—	1.057E+01
	Th-234 Plus Short-Lived Daughters			
Th-234	2.130E-02	24.1 days	100%	2.130E-02
Pa-234	1.088E+01	6.70 Hrs	0.16%	1.741E-02
Pa-234m	9.867E-02	1.16 min	100%	9.867E-02
Th-234+D	—	24.1 Days	—	1.374E-01

Half-Life and Branching Fraction Source: BNL 2020

Inhalation Dose — SC&A used Eq 2-2 to calculate the inhalation dose to the RCW from a PG road base with no cover. For consistency, whenever possible, the RESRAD parameter names have been used in the right side of Eq 2-2. Thus, the values used for these parameters can be easily obtained in Appendix C of the risk assessment.

$$D_H = INHALR \times FOTD \times FA2 \times MLINH \times \sum_{i=1}^{N} S1_i \times DCF2_i \qquad \text{Eq 2-2}$$

Where: D_H = Worker inhalation dose (mrem/yr)

$INHALR$ = Worker inhalation rate (m^3/yr)

= 11,400 m^3/yr

$FOTD$ = Fraction of time spent outdoors (on site)

= 0.23

$FA2$ = Area factor, see Eq 2-3

$MLINH$ = Mass loading for inhalation (g/m^3)
= 2.0E-04 g/m^3
$S1_i$ = PG radionuclide concentration (pCi/g) (see Table 2-7)
$DCF2_i$ = Dose conversion factors for inhalation (mrem/pCi) (see Table 2-7)
N = Number of radionuclides

Included in Eq 2-2 is an area factor ($FA2$), which is defined in "User's Manual for RESRAD Version 6" (ANL 2001, Section B.2) and is calculated via Eq 2-3.

$$FA2 = \frac{a}{\left(1 + b \times \left(\sqrt{AREA}\right)^{c}\right)} \qquad \text{Eq 2-3}$$

Where: $FA2$ = Area factor
= 0.13912
$AREA$ = Area of contaminated zone (m^2)
= 1500 m^2
a = 1.6819
b = 25.5076
c = -0.2278
(a, b, c:) least squares regression coefficients from ANL (2001, Table B.2) for an average wind speed of 2 m/s

The results of the inhalation hand calculation are shown in Table 2-7 and compared to the RESRAD results from Appendix C, RCW_RB_CENTER070319, p. 12. As Table 2-7 shows, there is good agreement (within about 1 percent) between the hand- and RESRAD-calculated inhalation doses.

Table 2-7 Inhalation Pathway Hand Calculation Comparison

Nuclide	DCF (mrem/pCi)	Concentration (pCi/g)	Calculated (mrem/yr)	RESRAD (mrem/yr)	Ratio
Bi-210	3.441E-04	13.5	3.389E-04	2.284E-04	1.48
Pb-210	2.072E-02	13.5	2.041E-02	2.738E-02	0.75
Po-210	1.591E-02	13.5	1.567E-02	6.972E-03	2.25
Ra-226	3.515E-02	13.5	3.462E-02	3.484E-02	0.99
Rn-222+D	1.073E-04	13.5	1.057E-04	1.379E-05	7.66
Th-230	3.700E-01	2.5	6.748E-02	6.748E-02	1.00
Th-234+D	2.849E-05	1.5	3.118E-06	2.980E-07	10.5
U-234	3.478E-02	1.6	4.060E-03	4.024E-03	1.01
U-238	2.960E-02	1.5	3.239E-03	3.213E-03	1.01
Total	—	—	1.459E-01	1.442E-01	1.01

The Table 2-7 inhalation doses are also applicable to the Road Construction Worker – Road Base No Cover_Edge scenario. When multiplied by the mixing factor of 0.20, the Table 2-7 inhalation doses are applicable to the two Road Construction Worker – Road Base with Surface Shield scenarios. The mixing factor and mixing depth are described in ANL 2001 (p. B-8) and discussed below in Section 2.2.2. Finally, when multiplied by the ratio of the Utility Worker to Road Base No Cover_Center fractions of time spent outdoors (i.e., 0.018 / 0.23 or 160 hrs / 2016 hrs), the Table 2-7 inhalation doses are also applicable to the utility worker.

Soil Ingestion Dose — SC&A used Eq 2-4 to calculate the inhalation dose to the RCW from a PG road base with no cover. Again, for consistency, whenever possible the RESRAD parameter names have been used in the right side of Eq 2-4. Thus, the values used for these parameters can be easily obtained in Appendix C of the risk assessment.

$$D_G = SOIL \times FOTD \times \sum_{i=1}^{N} S1_i \times DCF3_i \qquad \text{Eq 2-4}$$

Where:
- D_G = Worker soil ingestion dose (mrem/yr)
- $SOIL$ = Worker soil ingestion rate (g/yr) = 82.5 g/yr
- $FOTD$ = Fraction of time spent outdoors (on site) = 0.23
- $S1_i$ = PG radionuclide concentration (pCi/g) (see Table 2-8)
- $DCF3_i$ = Dose conversion factors for ingestion (mrem/pCi) (see Table 2-8)
- N = Number of radionuclides

The results of the inhalation hand calculation are shown in Table 2-8 and compared to the RESRAD results from Appendix C, RCW_RB_CENTER070319, p. 12. As Table 2-8 shows, there is good agreement (within about 5 percent) between the hand- and RESRAD-calculated soil ingestion doses.

Table 2-8 Soil Ingestion Pathway Hand Calculation Comparison

Nuclide	DCF (mrem/pCi)	Concentration (pCi/g)	Calculated (mrem/yr)	RESRAD (mrem/yr)	Ratio
Bi-210	4.810E-06	13.5	1.232E-03	1.603E-02	0.08
Pb-210	2.553E-03	13.5	6.540E-01	1.157E+00	0.57
Po-210	4.440E-03	13.5	1.137E+00	5.060E-01	2.25
Ra-226	1.036E-03	13.5	2.654E-01	2.780E-01	0.95
Rn-222+D	9.249E-07	13.5	2.369E-04	4.907E-04	0.48
Th-230	7.770E-04	2.5	3.686E-02	3.687E-02	1.00
Th-234+D	1.259E-05	1.5	3.583E-04	3.413E-05	10.5
U-234	1.813E-04	1.6	5.504E-03	5.456E-03	1.01
U-238	1.665E-04	1.5	4.739E-03	5.019E-03	0.94
Total	—	—	**2.106E+00**	**2.005E+00**	**1.05**

The Table 2-8 ingestion doses are also applicable to the Road Construction Worker – Road Base No Cover_Edge scenario. When multiplied by the mixing factor of 0.20, the Table 2-8 ingestion doses are applicable to the two Road Construction Worker – Road Base with Surface Shield scenarios. The mixing factor and mixing depth are described in ANL (2001, p. B-8) and discussed below in Section 2.2.2. Finally, when multiplied by the ratio of the Utility Worker time spent outdoors to Road Construction Worker – Road Base No Cover_Center time spent outdoors (i.e., 160 hrs / 2016 hrs, or expressed as FOTD, 0.018 / 0.23), the Table 2-8 ingestion doses are also applicable to the Utility Worker.

2.2.2 Hand Calculation Confirmation of All TFI RESRAD Scenarios

Examination of Eq 2-1, Eq 2-2, Eq 2-3, and Eq 2-4 reveals that there are a handful of scenario-specific main RESRAD input parameters that control the dose calculations. Therefore, it is possible to calculate the doses for the other scenarios by simply ratioing the Road Construction Worker – Road Base No Cover_Center doses, as shown in Eq 2-5, Eq 2-6, and Eq 2-7 for the ground shine, inhalation, and soil ingestion pathways, respectively.

$$D_{S(Scenario)} = D_{S(RB\_NC\_C)} \times \frac{PG_{Ra(Scenario)}}{PG_{Ra(RB\_NC\_C)}} \times \frac{SHF1_{(Scenario)}}{SHF1_{(RB\_NC\_C)}} \times \frac{FOTD_{(Scenario)}}{FOTD_{(RB\_NC\_C)}} \quad \text{Eq 2-5}$$

$$D_{H(Scenario)} = D_{H(RB\_NC\_C)} \times \frac{PG_{Ra(Scenario)}}{PG_{Ra(RB\_NC\_C)}} \times \frac{INHALR_{(Scenario)}}{INHALR_{(RB\_NC\_C)}} \times \frac{FOTD_{(Scenario)}}{FOTD_{(RB\_NC\_C)}} \times \frac{FA2_{(Scenario)}}{FA2_{(RB\_NC\_C)}} \times \frac{MLINH_{(Scenario)}}{MLINH_{(RB\_NC\_C)}} \quad \text{Eq 2-6}$$

$$D_{G(Scenario)} = D_{G(RB\_NC\_C)} \times \frac{PG_{Ra(Scenario)}}{PG_{Ra(RB\_NC\_C)}} \times \frac{SOIL_{(Scenario)}}{SOIL_{(RB\_NC\_C)}} \times \frac{FOTD_{(Scenario)}}{FOTD_{(RB\_NC\_C)}} \quad \text{Eq 2-7}$$

Table 2-9 lists these main input parameters and shows the values utilized by each scenario of TFI's risk assessment.

Table 2-9 Main Input Parameter Values for All TFI RESRAD Scenarios

TFI Appendix 2 RESRAD Scenario / TFI Acronym	Ra-226 Conc. (pCi/g)	PG/Cover Thick. (m)	Mixing Factor (Calculated)	Fraction Outdoors	Fraction Indoors	Soil Ingest. (g/yr)	Inhalation Rate (m^3/yr)	Dust Loading (g/m^3)	Shield Fact. External	Shield Fact. Inhalation
RCW-RB_NC_Center	13.5	25/0	1.0	0.23	N.U.	82.5	11,400	2×10^{-4}	0.7	N.U.
RCW-RB_NC_Edge	13.5	25/0	1.0	0.23	N.U.	82.5	11,400	2×10^{-4}	0.7	N.U.
RCW-RB_SS_Center	13.5	25/12	0.2	0.23	N.U.	82.5	11,400	2×10^{-4}	0.7	N.U.
RCW-RB_SS_Edge	13.5	25/12	0.2	0.23	N.U.	82.5	11,400	2×10^{-4}	0.7	N.U.
RCW-RS_Center	0.61	12/0	0.8	0.23	N.U.	82.5	11,400	2×10^{-4}	0.7	N.U.
RCW-RS_Edge	0.61	12/0	0.8	0.23	N.U.	82.5	11,400	2×10^{-4}	0.7	N.U.
NR_PG in RB	13.5	25/0	1.0	0.25	0.5	36.5	8,400	1×10^{-4}	0.7	0.4
UW_PG in RB	13.5	25/0	1.0	0.018	N.U.	82.5	11,400	2×10^{-4}	0.7	N.U.
RR_PG in RB_Center	10	10/20	N.U.	0.0	N.U.	N.U.	N.U.	N.U.	N.U.	N.U.

The hand calculation of the doses for the other RESRAD scenarios was performed by multiplying the RCW-RB_NC_Center doses by the ratio of any of the applicable Table 2-9 parameters, as shown in Eq 2-5, Eq 2-6, and Eq 2-7. For example, for the inhalation dose, the only parameter that differs between the RCW-RB_NC_Center and RCW-RB_SS_Center scenarios is the mixing factor, thus the RCW-RB_SS_Center inhalation dose was calculated to be (0.2 / 1.0) × 0.15 = 0.029 mrem/yr, as shown in Table 2-10, which also shows that this dose agrees with the RESRAD calculated dose.

Table 2-10 Hand Calculation Confirmation of All TFI RESRAD Scenarios

TFI Appendix 2 RESRAD Scenario	Ground Shine		Inhalation		Soil Ingestion	
	Hand Calc (mrem/yr)	Ratio to TFI, App 2	Hand Calc (mrem/yr)	Ratio to TFI, App 2	Hand Calc (mrem/yr)	Ratio to TFI, App 2
RCW-RB_NC_Center	2.3E+01	88%	1.5E-01	101%	2.1E+00	105%
RCW-RB_NC_Edge	1.2E+01	84%	1.5E-01	101%	2.1E+00	105%
RCW-RB_SS_Center	Not Hand Calculated		2.9E-02	101%	4.2E-01	105%
RCW-RB_SS_Edge	Not Hand Calculated		2.9E-02	101%	4.2E-01	105%
RCW-RS_Center	8.4E-01	86%	5.2E-03	102%	7.2E-02	105%
RCW-RS_Edge	4.2E-01	81%	5.2E-03	102%	7.2E-02	105%
NR_PG in RB	Turned Off		1.1E-01	101%	3.0E+00	105%
UW_PG in RB	Turned Off		1.1E-02	101%	1.6E-01	105%
RR_PG in RB_Center	Not Hand Calculated		Turned Off		Turned OFF	

Another example is the RCW-RS_Center ground shine dose, which is simply the RCW-RB_NC_Center ground shine dose multiplied by the ratio of their Ra-226 concentrations (i.e., 23 × [0.61 / 13.5] = 0.84 mrem/yr). Similarly, the "Edge" ground shine doses are simply half the "Center" doses, while the inhalation and ingestion "Edge" and "Center" doses are the same.

The hand calculations did reveal a couple of interesting points. First, for both RCW-RB_SS scenarios, the RESRAD models used to calculate the inhalation and ingestion doses are not consistent with the ground shine model. That is, for the ground shine model, RESRAD assumes that the PG road base is shielded by a 12-cm thick surface layer of solid cement. However, for the inhalation and ingestion models, RESRAD assumes that the surface layer is a 15-cm thick mixing layer of 80 percent cement and 20 percent PG. This inconsistency results in a slightly (i.e., <10 percent) higher total dose and is conservative.

Second, for both the RCW-RS scenarios, the RESRAD model assumes a mixing depth of 15 cm, which results in 3 cm of clean soil from beneath the PG road surface "somehow" being mixed with the 12 cm of PG road surface, and reduces the doses from these two scenarios by 80 percent. TFI should have reduced the RESRAD mixing depth to 12 cm so that the doses would result from the PG road surface, rather than be diluted by clean soil from below the road surface.

3.0 PHOSPHOGYPSUM RADIONUCLIDE CONCENTRATIONS

Phosphate formations contain concentrations of naturally occurring radionuclides of the uranium decay series. The uranium decay series is shown in Figure 3-1.

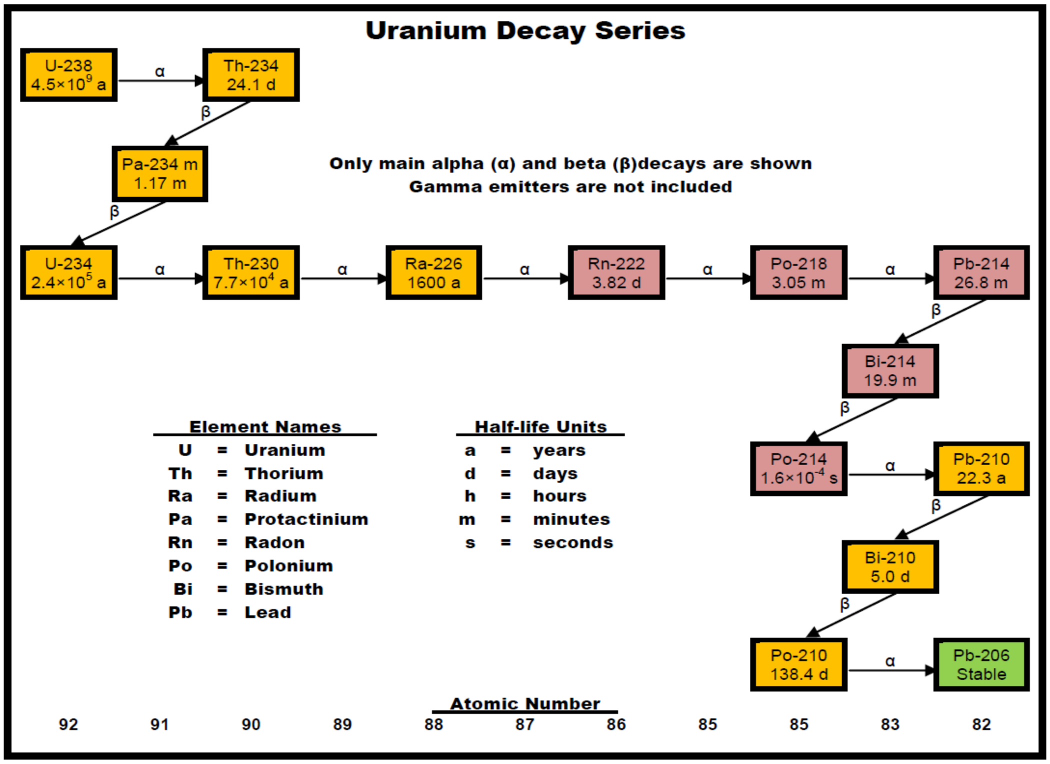

Figure 3-1 Uranium Decay Series

3.1 SC&A Confirmation of TFI Radionuclide Concentrations

Table 3-1 reproduces the PG, road base, and road surface source terms reported in TFI's risk assessment.

Table 3-1 TFI Source Terms

Radionuclide	Phosphogypsum (pCi/g)	Road Base (pCi/g)	Road Base (pCi/cm^3)	Road Surface (pCi/g)	Road Surface (pCi/cm^3)
U-238	2.9 ± 0.5	1.5	3.3	0.066	0.1
Th-234	2.9 ± 0.5	1.5	3.3	0.066	0.1
Pa-234m	2.9 ± 0.5	1.5	3.3	0.066	0.1
U-234	3.2 ± 0.5	1.6	3.6	0.073	0.1
Th-230	5 ± 0.4	2.5	5.6	0.11	0.2
Ra-226	27 ± 0.4	13.5	30.4	0.61	1.215
Rn-222	27 ± 0.4	13.5	30.4	0.61	1.215
Po-218	27 ± 0.4	13.5	30.4	0.61	1.215
Pb-214	27 ± 0.4	13.5	30.4	0.61	1.215
Bi-214	27 ± 0.4	13.5	30.4	0.61	1.215
Po-214	27 ± 0.4	13.5	30.4	0.61	1.215
Pb-210	27 ± 5.4	13.5	30.4	0.61	1.215
Bi-210	27 ± 5.4	13.5	30.4	0.61	1.215
Po-210	27 ± 5.4	13.5	30.4	0.61	1.215
	(Arcadis 2019, Table 2.2)	(Arcadis 2019, Table 2.3)		(Arcadis 2019, Table 2.4)	

Table 3-2 shows the results of SC&A's attempt to verify the Table 3-1 TFI source terms. As shown, SC&A started with the same PG source term specified by TFI. Regarding the road base concentration, Arcadis (2019) states that it is composed of "a 50/50 mixture of PG and soil" (p. 2-5) and that PG and the road base have densities of 1.12 and 2.25 g/cm^3, respectively (p. 2-9). SC&A observes that both of these statements cannot be true. The density of soil is 1.52 g/cm^3 (ANL 2015, Table 2.1.1), while the density of PG is 1.47–1.67 g/cm^3 (IAEA 2013, p. 116) and can be assumed to also be 1.52 g/cm^3, giving the road base a density of 1.52 g/cm^3. If that is the case, then the SC&A and TFI road base mass concentrations agree; however, the volume concentrations do not agree, as shown by comparing Table 3-1 to Table 3-2.

Table 3-2 SC&A Calculated Source Terms

Radio-nuclide	PG	Base: 1.52 g/cm^3 PG: 1.52 g/cm^3		Base: 2.25 g/cm^3 PG: 1.12 g/cm^3		Road Surface: 2.25 g/cm^3	
	(pCi/g)	(pCi/g)	(pCi/cm^3)	(pCi/g)	(pCi/cm^3)	(pCi/g)	(pCi/cm^3)
U-238	2.9	1.5	2.3	1.0	1.7	0.065	0.15
Th-234	2.9	1.5	2.3	1.0	1.7	0.065	0.15
Pa-234m	2.9	1.5	2.3	1.0	1.7	0.065	0.15
U-234	3.2	1.6	2.4	1.1	1.9	0.072	0.16
Th-230	5	2.5	3.8	1.7	2.9	0.11	0.25
Ra-226	27	13.5	20.5	9.0	15.2	0.61	1.37
Rn-222	27	13.5	20.5	9.0	15.2	0.61	1.37
Po-218	27	13.5	20.5	9.0	15.2	0.61	1.37
Pb-214	27	13.5	20.5	9.0	15.2	0.61	1.37
Bi-214	27	13.5	20.5	9.0	15.2	0.61	1.37
Po-214	27	13.5	20.5	9.0	15.2	0.61	1.37
Pb-210	27	13.5	20.5	9.0	15.2	0.61	1.37
Bi-210	27	13.5	20.5	9.0	15.2	0.61	1.37
Po-210	27	13.5	20.5	9.0	15.2	0.61	1.37

On the other hand, if the PG and the road base have densities of 1.12 and 2.25 g/cm^3, respectively, then the soil mixed with the PG must have a density of 1.69 g/cm^3—which is too large. Nonetheless, Table 3-2 also shows what the mass and volume concentrations would be under these TFI assumptions.

Finally, TFI assumed the road surface density was 2.25 g/cm^3 and further assumed that there was 15 percent PG in the cement and 15 percent cement in the concrete, or 2.25 percent PG in the concrete (Arcadis 2019, p. 2-5). SC&A believes these to be reasonable assumptions, and we were able to verify the road surface mass concentrations; however, the volume concentrations do not agree, as shown by comparing Table 3-1 to Table 3-2. This implies that there is an inconsistency in TFI's report, i.e., either the mass concentration, volume concentration, or density reported by TFI are incorrect. Because the exact nature of the inconsistency is unknown, it is also unknow what effect (if any) this mass and volume concentration inconsistency will have on the calculated doses/risks.

3.2 Impact of Nonequilibrium and Radiological Decay on Dose

It is noticed that the Table 3-1 uranium series radionuclides are not in equilibrium. This is explained in EPA 1992 by the following:

> 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 (…). (EPA 1992, p. 2-6)

Because of its 1,600-year half-life, the nonequilibrium of Ra-226 makes little difference when calculating doses to near-term individuals, such as road construction workers, road users, and nearest residents. However, if an exposure pathway has a long time developing, such as the ground water pathway, then the nonequilibrium of Ra-226 should be taken into account. Figure 3-2 shows the time varying Ra-226 PG concentration as it initially decays and then re-equilibrates with the Th-230 concentration. Due to their long half-lives, the PG concentrations of Th-230, U-234, and U-238 appear constant in Figure 3-2.

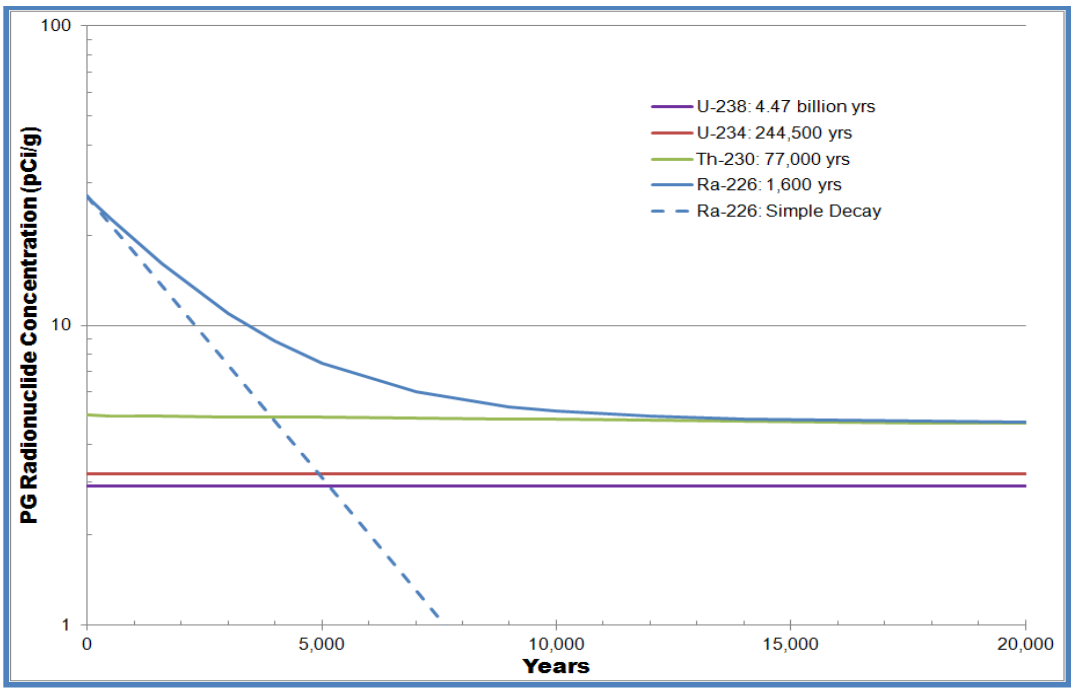

Figure 3-2 Time for Phosphogypsum Ra-226 to Re-equilibrate

Because different elements have different distribution coefficients (K_d), they travel at different rates in the groundwater. The RESRAD K_d for Ra-226 is significantly smaller than the K_d for its parent, Th-230 (see Table 5-2), meaning that Ra-226 would more readily leave the PG road base in the groundwater, while the Th-230 would remain within the road base. Thus, as the Ra-226 travels in the groundwater it would undergo radiological decay, and not be replenished by Th-230 decay. The dashed, blue curve on Figure 3-2 shows the simple decay of Ra-226. Section 5.3 presents more discussion of the groundwater pathway.

SC&A notes that the PG source term specified in Arcadis (2019, Table 2.3 [reproduced in Table 3-1]) was modified in the MicroShield® modeling. As specified in Section 2.4.1, "The radium concentration was 13.5 pCi/g (Ra-226). It was converted to pCi/cm^3 and increased by a factor of ten half-lives and input into MicroShield®. The decay function in MicroShield® was then used to decay the source by ten half-lives which generated all the daughters including the branching ratios." SC&A was unable to exactly replicate the exact source term shown in the MicroShield® output files; however, SC&A calculated a source term within the uncertainty specified in Table 3-1, assuming a radium concentration was 13.5 pCi/g. Additionally, the modeled values are within the 0.4 pCi/g uncertainty specified in Arcadis (2019, Table 2.3) with the exception of the first five radionuclides listed in Table 3-1.

TFI determined the radionuclides in the initial portion of the U-238 decay chain contributed less than 0.1 percent to the dose and thus omitted them from MicroShield® modeling. To verify this assertion, SC&A modeled the doses specified in Table 3-1, including the initial U-238 components for the trucker dose scenario, which assumes undiluted PG material. The results of this assessment are shown in Table 3-3. SC&A notes that at 0.5 percent, the cumulative impact of the source term changes is larger than 0.1 percent of the source term modifications, but nonetheless negligible.

Table 3-3 Comparison of Source Term Modeled with Source Term Specified in Table 3-1 for Truck Driver Exposure Scenario

Location	Dose Rate (mR/hr)		Ratio
	TFI	SC&A	SC&A/TFI
Truck driver model	1.857e-02	1.866E-02	1.005

3.3 Phosphogypsum Radionuclide Concentrations from Other References

As for the Ra-226 activity in the PG waste, the 1992 EPA Background Information Document (EPA 1992) provides mean concentrations from 5 different stacks in Florida, where 10 separate samples and analysis were conducted on each stack. These Florida averages range from a stack low of 25+/-4 pCi/g to a stack high of 34+/-18 pCi/g. However, the range of the Florida concentrations was wider, from a lowest sample Ra-226 concentration reported at 16 pCi/g (Royster site) to a highest sample at 81 pCi/g (Conserv site). Additional explanation and justification should be provided, which could affect other model inputs and results.

Also, the following statement by the Florida Institute of Phosphate Research (FIPR) indicates that assuming an upper limit of 27 pCi/g Ra-226 concentration might not be sufficient to envelope all of Florida's PG:

> Phosphogypsum produced in North Florida contains roughly 5 – 10 picocuries per gram (pCi/g) of radium while phosphogypsum from Central Florida contains about 20 – 35 pCi/g radium. (FIPR 2020)

Subsequent to providing EPA with the risk assessment (Arcadis 2019), TFI provided EPA with 10 PG Ra-226 sample results from each of nine stacks collected from across the United States (i.e., central Florida, Louisiana, and western U.S.), as shown in Table 3-4. Notice that only three of the 90 sample results had Ra-226 concentrations above the 27 pCi/g values assumed in TFI's risk assessment (shown in red in Table 3-4), and that all samples were below 28 pCi/g.

Table 3-4 Aggregate PG Ra-226 Data from September 2019 (Reported as pCi/g)

Sample No.	Central Florida						Louisiana	Western U.S.	
	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7	Stack 8	Stack 9
1	23.3	24.9	16.6	19.9	27.9	19.2	19.8	24.2	8.51
2	27.0	24.5	17.3	9.0	17.7	7.23	18.9	24.3	8.38
3	16.1	25.4	17.5	25.8	23.8	17.1	16.2	22.3	7.82
4	24.1	26.6	19.3	20.3	22.4	27.2	15.9	21.3	6.83
5	18.9	24.2	10.3	21.6	14.6	24.8	16.1	25.5	6.32
6	21.7	20.6	18.6	19.5	17.7	19.1	21.9	24.8	8.17
7	21.4	24.2	10.4	24.7	18.2	21.4	16.7	25.1	7.37
8	25.0	25.6	11.0	18.5	18.9	12.6	19.2	25.3	6.88
9	19.5	27.8	13.8	17.1	23.8	7.27	18.7	25.2	6.80
10	14.9	23.1	15.3	22.7	16.6	13.3	17.9	24.3	7.50
Average	21.19	24.69	15.01	19.91	20.16	16.92	18.13	24.23	7.46
Median	21.55	24.70	15.95	20.10	18.55	18.10	18.30	24.55	7.44

As stated above, TFI assumed "a 50/50 mixture of PG and soil" (Arcadis 2019, p. 2-5) and preformed their risk assessment based upon that assumption. That means that any conclusions based on TFI's risk assessment presented in this report by SC&A, or elsewhere by the EPA, are applicable to no more than a 50/50 mixture of PG. For perspective, in the late 1980s, 11 test road beds containing various amounts of PG were constructed in the Houston, Texas, vicinity (Roessler 1990). The amount of PG in those 11 test road beds ranged from 18.8 percent to 94 percent. One of the forms of PG used in the tests was referred to as "stabilized phosphogypsum (SPG), a mixture of 94% PG and 6% portland cement." Also, in the late 1980s, SPG was tested as a base in State Highway 146 in La Porte, Texas (Wong and Ho 1988). Two variations of SPG were tested: the first with 94 percent PG and 6 percent cement, and the second with 91 percent PG and 9 percent cement. These are examples where road bases were constructed using larger amounts of PG than assumed in TFI's risk assessment, and as such, they would not have been covered by TFI's risk assessment.

Additionally, Wong and Ho (1988) expressed the following concerns and observations regarding the use of SPG as a road base:

> 1) early cracking of the base top and asphaltic concrete pavement;
> 2) dissolution of the phosphogypsum;
> 3) possible false moisture readings from the nuclear gauge; and
> 4) significant percentage of nuclear density readings not meeting specified minimum compaction.
>
> … if phosphogypsum is to be used in highway construction as base material, it must be blended with other aggregates in order to increase its strength. Also, fly ash or other stabilizing agents should be considered to reduce cracking due to shrinkage. (Wong and Ho 1988)

SC&A is unaware whether these concerns expressed by Wong and Ho (1988) are still valid, or if they have been resolved.

4.0 TFI ANALYZED EXPOSURE SCENARIOS

4.1 Road Construction Worker

Figure 4-1 is a schematic of the road cross-section modeled by Arcadis (2019) for TFI's risk assessment. In Figure 4-1, the road base ends at the edge of the paving, and an examination of the RESRAD and MicroShield® input and results shows that this arrangement is what has been analyzed for the road construction workers' dose.

Figure 4-1 Schematic Cross-Section of the Road Modeled by Arcadis 2019
(Source: TFI 2019, Appendix 1, Figure S-1)

The Federal Highway Administration (FHWA) provides the following information concerning road bases.

> The thickness of the base generally depends on the degree of support required for the construction equipment and type and condition of the underlying subgrade. Base thicknesses in the range of 4 to 6 inches are most common. Bases are typically extended 3 to 4 feet beyond the edge of pavement …
>
> Unstabilized bases, also frequently referred to as granular bases, are the most commonly used base types for concrete pavements. Adequately designed and properly constructed, unstabilized bases exhibit excellent field performance at a lower cost than stabilized bases. A wide variety of materials can be used as unstabilized bases, including crushed stone, sand-gravels, sands, and a variety of waste and byproducts. (FHWA 2017)

The above shows that TFI's road base is conservatively about twice as thick (i.e., 25 cm) as the FHWA's most common road base thickness (i.e., 10.2 to 15.2 cm [4 to 6 inches]). However, TFI's model ends the road base at the edge of the road cover, while the FHWA's road base extends 3 to 4 feet (91 to 122 cm) beyond the road cover. Increasing the road base's width from 1,500 cm to 1,744 cm would have the greatest impact on the RCW-RB_SS_Edge ground shine dose rate since the worker would now be exposed to 122 cm of the uncovered road base material. The increase in the road bases' surface area has a negligible impact on RESRAD's calculation of the area factor (see Eq 2-3) and thus the inhalation doses. However, the uncovered edges of the road base provide a source of airborne contamination for the two RCW-RB_SS scenarios. Additionally, the extended road bases would result in potentially direct, shine doses to the Nearest Resident and Road User scenarios. In TFI's risk assessment, both Nearest Resident and Road User were shielded by the road surface. Section 4.3 provides additional discussion of the potential impact of the extended PG road base on these two scenarios.

4.1.1 Exposure Time

TFI assumed that the Road Construction Worker (RCW) was exposed to PG material over a total of 5 years during his/her working career (TFI 2019, Appendix 2, p. ES-2). TFI also explained the RCW exposure interval is based on an assumed 25-year worker tenure[4] in road construction, of which only 5 years (20 percent) is spent in constructing roads with PG waste materials (TFI 2019, Appendix 2, p. 2-9). As apparent justification for a 5-year RCW exposure interval, TFI cites the Florida Department of Transportation's (FDOT's) largest highway construction project, the "I-4 Ultimate," a 7-year, 21-mile project (7 years × 0.7 = 5 years). However, no detail was provided on how many construction companies and subcontractors were involved in placement of subgrade materials or pavement. Road construction by smaller county and city governments may use fewer earthwork and pavement contractors or have smaller construction budgets than FDOT.

SC&A's review of the 2014 EPA Memorandum (EPA 2014, Attachment 1) confirmed that EPA recommended a 25-year career be assumed for an outdoor worker (ibid., p. 15). The source of this EPA default value is "EPA Human Health Evaluation Manual, Supplemental Guidance" (EPA 1991). EPA (1991) explains that outdoor worker exposure would consist of 8-hour days for 250 days/year, or 2,000 hours/year (ibid., p.9). SC&A notes that the 2014 EPA Memorandum provided three different worker exposure frequencies: 1) for a general worker, based on 8 hours/day × 250 days/year = 2,000 hours/year, 2) the same frequency for an indoor worker, and 3) for an outdoor worker,8 hours/day × 225 days/year = 1,800 hours/year. TFI assumed the RCW would be exposed to PG waste materials for 2,000 hours/year (TFI 2019, Appendix 2, p. 2-11), which is conservative.

SC&A's review of U.S. Bureau of Labor Statistics found that a 40-hour work week (or 2,000 hours/year) for RCW exposure is appropriate given recent U.S. government research, as found in Table 4-1, and concludes that 40 hours is a valid assumption for the a construction worker's average weekly hours working.

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[4] TFI reports the 25-year total RCW career tenure is based on a February 6, 2014, EPA Superfund Program Memorandum, OSWER Directive 9200.1-120.

Table 4-1 Average Weekly Hours for Construction Production and Nonsupervisory Employees

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2009	37.7	38.1	37.7	37.6	37.7	37.6	37.8	37.7	37.3	37.0	37.9	37.4
2010	37.8	37.3	37.7	39.0	38.1	38.3	38.2	38.6	38.5	38.9	38.8	38.8
2011	37.7	39.1	38.5	39.2	39.1	39.0	39.0	39.0	39.1	38.8	39.1	39.2
2012	39.2	39.3	39.2	39.2	39.1	39.1	39.1	39.0	39.2	39.3	39.1	39.5
2013	39.6	39.6	39.8	39.5	39.8	39.5	39.4	39.5	39.5	39.3	39.7	38.9
2014	39.0	38.5	39.8	39.4	39.5	39.5	39.8	39.7	39.8	39.7	39.6	39.8
2015	39.6	40.1	39.5	39.6	39.2	39.7	39.3	39.8	39.1	40.5	39.6	40.2
2016	39.8	40.0	39.4	39.7	39.4	39.6	39.7	39.4	39.5	39.7	39.8	39.4
2017	39.6	39.6	39.3	39.7	39.8	39.6	39.6	39.6	39.2	39.6	39.7	40.0
2018	39.7	39.8	40.0	40.0	40.3	39.9	40.1	39.8	39.6	39.4	39.3	39.9
2019	40.6	39.0	39.9	39.6	39.7	39.9	39.6	39.9	40.2	39.7(P)	39.5(P)	—
Average	39.1	39.1	39.2	39.3	39.2	39.2	39.2	39.3	39.2	39.3	39.3	39.3

P = preliminary
Source: BLS 2020

4.1.2 Ground Shine Dose Factors

Comparison to MicroShield

To check the RCW-RB_NC_Center ground shine calculation, SC&A developed a MicroShield® model that consisted of a rectangular source 10,000 cm long by 1,500 cm wide by 25 cm deep of 2.25 g/cm^3 concrete to represent the PG road base. The source term from Arcadis (2019, Table 2.3) was specified. The dose receptor location was specified as being in the middle of (i.e., 5,000 cm by 750 cm) and 1 m above (i.e., 125 cm above the axis) the road base. With this model, MicroShield® calculated a dose rate (with buildup) of 0.024 mR/hr. To convert its calculated air dose to an effective dose to humans, MicroShield® is provided with ICRP 74 conversion factor for six source-to-receptor relationships, including the source in front of the human (i.e., antero-posterior), the source to the left of the human (i.e., left lateral), and so forth, but not one with the source beneath the human. Nevertheless, using the ICRP 74 conversion factors, the effective dose ranges from 0.014 to 0.021 mrem/hr. Converting the hourly effective dose rate to an annual effective dose to the RCW by assuming an exposure time of 0.23 × 8766 hrs and the shielding factor of 0.7, the MicroShield® calculated RCW effective dose ranges from 19.6 to 29.9 mrem/yr, which is about 74 percent to 113 percent of TFI's RCW-RB_NC_Center calculated ground shine dose of 26.51 mrem/yr (see Table 2-5).

To check the RCW-RB_SS_Center ground shine calculation, SC&A modified the RCW-RB_NC_Center MicroShield® model by locating a 12-cm-thick layer of 2.25 g/cm^3 concrete above the PG road base to represent the road surface. The dose receptor location was again specified as being in the middle of and 1 m above (i.e., 137 cm above the axis) the road surface. With this model, MicroShield® calculated a dose rate (with buildup) of 0.0041 mR/hr. Using the ICRP 74 conversion factors, the effective dose ranges from 0.0024 to 0.0037 mrem/hr. Converting the hourly effective dose rate to an annual effective dose to the RCW by assuming an exposure time of 0.23 × 8766 hrs and the shielding factor of 0.7, the MicroShield®-calculated

RCW effective dose ranges from 3.4 to 5.2 mrem/yr, which is about 107 percent to 163 percent of TFI's RCW-RB_SS_Center calculated ground shine dose of 3.154 mrem/yr (Arcadis 2019, pdf p. 110).

Comparison to Federal Guidance Report 15 Dose Conversion Factors

Arcadis (2019, p. 3-5) states that "dose coefficients for external radiation that were used in RESRAD from ICRP 60 do not vary any age group." While SC&A agrees with that statement, we also point out that recently (August 2019) EPA published age-dependent external dose coefficients in Federal Guidance Report (FGR) 15, "External Exposure to Radionuclides in Air, Water and Soil" (EPA 2019). Table 4-2 shows how the dose to the adult would change if TFI's risk assessment had used the FGR 15 age-specific dose coefficients.

Table 4-2 Ground Shine Dose Calculated with Federal Guidance Report 15 Dose Conversion Factors

Nuclide	RESRAD Ground	FRG 15 - Adult - Infinite Depth		Ground Shine Dose (mrem/yr)	
	(mrem/yr) / (pCi/g)	(Sv/s) / (Bq/m^3)	(mrem/yr) / (pCi/g)	RESRAD Hand Calc.	FGR 15
At-218	4.878E-03	2.82E-21	5.27E-04	Included in Rn-222+D	
Bi-210	5.476E-03	6.88E-19	1.29E-01	1.190E-02	2.793E-01
Bi-214	9.325E+00	5.02E-17	9.38E+00	Included in Rn-222+D	
Pa-234	1.088E+01	4.44E-17	8.29E+00	Included in Th-234+D	
Pa-234m	9.867E-02	2.39E-18	4.46E-01	Included in Th-234+D	
Pb-210	1.981E-03	1.26E-20	2.35E-03	4.306E-03	5.116E-03
Pb-214	1.243E+00	6.97E-18	1.30E+00	Included in Rn-222+D	
Po-210	4.934E-05	3.00E-22	5.60E-05	1.072E-04	1.218E-04
Po-214	4.840E-04	2.56E-21	4.78E-04	Included in Rn-222+D	
Po-218	5.326E-05	1.21E-23	2.26E-06	Included in Rn-222+D	
Ra-226	2.915E-02	1.72E-19	3.21E-02	6.336E-02	6.983E-02
Rn-222	2.186E-03	1.13E-20	2.11E-03	Included in Rn-222+D	
Rn-222+D	1.069E+01	Not Given	1.08E+01	2.323E+01	2.348E+01
Th-230	1.071E-03	6.21E-21	1.16E-03	4.311E-04	4.669E-04
Th-234	2.130E-02	1.60E-19	2.99E-02	Included in Rn-222+D	
Th-234+D	1.374E-01	Not Given	4.90E-01	3.318E-02	1.182E-01
Tl-210	1.661E+01	9.27E-17	1.73E+01	Included in Rn-222+D	
U-234	3.439E-04	1.88E-21	3.51E-04	8.859E-05	9.046E-05
U-238	7.961E-05	9.20E-22	1.72E-04	1.923E-05	4.150E-05
Total	—	—	—	**23.34**	**23.95**

As Table 4-2 indicates, the use of the more recent FGR 15 adult external dose coefficients results in almost no change to the calculated annual dose.

4.1.3 Inhalation Rate

It is difficult to evaluate the assumed inhalation rates TFI used in Appendix 2, in part owing to a lack of detail in discussion of road base and pavement construction process, procedures, and equipment. Further, recent EPA guidance is available on average inhalation rates, based on gender and activity level (see "EPA Exposure Factors Handbook," Chapter 6 [EPA 2011b]), which indicates TFI's assumed inhalation rates may be artificially low.

As stated in TFI (2019, Appendix 2, p. 2-11):

> The RESRAD default inhalation rate of 8,400 cubic meters per year (m^3/yr) was used for the nearby resident receptor. A higher inhalation rate of 11,400 m^3/yr was assumed for road construction workers and utility workers. This value was the RESRAD version 6 default for industrial workers and assumes an hourly rate of 1.3 m^3/hr (…).

When 11,400 m^3/yr is multiplied by FOTD (on site), the result is the RCW annual inhalation rate of 2,622 m^3/yr. This value is about 9 percent larger than the worker inhalation rate used by the International Commission on Radiological Protection (ICRP 2002), see Table 4-3.

Table 4-3 ICRP Worker Inhalation Rate

Activity	Time	Breathing Rate		
	(hr/day)	(m^3/hr)	(m^3/day)	(m^3/yr)
Light exercise	5.5	1.5	8.25	2,062.5
Sitting	2.5	0.54	1.35	337.5
Overall	8	1.2	9.6	2,400

Source: ICRP 2002 (Supporting Guidance 3), Table A3

The EPA "Exposures Factors Handbook" (EFH) (EPA 2011b, Chapter 6 *Inhalation Rates*), Tables 6-1 and 6-28 suggest that the RESRAD inhalation rates may be artificially low. Table 4-4 presents the EPA inhalation rates for moderate and heavy activities, the RESRAD rate of 1.3 m^3/hr is 0.81 and 0.27 times the smallest (1.6 m^3/hr) and largest (4.8 m^3/hr) EFH worker inhalation rate, respectively.

Table 4-4 EPA Inhalation Rates by Gender and Activity Level (Summary)

Gender	Inhalation Rate, Moderate Activity (Table 6-28) (4)		
	m^3/hr (1)	m^3/day (2)	m^3/yr (3)
Adult, male	2.5	20	5,000
Adult, female	1.6	12.8	3,200
	Inhalation Rate, Heavy Activity (Table 6-28) (5)		
Adult, male	4.8	38.4	9,600
Adult, female	2.9	23.2	5,800
	Inhalation Rate, Adult, male and female combined (Table 6-1)		
Adult, average (6)	n/a	16.0	4,000

(1) Original EPA average values reported in EPA 2011b, Chapter 6
(2) Equivalent rate based on 8-hour workday
(3) Equivalent rate based on 250 workdays/year
(4) Includes heavy indoor cleanup, major indoor repairs and alterations, and climbing stairs
(5) Includes vigorous physical exercise and climbing stairs carrying a load
(6) EPA average value for males and females, combined, age groups 31 to <41 and 41 to <51 (i.e., maximum rates listed on EPA Table 6-1

When a contaminated area is covered with noncontaminated material, such as a road surface (in the two Road Construction Worker – Road Base with Surface Shield scenarios), RESRAD assumes that the contamination is uniformly distributed in a mixing layer of user-specified thickness. For these two scenarios, TFI used the RESRAD default depth of soil mixing of 0.15 meters coupled with the road surface depth of 0.25 meter, resulting in a depth factor of (1 - 0.12/0.15 =) 0.20 (ANL 2001, p. B-8). The RESRAD parameter distribution assignment document describes the depth factor as:

> The depth factor is the fraction of resuspendable soil particles at the ground surface that are contaminated. It is calculated by assuming that mixing of the soil with contamination will occur within the uppermost soil layer. The thickness of this layer is equal to the depth of the soil mixing layer.
>
> Mixing of the upper soil layer can occur through atmospheric (wind or precipitation/runoff) and mechanical disturbances. For a residential farmer scenario, the greatest affected depths, on a routine basis, result from mechanical disturbances. Such disturbances include use of farm equipment (e.g., plowing) and foot and vehicle traffic. On relatively undisturbed portions of the land, a mixing layer depth close to 0 is expected. (ANL 2000, Attachment C, Section 3.12)

It is believed that an asphalt or cement road surface would not mix with the road base material, and that a mixing depth of 0.0 m would be appropriate for the two Road Base with Surface Shield scenarios. However, TFI's use of a 0.15 m mixing depth is conservative (i.e., it tends to overestimate the inhalation and ingestion doses) and therefore, no change is necessary.

4.1.4 Soil Ingestion Rates

EPA research on soil ingestion rates can be found in OSWER Directive No. 9200.1-120 (EPA 2014) and have been reproduced in Table 4-5.

Table 4-5 OSWER Soil Ingestion Rates

Definition	Soil Ingestion Rate*	
	(mg/day)	(g/yr)*
TFI Road Construction Worker	330	82.5
TFI Nearest Resident	104.3	36.5
OSWER Directive No. 9200.1-120 (EPA 2014) Recommended Values		
Resident Child	200	70
Resident Adult	100	35
Indoor Worker	50	12.5
Outdoor Worker	100	25

* Based on 350 days/yr for the Resident and 250 days/yr for the Worker (EPA 2014)

More recent EPA research is available in the EPA "Exposure Factors Handbook," Chapter 5, *Soil and Dust Ingestion*, updated in September 2017 (EPA 2017). There, EPA summarizes multiple soil ingestion studies to arrive at daily ingestion rates for seven different age groups, each expressed in terms of a central tendency rate (mean) and a 95th percentile. Child ingestion rates are separated into six different age groups between ages < 6 months to <12 years. Overall, children exhibit higher central tendency ingestion rates of soil + dust ranging between 40 to 90 mg/day, with a 95th percentile ranging from 100–200 mg/day. The highest child ingestion rate central tendency was found for children ages 1 to <2 years to be 90 mg/day.

People 12 years and older, on average, ingest lesser amounts with a central tendency rate of 30 mg/day of soil + dust and a 95th percentile intake of 100 mg/day. Perhaps outdoor workers and road and building construction workers fall close to the 95^{th} percentile intake rate of 100 mg/day. The EPA recommended values for general population soil and dust ingestion rates are reproduced in Table 4-6. Note that the recent EPA 95^{th} percentile ingestion rate of 100 mg/day for ages 12 years thru adult (provided in Table 4-6) is equal to the Outdoor Worker rate found in the EPA (2014) research listed in Table 4-5.

Table 4-6 EPA Recommended Values for General Population Ingestion Rates (Summary)

Age Group	General Population Ingestion Rates (mg/day)					
	Soil + Dust		Soil		Dust	
	Central Tendency	Upper 95^{th} Percentile	Central Tendency	Upper 95^{th} Percentile	Central Tendency	Upper 95^{th} Percentile
<6 months	40	100	20	50	20	60
6 months to <1 yr	70 (60-80)	200	30	90	40	100
1 to < 2 yrs	90	200	40	90	50	100
2 to < 6 yrs	60	200	30	90	30	100
1 to 6 yrs	80 (60-100)	200	40	90	40	100
6 to <12 yrs	60	200	30	90	30	100
12 yrs thru adult	30 (4-50)	100	10	50	20	60

4.2 Resident Living Near Road

SC&A investigated the following statement on page 3-3 of TFI's risk assessment (Arcadis 2019, p 3-3):

> After construction, shielding of the PG amended road base is provided by the fill in the road shoulders and the concrete paving.
>
> Some inherent limitations with the MicroShield® code prevent the geometry of the shielding for this configuration to be calculated directly. Specifically, the shield and receptor heights must be the same, which is not the case here with a 25 cm shield and 100 cm receptor. However, estimates of the reduction in dose were determined. For the dose from the 25 cm edge of the road, a six-foot (2-meter) soil "road shoulder" was assumed and calculated using MicroShield®. This reduced the dose from this face by six orders of magnitude – essentially zero dose. The second face contributing to the dose is the road surface. The dose from the top face of the road is reduced by the concrete paving. A five- to six-inch (13 to 15 cm) concrete shield will reduce the surface dose by a factor if 3 to 4 (Schiager, 1974). Assuming linearity, the estimated dose using a reduction factor of 3.5 following construction of shoulder and placement of road surface over road base, …

The first problem with the above statement is that Arcadis (2019) refers to "Schiager, 1974" and that reference has not been documented. SC&A identified two possible journal articles that Arcadis (2019) could be referencing, namely:

> Schiager, Keith J., 1974, "Analysis of Radiation Exposures On or Near Uranium Mill Tailings Piles," Radiation Data and Reports, pp. 411–425, Vol 15, June 1974.

or

> Schiager, Keith J., 1974, "Reduction of Natural Radiation Intensity in a Large Storage Area," Health Physics, 27(5):433–445, November 1974.

Regardless of its source, the 3.5 dose reduction utilized by TFI was verified by SC&A with MicroShield®. Figure 4-2 shows the results of the MicroShield® run and shows that 12 cm would reduce the dose by about a factor of 5.8, or 57 percent more dose reduction than the 3.5 factor used by TFI. Therefore, TFI's assumption was shown to be conservative in the amount of shielding provided by the concrete shield.

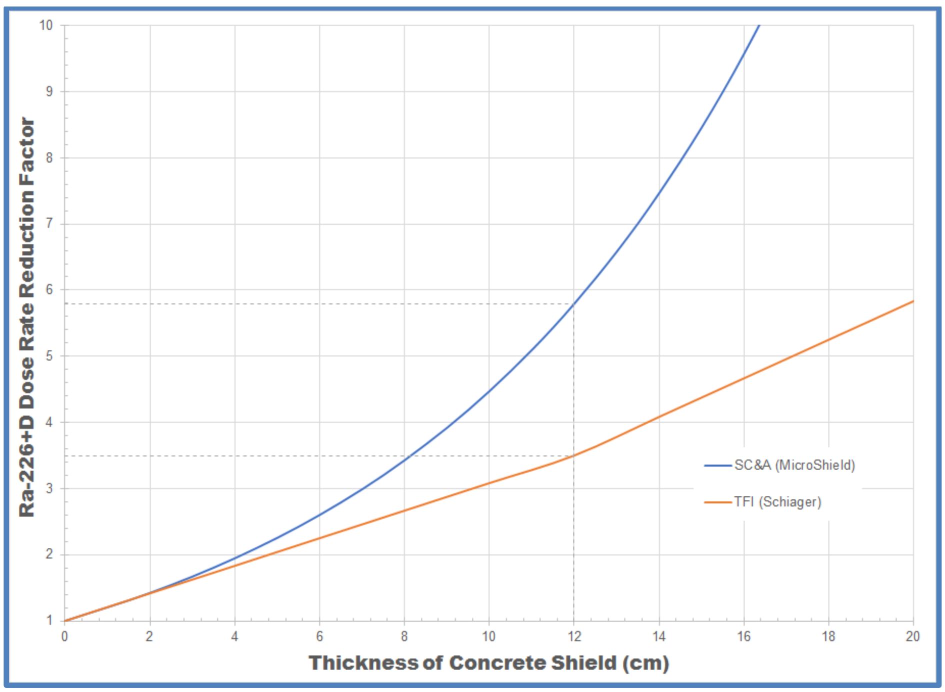

Figure 4-2 Comparison of Dose Reduction Factors

SC&A notes the scenario only assumes a PG contaminated road base (25 cm) with a 12 cm shield of uncontaminated concrete. Arcadis (2019, Section 2.1) identified the following three road construction uses for PG:

- PG in road base during construction with no surface material present.
- PG in road base (mixed with soil and compacted) and PG in the concrete paving on the road surface.

- Road base without PG and PG in the concrete paving on the road surface.

The Nearest Resident scenario that was analyzed by Arcadis (2019, Section 3.2.1), namely PG in the road base with uncontaminated paving, does not comply with any of the three identified uses of PG, i.e., 1) PG in road base (no cover), 2) PG in road base and in concrete paving, and 3) Road base without PG and PG in the concrete paving. Rather, TFI's risk assessment Section 3.2.1 model accounts for the shielding the road surface provides to the PG in the road base, but fails to account for the dose contribution from the unshielded PG in the road paving. To model this component, SC&A modeled a 12-cm-thick road surface with activities presented in Arcadis (2019, Table 2.4 [reproduced in the right two columns of Table 3-1]). No shielding was assumed from the road shoulder because it was assumed that the road surface and shoulder are flush. Elevated road shoulder would significantly shield locations 20 ft and 50 ft from the road. The MicroShield®-calculated dose rates are shown in Table 4-7.

Table 4-7 SC&A Calculated Does Rates from the PG Contaminated Road Surface

Location	Dose Rate (mR/hr)
1 m above road center	7.913E-4
20 ft from road	4.074E-5
50 ft from road	6.369E-6

Considering the analysis Arcadis (2019, Section 3.2.1) did perform, because the nearest Nearest Resident is assumed to be located 20 ft from the edge of the road, any gamma radiation leaving the road base would need to travel through significantly more than 12 cm of material. This is shown in Figure 4-3, which provides a schematic of the after construction, Nearest Resident exposure pathway (only the edge of the road nearest the resident is shown). Working out the geometry, gamma radiation leaving the road base would need to travel through about 74 cm of material. However, not all of the material would be cement road surface, as Figure 4-3 shows; some of the material would be the road's shoulder and may also include soil.

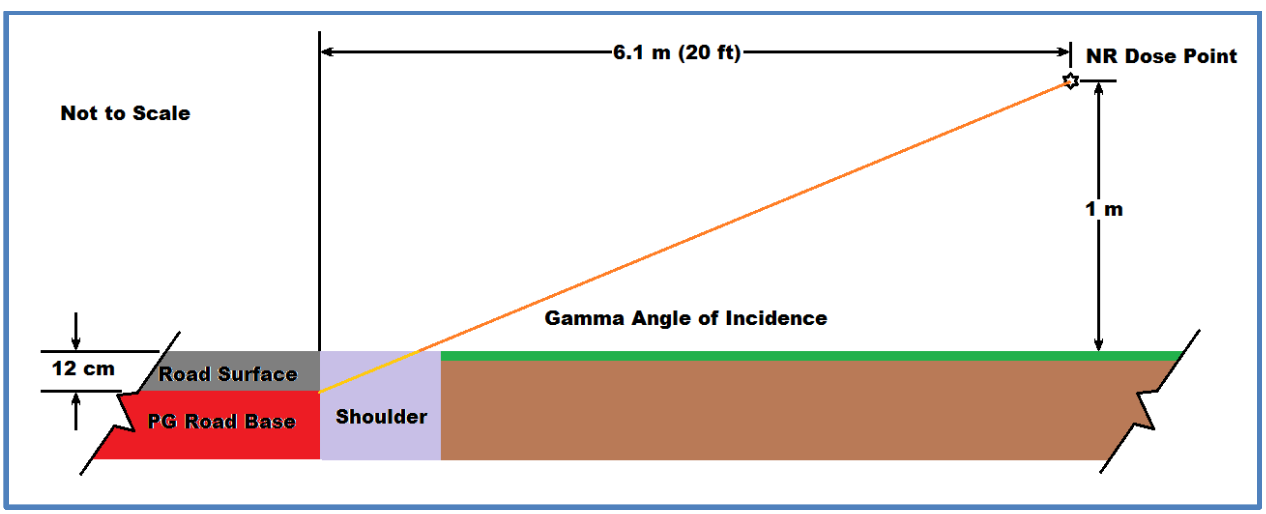

Figure 4-3 Schematic of the After Construction, Nearest Resident Exposure Pathway

Arcadis (2019, p. 3-3) states that "Some inherent limitations with the MicroShield® code prevent the geometry of the shielding for this configuration to be calculated directly. Specifically, the shield and receptor heights must be the same, which is not the case here with a 25 cm shield and 100 cm receptor." It is assumed that the 25 cm shield is referring to the road pavement, however, in Section 2.1, the road surface (i.e., pavement) is given as 12 cm, rather than 25 cm. Although we are not sure what the "25 cm shield" is referring to, SC&A does agree that MicroShield® cannot directly calculate the dose with the source-receptor geometry shown in Figure 4-3.

Using the concept of superposition, SC&A developed a model to estimate the direct exposure of the 20-foot Nearest Resident due to PG in the road base covered with a non-PG containing road surface. As shown conceptually in Figure 4-4, the dose model consists of two end-to-end elements: the 1,500 m wide road (shown on the left in Figure 4-4) and a pseudo road of varying widths from 0 to 700 cm. Each element has a non-PG containing surface (or shield) layer (shown in gray in Figure 4-3) and PG containing road base (or source) layer (shown in red in Figure 4-3). MicroShield® was first run to calculate the dose rate at the right edge of the combined road and pseudo road as it was varied from 1,500 cm to 2,200 cm (it was found that the dose rate did not change). Next, the dose rate at the edge of the pseudo road was calculated with MicroShield®, as its width was varied from 0 to 700 cm. Finally, the pseudo road dose rate was subtracted from the combined dose rate, resulting in the dose rate at various distances from the side of the road.

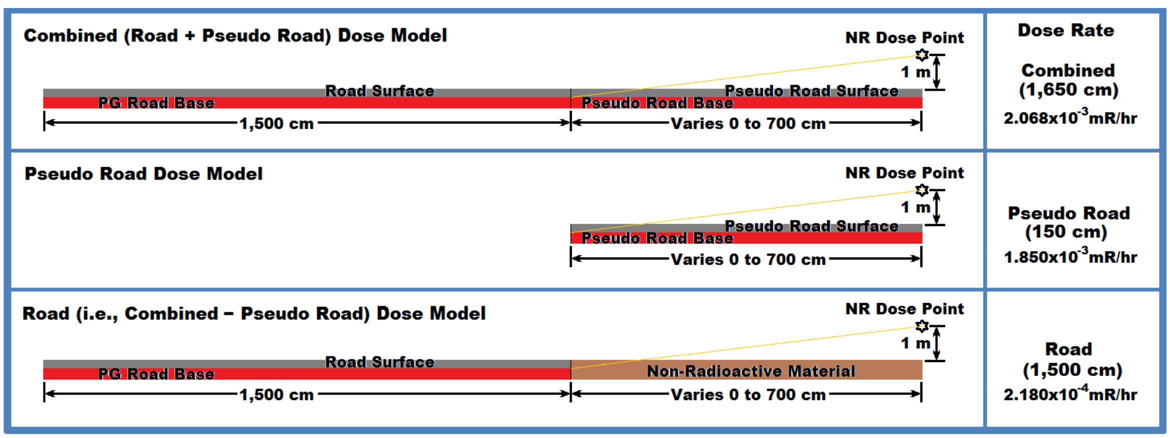

Figure 4-4 After Construction, Nearest Resident MicroShield® Dose Models

For example, when the pseudo road is 150 cm wide, the dose rate is first calculated using the combined road width of 1,650 cm as the source term, with the dose point on its edge. This is shown in the top portion of Figure 4-4. Then, a second MicroShield® run is made with a pseudo road width of 150 cm as the source term, with the dose point again on the edge. The middle portion of Figure 4-4 shows this. Subtracting the pseudo road dose rate (the second MicroShield® run) from the combined road dose rate (the first MicroShield® run) removes the contribution to the dose rate of the 150 cm of the road base nearest the dose point, leaving a 1,500 cm wide road base source term located 150 cm from the dose point, as shown by the bottom portion of Figure 4-4. The right portion of Figure 4-4 shows the MicroShield® calculated dose rates for the combined and pseudo road dose models (i.e., 2.068×10^{-3} and 1.850×10^{-3} mR/hr, respectively), and the resulting dose rate for the road dose model (i.e., 2.180×10^{-4} mR/hr).

A concern with this model is that MicroShield® requires the same material densities in the road and pseudo road. A density of 2.25 g/cm^3 is used for both the road surface and road base, as assumed by TFI, and would be appropriate for the radiation exiting the road surface but would under calculate the radiation that travels through the pseudo road. Alternatively, a density of 1.6 g/cm^3 is appropriate for radiation exiting the side of the road and traveling through the pseudo road but would over calculate radiation exiting the road surface. To address this concern, SC&A ran MicroShield® with both sets of densities. The results are shown in Figure 4-5.

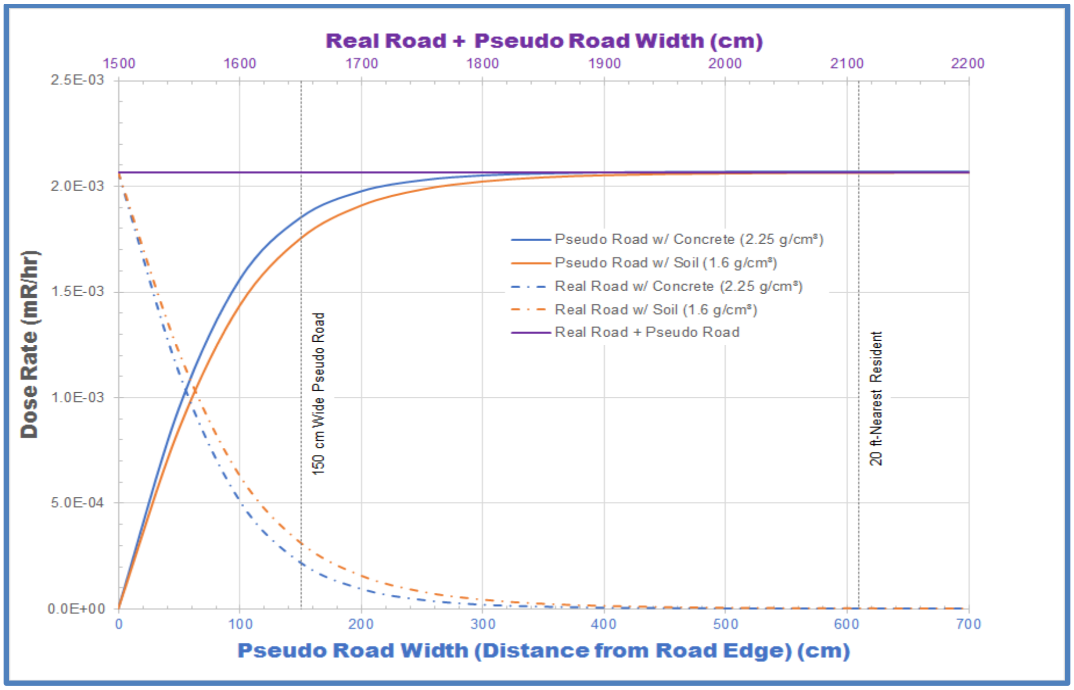

Figure 4-5 After Construction, Nearest Resident MicroShield® Model Results

The Figure 4-5 top axis shows the width of the combined real and pseudo roads, and the solid purple horizontal line shows that when the road width is over 1,500 cm, the dose rate does not vary with road width (i.e., a constant 0.0021 mR/hr). The solid blue line shows that as the concrete pseudo road gets wider (i.e., the dose receptor moves further from the side of the real road), the pseudo road dose rate increases until it approaches 0.0021 mR/hr at about 300 cm (the Figure 4-5 bottom axis). In other words, when the receptor is 300 cm, or more, from the edge of the concrete real road the real road dose approaches zero. This is shown by the dashed blue line in Figure 4-5. The orange lines in Figure 4-5 are similar to the blue lines, except they represent soil, rather than concrete, roads.

As Figure 4-5 shows, the dose rate from the covered PG road base decreases rapidly with distance away from the side of the road, regardless of which material density is assumed. The two vertical dotted line in Figure 4-5 can be used to locate the calculated dose rates with a 150 cm wide pseudo road, as used in the above example, and at the 20-foot Nearest Resident. Rather than the reduction factor of 3.5 utilized in Section 3.2.1 of TFI's risk assessment, Figure 4-5 shows a dose rate reduction of more than three orders of magnitude for an urban Nearest Resident living 20 feet from the side of the road, i.e., the dose rate from the real road is negligible. The reduction would be greater for a suburban Nearest Resident living 50 feet from the side of the road. Thus, although SC&A does not agree with the Nearest Resident doses presented in Arcadis (2019, Section 3.2.1), the doses are conservative.

A final observation on the Nearest Resident dose, Arcadis (2019, p. 3-5) states: "dose coefficients for external radiation that were used in RESRAD from ICRP 60 do not vary any age group." SC&A concurs with this statement, but also points out that EPA has recently published age-specific external dose coefficients (EPA 2019) that could/should have been utilized in TFI's risk assessment.

4.3 Road Users – Motorist/Bicyclist

Usage Factor

TFI assumed two scenarios for road users: a driver of a car and a bicyclist. For both scenarios, no shielding was assumed to protect the operator other than air. Drivers are assumed to spend 500 hours per year driving/cycling on the road annually, which is equivalent to roughly 82 minutes per day or 6 percent of a year. Figure 4-6 compares this value to the EPA "Exposure Factors Handbook" (EPA 2011b, Table 16-24), it is apparent that this value represents approximately the 60th percentile of hours an American drives in a given day.

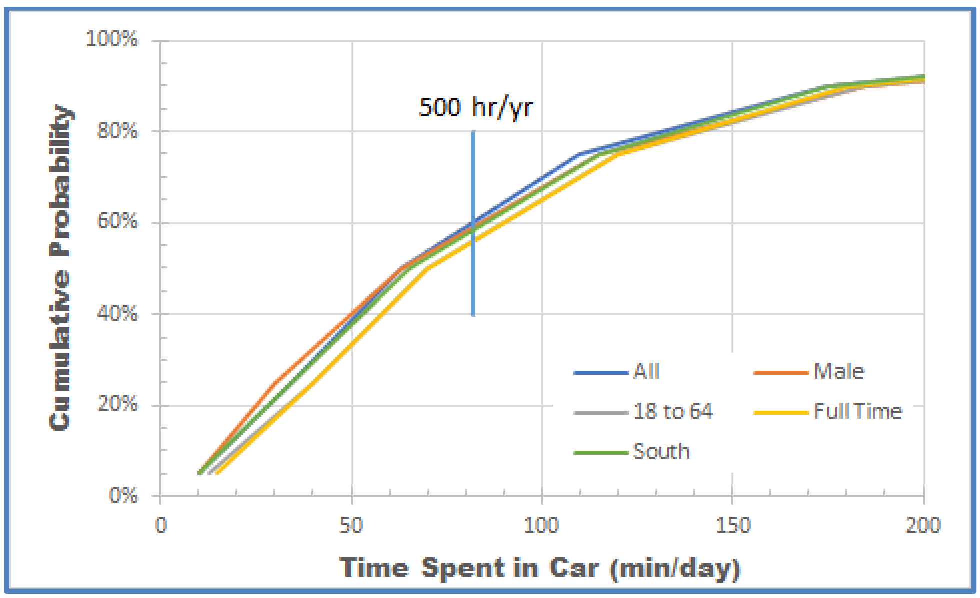

Figure 4-6 Exposure Factors Handbook (EPA 2011b) Time Spent in Car

The EFH categorizes its data by sex, age, race, employment status, education, census region, day of week, and season—about 50 categories in total. For clarity only five EFH categories are shown in Figure 4-6, and for those five categories the data range is small. On the other hand, the AAA Foundation for Traffic Safety found that "[d]rivers spent an average of 51 minutes driving per day in 2016-2017" (FTS 2019), which is about the 40th percentile of the EFH data and much smaller than the 500 hr/yr used by TFI.

Likewise, Figure 4-7 shows the time spent traveling on a bicycle/skate board/roller-skate from EPA (2011b, Table 16-26). For this comparison SC&A assumed that all of the time specified in EPA (2011b), Table 16-26 was spent on a bicycle.

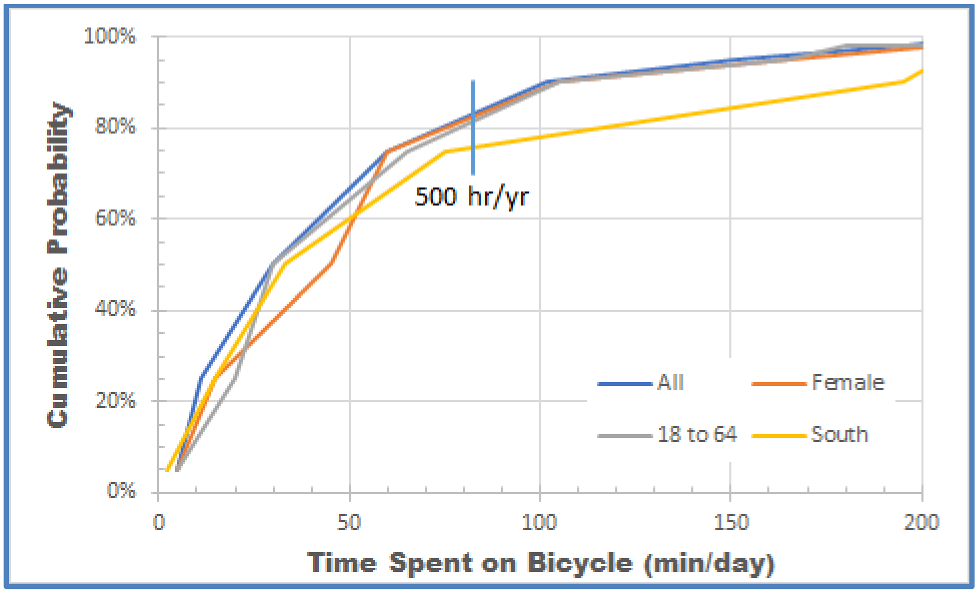

Figure 4-7 Exposure Factors Handbook (EPA 2011b) Time Spent on Bicycle

As for the car driver, the EFH categorizes its bicycle user data by about 50 categories. For clarity only four EFH categories are shown in Figure 4-7, and for those four categories the data range is small, although larger than for the car driver. Thus, SC&A has concluded that TFI's use of 500 hours per year spent driving and/or bicycling on the road is acceptable for a nonoccupational driver.

Include Dose Rate Due to Phosphogypsum in Paving

TFI's risk assessment for the Motorist/Bicyclist assigns the average road user a dose of 1.1 mrem per year. As a means of verifying the calculations performed by TFI, SC&A modeled a Motorist/Bicyclist in the center of the road, assuming a height of 1 m above the road in MicroShield®. Consistent with the scenarios described in Arcadis (2019, Section 2.1 [see p. 23, above]), this model had two dose components: 1) road base shielded by the road surface and 2) the road paving with no shielding. Each component was modeled individually and summed to represent the total dose rate. Table 4-8 shows the results of this modeling.

Table 4-8 SC&A Calculated Dose Rates and Dose to the Motorist/Bicyclist

Dose Component	Dose Rate (mrem/hr)	Annual Dose* (mrem)	26-Year Dose (mrem)
Road Base, shielded by Paving	4.136E-3	2.068	53.768
Paving	7.913E-4	0.395	10.27
Total	4.926E-3	2.463	64.038

* Assuming 500 hours per year on the road.

SC&A calculates an annual dose to the road user from external factors of more than double TFI's calculated dose. Although the modeled dose is larger, it still provides a very modest dose to the average road user.

Include Dose Rate Due to Phosphogypsum in Shoulder

Section 4.1 describes that roads usually include a 3 or 4 foot wide shoulder, that was not included in TFI's analysis. If a 4 foot wide shoulder is composed of PG with the same radionuclide concentration as shown in Table 3-1 for road base material, then the dose rate at various locations on the shoulder and road are shown in Figure 4-8.

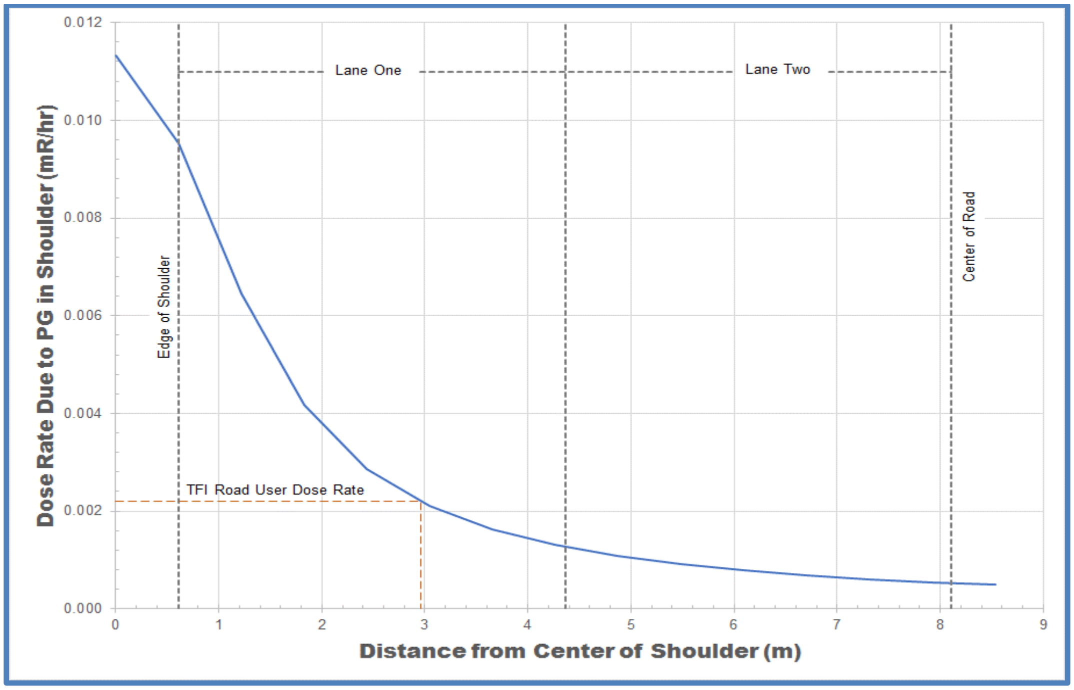

Figure 4-8 Dose Rate Due to Phosphogypsum in Shoulder

Arcadis 2019, Section 3.3.1 gives the Road User dose is given as 1.1 mrem/yr, with a usage factor of 500 hr/yr (Arcadis 2019, p. 2-11), the dose rate is 0.0022 mrem/hr. Figure 4-8 shows that a passenger riding in a car in Lane One or a bicyclist riding near or on the shoulder would receive a dose from the PG in the shoulder that is three to five times greater than the dose reported in Arcadis 2019. Even with a factor of five increase, the risk would be 3.3E-6 per year, or 3.3 in a million per year, well within the 3 in 10,000 criteria for any reasonable exposure period.

Occupational Drivers

This scenario fails to address motorists that drive/cycle as part of their occupation, such as delivery drivers and taxi drivers. These drivers are believed to be on the road 8 to 12 hours a workday in addition to their normal transportation needs. Section 5.2 provides an evaluation of the dose received by an occupational driver.

4.4 Utility Trench Worker

TFI assumed that the Utility Worker spent 160 hr/yr within the contaminated trench (Arcadis 2019, Section 2.4.2), or approximately 8 percent of a 2,000-hour work-year. If a Utility Worker's only job involved trench work and all those trenches were in roads with PG bases, then his/her annual dose would increase by a factor of 12.5.

4.5 Truck Driver

During construction of the Polk County Experimental Road, "3" of phosphogypsum … was spread on the road and mixed with a pulvimixer to a depth of approximately 12" of loose mixture. This is the procedure that would have been used with clay as a subgrade stabilizer. The mixture was then compacted …" (UM 1989, p. 27). While during construction of the Columbia County Experimental Road, "[t]ruck loads of dihydrate phosphogypsum … were hauled to the site in November 1986 and spread to an average depth of 5 inches. It was mixed into the existing soil (A-3 fine sand according to ASSHTO classification) with a rotomixer to a depth of about 14 inches. A total of three passes of the rotomixer was made to achieve uniform blending of the mixture" (UM 1989, p. 29). The scenario described in Arcadis (2019, Section 3.1.1) for the Truck Driver is similar to these two actual cases.

SC&A reviewed TFI's risk assessment Truck Driver scenario and has no comments at this time.

4.6 Reclaimer

One of the key assumptions for the Reclaimer Exposure scenario identified in TFI's risk assessment, Section 3.4.1 is:

> Site grading for construction will almost certainly reduce the thickness of the layer containing PG; however, for present purposes, we have assumed that site preparation will reduce the PG layer to about 10 centimeters (cm) in thickness and the concentration of Ra-226 in the remaining layer to about 10 pCi/g.

No justification is given for either of the values provided. At least TFI's risk assessment describes "site grading" as a plausible means for reducing the PG layer thickness, although there is no justification for selecting 10 cm as the final thickness, as opposed to 15 cm or 20 cm. TFI's risk assessment does not describe any means for achieving the reduction of the Ra-226 concentration, much less justification for using 10 pCi/g. For these reasons, SC&A will utilize a PG layer thickness of 25 cm and a Ra-226 concentration of 27 pCi/g in our confirmatory calculations.

U.S. Nuclear Regulatory Commission's (NRC's) Regulatory Guide (RG) 3.64 (NRC 1989, Equation 9) can be used to calculate the radon flux at the surface from the decay of Ra-226 within a tailings pile. The terms presented in RG 3.64, Equation 9 have been converted to reflect a road base, rather than a tailings pile, as shown in Eq 4-1:

$$J_b = 10^4 R_b \, \rho_b \, E_b \sqrt{\lambda \, D_b} \; \tanh\left(x_b \sqrt{\lambda / D_b}\right) \qquad \text{Eq 4-1}$$

Where:
J_b = Radon-222 flux on the road base surface (pCi m^{-2} s^{-1})
10^4 = Units conversion (cm^2 m^{-2})
R_b = Radium-226 concentration in the road base (pCi g^{-1})
= 13.5 — (Arcadis 2019, Table 2.3)
ρ_b = Road base bulk density (g cm^{-3})
= 2.25 (g cm^{-3}) — (Arcadis 2019, Section 2.4.1)
E_b = Radon emanation factor of the road base (dimensionless)
= 0.13 — (ANL 2015, Tables 4.2.2 and 4.2.4)
λ = Radon decay constant (s^{-1})
= 2.1×10^{-6} (s^{-1})
D_b = Road base radon diffusion coefficient (cm^2 s^{-1})
= 0.02 — (ANL 2000, Table 2.1 [contamination])
x_b = Thickness of the road base (cm)
= 25 cm — (Arcadis 2019, Section 2.1)

As Eq 4-1 shows, the radon flux is directly proportional to the emanation coefficient and the square root of the diffusion coefficient. Arcadis (2019) obtained values for the emanation factor from Rogers et al. (1994) and for the diffusion coefficient from Chauhan and Kumar (2015). The concern with both of these values is that they were derived from intact concrete and may not be representative of crushed, compacted PG of the road base.

For the emanation factor, ANL (2000, Table 2.1) gives a default Rn-222 emanation factor of 0.25, while ANL (2015, Table 4.2.2) provides an emanation factor of 0.13 for rocks and the same 0.13 factor in Table 4.2.4 for phosphate (a PG-specific emanation factor is not provided), and NRC (1989), the source for Eq 4-1, states that the "reference value of the radon emanation coefficient used by the NRC staff is 0.35 for all materials." In their 1992 risk assessment, EPA used an emanation factor of 0.3 (EPA 1992, Table 4-5). For the verification analysis, SC&A has chosen to utilize a radon emanation factor from ANL (2015) of 0.13.

For the radon diffusion coefficient, ANL (2000, Table 2.1) gives a RESRAD default value of 0.02 cm^2/s for the contamination layer, while diffusion coefficients for some materials are provided in ANL (2015, Table 4.1.1), including 0.025 to 0.032 cm^2/s for compacted, unconsolidated soil, 0.01 to 0.04 cm^2/s for gypsum, and 0.00012 to 0.0052 cm^2/s for concrete. For the verification analysis, SC&A has chosen to utilize the RESRAD contamination zone diffusion coefficient of 0.02 cm^2/s from ANL (2000) as the road base radon diffusion coefficient.

The results of SC&A's Eq 4-1 road base surface calculation are provided in Figure 4-9. Two sets of results are provided: the first with the road base's Ra-226 concentration of 13.5 pCi/g from Table 3-1 and the second with a 1 pCi/g Ra-226 concentration for comparison to Arcadis (2019, Figure 3.2). Arcadis (2019, p. 3-9) reported a *radon flux through the surface of a PG amended soil layer ... would be about 0.25 pCi/m^2-s*, while Figure 4-9 shows this flux to be about 2 pCi/m^2-s.

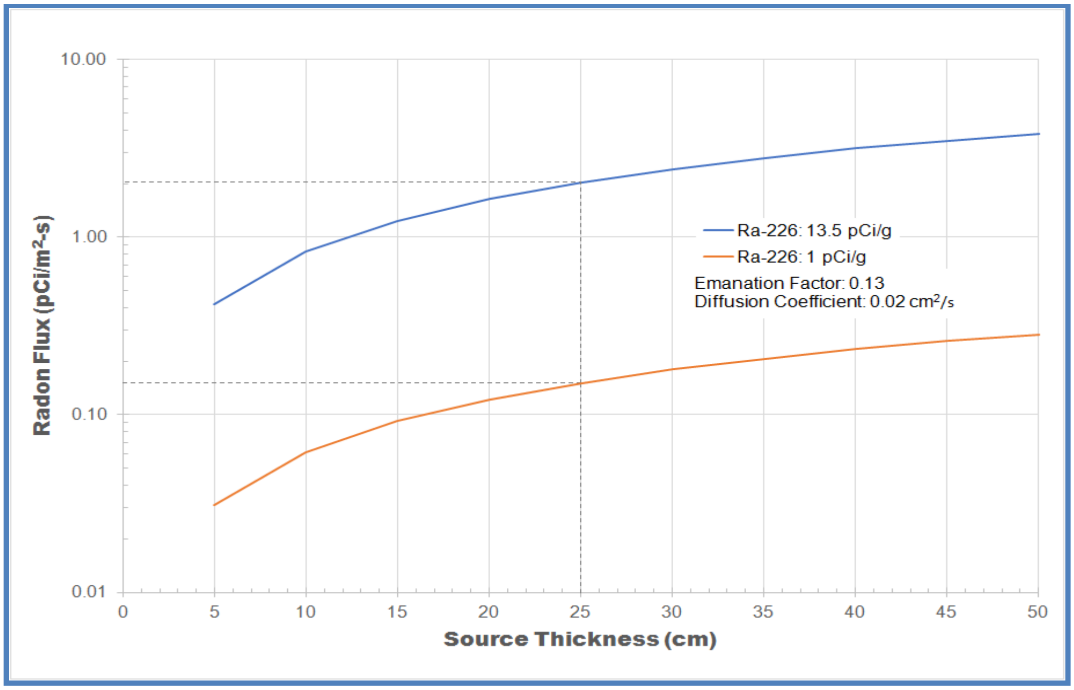

Figure 4-9 SC&A Calculated Effect of Source Thickness on Radon Surface Flux

NRC's Regulatory Guide 3.64 (NRC 1989: Equation 12) can be used to calculate the radon flux from the decay of Ra-226 above the surface of a cover over a tailings pile. The terms presented in NRC (1989, Equation 12) have been converted to reflect a road base, rather than a tailings pile, as shown in Eq 4-2:

$$J_f = \frac{2\, J_b\, e^{(-b_f\, x_f)}}{1 + \sqrt{a_b/a_f}\, \tanh(b_b\, x_b) + \left[1 - \sqrt{a_b/a_f}\, \tanh(b_b\, x_b)\right] e^{(-2 b_f x_f)}} \qquad \text{Eq 4-2}$$

Where: J_f = Radon-222 flux on the foundation surface (pCi m^{-2} s^{-1})

J_b = Radon-222 flux on the road base surface, see Eq 4-1 (pCi m^{-2} s^{-1})

$$b_f = \sqrt{\lambda/D_f} \qquad \text{Eq 4-3}$$

x_f = Thickness of the foundation (cm)

= 10 cm — Arcadis (2019, Section 3.4.1)

$$a_b = n_b^2\, D_b\, [1 - (1-k)\, m_b]^2 \qquad \text{Eq 4-4}$$

n_b = Porosity of the road base

= 0.4 — ANL (2000: Table 2.1 [contamination])

D_b = Road base radon diffusion coefficient (cm^2 s^{-1})

= 0.02 — ANL (2000, Table 2.1 [contamination])

k = Equilibrium distribution coefficient

= 0.26 — ANL (2000, Table 2.1)

m_b = Road base moisture saturation fraction

= 0.05 — ANL (2000, Table 2.1 [contamination])

a_f = $n_f^2 \, D_f \left[1 - (1-k)\, m_f\right]^2$ Eq 4-5
n_f = Porosity of the foundation
= 0.1 — ANL (2000, Table 2.1)
D_f = Foundation radon diffusion coefficient ($cm^2 \, s^{-1}$)
= 0.003 — ANL (2000, Table 2.1)
m_f = Foundation moisture saturation fraction
= 0.03 — ANL (2000, Table 2.1)
b_b = $\sqrt{\lambda / D_b}$ Eq 4-6
x_b = Thickness of the road base (cm)
= 25 cm — Arcadis (2019, Section 2.1)

In the spreadsheet that accompanied Arcadis (2019), the Eq 4-2 term $\sqrt{a_b / a_f}$ was not included, which essentially means that it was set equal to 1.0. For this to be true, the porosity, radon diffusion coefficient, and moisture content of the road base must be equal to the porosity, radon diffusion coefficient, and moisture content of the foundation. As shown above, based on data from ANL (2000), SC&A does not believe that to be the case. Additionally, the spreadsheet incorrectly evaluated Eq 4-2 (i.e., instead of multiplying the entire square bracket term by the exponential, cells 'Diffi Co 2 unit conc (2)'!F46:F55 only multiply the hyperbolic tangent portion of the term by the exponential).

Arcadis (2019) used a radon diffusion coefficient for the foundation of 4×10^{-4} cm^2/s, which is from Chauhan and Kumar (2015) for intact concrete. The RESRAD default radon diffusion coefficient is 0.003 cm^2/s for the reason described below.

> The 3.0×10^{-7} m^2/s default radon diffusion coefficient for the concrete slab is a conservative value compared with the value of 6.0×10^{-9} m^2/s used by the U.S. Nuclear Regulatory Commission (…). It is used to account for possible cracks and other penetrations that may develop in the foundation as the house ages. (ANL 2001, p. C-12)

SC&A believes that the RESRAD default radon diffusion coefficient for foundations should be used.

The results of SC&A’s Eq 4-2 radon flux through a concrete foundation calculation are provided in Figure 4-10. Arcadis (2019, p. 3-8) stated that “Radon flux is reduced due to a 6-millimeter (mm) poly layer as a moisture barrier currently common in building codes. Such a layer would be expected to reduce the radon flux by at least a factor of 10 (Kitto and Perazzo, 2010).” SC&A obtained a copy of Kitto and Perazzo (2010), confirmed the factor of 10 reduction, and included that reduction in the radon fluxes presented in Figure 4-10. Arcadis (2019, p. 3-9) reported the “radon flux into the home is 0.009 pCi/m^2-s,” while Figure 4-10 shows this flux to be about 0.12 pCi/m^2-s.

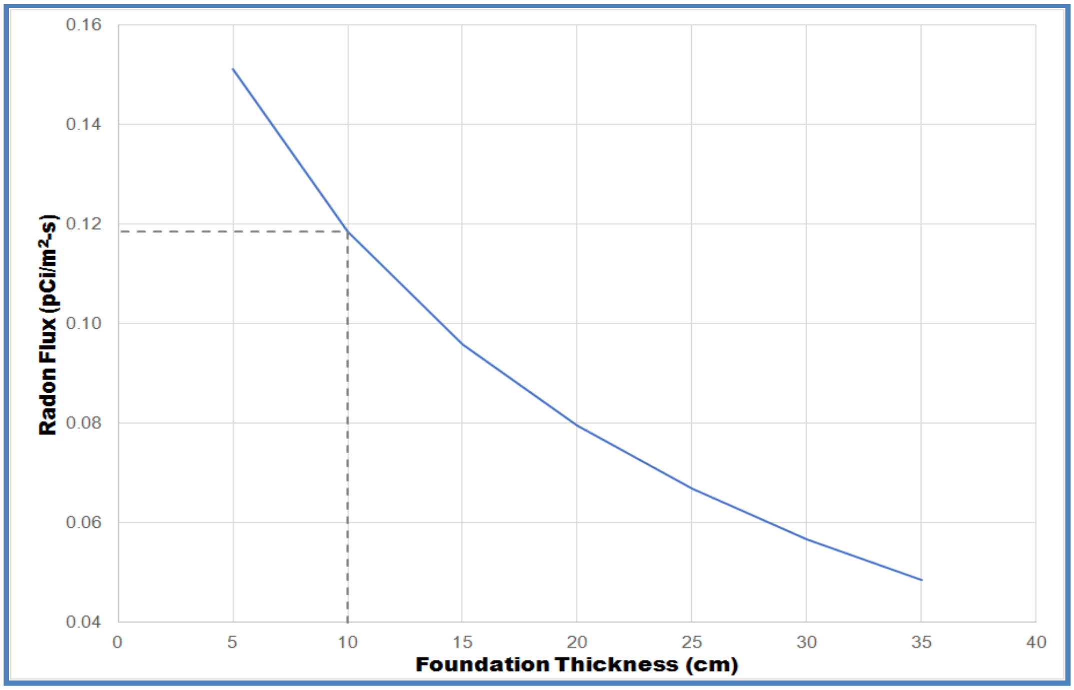

Figure 4-10 SC&A Calculated Radon Flux Through the Foundation with a 6-mm Poly Vapour Barrier

For the buildup of radon and its progeny inside of a house or other building, ANL 2001 provides Equation C.12 for radon and Equation C.21 for radon progeny, which have been reproduced below as Eq 4-7 and Eq 4-8, respectively. The equation used to calculate the radon buildup in the home for TFI's risk assessment is missing from Arcadis (2019, Section 3.4.1) but is provided in cell 'Diffi Co 2 unit conc (2)'!C79 of TFI's provided supporting spreadsheet, and is equivalent to Eq 4-7. Rather than use Eq 4-8 or its equivalent to calculate the buildup of radon daughter products within the home, TFI's risk assumed (without providing any justification) "an equilibrium factor of 0.4."

$$C_{i_{(n)}} = \frac{\left(\frac{J_f\, F_{ai}}{H_i} + vC_{o_{(n)}}\right)}{(\lambda_n + v)}, n = 1 \quad \text{Eq 4-7}$$

$$C_{i_{(n)}} = \frac{\lambda_n C_{i_{(n-1)}} + vC_{o_{(n)}}}{(\lambda_n + v)}, n = 2, 3, 4 \quad \text{Eq 4-8}$$

Where:
- $C_{i_{(n)}}$ = n^{th} radon/progeny indoor concentration (pCi/m^3)
- n = 1, 2, 3, and 4 represent Rn-222, Po-218, Pb-214, and Bi-214, respectively
- $C_{o_{(n)}}$ = n^{th} radon/progeny outdoor concentration (pCi/m^3)
  = 0.0 (pCi/m^3) — assumed
- J_f = Radon-222 flux on the foundation surface, see Eq 4-2 (pCi m^{-2} s^{-1})
- H_i = Building height (m)
  = 2.5 m — Arcadis (2019, p. 3-10) V/A = 250 m^3/100 m^2

F_{ai} = Indoor area factor (dimensionless)
= 1 — assumed, conservative
λ_n = n^{th} nuclide decay constant, see Table 4-9 (s^{-1})
v = Ventilation rate of the house (s^{-1})
= 1/3600 (s^{-1}) = 1 (hr^{-1}) (ANL 2001, Table C-1)

For this analysis, SC&A has assumed that the outdoor radon and its progeny concentrations (i.e., $C_{o_{(n)}}$) are zero.

For radon and its progeny, the inhalation dose factors were obtained from Kendall and Smith (2002), as shown in Table 4-9.

Table 4-9 Radon and Progeny Inhalation Dose Factors

Nuclide	Half-life	Decay Constant (s^{-1})	Type of Decay	Dose Factor	
				Sv/Bq[1]	mrem/pCi
Rn-222	3.8 day	2.1E-06	α	1.9E-10	7.1E-07
Po-218	3.1 min	3.7E-03	α	3.3E-09	1.2E-05
Pb-214	27 min	4.3E-04	β	1.6E-08	5.9E-05
Bi-214	20 min	5.8E-04	β	1.4E-08	5.2E-05
Po-214	164 μsec	Not Used	α	Not Used	Not Used

[1] Source: Kendall and Smith (2002, Table 2)

Regarding Rn-222's fourth short-lived decay product, Po-214, Kendall and Smith (2002) states the following:

> … the immediate decay product of ^{214}Bi, ^{214}Po, gives negligible doses because of its very short half-life and intakes of this nuclide in its own right can be ignored. Ingrowth of ^{214}Po from ^{214}Bi (i.e. ^{214}Po produced by decay of ^{214}Bi in the body) is, of course, considered in the calculated dose coefficients. (Kendall and Smith 2002, p. 392)

Once the indoor concentrations have been calculated, the inhalation dose to the reclaimer is calculated by multiplying the concentration by the breathing rate, then by the time spent indoors, and finally by the Table 4-9 dose factors. The Arcadis (2019) Working Level Month (WLM) methodology does not require a breathing rate, so SC&A used the Nearest Resident value of 8,400 m^3/yr. Arcadis (2019, p. 3-11) states that the reclaimer spent *6000 hours per year of time indoors*, however, 'Diffi Co 2 unit conc (2)'!C81 of TFI's provided supporting spreadsheet shows that the WLM was calculated by assuming (0.5 × 24 hrs/day × 200 days/yr =) 2,400 hrs/yr. Based on ICRP Report 65, SC&A chose to use 7,000 hrs/yr.

The results of SC&A's radon buildup in the home and reclaimer inhalation dose calculations are provided in Table 4-10. Arcadis (2019, p. 3-11) gives the home Rn-222 concentration as 0.013 pCi/L (13 pCi/m^3), while Table 4-10 gives the concentration as 169 pCi/m^3. Almost all of the difference in the home Rn-222 concentration is due to the difference in the calculated radon flux through the foundation. Arcadis (2019, p. 3-11) goes on to give the reclaimer's inhalation dose as 1.8 mrem/yr, while Table 4-10 gives the reclaimer's dose as 63.3 mrem/yr. This difference in the reclaimer's inhalation dose is the result of differences in the calculated foundation radon fluxes, assumed inhalation rates, and assumed radon daughter equilibrium factors.

Table 4-10 SC&A Calculated Home Radon Concentration and Annual Reclaimer Inhalation Dose

Nuclide	Concentration (pCi/m^3)		Percentage Equilibrium with Rn-222	Dose (mrem/yr)	
	$1\ pCi/m^2$-s	10 cm Cover ($0.12\ pCi/m^2$-s)		$1\ pCi/m^2$-s	10 cm Cover ($0.12\ pCi/m^2$-s)
Rn-222	1.43E+03	1.69E+02	100%	6.81E+00	8.06E-01
Po-218	1.33E+03	1.58E+02	93%	1.07E+02	1.27E+01
Pb-214	8.06E+02	9.55E+01	56%	3.19E+02	3.78E+01
Bi-214	5.45E+02	6.45E+01	38%	1.90E+02	2.25E+01
Total	—	—	—	6.23E+02	7.38E+01

Recent studies have shown that sewer pipes can become a conduit for bring sewer gas, volatile organic compounds, and radon into a building (McHugh, et al 2017, Pennell, et al 2013, Reichman, et al 2017). Additionally, home inspectors have found that if they perform a radon test too soon after performing a sewer inspection, they will observe unusually high radon levels (EcoTech 2015). Thus, when the sewer pipe is opened (e.g., a toilet is removed, sewer cleanout is performed) or if there is something wrong with the plumbing (e.g., a dry trap, a damaged trap, a damaged drain line, a faulty fixture seal, a damaged or plugged vent), radon can enter the home's indoor air. If one or more of these conditions existed, sewer gas would also leak into the home, the sewer gas odor would be detected (i.e., a rotten egg smell), and the condition fixed. Of course, leaks could occur that result in sewer gas concentrations below the human odor threshold, but these leaks would also likely result in low radon concentrations. Therefore, it is concluded that for this risk assessment this potential radon exposure pathway does not need to be evaluated.

In addition to the radon inhalation dose, TFI's risk assessment presented the dose to the reclaimer due to ground shine through the foundation. Arcadis (2019) used RESRAD, rather than MicroShield®, to calculate this shine dose. A foundation thickness of 20 cm (Arcadis 2019, pdf p. 229) was specified in the RESRAD input, rather than the 10 cm specified in Arcadis (2019, p. 3-9)—it looks like they may have taken credit for a 10 cm granular fill layer that is shown in Arcadis (2019, Figure 3.1) but is not otherwise discussed. No other reclaimer exposure pathways were analyzed, e.g., ground shin from time spent in the yard, inhalation and soil ingestion from working in the garden, consumption of vegetables grown in the garden, consuming water from an onsite well. For example, in addition to radon diffusing through the floor slab, EPA (1992) evaluated both of these latter two pathways as potentially contributing to the reclaimer's dose:

> 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. (EPA 1992, p. 4-10)

5.0 POTENTIAL EXPOSURE PATHWAYS NOT ANALYZED BY TFI

In this section, SC&A analyzes four potential exposure pathways that were not analyzed in TFI's risk assessment, namely: 1) Phosphogypsum Stacks – Backhoe Operator, 2) Road Users – Occupational Drivers, 3) Groundwater, and 4) Ingestion of Crayfish.

Dose to Risk Factor

The most significant health risk that results from radiation exposure is cancer fatality or more often referred to as "latent" cancer fatality (LCF) because it may take many years for the cancer to develop and for death to occur. In 2002, the Interagency Steering Committee on Radiation Standards (ISCORS) recommended that federal agencies use conversion factors of 0.0006 fatal cancer per rem for mortality and 0.0008 cancer per rem for morbidity when making qualitative or semi-quantitative estimates of risk from radiation exposure to members of the general public (ISCORS 2002). Publications by the EPA, the Biological Effects of Ionizing Radiation (BEIR) Committee, and the ICRP support the continued use of the ISCORS-recommended risk values.

In 2011, the EPA provided the cancer mortality dose-to-risk coefficients for different ages at exposure for males and females from uniform whole body exposure shown in Table 5-1. EPA (2011a) presented the risk coefficients in inverse units of absorbed dose or gray (i.e., energy deposited per unit of matter [joules per kilogram]), but for this report, the absorbed dose has been converted to a dose to humans in inverse units of rem. Although the EPA (2011a) data shown in Table 5-1 are for low linear energy transfer (LET) radiation (i.e., beta particles and gamma rays emitted by radionuclides such as cesium-137, strontium-90, and tritium), once the conversion to a dose to humans has been made, the risk coefficients are also applicable to high-LET radiation (i.e., alpha particles emitted by radionuclides such as Ra-226 and U-238). The Table 5-1 age-dependent dose-to-risk coefficients encompass the ISCORS-recommended 0.0006 cancer fatalities per rem.

Table 5-1 Additional Cancer Mortality Total Dose-to-Risk Coefficients

Sex	Age at Exposure										
	0	5	10	15	20	30	40	50	60	70	80
	Cancer Mortality Risk (per 10,000 person-Gy)[a]										
Male	1,170	912	758	638	542	396	390	375	339	272	170
Female	2,060	1,590	1,290	1,060	878	601	547	496	429	331	203
	Cancer Mortality Risk (per person-rem)										
Male	1.2×10^{-3}	9.1×10^{-4}	7.6×10^{-4}	6.4×10^{-4}	5.4×10^{-4}	4.0×10^{-4}	3.9×10^{-4}	3.8×10^{-4}	3.4×10^{-4}	2.7×10^{-4}	1.7×10^{-4}
Female	2.1×10^{-3}	1.6×10^{-3}	1.3×10^{-3}	1.1×10^{-3}	8.8×10^{-4}	6.0×10^{-4}	5.5×10^{-4}	5.0×10^{-4}	4.3×10^{-4}	3.3×10^{-4}	2.0×10^{-4}

[a] Source: EPA (2011a, Tables 3-13a and 3-13b)

Likewise, "Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2" (National Research Council 2006) reported fatal cancer risk factors of 0.00048 per rem for males and 0.00066 per rem for females in a population with an age distribution similar to that of the entire U.S. population (average value of 0.00057 per rem for a population with equal numbers of males and females). ICRP Publication 103 (ICRP 2007) recommends nominal cancer risk coefficients of 0.00041 and 0.00055 per rem for adults and the general population, respectively, and estimates the risk from heritable effects to be about 3 to 4 percent of the nominal fatal cancer risk.

Accordingly, this report uses a risk factor of 0.0006 LCF per rem to estimate risk due to the calculated radiation doses for the scenarios evaluated in this section. Arcadis 2019, Section 1.2 states that it used a risk factor of 0.0005 per rem, which is also acceptable.

5.1 Phosphogypsum Stacks – Backhoe Operator

It has been assumed that a backhoe operator would spend all of his/her time on the stacks loading PG into trucks for transport to a batching facility where it would be mixed with soil before being delivered to the road construction site. The backhoe operator's exposure pathways have been assumed to be the same as those analyzed by TFI for the Road Construction Worker – Road Base No Cover_Center, except the backhoe operator would be exposed to undiluted PG. Therefore, the backhoe operator's dose would be twice the Road Construction Worker's dose, or about 57.3 mrem/yr, which translates to an LCF risk of 3.4E-5 yr^{-1}. If the backhoe operator were to perform this task for 8.7 years, his/her LCF risk would be at EPA's reference risk of 3 in 10,000.

5.2 Road Users – Occupational Drivers

TFI calculated the dose to a Road User who spent 500 hours per year on the road. Assuming a 250-day work-year, this implies that the Road User may be commuting 1 hour each way to his/her job. However, there are jobs that require a worker to spend much of their workday on the road, e.g., taxi drivers, mailman, pizza delivery, local delivery, heavy-duty truckers. A 2003 Nationwide Truck Survey found that heavy-duty truckers spent a mean of 10.4 hours per day and 292 days per year driving (Lutsey et al. 2004). Thus, these truckers would be on the road approximately 3,000 hrs/yr, rather than the 500 hrs/yr assumed in the risk assessment for road users.

In order to bound the potential exposure to future road users, TFI's calculated Road User annual dose has been increased by a factor of (3,000 hrs/yr / 500 hrs/yr =) six (6) to 6 mrem/yr, which translates to an LCF risk of 3.6E-6 yr^{-1}. Even with this conservative assumption, to be at EPA's reference risk of 3 in 10,000 would require the Road User to work for 83 years, well beyond an individual's working lifetime.

5.3 Groundwater

Review of TFI's risk assessment (Arcadis 2019) shows no discussion of groundwater flow or contaminant transport modeling or calculations for their proposed use of PG as road base material. Perhaps the reason for the lack of this information was that past experiments with using PG as road base material has shown that there was "no measurable impact on the quality of the groundwater":

> The environmental impact of the experimental road bases constructed in Texas, USA, in the early 1990s was evaluated through TCLP [Toxicity characteristic leaching procedure] analysis of the mixture components along with analysis of the groundwater, surface water and leachates […]. The concentrations of leached chemicals were found to be below levels of environmental concern and in many

> cases negligible. In central Florida, USA, groundwater monitoring adjacent to one of the two experimental roads constructed in 1986–1987 was undertaken four months prior to construction and thereafter for 27 further months, resulting in a total monitoring period of 31 months […]. Follow-up monitoring continued until 2008. … No significant impact on the groundwater was detected, with the concentrations of leached chemicals all remaining below levels of environmental concern […]. Groundwater monitoring of the second of the two experimental roads constructed in 1986–1987 was carried out in a similar manner and, again, the experimental road was found to have no measurable impact on the quality of the groundwater. (IAEA 2013, pp. 151-153)

However, because the radionuclides of concern are long-lived (e.g., as shown in Figure 3-1, Ra-226 has a 1,600-year half-life and is one of the shorter lived radionuclides of concern), SC&A believes that TFI should include in their risk assessment a demonstration that the groundwater pathway does not present an exposure pathway that could result in a greater-than-3-in-10,000 risk to the population.

Because RESRAD only has the capability to assess the groundwater pathway at a well located immediately adjacent to the contaminated zone (i.e., at the edge of the road base) (ANL 2001, Figure E.1), it is inappropriate for the evaluation of the groundwater pathway. Rather the RESRAD-OFFSITE (ANL 2016a) computer code was used by SC&A to perform a scoping analysis to estimate the extent of the potential impact from the groundwater pathway.

The RESRAD-OFFSITE groundwater pathway analysis requires that assumptions be made for over two dozen parameters. Rather than attempt to tailor the analysis to Florida, or any other specific area, for this scoping analysis, SC&A used the RESRAD default parameter values. Regarding the RESRAD default parameter assumptions, ANL (1993) says the following:

> The [RESRAD] default parameter values … have been carefully selected and are realistic, although conservative, parameter values. (In most cases, use of these values will not result in underestimation of the dose or risk.) Site-specific parameters should always be used whenever possible. Therefore, use of default values that significantly overestimate the dose or risk for a particular site is discouraged. (ANL 1993)

In addition to the default parameters, radionuclide-specific distribution coefficients are important to evaluating the groundwater pathway. For the radionuclide-specific distribution coefficients, SC&A utilized the three sets of values shown in Table 5-2. Although ANL (2000, Table 3.9-2) provides distribution coefficients for sand, loam, clay, and organic soil types, SC&A chose to use only the sand coefficients based on:

> **Florida's "soil" is mostly sand.** [emphasis added]
>
> This gray, fine soil is called Myakka, … Only found in Florida, Myakka covers the majority of the state—more than 1½ million acres—and is actually our official state soil.

While the majority of the state is covered in Myakka, soil properties can vary widely. The soils of North and Central Florida are typically very sandy, while in the panhandle, the soil can contain substantial amounts of clay. Clay soils compact more easily and drain slower than sandy soils.

Meanwhile, down south in the Everglades, soils tend to be peat-based and extremely fertile. If you live in this area, you may not need to amend your soil. Finally, in extreme South Florida, soils are often shallow and have a high pH due to the influence of the limestone bedrock. (UF 2020)

Table 5-2 RESRAD Distribution Coefficients

Nuclide	Distribution Coefficient (K_d) (cm^3/g)		
	Default Table 2.4	**Mean Table 3.9-1**	**Sand Table 3.9-2**
Bi-210	0	105	100
Pb-210	100	2,392	270
Po-210	10	181	150
Ra-226	70	3,533	500
Rn-222	0	0	0
Th-230	60,000	5,884	3,200
Th-234	60,000	5,884	3,200
U-234	50	126	35
U-238	50	126	35

Source: ANL 2000

The remaining parameter to be defined for the SC&A RESRAD-OFFSITE runs is the distance from the road base to the well. TFI's risk assessment evaluated two distances: 20 feet, which was "considered representative of urban settings" and 50 feet, which was "representative of [a] more suburban setting." Since it is believed unlikely that a well would be located in an urban setting, SC&A used 50 feet as the distance between the road base and the well. RESRAD-OFFSITE contains a default distance from downgradient edge of contamination to the well of 100 meters. SC&A also evaluated a well at 100 meters. In summary, the four RESRAD-OFFSITE runs that SC&A made to evaluate the groundwater pathway are:

- Well at 50 feet, default distribution coefficients.
- Well at 50 feet, mean distribution coefficients.
- Well at 50 feet, sand distribution coefficients.
- Well at 100 meters, default distribution coefficients.

Table 5-3 summarizes the results of the SC&A groundwater pathway scoping analyses. Consistent with the approach taken in TFI's risk assessment, the lifetime dose was calculated by assuming that the individual lived at that location for 26 years.

Table 5-3 Summary of SC&A Groundwater Pathway Scoping Analyses

Well Distance	Distribution Coefficients	Peak Dose (mrem/yr)	Time of Peak Dose	Lifetime Dose (mrem)	LCF Risk	Risk Less Than 3 in 10,000?
50 feet	Default	14.1	1,170	367.5	2.2E-04	Yes
50 feet	Mean	0.011	3,280	0.30	1.8E-07	Yes
50 feet	Sand	0.059	780	1.53	9.2E-07	Yes
100 meters	Default	6.9	3,280	178.9	1.1E-04	Yes

Table 5-3 shows that for the four cases analyzed, the lifetime risk was below the accepted risk level of 3 in 10,000 and that that risk would not be exhibited until hundreds of years into the future. Based on the results of this scoping analysis, at this time SC&A does not recommend any further study of the groundwater potential exposure pathway.

5.4 Ingestion of Crayfish

The following statement indicates that the leaching of radionuclide from PG is a concern:

> The gypsum stockpiles are surrounded by ditches to retain rain water drainage. In the water accumulated in the ditches high concentrations of ^{226}Ra were measured as well as relatively high concentrations of ^{210}Pb and ^{210}Po, although these ones associated mainly to suspended particles. (Carvalho 2001)

For this scenario, it is assumed that the road base extends 4 feet beyond either side of the road surface. Rain falls on this exposed road base and leaches radionuclides. The rainwater then collects in ditches or depressions near the side of the road. Crayfish, sometimes referred to as "mud bugs," live in these water-filled depressions and are harvested and consumed by local residents.

The following provides some background information on crayfish:

> Crayfish live in a range of habitats including clean, flowing waters (streams, rivers) and standing waters (ponds, lakes, marshes, swamps). They are found in almost any wetland, including drainage ditches; wherever there is water. … Crayfish also are a flavorful, nutritious, and valuable human food (similar to lobster) and are sold in fish markets throughout the world. Every year, nearly 75,000 tons, valued at over $50 million, are produced in the United States alone. (VT 2009)

A conservative upper estimate of the potential dose from this scenario was calculated by Eq 5-1:

$$D_{cf} = I_{cf} \sum_{i=1}^{N} \left(\frac{S1_i}{K_{d,i}} \right) B_{iv,i} \ DCF3_i \qquad \text{Eq 5-1}$$

Where: D_{cf} = Crayfish ingestion dose (mrem/yr)
I_{cf} = Crayfish ingestion rate (kg/yr)
= 0.9 (kg/yr) — ANL (2001)

$S1_i$ = PG radionuclide concentration (pCi/g) (see Table 2-8)
$K_{d,i}$ = Distribution coefficient (cm^3/g) (see Table 5-2)
$B_{iv,i}$ = Crayfish bioaccumulation factor (g/cm^3) (see Table 5-4)
$DCF3_i$ = Dose conversion factors for ingestion (mrem/pCi) (see Table 2-8)

As shown in Table 5-4, the SC&A-calculated conservative, upper bound crayfish ingestion annual dose is unacceptably large[5]. The dose is due primarily to Po-210, but Pb-210 and Ra-226 also result in significant crayfish ingestion doses.

Table 5-4 SC&A Calculated Conservative, Upper Bound Crayfish Ingestion Dose

Nuclide	Water Concentration (pCi/cm^3)			Bio-factors* (cm^3/g)	Dose (mrem/yr)		
	Default	Mean	Sand		Default	Mean	Sand
Bi-210	1.4E-01	1.3E-01	1.4E-01	10	5.8E-03	5.6E-03	5.8E-03
Pb-210	1.4E-01	5.6E-03	5.0E-02	100	3.1E+01	1.3E+00	1.1E+01
Po-210	1.4E+00	7.5E-02	9.0E-02	20,000	1.1E+05	6.0E+03	7.2E+03
	Equilibrium with Pb-210				1.1E+04	4.5E+02	4.0E+03
Ra-226	1.9E-01	3.8E-03	2.7E-02	250	4.5E+01	8.9E-01	6.3E+00
Rn-222	1.9E-01	3.8E-03	2.7E-02	0	4.0E-02	8.0E-04	5.6E-03
Th-230	4.2E-05	4.2E-04	7.8E-04	500	1.5E-02	1.5E-01	2.7E-01
Th-234	2.5E-05	2.5E-04	4.7E-04	500	1.4E-04	1.4E-03	2.7E-03
U-234	3.2E-02	1.3E-02	4.6E-02	60	3.1E-01	1.2E-01	4.5E-01
U-238	3.0E-02	1.2E-02	4.3E-02	60	2.7E-01	1.1E-01	3.9E-01
Total	—	—	—	—	**1.1E+05**	**6.0E+03**	**7.2E+03**
					1.1E+04	**4.5E+02**	**4.0E+03**

* Source: ANL (2000, Table 2.6, crustacea)

One of the reasons the Table 5-4 crayfish ingestion doses are considered to be conservative, upper bound is that road base runoff was assumed to be the only source of the water in which the crayfish live (i.e., no dilution from noncontaminated water sources [e.g., rainfall, nonroad base drainage]).

Also, Po-210 is by far the major contributor to the Table 5-4 crayfish ingestion dose, but Po-210 has a short half-life (i.e., about 138 days) and would likely decay to insignificance before it could contaminate the crayfish. However, the Po-210 would be replenished by Pb-210 decay, however, because Pb-210 has a larger distribution coefficient than Po-210, its concentration in the crayfish water would be less, as shown in the left three columns of Table 5-4. To address this concept, Table 5-4 contains a row in which the Po-210 dose is calculated by assuming the Po-210 has the same water concentration as Pb-210. When this is done, the Po-210 crayfish ingestion dose is reduced by less than a factor of two to an order of magnitude, depending on which set of distribution coefficients are used.

[5] For a 3-in-10,000 risk and a risk factor of 0.0006 LCF per rem, an acceptable dose would be 0.5 rem, or 500 mrem. An acceptable annual dose would be 500 mrem divided by the number of years exposed. For the Nearest Resident, TFI assumed a 26-year exposure period, giving an acceptable annual dose of about 19 mrem/yr.

In addition, it was assumed that the road base runoff water radionuclide concentration was simply the PG road base concentration divided by the distribution coefficient (i.e., the term in parenthesis in Eq 5-1). EPA (1999, p. 1.1) defines the distribution coefficient (K_d) as "the ratio of the contaminant concentration associated with the solid to the contaminant concentration in the surrounding aqueous solution when the system is at equilibrium," or expressed mathematically:

$$K_d = \frac{C_{eq,soil}}{C_{eq,water}} \qquad \text{Eq 5-2}$$

Where: K_d = Distribution coefficient (cm^3/g)
$C_{eq,soil}$ = Equilibrium concentration in soil (pCi/g)
$C_{eq,water}$ = Equilibrium concentration in water (pCi/cm^3)

The key word here is "equilibrium," in other words, the distribution coefficient is representation under equilibrium conditions. The concern is that the runoff water may not have sufficient time in contact with the road base PG to reach equilibrium conditions, and therefore, much less radioactivity would be leached from the PG road base. SC&A was unable to locate any nonequilibrium soil to water concentration ratios for use in Eq 5-1.

The Po-210 crayfish (i.e., crustacea) bioaccumulation factor is a significant reason for the unacceptably large crayfish ingestion dose. At 20,000 cm^3/g, the Po-210 bioaccumulation factor is 80 and 200 times larger than the Ra-226 and Pb-210 bioaccumulation factors, respectively. This large discrepancy between the Po-210 and its parents' crayfish bioaccumulation factors does not appear for the fish bioaccumulations factors or the plant, meat, and milk transfer factors (ANL 2000, Tables 2.5 and 2.6). SC&A checked two other sources (IAEA 2017, Table 7.2 [9,300 to 16,000 cm^3/g] and Hameed et al. 1997, Table 1 [20.4 Bq/kg / 1.4 mBq/L = 14,600 cm^3/g]), which confirmed the RESRAD default Po-210 bioaccumulation factor to within about a factor of two.

Crayfish are part of nature's food chain. They can be eaten by owls, fox, raccoons, snakes, muskrats, turtles, yellow perch, and blue gills, as well as people. Additionally, crayfish carcasses are being studied as an alternative source for the protein and minerals necessary to raise chickens (CNN 2008). Table 5-5 presents the aquatic food bioaccumulation factors and agricultural pathway transfer factors for Po-210, Pb-210, and Ra-226. Table 5-5 shows that relative to its two longer lived parents, Po-210 concentrates more in meat and poultry, however not to the extent that it does in crayfish (i.e., crustacea).

Table 5-5 Bioaccumulation and Transfer Factors

Nuclide	Bioaccumulation Factor (L/kg)		Transfer Factor (d/kg)	
	Crustacea	Fish	Meat	Poultry
Po-210	20,000	100	0.005	0.9
Pb-210	100	300	0.0008	0.2
Ra-226	250	50	0.001	0.03
Source:	ANL 2000, Table 2.6	ANL 2000, Table 2.6	ANL 2000, Table 2.5	PNL 1992, Table 6.18

While acknowledging that they are conservative, upper bound estimates, SC&A believes that the Table 5-4 crayfish ingestion doses are so large that TFI should be requested to further investigate this potential exposure pathway, as well as the crayfish-to-meat/poultry-to-man food chain.

6.0 SUMMARY OF RESULTS

Sections 2.0 through 5.0 provide SC&A's detailed critique of TFI's risk assessment (Arcadis 2019). This section provides a summary of the major findings of that critique.

6.1 Road Base Width

Arcadis (2019, Section 2.1) indicates that "a four-lane county road with two lanes in each direction that is 15 m wide (about 12 feet [ft] per lane)" was used in TFI's models. The road base analyzed in the 1992 Environmental Impact Statement Background Information Document (BID, EPA 1992) was 9.15 m (30 ft) wide, thus TFI's road is conservative when compared to the BID road base.

However, TFI's model assumed that the road surface extended over the entire width of the road base, leaving none exposed. As explained in Section 4.1.2, this assumption is inconsistent with information from the FHWA (2017), which indicates that road bases "are typically extended 3 to 4 feet beyond the edge of the pavement." Extending the road base beyond the road surface would increase the ground shine dose for a number of TFI's evaluated scenarios, including the RCW-RB_SS_Edge and Road User scenarios. It is recommended that TFI be requested to re-evaluate all affected scenarios, assuming a road base that extends 4 feet from the edge of the road surface.

6.2 RESRAD Mixing Depth

In all of their RESRAD runs, TFI utilized the depth of soil mixing layer (DM) default value of 15 cm. As discussed in Section 2.2.2, this results in inconsistencies between the ground shine and the inhalation and ingestion exposure pathways (i.e., the road surface was assumed to be non-PG contaminated cement for the ground shine pathway, but for the inhalation and ingestion pathways it was assumed to have PG mixed with the cement). Section 2.2.2 identified the two RCW-RB_SS and two RCW-RS scenarios as being affected with this inconsistency.

It is recommended that TFI re-do the RESRAD runs with the appropriate DMs for the two RCW-RB_SS and two RCW-RS scenarios.

6.3 Resident Living Near Road

As discussed in Section 4.2 and elsewhere, SC&A has identified the following four concerns regarding TFI's risk assessment Nearest Resident analysis:

- The RESRAD runs specify a mixing depth of 15 cm, which would bring road base material to the surface for release into the air. This affects the inhalation and soil ingestion pathways calculations and is inconsistent with the ground shine assumptions."

- The ground shine calculation assumes that the PG-contaminated road base is covered with a non-PG containing layer of paving. This is inconsistent with the any of the three road construction scenarios definitions identified by TFI, i.e., 1) PG in road base (no cover), 2) PG in road base and in concrete paving, and 3) Road base without PG and PG in the concrete paving. SC&A performed an analysis of the PG-contaminated road base covered by PG-contaminated paving—the scenario Arcadis (2019, Figure 2.1) identifies as being associated with the Nearest Resident evaluation. As shown in Table 2-1, the SC&A calculated dose rates 20 ft and 50 ft from the road edge were 4.1E-5 and 6.4E-6 (mR/hr), respectively. The lower SC&A dose rates compared to the dose rates reported in Arcadis 2019, Table 3.2 is due to the manner in which Arcadis calculated doses offset from the shielded road (see the last bullet and Section 4.2).
- TFI's risk assessment assumed that the PG road base was completely covered by the paving. The FHWA indicates that the road base normally extends 3 to 4 feet on either side of the road. This source of Nearest Resident exposure has not been accounted for in TFI's risk assessment.
- SC&A found that the approach used to evaluate the dose rate at the Nearest Resident locations (i.e., 20 and 50 feet from the edge of the road) was inappropriate.

In conclusion, TFI's evaluation of the Nearest Resident exposure pathways needs to be revised to address these concerns.

6.4 Reclaimer Radon Exposure

In Section 4.6, SC&A independently calculated the reclaimer radon inhalation dose presented in Arcadis (2019, Section 3.4.1). SC&A utilized the same mathematical equations from U.S. NRC Regulatory Guide 3.64 (NRC 1989) as used by Arcadis (2019) to calculate the radon flux through the home's foundation. However, SC&A took a different approach than Arcadis (2019) to calculate the buildup of radon and its daughter products within the home and the resulting inhalation dose (see Section 4.6 for the approach used by SC&A).

However, the largest difference between the Arcadis (2019) and SC&A-calculated radon inhalation doses is due to the different assumptions made regarding the values for the radon emanation factor and the PG and foundation radon diffusion coefficients. For each of these parameters, Arcadis (2019) selected values that are representative of intact solid concrete. SC&A believes that it is not appropriate to model either the PG or the home's foundation as intact solid (i.e., without cracks) concrete. The basis for SC&A's selection of the values for these parameters is described in Section 4.6.

It is recommended that TFI be requested to revise their reclaimer radon exposure dose calculation using more realistic (i.e., less optimistic) parameter values, or provide additional justification for the values that are in Arcadis (2019, Section 3.4.1).

6.5 Groundwater Pathway

TFI's risk assessment is silent on the groundwater pathway (i.e., it does not even provide a rationale for not analyzing the groundwater pathway). Section 5.3 presents the results of SC&A's evaluation of four groundwater pathway scenarios. These results show that it is likely that the risk associated with the groundwater pathway would be less than 3 in 10,000; however, there is much uncertainty in the values assumed for the many parameters involved in evaluating the groundwater pathway, and further evaluation by either TFI or SC&A may be necessary.

6.6 Crayfish Ingestion Potential Exposure

In Section 5.4, a conservative, upper bound estimate was made of the potential exposure due to the ingestion of crayfish living in water contaminated by runoff from the PG road base. One of the reasons for the conservatism of the estimate is the assumption that the runoff radionuclide concentration is equal to the road base concentration divided by its distribution coefficient. However, because the ingestion dose estimated in Section 5.4 is so large, it is recommended that TFI be requested to further investigate this potential exposure pathway.

6.7 Miscellaneous Secondary Findings

Sections 6.1 through 6.6 present the most significant findings of this review. There are numerous secondary findings throughout Sections 2.0 through 5.0 that may change the numerical value of the result, but are not expected to change the overall conclusion. For example, as described in Section 4.1.3, if the EFH heavy activity inhalation rate is used instead of the RESRAD industrial worker default, the inhalation dose would increase by about a factor of 3.7. However, since the inhalation pathway is a negligible contributor to the overall RCW dose (Table 2-10), this increase would be insignificant to the overall conclusion regarding the acceptability of the RCW's total dose.

It is recommended TFI review Sections 2.0 through 5.0 and incorporate the alternative parameter values and exposure scenarios presented therein into their risk assessment, as appropriate.

7.0 REFERENCES

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APPENDIX A – DOCUMENT ASSESSMENT FORMS/CHECKLISTS

The Quality Assurance Project Plan (QAPP) for this task requires that the documents used to develop the report be assessed against the following criteria:

1. Soundness: *The extent to which the scientific and technical procedure, measures, methods or models employed to generate the information are reasonable for, and consistent with, the intended application.*
2. Applicability and Utility: *The extent to which the information is relevant for the agency's use.*
3. Clarity and Completeness: *The degree of clarity and completeness with which the data, assumptions, methods, quality assurance, sponsoring organizations and analyses employed to generate the information are documented*.
4. Uncertainty and Variability: *The extent to which the variability and uncertainty (quantitative and qualitative) in the information or in the procedures, measures, methods or models are evaluated and characterized.*
5. Evaluation and Review: *The extent of independent verification, validation and peer review of the information or of the procedures, measures, methods or models.*

SC&A obtained data and/or information from a number of references during the course of our review of TFI's risk assessment. The following document assessments of those references are focused on the data and/or information that SC&A acquired from the reference, not necessarily the entire reference. For example, one of the two questions asked to evaluate Soundness assessment factor is: "Is the stated purpose of the report consistent with its approach and conclusions, and are the conclusions supported by the data provided in the report?" Since SC&A is most often only interested in data presented in the references and not specifically the conclusions of the report, the answer to this question would almost always be **No**, resulting in a **Marginal** evaluation for the Soundness assessment factor.

One reference is TFI's risk assessment, **Arcadis 2019**, and another is The Fertilizer Institute's supplemental data, **TFI 2019**, both of these references were provided by the EPA for SC&A to review and/or use. A third reference, **Kitto and Perazzo 2010**, is referred to by TFI's risk assessment. Since these are not SC&A-generated references, this document assessment is not applicable to them.

Documents produced by the following United States government identities are considered to be "peer reviewed": Argonne National Laboratory (**ANL**), Bureau of Labor Statistics (**BLS**), Brookhaven National Laboratory (**BNL**), Environmental Protection Agency (**EPA**), Federal Highway Administration (**FHWA**), and Nuclear Regulatory Commission (**NRC**). Similarly, documents produced by the International Atomic Energy Agency (**IAEA**) and by state government agencies (i.e., **Wong and Ho 1988**) are considered to be "peer reviewed."

Four references were either presented at professional meeting, **Roessler 1990**, **Carvalho, F.P. 2001**, or in professional publications, **Lutsey, et al. 2004, Hameed et al. 1997**; these professional presentations/publications are considered to be "peer reviewed." One reference was produced by the American Automobile Association's Foundation for Traffic Safety, **FTS 2019**, as a research arm of the AAA FTS publications are considered to be "peer reviewed."

Three references were produced as formal publications by accredited universities, **UM 1989**, **VT 2009**, as well as **FIPR 2020**, which is part of Florida Polytechnic University. Each of these is assumed to have been "peer reviewed" prior to its publication. Although not a technical publication, **UF 2020** was produced by the University of Florida, and since it was referred to only for information and not for any numerical data used in SC&A's evaluation, it is considered "acceptable." One reference, **EcoTech 2015**, is considered to be "professional opinion" and was not "peer reviewed", however, since this reference was only used to provide background information on the extent of radon migration through sewer piping, and did not form the basis for any calculations or recommendations, it was deemed "marginally" acceptable.

MicroShield, a widely used gamma radiation shielding program, and its User's Manual, **Grove 2009**, have undergone extensive quality assurance and have a verification and validation (V&V) package available. SC&A considers MicroShield to be "peer reviewed."

The table below summarizes the results of our quality assessment for each type of document.

Citation	Reference Type	Evaluation Criteria				
		Soundness	**Applicability and Utility**	**Clarity and Completeness**	**Uncertainty and Variability**	**Evaluation and Review**
ANL 1993.	U.S. government	Marginal	Acceptable	Acceptable	Acceptable	Acceptable
ANL 2000.	U.S. government	Marginal	Acceptable	Acceptable	Acceptable	Acceptable
ANL 2001.	U.S. government	Marginal	Acceptable	Acceptable	Not applicable	Marginal
ANL 2015.	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
ANL 2016a.	U.S. government	Marginal	Acceptable	Acceptable	Not applicable	Marginal
ANL 2016b.	U.S. government	Marginal	Acceptable	Acceptable	Not applicable	Marginal
ANL 2018.	U.S. government	Marginal	Acceptable	Acceptable	Not applicable	Marginal
Arcadis 2019.	EPA provided	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
BLS 2020.	U.S. government	Marginal	Acceptable	Acceptable	Not applicable	Marginal
BNL 2020.	U.S. government	Marginal	Acceptable	Acceptable	Not applicable	Acceptable
Carvalho, F.P. 2001.	Professional publication	Marginal	Acceptable	Acceptable	Acceptable	Marginal
Chauhan, R.P. and A. Kumar 2015.	Professional publication	Marginal	Acceptable	Acceptable	Not applicable	Marginal
EcoTech 2015	Professional opinion	Marginal	Marginal	Marginal	Marginal	Marginal
EPA 1991.	U.S. government	Marginal	Acceptable	Acceptable	Not applicable	Acceptable

Citation	Reference Type	Evaluation Criteria				
		Soundness	Applicability and Utility	Clarity and Completeness	Uncertainty and Variability	Evaluation and Review
EPA 1992.	U.S. government	Marginal	Acceptable	Acceptable	Acceptable	Acceptable
EPA 1999.	U.S. government	Marginal	Acceptable	Acceptable	Acceptable	Acceptable
EPA 2011a.	U.S. government	Marginal	Acceptable	Acceptable	Acceptable	Acceptable
EPA 2011b.	U.S. government	Marginal	Acceptable	Acceptable	Acceptable	Acceptable
EPA 2014.	U.S. government	Marginal	Acceptable	Acceptable	Not applicable	Acceptable
EPA 2017.	U.S. government	Marginal	Acceptable	Acceptable	Acceptable	Acceptable
EPA 2019.	U.S. government	Marginal	Acceptable	Acceptable	Acceptable	Marginal
FHWA 2017.	U.S. government	Marginal	Acceptable	Acceptable	Not applicable	Marginal
FIPR 2020.	University published	Marginal	Acceptable	Acceptable	Acceptable	Marginal
FTS 2019.	Professional publication	Marginal	Acceptable	Acceptable	Not applicable	Marginal
Grove 2009.	Peer reviewed	Marginal	Acceptable	Acceptable	Not applicable	Marginal
Hameed et al. 1997.	Professional publication	Marginal	Acceptable	Acceptable	Acceptable	Marginal
IAEA 2013.	International agency	Marginal	Acceptable	Acceptable	Acceptable	Acceptable
IAEA 2017.	International agency	Marginal	Acceptable	Acceptable	Acceptable	Acceptable
ICRP 1991.	Professional publication	Marginal	Acceptable	Acceptable	Acceptable	Acceptable
ICRP 1993.	Professional publication	Marginal	Acceptable	Acceptable	Acceptable	Acceptable
ICRP 1996.	Professional publication	Marginal	Acceptable	Acceptable	Acceptable	Acceptable
ICRP 2002.	Professional publication	Marginal	Acceptable	Acceptable	Acceptable	Acceptable
ICRP 2007.	Professional publication	Marginal	Acceptable	Acceptable	Acceptable	Acceptable
ISCORS 2002.	U.S. government	Marginal	Acceptable	Acceptable	Acceptable	Acceptable
Kendall G.M., and T.J. Smith 2002.	Professional publication	Marginal	Acceptable	Acceptable	Not applicable	Marginal
Kitto and Perazzo 2010.	TFI referenced	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
Lutsey, et al. 2004.	Professional publication	Marginal	Acceptable	Acceptable	Not applicable	Marginal
McHugh, et al 2017	Professional publication	Marginal	Acceptable	Acceptable	Not applicable	Marginal

Citation	Reference Type	Evaluation Criteria				
		Soundness	Applicability and Utility	Clarity and Completeness	Uncertainty and Variability	Evaluation and Review
National Research Council 2006.	Professional publication	Marginal	Acceptable	Acceptable	Acceptable	Acceptable
NRC 1989.	U.S. government	Marginal	Acceptable	Acceptable	Not applicable	Acceptable
Pennell, et al 2013	Professional publication	Marginal	Acceptable	Acceptable	Not applicable	Marginal
Reichman, et al 2017	Professional publication	Marginal	Acceptable	Acceptable	Not applicable	Marginal
Roessler 1990.	Professional publication	Marginal	Acceptable	Acceptable	Not applicable	Marginal
Rogers, et al. 1994.	U.S. government	Marginal	Acceptable	Acceptable	Acceptable	Acceptable
TFI 2019.	EPA provided	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
UF 2020.	University produced	Marginal	Acceptable	Acceptable	Not applicable	Marginal
UM 1989.	University published	Marginal	Acceptable	Acceptable	Acceptable	Marginal
VT 2009.	University published	Marginal	Acceptable	Acceptable	Acceptable	Marginal
Wong and Ho 1988.	Texas government	Marginal	Acceptable	Acceptable	Acceptable	Marginal