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Biosphere Dose Assessment: Review of Dose Consequence of Radionuclides in the Uranium-238 Series Decay Chain

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SSM perspektiv

Bakgrund

Strålsäkerhetsmyndigheten (SSM) granskar Svensk Kärnbränslehantering AB:s (SKB) ansökningar enligt lagen (1984:3) om kärnteknisk verksamhet om uppförande, innehav och drift av ett slutförvar för använt kärnbränsle och av en inkapslingsanläggning. Som en del i granskningen ger SSM konsulter uppdrag för att inhämta information i avgränsade frågor. I SSM:s Technical note-serie rapporteras resultaten från dessa konsultuppdrag.

Projektets syfte

Syftet med detta granskningsuppdrag är att utföra överslagsberäkningar för att utvärdera eventuell betydande dos i samband med radionuklider i sönderfallskedjan för uran-238 och göra jämförelser med SKB: s motsvarande resultat.

Författarnas sammanfattning

Som en del av den Strålsäkerhetsmyndigheten (SSM) inledande granskningsfas av Svensk Kärnbränslehantering AB (SKB) SR-Site säkerhetsanalys för ett slutförvar för använt kärnbränsle i Sverige dokumenterar denna *Technical Note* Center for Nuclear Waste Regulatory Analyses (CNWRA®) granskning av potentiella effekter på SKB dosberäkningar från radioaktiva ämnen med koppling till uran över långa tidsperioder. Uran förekommer i både naturen och använt kärnbränsle. Radioaktivt sönderfall skapar element med olika kemiska och radiologiska egenskaper. CNWRA utvärderade om SKB:s förhållningssätt till att redogöra för processen av uranets radioaktiva sönderfall, i synnerhet i grundvattentransport och vid dosberäkningar för biosfären, har utelämnat några aspekter som väsentligt kan påverka dosresultatet. CNWRA granskade relevanta delar av SR-Site säkerhetsanalysen (SKB, 2011), Biosfär Analyser för säkerhetsanalysen SR-Site Syntes och sammanfattning av resultaten (SKB, 2010a), radionuklidtransport Rapport för säkerhetsanalysen SR-Site (SKB, 2010b) och andra relevanta dokument.

CNWRA utförde avgränsningsberäkningar på potentiell avvikelse från jämvikt mellan uranets sönderfallsprodukter vid geosfärs transport. Ett gemensamt modelleringsantagande (hos organisationer som arbetar med hantering av radioaktivt avfall) för rörelse av radionuklider i ett naturligt system är att produkterna av radioaktivt sönderfall existerar i jämvikt med grundmaterialet. Eftersom olika material (eller element) kan ha olika kemiska egenskaper och rörelsebeteende i det naturliga systemet (kallat transportegenskaper), kan radioaktiva sönderfallsprodukter existera vid olika koncentrationer längs transportvägen jämfört med grundmaterialet. Denna obalans kan öka koncentrationen av specifika delar på vissa platser längs transportvägen och kan resultera i högre uppskattade koncentrationer i förhållande till en modell baserad på antagande om jämvikt mellan det radioaktiva grundmaterialet och dess sönderfallsprodukter. Genom bekräftande beräkningar, kontrollerade CNWRA specifika SKB beräkningar av utomhus- och inomhusdoser från ett antaget radonutsläpp samt SKB: s parameter som omvandlar radonexponering till dos.

Från denna inledande granskning konstaterade CNWRA att SKB:s urandosberäkningar i allmänhet är kompletta även om ytterligare analyser eller kompletterande dokumentation av befintliga beräkningar skulle klargöra den tekniska grunden för att utesluta specifika radioaktiva sönderfallsprodukter från uran från säkerhetsanalysen. CNWRA:s överslagsberäkning visade att retentionen i geosfären av ^{230}Th, en sönderfallsprodukt av uran, efter utsläpp och transport har potential att väsentligt bidra till flux av sin sönderfallsprodukt (^{226}Ra) i biosfären under långa tidsperioder. Säkerhetsbetydelsen av detta resultat beror på vilken ytterligare kvantitativ information om modelleringsresultat för ^{230}Th och ^{226}Ra som SKB kan visa. För att bekräfta rimligheten i SKB:s modellering, behövs information om de ackumulerade belopp och särskild lokalisering av förekomst för ^{230}Th och ^{226}Ra över långa tidsperioder jämfört med utsläppshastigheten för ^{230}Th och ^{226}Ra från avfallet. CNWRA:s bekräftande beräkningar av inomhus- och utomhusradon dosberäkningar stämmer överens med SKB:s resultat, men vid användning av rimliga alternativa parametrar för husvolym och ventilationshastighet i inomhusdosberäkningen ökade resultaten med en faktor två relativt SKB:s redovisade värden.

CNWRA fann att transport- och biosfäranalyserna i allmänhet var baserade på sunda och välkända vetenskapliga metoder, men SKB: s dokumentation angav inte alltid tekniska grunder för metoder, antaganden och slutsatser som har noterats i den detaljerade tekniska beskrivningen. Generellt använde sig SKB effektivt av grafik för att förmedla komplex information. I vissa fall var dock presentationen av detaljerad information relaterad till sammanhanget i säkerhetsanalysen oklar och förhindrade en fullständig förståelse av modellens detaljer. I allmänhet kunde information som presenteras i SKB:s dokument spåras till källdokumentationen med viss ansträngning, men det fanns flera exempel på ofullständiga referenser till relaterade eller stödjande analyser. Frekvent användning av indirekt, passivt, och/eller tvetydigt språk påverkade insyn i de SKB-dokument som granskats.

Referenser

SKB. “Long-term safety for the final repository for spent nuclear fuel at Forsmark: main report of the SR-Site project.” TR–11–01, Vol. 1–3. Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Company. 2011.

SKB. “Biosphere analyses for the safety assessment SR-Site — synthesis and summary of results.” TR–10–09. Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Company. 2010a.

SKB. “Radionuclide transport report for the safety assessment SR-Site.” TR–10–50. Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Company. 2010b.

Projektinformation

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Diarienummer avrop: SSM2011-4542
Aktivitetsnummer: 3030007-4035

SSM perspective

Background

The Swedish Radiation Safety Authority (SSM) reviews the Swedish Nuclear Fuel Company's (SKB) applications under the Act on Nuclear Activities (SFS 1984:3) for the construction and operation of a repository for spent nuclear fuel and for an encapsulation facility. As part of the review, SSM commissions consultants to carry out work in order to obtain information on specific issues. The results from the consultants' tasks are reported in SSM's Technical Note series.

Objectives of the project

The objective of this review task is to perform scoping calculations to evaluate potential for significant dose related to radionuclides in the uranium-238 series decay chain and make comparisons with SKB's corresponding results.

Summary by the authors

As part of the Swedish Radiation Safety Authority (SSM) initial phase review of the Swedish Nuclear Fuel and Waste Management Company (SKB) SR-Site safety assessment for a spent nuclear fuel repository in Sweden, this technical note documents Center for Nuclear Waste Regulatory Analyses (CNWRA®) review of potential effects on SKB dose calculations from radioactive elements associated with uranium over long time periods. Uranium is present in both nature and spent nuclear fuel. Radioactive decay creates elements with differing chemical and radiological properties. CNWRA evaluated whether the SKB approach to account for the process of uranium radioactive decay, in particular in groundwater transport and biosphere dose calculations, has omitted any aspects that could significantly affect dose results. CNWRA reviewed pertinent sections of the SR-Site safety assessment report (SKB, 2011), Biosphere Analyses for the Safety Assessment SR-Site Synthesis and Summary of Results (SKB, 2010a), Radionuclide Transport Report for the Safety Assessment SR-Site (SKB, 2010b), and other relevant documents.

CNWRA performed scoping calculations on the potential for disequilibrium of uranium decay products during geosphere transport. A common modelling assumption (by organizations working in radioactive waste management) for the movement of radionuclides in a natural system is that the products of radioactive decay exist in equilibrium with the parent material. Because different materials (or elements) can have different chemical properties and movement behaviour in the natural system (referred to as transport characteristics), it is possible for radioactive decay products to exist at different concentrations along the transport path compared to the parent material. This disequilibrium can enhance the concentration of specific elements at certain locations along the transport path and may result in higher estimated concentrations relative to a model based on assumed equilibrium between the radioactive parent and its decay products. By confirmatory calculations, CNWRA verified specific SKB calculations of outdoor and indoor doses from an assumed radon release and the SKB parameter that converts radon exposure to dose.

From this initial review, CNWRA concluded that SKB uranium dose calculations are generally complete although additional analyses or supplemental documentation of existing calculations would clarify the technical basis for excluding specific uranium radioactive decay products from the performance assessment. The CNWRA scoping calculation indicated that retention in the geosphere of ^{230}Th, a decay product of uranium, following its release and transport has the potential to contribute significantly to the flux of its decay product (^{226}Ra) into the biosphere over long time periods. The safety significance of this result depends on obtaining additional quantitative information on SKB modelling results for ^{230}Th and ^{226}Ra. To confirm the appropriateness of SKB modelling, information is needed on the accumulated amounts and specific locations of ^{230}Th and ^{226}Ra over long time periods compared to the release rate of ^{230}Th and ^{226}Ra from the waste. CNWRA confirmatory calculations of indoor and outdoor radon dose calculations agreed with SKB results although the use of reasonable alternative parameter selections for house volume and ventilation rate in the indoor dose calculation increased the range of results by a factor of two relative to SKB reported values.

CNWRA found the transport and biosphere analyses were, in general, based on sound and familiar scientific methods, but the SKB documentation did not always provide technical bases for methods, assumptions, and conclusions, which have been noted in the detailed technical note. Overall, SKB used graphics effectively to convey complex information. However in some instances, the performance assessment context for presenting detailed information was unclear and prevented a complete understanding of modelling details. Information presented in SKB documents could, in general, be traced to the source documentation usually with some effort, but there were several instances of incomplete referencing of related or supporting analyses. Frequent use of indirect, passive, and/or ambiguous language affected transparency in the SKB documents reviewed.

References

SKB. “Long-term safety for the final repository for spent nuclear fuel at Forsmark: main report of the SR-Site project.” TR–11–01, Vol. 1–3. Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Company. 2011.

SKB. “Biosphere analyses for the safety assessment SR-Site — synthesis and summary of results.” TR–10–09. Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Company. 2010a.

SKB. “Radionuclide transport report for the safety assessment SR-Site.” TR–10–50. Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Company. 2010b.

Project information

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Biosphere Dose Assessment: Review of Dose Consequence of Radionuclides in the Uranium-238 Series Decay Chain

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Content

1. Introduction

This technical note documents Center for Nuclear Waste Regulatory Analyses (CNWRA®) input to the Swedish Radiation Safety Authority (SSM) initial phase review of the Swedish Nuclear Fuel and Waste Management Company (SKB) SR-Site safety assessment for a spent nuclear fuel repository in Sweden. For this task, CNWRA reviewed the dose consequence of radionuclides in the Uranium-238 series decay chain as part of the SSM framework agreements covering Biosphere Dose Assessment. The scope of the assignment included review for completeness, scientific soundness, and quality of the pertinent sections of the SR-Site safety assessment report, TR–01–11 (SKB, 2011): two mandatory reports: Biosphere analyses for the safety assessment SR-Site–synthesis and summary of results, TR–10–09 (SKB, 2010a) and Radionuclide transport report for the safety assessment SR-Site, TR–10–50 (SKB, 2010b); and other relevant references, as appropriate. The assignment description noted that the SR-Site safety assessment showed radionuclides in the ^{238}U decay chain, primarily ^{226}Ra, are dominant contributors to dose/risk in most of the calculation cases yet modelled releases were shown to be lower than naturally occurring fluxes at Forsmark. SSM therefore requested scoping calculations to examine the potential for significant dose consequences related to radionuclides of the ^{238}U decay chain and make comparisons with SKB results to evaluate reasonableness. Example calculations identified in the assignment included modelling domains of geosphere transport and biosphere dose calculations. The potential for disequilibrium of decay products in groundwater based on differences in ^{222}Rn transport properties (as a gas) was noted as an example of a relevant issue that could be explored.

The CNWRA approach to this review included a familiarization review of the assigned reports and related references to identify methods and assumptions that could underestimate dose from ^{238}U and its decay products, including any important assumptions or conclusions that should be evaluated further in scoping or confirmatory calculations. The familiarization review also considered clarity of SKB documentation for describing ^{238}U dose calculations and adequacy of technical bases provided by SKB for ^{238}U dose calculations. CNWRA estimated the potential for disequilibrium of ^{238}U decay products ^{230}Th and ^{226}Ra during geosphere transport in a scoping calculation. Details of the safety significance, technical bases, methods, assumptions, and results of the scoping calculations are documented in Section 2 of this technical note. CNWRA performed confirmatory calculations on the outdoor and indoor effective doses from a single canister radon pulse release and the ^{222}Rn dose coefficient used by SKB. Details of the safety significance, technical bases, methods, assumptions, and results of the confirmatory calculations are documented in Section 3 of this technical note.

2. Scoping calculation

During the initial review phase, insufficient information on the SKB model was available to quantify and verify contributions from radionuclide buildup following the availability of radionuclides for release and transport. In Report TR–10–50 (SKB, 2010b, Figure 4-5), ^{226}Ra provided a dominant contribution to the mean

annual effective dose for the central corrosion case. In Report TR–11–01 (SKB, 2011, p. 658), SKB states:

The dose equivalent releases from the near field and the dose after transport through the geosphere are both dominated by Ra-226. Much of the Ra-226 released from the near field is transmitted through the geosphere, since the failed canisters are located in deposition holes intersected by large, highly transmissive fractures with low retention. The release of Ra-226 from the geosphere is almost exclusively due to Ra released from the near field and not to in-growth in the geosphere. This, in turn, is related to the fact that the parent nuclide Th-230 is assumed to be confined to the near field.

In Report TR–10–50 (SKB, 2010b, p. 109), SKB states:

It is also noted that chain decay in the geosphere is not accounted for when applying the transmission factors for geosphere retention. The theory for a full, analytical treatment of chain decay in transmission factors has been developed, but is not yet implemented in the analytical model. Using the numerical models, it has been demonstrated that chain decay of parent nuclides of Ra-226 in the far field has a negligible impact on the releases of Ra-226 in the corrosion scenario.

To investigate the SKB assumption of complete ^{230}Th retention, a scoping calculation was performed on two radionuclides (^{230}Th and ^{226}Ra). Details of the scoping calculation are provided in Appendix 4. Two compartment models were constructed for partial ^{238}U decay chain transport in the geosphere from continuous releases. The two models differed in the treatment of thorium transport. Model 1 did not include thorium transport in the geosphere. In contrast, Model 2 included thorium release from the near field and transport in the geosphere.

The steady-state ratio of ^{226}Ra fluxes into the biosphere, shown in Appendix 4, Eq. (A-35), was used to obtain insights on the importance of thorium retention and buildup in the geosphere. Ratio values greater than one indicate greater ^{226}Ra fluxes with thorium transport included. A complete parameter description is provided in Appendix 4, Table A-1. Regarding transport characteristics out of the near field into the geosphere (g_{Ra} and g_{Th} in the models), the steady-state ratio increases as g_{Th} / g_{Ra} increases (i.e., increases in the transport characteristics of ^{230}Th out of the near field compared to that for ^{226}Ra). Values of g_{Th} / g_{Ra} less than one tend to result in steady-state ratios greater than one. Values of g_{Th} / g_{Ra} much less than one ($<< 1$) result in a steady-state ratio equal to unity. Regarding transport characteristics out of the far field into the biosphere (h_{Ra} and h_{Th} in the models), the steady-state ratio is insensitive to h_{Ra} but decreases to unity, implying no difference between model results, as h_{Th} increases.

Example calculations were performed to obtain quantitative insights. Transfer constants used in the compartment models are abstracted quantities, intended to elucidate general behaviors of decay chain radionuclides in the natural system. Values for transfer parameters in the example calculations were estimated to be consistent with expected repository conditions; they were not derived from measurement data due to time and resource limitations during the initial review phase. Due to the slow dissolution rate of the waste form, small values were selected for the transfer constant of radium and thorium out of the near field (g_{Ra} and g_{Th}). Because thorium retention in the near field is expected to be greater than the radium retention, g_{Ra} and g_{Th} were estimated to be 0.0001 ka^{-1} and 0.00001 ka^{-1}, respectively. Although larger values for g_{Ra} / g_{Th} would increase the steady-state

flux ratio, values of g_{Ra} and g_{Th} were not changed for the example calculations presented in this report. Example calculations were performed for three different cases for thorium retention in the far field:

(i) Low thorium retention in the far field was approximated by $h_{Th} = 0.05$ ka^{-1}, which implies 85 percent of ^{230}Th in the far field enters the biosphere compared to 15 percent decaying to ^{226}Ra in the far field

(ii) Moderate thorium retention in the far field was approximated by $h_{Th} = 0.007$ ka^{-1}, which implies 45 percent of ^{230}Th in the far field enters the biosphere compared to 55 percent decaying to ^{226}Ra in the far field

(iii) High thorium retention in the far field was approximated by $h_{Th} = 0.001$ ka^{-1}, which implies 10 percent of ^{230}Th in the far field enters the biosphere compared to 90 percent decaying to ^{226}Ra in the far field

Steady-state flux ratios were computed for the three cases.

For low thorium retention in the far field ($h_{Th} = 0.05$ ka^{-1}), steady-state ^{226}Ra flux into the biosphere is 1.7 times greater when ^{230}Th transport is included.

$$\frac{\text{Model 2 } ^{226}\text{Ra Flux to Biosphere}}{\text{Model 1 } ^{226}\text{Ra Flux to Biosphere}} = \frac{0.0087}{0.0087 + 0.00001}\left[1 + \frac{0.4331 + 0.0001}{0.0001}\frac{0.00001}{0.0087 + 0.05}\right] = 1.7$$

For moderate thorium retention in the far field ($h_{Th} = 0.007$ ka^{-1}), steady-state ^{226}Ra flux into the biosphere is 3.8 times greater when ^{230}Th transport is included.

$$\frac{\text{Model 2 } ^{226}\text{Ra Flux to Biosphere}}{\text{Model 1 } ^{226}\text{Ra Flux to Biosphere}} = \frac{0.0087}{0.0087 + 0.00001}\left[1 + \frac{0.4331 + 0.0001}{0.0001}\frac{0.00001}{0.0087 + 0.007}\right] = 3.8$$

For high thorium retention in the far field ($h_{Th} = 0.001$ ka^{-1}), steady-state ^{226}Ra flux into the biosphere is 5.5 times greater when ^{230}Th transport is included.

$$\frac{\text{Model 2 } ^{226}\text{Ra Flux to Biosphere}}{\text{Model 1 } ^{226}\text{Ra Flux to Biosphere}} = \frac{0.0087}{0.0087 + 0.00001}\left[1 + \frac{0.4331 + 0.0001}{0.0001}\frac{0.00001}{0.0087 + 0.001}\right] = 5.5$$

Sorption of ^{230}Th following its release and transport can contribute significantly to the flux of ^{226}Ra into the biosphere over long time periods. This conclusion is supported by scoping calculation results that showed the release of ^{230}Th and its retention in the geosphere over long timeframes can result in larger fluxes of ^{226}Ra into the biosphere compared to a model assuming no thorium transport.

3. Confirmatory calculations

In evaluating the dose potential for ^{238}U decay chain radionuclides, CNWRA evaluated the assigned and referenced SKB documentation to identify the radionuclides included, either explicitly or implicitly, in transport and biosphere calculations. SKB transport analysis documentation (SKB, 2010b, Appendix D, p. 258) included detailed information on the selection of radionuclides for the analysis that confirmed short-lived decay products (including ^{222}Rn and its decay products prior to ^{210}Pb in the chain) were excluded from transport calculations. This is a common and reasonable assumption when the expected geosphere groundwater transport time exceeds the life of the radionuclide (e.g., greater than 28 days for

^{222}Rn and its short-lived decay products). Regarding the SKB biosphere calculations, the SKB biosphere synthesis report (SKB, 2010a, p. 37) analyzes the exclusion of ^{222}Rn:

In SR-Site, only outdoor exposure (hundred percent of time) was considered, which in most cases gives a conservative estimate, as the radionuclide contamination of the air comes from resuspension of soil particles. The situation could, however, be different for isotopes of elements that can exist in gas form in the environment. No separate biosphere assessment is carried out for such radionuclides. However, isotopes that are likely to enter the gas phase to any significant extent are assessed in Section 13.8 in the SR-Site Main Report.

As noted above, the SKB biosphere synthesis report cites Section 13.8 of the SR-Site report TR–11–01 (SKB, 2011) entitled *Radionuclide transport in the gas phase*, which further cites supplemental reports R–06–81 (SKB, 2006a) and R–06–82 (SKB, 2006b).

The SKB landscape dose factor report TR–10–06 (SKB, 2010c, p. 58) notes a potential for ^{222}Rn to affect the ^{226}Ra Landscape Dose Factor (LDF) but states ^{222}Rn is not included in LDF's:

Although, it should be recognised that doses from Radon inhalation could have a potential impact on LDFs for Ra-226, these have not been included in the derivation of baseline LDFs. It has been considered that in conditions where doses from "repository originated" Radon could be important, these will be outset by much higher doses from "natural" Radon.

The CNWRA review focused on the analysis in Section 13.8 of the SR-Site report (SKB, 2011), as it was the only traceable supporting analysis for the exclusion of ^{222}Rn from the biosphere calculations identified in the documents reviewed. The SKB SR-Site Report Section 13.8 analysis includes both outdoor and indoor dose calculations to a pulse release of the radon inventory of a single canister. Sections 3.1 and 3.2 provide the details of the CNWRA confirmatory calculations of the SKB radon analyses.

3.1. Outdoor exposure to a radon pulse release from a single canister

Confirmatory calculations were performed on (i) the effective dose due to a radon pulse release from a single canister and (ii) the ^{222}Rn dose conversion factor.

For 2.5×10^{10} Bq ^{222}Rn released with SKB parameter values for emission area at the surface of 10,000 m^2, mixing height of 20 m, wind speed of 2 m s^{-1}, and an average daily breathing rate of 0.925 m^3 hr^{-1}, an air concentration of 1.25×10^5 Bq m^{-3}, 50-second exposure, and total 1600 Bq ^{222}Rn inhaled were calculated. A different radon dose conversion factor was intentionally selected by CNWRA for the confirmatory calculation to ascertain its influence on the result. Specifically, 1.35×10^{-8} Sv/Bq was obtained from the allowable limit on intake for occupational exposure to radon with decay progeny present in the U.S. Code of Federal Regulations (2012). The calculated radon dose equaled 0.022 mSv for decay progeny equilibrium or 0.013 mSv when the SKB equilibrium factor of 0.6 was applied. This confirmatory result compares well with the SKB value of 0.011 mSv

in R–06–82, (SKB, 2006b, Table 8-10). However, a clarification is needed because different results were presented in other reports, as described in Appendix 2.

The SKB value of 32 μSv/yr per Bq/m^3 for indoor radon exposure falls within Health Physics Society "best estimate" range of 20–47 μSv/yr per Bq/m^3 for indoor radon, obtained by converting range of 3–7 mSv/yr per 4 pCi/L of indoor radon (Health Physics Society, 2009). The SKB value of 47 μSv/yr per Bq/m^3 for outdoor radon exposure arises from a greater degree of radon decay progeny equilibrium. SKB values are reasonable. SKB adopted commonly used equilibrium factor of 0.4 for indoor radon exposure and used increased equilibrium factor to 0.6 for outdoor radon exposure.

3.2. Indoor exposure to a radon pulse release from a single canister

The SKB indoor dose calculations for ^{222}Rn are documented in Section 7.3 of Report R–06–81 (SKB, 2006a). Here, the activity concentration of ^{222}Rn indoors is calculated as:

$$C = \frac{E * A}{V * v}$$

Where

C = airborne activity concentration of ^{222}Rn (1.25×10^5 Bq-hr/m^3)
E = pulse release of ^{222}Rn from the ground surface (2.5×10^6 Bq/m^2)
A = house foundation area (100 m^2)
V = volume of the house (1,000 m^3)
v = house ventilation rate (2 h^{-1})

SKB calculated E, the pulse release of ^{222}Rn by assuming half of the inventory of ^{222}Rn in a canister is released as a pulse after 100,000 years resulting in a 25 GBq release at the ground surface (transport through buffer and geosphere to biosphere was conservatively not accounted for by SKB). The release was assumed by SKB to occur over a ground surface area of 10,000 m^2 for a value of E of 2.5×10^6 Bq/m^2. The indoor inhalation dose calculation was not explicitly documented in SKB Report R–06–81 (SKB, 2006a) but was inferred by CNWRA from the listed input parameters in Table 7.3 as follows:

$$D = C * DC * F$$

Where

D = inhalation dose from airborne ^{222}Rn (228 μSv)
C = airborne activity concentration of ^{222}Rn (1.25×10^5 Bq-hr/m^3)
DC = inhalation dose coefficient for ^{222}Rn with decay products in equilibrium (32 μSv per Bq-yr/m^3 documented by SKB and converted by CNWRA to 3.65×10^{-3} μSv per Bq-hr/m^3 by dividing the SKB value by 8,760 hr/yr)
F = occupancy factor (fraction of year exposed = 0.5)

The CNWRA calculated value of D, the inhalation dose from airborne ^{222}Rn, agrees with the value reported by SKB in R–06–81 of 230 μSv when rounded to two significant digits. CNWRA further reviewed the calculation inputs for

reasonableness. Although not specifically cited to a source in the SR-Site Section 13.8 analysis (SKB, 2011), the value of the pulse release of ^{222}Rn of 25 GBq was found to bound the reported canister inventories for ^{238}U in Table 6-4 of SKB Report TR–10–13 (SKB, 2010d). SKB cites the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2000) for the ^{222}Rn dose coefficient (reviewed in Section 5.1 of this technical note). SKB does not similarly follow the UNSCEAR recommendation for an occupancy factor of 0.8, however, the value appeared conservative and not representative of the general population. Other factors, such as the house area, volume, and ventilation rate were not referenced by SKB to any source. Appendix B of UNSCEAR (2000) includes recommendations for a model masonry house with a floor surface area of 100 m^2, volume of 250 m^3, and ventilation rate of 1 hr^{-1} (SKB used this ventilation rate to evaluate a range of values). No data for rural Sweden could be located; however, values were compared with U.S. random sample survey data from U.S. Environmental Protection Agency (EPA) (2011) that show a mean house volume of 492 m^3 and median ventilation rate of 0.45 hr^{-1}. Both comparison references supported using lower house volume than what SKB assumed. CNWRA used the UNSCEAR volume and ventilation rate in the SKB radon indoor exposure calculation, and it increased the SKB point estimate of dose by a factor of 7.9 (1,800 µSv) and alternately by a factor of four (930 µSv) if the EPA reported U.S. average house volume were used. The lower of these two results is close to the SKB reported maximum and the higher result (1,800 µSv) is two times the SKB reported maximum. While CNWRA considers the calculation to be based on conservative assumptions, the elevated doses from the confirmatory calculations add variability to the SKB results and support additional comments requesting clarification of the purpose and conclusions from the SKB analysis. Overall, both outdoor and indoor radon calculations provide insights into the radon hazard from a canister release at a point in time but do not alone provide a strong basis for excluding radon from biosphere modelling.

4. Main review findings

The CNWRA initial review of dose consequences from radionuclides in the Uranium-238 series decay chain culminated in the following findings. Finding topics were derived from SSM general guidelines for the review.

- Completeness of safety assessment: ^{238}U dose calculations are generally complete although additional supplemental analyses would clarify the technical basis for excluding specific ^{238}U decay products.
- Scientific soundness and quality: Overall, the transport and biosphere analyses are based on sound and familiar scientific methods although in specific areas noted, the documentation did not always provide technical bases for methods, assumptions, and conclusions (e.g., how radioactive decay was incorporated in transport and biosphere calculations; indoor and outdoor radon dose calculations and applicable input parameters; exclusion of radon from biosphere calculations).
- Data and model adequacy: Specific data and models reviewed under this initial review phase appeared generally adequate for their intended purpose.
- Treatment of uncertainties: Supplemental sensitivity analyses provided useful insights; however, the performance assessment model included limited propagation of uncertainties.
- Safety significance: Potential safety significant issues were identified for further consideration in the main review phase.
- Transparency and traceability: Information could generally be traced to source documentation but with some effort; graphics were effective at

conveying complex information; several instances were found of incomplete referencing of related/supporting analyses; frequent use of indirect, passive, and/or ambiguous language affected transparency in all documents reviewed.

5. Recommendations

Potential enhanced release of radon gas and its decay products, such as ^{210}Pb, from the waste form present the possibility of additional dose consequence from the ^{238}U decay chain that is not presently accounted for. (*Refer to CNWRA Report on Independent Radionuclide Transport Modeling: Reproducing Results for Main Scenarios)*

The radionuclide ^{230}Th, parent of ^{226}Ra, is assumed to be confined to the near field (SKB, 2011, p. 658). Given the high degree of sorption expected for thorium following its release from the waste canister, reasons for the lack of appreciable thorium build-up in the far field should be examined further or documented more completely.

Radon is not explicitly modelled in groundwater contamination scenarios. Due to different sorption behaviours between radium and its noble gas decay product (radon), groundwater concentrations of radon and its decay progeny can be significantly enhanced compared to the calculated groundwater plume concentration of radium, if favourable sorption conditions for radium exist in the transport path. Therefore, the outcomes of hydrologic and geochemical reviews of the SKB geosphere transport modelling have potential implications regarding whether this enhancement should be assessed with respect to ^{222}Rn and ^{210}Pb concentrations in the biosphere.

Any future consideration or analysis related to ^{222}Rn enhancement in the biosphere should be coupled with an evaluation of applicable potential exposure scenarios. Based on the short half life of ^{222}Rn, its physical property as a gas, and site-specific characteristics such as low potential for long term irrigation that could build up ^{226}Ra in soil, potential pathways for human exposure to ^{222}Rn by inhalation appear limited. While the human dose potential for ^{222}Rn is lower per unit intake for ingestion relative to inhalation, based on the initial review of the biosphere characteristics documented by SKB, a drinking water exposure scenario appears more likely than a gas inhalation scenario.

6. References

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SKB. "Long-term safety for the final repository for spent nuclear fuel at Forsmark: main report of the SR-Site project." TR–11–01, Vol. 1–3. Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Company. 2011.

SKB. "Biosphere analyses for the safety assessment SR-Site — synthesis and summary of results." TR–10–09. Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Company. 2010a.

SKB. "Radionuclide transport report for the safety assessment SR-Site." TR–10–50. Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Company. 2010b.

SKB. "Landscape dose conversion factors used in the safety assessment SR-Site." TR–10–06. Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Company. 2010c.

SKB. "Spent nuclear fuel for disposal in the KBS-3 repository." TR–10–13. Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Company. 2010d.

SKB. "The ecosystem models used for dose assessments in SR-Can." R–06–81. Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Company. 2006a.

SKB. "The biosphere at Forsmark data, assumptions and models used in the SR-Can assessment." R–06–82. Stockholm, Sweden: Swedish Nuclear Fuel and Waste Management Company. 2006b.

UNSCEAR. "Sources and effects of ionizing radiation; Report to the General Assembly of the United Nations with Scientific Annexes." Vol. 1. 2000. <http://www.unscear.org/unscear/en/publications/2000_1.html> (May 1, 2012). 2000.

Appendix 1: Coverage of SKB reports

Reviewed report	Reviewed sections	Comments
TR–11–01, Long-term safety for the final repository for spent nuclear fuel at Forsmark: main report of the SR-Site project	Biosphere and radionuclide transport in Summary; Chapter 6; Section 7.5; Chapters 8, 10, and 13; Biosphere in Chapter 15	Refer to Appendices 2 and 3
TR–10–09, Biosphere analyses for the safety assessment SR-Site—synthesis and summary of results	Chapters 4, 6, 7, 8, 9, 10, and 12	Refer to Appendices 2 and 3
TR–10–50, Radionuclide transport report for the safety assessment SR-Site	Sections 3.1, 4.1.2, 4.4, 4.9, 4.10, 6.4.5, and 6.5	Refer to Appendices 2 and 3
TR–10–07 Element-specific and constant parameters used for dose calculations in SR-Site	6.1.1 and 6.1.2	Refer to Appendices 2 and 3
TR–10–06, Landscape dose conversion factors used in the safety assessment SR-Site	Chapters 4, 5, and 6	Refer to Appendices 2 and 3
R–06–82, The biosphere at Forsmark Data, assumptions and models used in the SR-Can assessment	Section 8.2.4	Refer to Appendices 2 and 3
R–06–81, The ecosystem models used for dose assessments in SR-Can	Chapter 7	Refer to Appendices 2 and 3
TR–10–13, Spent nuclear fuel for disposal in the KBS–3 repository	Section 6.2.3	Refer to Appendices 2 and 3
TR–10–02, The limnic ecosystems at Forsmark and Laxemar-Simpevarp	Sections 10.3 and 10.4; Appendixes 7 and 8	
TR–10–45, FEP report for the safety assessment SR-Site	Appendix 10	

Appendix 2: Suggested needs for complementary information from SKB

I. Needs important to safety

1. Radiological dose was calculated due to gas phase transport of radon for a pulse release from a single canister (TR–11–01, Section 13.8, Table 13-11), and corrosion rate was mentioned to influence gas releases after the pulse. The production rate of ^{222}Rn will be continuous from the radioactive decay of ^{226}Ra. Continuous ^{222}Rn release following the initial pulse release of ^{222}Rn may be significant based on the potential to accumulate additional dose with time relative to a single pulse release. Provide additional information on the continuous ^{222}Rn release or justify why its further consideration is unnecessary.
2. SKB reports a smaller landscape dose factor for ^{226}Ra than the value for ^{238}U (e.g., mean values in Figure 5-40 and Table 5-5 of TR–10–06). Because the ingestion dose coefficient used to calculate the landscape dose factor is higher for ^{226}Ra than ^{238}U (TR–10–07, Table 6-2), these results should be checked or explained further.
3. After a wetland is drained, further contamination of the soil through groundwater is not modeled because irrigation with surface water is assumed to be the dominant pathway (TR–11–01, p. 635). Discuss how this biosphere feature (no groundwater contributions for wetlands, reliance on surface water) affects ^{226}Ra deposition, ^{222}Rn transport, and the overall potential for radon concentrations in the biosphere. Because surface water radionuclide concentrations in the biosphere appear to be further mediated by dilution and sorption processes relative to groundwater in the geosphere, the SKB assumption of biosphere soil contamination only from a surface water source would lower the calculated dose relative to a assuming a direct geosphere groundwater source.

II. Needs for clarity and consistency

1. The magnitudes of ^{222}Rn effective dose results from the same pulse release calculation do not match in various reports (Table 13-11 in TR–11–01, Table 8-10 in R–06–82, and Tables 7-2 and 7-3 in R–06–81). Please explain the differences.
2. The caption of Table 8-11 (R–06–82) indicates that the annual lifetime risk was estimated by "dividing the dose with 50 years." Clarify if the ^{222}Rn effective doses in Tables 8-10 and 8-11 in R–06–82 included division by 50 years.
3. Clarify if radionuclide buildup in groundwater during glacial periods was considered. Include discussion of access to any built-up radionuclide concentrations at the end of the glacial period and brought into the biosphere.
4. Inconsistent/imprecise statements identified in various SKB documents regarding the treatment of decay products in calculations should be clarified. For example,

a. Transport analysis documentation (TR–10–50, Appendix D, Section D.3) states "Daughters with short half-lives can be assumed to be in equilibrium with their parent nuclide, and hence, the nuclide is excluded from the radionuclide transport calculations. However, they are included in the LDF for their parent nuclide." Landscape Dose Factor (LDF) documentation in TR–10–06 shows no LDFs for ^{222}Rn or decay products and no explicit or implicit inclusion in ^{222}Rn in LDFs. TR–10–06 states ^{222}Rn is not included in LDF's.
b. TR–10–06 states dose coefficients used to calculate LDF's included short-lived daughters citing an EU directive as the source, however, the EU directive suggests that ^{222}Rn and decay products were not included in ^{226}Ra dose coefficient. Specifically, LDF input parameters were documented in Appendix B of TR–10–06, which cited TR–10–07 for dose coefficients. Section 6.1.2 of TR–10–07 cited a 1996 EU Directive, which cited EU legislation (1996) for actual dose coefficient tables. TR–10–06 indicates that dose coefficients for radionuclides with decay chains include contributions from short-lived progeny and cited a table in the 1996 EU directive; however, the cited table is explicitly linked to concentration threshold limits and not the tables of dose coefficients. Upon initial review, it appears the tables of dose coefficients provide no clear documentation regarding implicit consideration of short-lived progeny and also do not contain dose coefficients for ^{222}Rn (but do provide separate values for ^{226}Ra and ^{210}Pb). The dose coefficient table values are described in directive text as "except for radon progeny…"

5. Frequent use of indirect, passive, and/or ambiguous language affected transparency in all documents reviewed. Examples include:
    a. Transport analysis documentation (TR–10–50, Appendix D, Section D.3) states "Daughters with short half-lives can be assumed to be in equilibrium with their parent nuclide, and hence, the nuclide is excluded from the radionuclide transport calculations." It is important to directly state what has been done in the modelling rather than what can be done.
    b. TR–10–50, Appendix D, Section D.2 states: "It should be rather straightforward to *i*) exclude any nuclide with a half-life less than 10 years, *ii*) any nuclide with a total hazard index less than 0.01 since e.g. the readily transported I-129 has a hazard index of around 10^2."
    c. TR–10–06 indicates that dose coefficients for radionuclides with decay chains include contributions from short-lived progeny without any clarification about which short-lived progeny are being referred to.
    d. TR–11–01, Section 13.8, Paragraph 6 states: "The full inventory of Rn-222 is also assumed to be in the gaseous phase" without specifying what inventory is being discussed. Similarly, the next paragraph states: "At the time of breakthrough, half of the inventory of C-14 and Rn-222 is taken to be released immediately to the biosphere. The remaining gaseous inventory (and the Rn-222 that is produced) is then taken to be released together with

the gas that is produced continuously." Again, the text does not describe nor provide any supporting reference for the inventory.

6. Instances of incomplete referencing of related/supporting analyses or data were identified including:
    a. TR–10–06, p. 58, states that under conditions where repository radon could be important it would be "outset" by higher doses from natural radon but provides no citation to a technical basis. SKB should cite the technical bases for conclusive statements in their documentation.
    b. TR–11–01, Section 3.8, provides no reference for the inventory SKB used to derive the 25 GBq release that was used in radon dose calculations.
    c. R–06–81, Section 7.3, provides no supporting references or technical bases for various input parameters used in the indoor radon calculation including the house volume, house area, occupancy factor, house ventilation rate.

Appendix 3: Suggested review topics for SSM

1. Potential enhanced release of radon and its decay products, such as ^{210}Pb, from the waste form (*Refer to CNWRA Technical Note on Independent Radionuclide Transport Modeling: Reproducing Results for Main Scenarios)*
2. The radionuclide ^{230}Th, decay parent to ^{226}Ra, is assumed to be confined to the near field (TR–11–01, p. 658). SKB analyzed an alternative case allowing ^{230}Th mobility in the near field and indicated ^{226}Ra effective doses from the far field were lower than the ^{226}Ra effective dose for the basecase, in which all thorium was retained in the near field. Given the high degree of sorption expected for thorium following its release from the waste canister, reasons for the lack of appreciable thorium build-up in the geosphere should be examined further.
    a. Far field and near field results seem to indicate significant retention of ^{226}Ra in the geosphere, implied from the approximate 20-times reduction in ^{226}Ra contributions from the far field compared to those from the near field (TR–10–50, Figures 6-63 and 6-64).
    b. By neglecting the buildup of ^{230}Th in the geosphere and its subsequent decay to ^{226}Ra, the flux of ^{226}Ra into the biosphere at long time periods may be underestimated (*Refer to CNWRA Scoping Calculation*).
3. Radon is not explicitly modeled in groundwater contamination scenarios. Due to significantly different sorption behaviors between radium and its noble gas decay product (radon), groundwater concentrations of radon and its decay progeny can be significantly enhanced compared to the groundwater concentration of radium. Implications of this enhancement should be assessed with respect to ^{222}Rn and ^{210}Pb concentrations in the biosphere.
4. Any future consideration or analysis related to ^{222}Rn enhancement in the biosphere should be coupled with an evaluation of applicable potential exposure scenarios. Based on the short half life of ^{222}Rn, its physical property as a gas, and site specific characteristics such as low potential for long term irrigation that could build up ^{226} Ra in soil, potential pathways for human exposure to ^{222}Rn by inhalation appear limited. While the human dose potential for ^{222}Rn is lower per unit intake for ingestion relative to inhalation, based on the initial review of the biosphere characteristics documented by SKB, a drinking water exposure scenario appears more likely than a gas inhalation scenario. A complete understanding of local and regional human practices would inform any evaluation of potential exposure scenarios.

Appendix 4: Compartment modelling for radionuclide decay chain release and transport

Two compartment models were constructed for partial ^{238}U decay chain transport in the geosphere from continuous releases. As shown in Figure A-1, two models used for the comparison differed in the treatment of thorium transport. Parameter descriptions are presented in Table A-1. Thorium transport in the geosphere was not included in Model 1. In contrast, Model 2 included thorium release from the near field and transport in the geosphere.

In this appendix, the geosphere is the natural geologic setting surrounding the waste canisters. The geosphere is separate and distinct from the biosphere. Instead of including separate compartments for the waste form or waste canisters in these models, contributions from the source of radioactive waste are considered within the near field compartment by using a production term. To simplify the calculations, a constant production rate of ^{230}Th was used as the input for both models. Time-dependent production could be modelled to account for the change in radionuclide inventories over time, but this added complexity was unnecessary for comparing two models with identical production inputs. Because model behaviour over long time frames was of interest, steady-state results were obtained from time-dependent solutions. Fluxes of ^{226}Ra into the biosphere were calculated and compared.

Table A-1. Scoping calculation parameter description.

Parameter	Description
P	Production rate of ^{230}Th in the near field (atoms ka^{-1})
$NF_{Th}(t)$	Time-dependent amount of ^{230}Th in the near field (atoms)
$FF_{Th}(t)$	Time-dependent amount of ^{230}Th in the far field (atoms)
g_{Th}	^{230}Th transfer constant from near field to far field (ka^{-1})
h_{Th}	^{230}Th transfer constant from far field to biosphere (ka^{-1})
λ_{Th}	^{230}Th radioactive decay constant (ka^{-1})
$NF_{Ra}(t)$	Time-dependent amount of ^{226}Ra in the near field (atoms)
$FF_{Ra}(t)$	Time-dependent amount of ^{226}Ra in the far field (atoms)
g_{Ra}	^{226}Ra transfer constant from near field to far field (ka^{-1})
h_{Ra}	^{226}Ra transfer constant from far field to biosphere (ka^{-1})
λ_{Ra}	^{226}Ra radioactive decay constant (ka^{-1})

Model 1: Thorium Retained in the Near Field

Time-dependent solutions were derived for the three compartments in Model 1, $NF_{Th}(t)$, $NF_{Ra}(t)$, and $FF_{Ra}(t)$ shown in Figure A-1. Parameter descriptions are provided in Table A-1.

The differential equation for the $NF_{Th}(t)$ compartment is

$$\frac{dNF_{Th}(t)}{dt} = P - \lambda_{Th}\, NF_{Th}(t). \quad \text{(A-1)}$$

The general form of the differential equation and its solution are

$$\frac{dy(t)}{dt} + R(t)y(t) = Q(t) \quad \text{(A-2)}$$

and

$$y(t)e^{\int R(t)dt} = \int e^{\int R(t)dt}\, Q(t)dt. \quad \text{(A-3)}$$

The combination of Eqs. (A-1), (A-2), and (A-3) yields

$$NF_{Th}(t)e^{\int \lambda_{Th}dt} = \int e^{\int \lambda_{Th}dt}\, P\, dt. \quad \text{(A-4)}$$

Integration results in an integration constant, C,

$$NF_{Th}(t)e^{\lambda_{Th}t} = \frac{P}{\lambda_{Th}}\, e^{\lambda_{Th}t} + C. \quad \text{(A-5)}$$

The boundary condition, $NF_{Th}(t) = 0$ at $t = 0$, is applied to solve for C,

$$0 = \frac{P}{\lambda_{Th}} + C. \quad \text{(A-6)}$$

The combination of Eqs. (A-5) and (A-6) results in

$$NF_{Th}(t)e^{\lambda_{Th}t} = \frac{P}{\lambda_{Th}}\, e^{\lambda_{Th}t} - \frac{P}{\lambda_{Th}}. \quad \text{(A-7)}$$

The solution for the amount of ^{230}Th in the near field over time for Model 1 is

$$NF_{Th}(t) = \frac{P}{\lambda_{Th}}\left(1 - e^{-\lambda_{Th}t}\right). \quad \text{(A-8)}$$

The differential equation for the $NF_{\mathrm{Ra}}(t)$ compartment is

$$\frac{dNF_{\mathrm{Ra}}(t)}{dt} = \lambda_{\mathrm{Th}} NF_{\mathrm{Th}}(t) - (\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}})\, NF_{\mathrm{Ra}}(t). \quad \text{(A-9)}$$

Eq. (A-8) is substituted into Eq. (A-9), arranged into the form of the general solution

$$NF_{\mathrm{Th}}(t) e^{\int(\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}})dt} = P\Big[\int e^{\int(\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}})dt}\, dt - \int e^{\int(\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}})dt}\, e^{-\lambda_{\mathrm{Th}} t} dt\Big], \quad \text{(A-10)}$$

and integrated to obtain

$$NF_{\mathrm{Th}}(t)\, e^{(\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}})t} = P\left[\frac{e^{(\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}})t}}{\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}}} - \frac{e^{(\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}} - \lambda_{\mathrm{Th}})t}}{\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}} - \lambda_{\mathrm{Th}}}\right] + C. \quad \text{(A-11)}$$

The boundary condition, $NF_{\mathrm{Th}}(t) = 0$ at $t = 0$, is applied to solve for C,

$$0 = P\left[\frac{1}{\lambda_{Ra} + g_{Ra}} - \frac{1}{\lambda_{Ra} + g_{Ra} - \lambda_{Th}}\right] + C. \quad \text{(A-12)}$$

The combination of Eqs. (A-11) and (A-12) results in

$$NF_{\mathrm{Ra}}(t) e^{(\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}})t} = P\left[\frac{e^{(\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}})t} - 1}{\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}}} - \frac{e^{(\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}} - \lambda_{\mathrm{Th}})t} - 1}{\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}} - \lambda_{\mathrm{Th}}}\right]. \quad \text{(A-13)}$$

The solution for the amount of ^{226}Ra in the near field over time in Model 1 is

$$NF_{\mathrm{Ra}}(t) = P\left[\frac{1 - e^{-(\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}})t}}{\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}}} - \frac{e^{-\lambda_{\mathrm{Th}} t} - e^{-(\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}})t}}{\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}} - \lambda_{\mathrm{Th}}}\right]. \quad \text{(A-14)}$$

The differential equation for the $FF_{\mathrm{Ra}}(t)$ compartment is

$$\frac{dFF_{\mathrm{Ra}}(t)}{dt} = g_{\mathrm{Ra}}\, NF_{\mathrm{Ra}}(t) - (\lambda_{\mathrm{Ra}} + h_{\mathrm{Ra}})\, FF_{\mathrm{Ra}}(t). \quad \text{(A-15)}$$

Eq. (A-14) is substituted into Eq. (A-15), arranged into the form of the general solution

$$FF_{\mathrm{Ra}}(t)\, e^{\int(\lambda_{\mathrm{Ra}} + h_{\mathrm{Ra}})dt} = \frac{g_{\mathrm{Ra}} P}{\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}}} \int \left[1 - e^{-(\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}})t}\right] e^{\int(\lambda_{\mathrm{Ra}} + h_{\mathrm{Ra}})dt}\, dt - \frac{g_{\mathrm{Ra}} P}{\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}} - \lambda_{\mathrm{Th}}} \int \left[e^{-\lambda_{\mathrm{Th}} t} - e^{-(\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}})t}\right] e^{\int(\lambda_{\mathrm{Ra}} + h_{\mathrm{Ra}})dt}\, dt, \quad \text{(A-16)}$$

and partially integrated to obtain

$$FF_{\mathrm{Ra}}(t)e^{(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})t} = \frac{g_{\mathrm{Ra}}P}{\lambda_{\mathrm{Ra}}+g_{\mathrm{Ra}}}\int\left[e^{(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})t} - e^{(h_{\mathrm{Ra}}-g_{\mathrm{Ra}})t}\right]dt - \frac{g_{\mathrm{Ra}}P}{\lambda_{\mathrm{Ra}}+g_{\mathrm{Ra}}-\lambda_{\mathrm{Th}}}\int\left[e^{(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}-\lambda_{\mathrm{Th}})t} - e^{(h_{\mathrm{Ra}}-g_{\mathrm{Ra}})t}\right]dt. \quad \text{(A-17)}$$

Completing the integration yields

$$FF_{\mathrm{Ra}}(t)e^{(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})t} = \frac{g_{\mathrm{Ra}}P}{\lambda_{\mathrm{Ra}}+g_{\mathrm{Ra}}}\left[\frac{e^{(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})t}}{\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}} - \frac{e^{(h_{\mathrm{Ra}}-g_{\mathrm{Ra}})t}}{h_{\mathrm{Ra}}-g_{\mathrm{Ra}}}\right] - \frac{g_{\mathrm{Ra}}P}{\lambda_{\mathrm{Ra}}+g_{\mathrm{Ra}}-\lambda_{\mathrm{Th}}}\left[\frac{e^{(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}-\lambda_{\mathrm{Th}})t}}{\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}-\lambda_{\mathrm{Th}}} - \frac{e^{(h_{\mathrm{Ra}}-g_{\mathrm{Ra}})t}}{h_{\mathrm{Ra}}-g_{\mathrm{Ra}}}\right] + C. \quad \text{(A-18)}$$

The boundary condition, $FF_{\mathrm{Ra}}(t) = 0$ at $t = 0$, is applied to solve for C,

$$0 = \frac{g_{\mathrm{Ra}}P}{\lambda_{\mathrm{Ra}}+g_{\mathrm{Ra}}}\left[\frac{1}{\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}} - \frac{1}{h_{\mathrm{Ra}}-g_{\mathrm{Ra}}}\right] - \frac{g_{\mathrm{Ra}}P}{\lambda_{\mathrm{Ra}}+g_{\mathrm{Ra}}-\lambda_{\mathrm{Th}}}\left[\frac{1}{\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}-\lambda_{\mathrm{Th}}} - \frac{1}{h_{\mathrm{Ra}}-g_{\mathrm{Ra}}}\right] + C. \quad \text{(A-19)}$$

The combination of Eqs. (A-18) and (A-19) results in

$$FF_{\mathrm{Ra}}(t)e^{(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})t} = \frac{g_{\mathrm{Ra}}P}{\lambda_{\mathrm{Ra}}+g_{\mathrm{Ra}}}\left[\frac{e^{(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})t}-1}{\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}} - \frac{e^{(h_{\mathrm{Ra}}-g_{\mathrm{Ra}})t}-1}{h_{\mathrm{Ra}}-g_{\mathrm{Ra}}}\right] + \frac{g_{\mathrm{Ra}}P}{\lambda_{\mathrm{Ra}}+g_{\mathrm{Ra}}-\lambda_{\mathrm{Th}}}\left[\frac{e^{(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}-\lambda_{\mathrm{Th}})t}-1}{\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}-\lambda_{\mathrm{Th}}} - \frac{e^{(h_{\mathrm{Ra}}-g_{\mathrm{Ra}})t}-1}{h_{\mathrm{Ra}}-g_{\mathrm{Ra}}}\right]. \quad \text{(A-20)}$$

The solution for the amount of ^{226}Ra in the far field over time for Model 1 is

$$FF_{\mathrm{Ra}}(t) = \frac{g_{\mathrm{Ra}}P}{\lambda_{\mathrm{Ra}}+g_{\mathrm{Ra}}}\left[\frac{1-e^{-(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})t}}{\lambda_{Ra}+h_{\mathrm{Ra}}} - \frac{e^{-(\lambda_{\mathrm{Ra}}+g_{\mathrm{Ra}})t}-e^{-(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})t}}{h_{\mathrm{Ra}}-g_{\mathrm{Ra}}}\right] + \frac{g_{\mathrm{Ra}}P}{\lambda_{\mathrm{Ra}}+g_{\mathrm{Ra}}-\lambda_{\mathrm{Th}}}\left[\frac{e^{-\lambda_{\mathrm{Th}}t}-e^{-(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})t}}{\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}-\lambda_{\mathrm{Th}}} - \frac{e^{-(\lambda_{\mathrm{Ra}}+g_{\mathrm{Ra}})t}-e^{-(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})t}}{h_{\mathrm{Ra}}-g_{\mathrm{Ra}}}\right]. \quad \text{(A-21)}$$

Model 2: Thorium Transport Included

Time-dependent solutions were derived for the three compartments in Model 2, $FF_{Th}(t)$, $NF_{Ra}(t)$, and $FF_{Ra}(t)$ shown in Figure A-2. To avoid unnecessary complexity, a separate near field compartment for ^{230}Th was not included. Instead, the ^{230}Th production rate was divided into contributions for the production of ^{226}Ra in the near field due to radioactive decay and the transfer rate of ^{230}Th into the far field. This simplification has the effect of increasing the radionuclide amounts in the compartments at short times but does not influence the steady state results. Because the steady-state results are used, model comparison results are not altered by this simplification. Parameter descriptions are provided in Table A-1.

The differential equation for the $FF_{Th}(t)$ compartment is

$$\frac{dFF_{\mathrm{Th}}(t)}{dt} = \frac{g_{\mathrm{Th}}}{\lambda_{\mathrm{Th}} + g_{\mathrm{Th}}} P - (\lambda_{\mathrm{Th}} + h_{\mathrm{Th}})\, FF_{\mathrm{Th}}(t). \qquad \text{(A-22)}$$

Due to the similarity of Eq. (A-22) to Eq. (A-1), the solution form of Eq. (A-8) is applied. The solution for the amount of ^{230}Th in the near field over time for Model 2 is

$$FF_{\mathrm{Th}}(t) = \frac{g_{\mathrm{Th}}}{(\lambda_{\mathrm{Th}} + g_{\mathrm{Th}})(\lambda_{\mathrm{Th}} + h_{\mathrm{Th}})} P\left[1 - e^{-(\lambda_{\mathrm{Th}} + h_{\mathrm{Th}})t}\right]. \qquad \text{(A-23)}$$

The differential equation for the $NF_{Ra}(t)$ compartment is

$$\frac{dNF_{\mathrm{Ra}}(t)}{dt} = \frac{\lambda_{\mathrm{Th}}}{\lambda_{\mathrm{Th}} + g_{\mathrm{Th}}} P - (\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}})\, NF_{\mathrm{Ra}}(t). \qquad \text{(A-24)}$$

Based on similarities of Eq. (A-24) to Eq. (A-1), the solution form of Eq. (A-8) is applied again. The solution for the amount of ^{226}Ra in the near field over time for Model 2 is

$$NF_{\mathrm{Ra}}(t) = \frac{\lambda_{\mathrm{Th}}}{(\lambda_{\mathrm{Th}} + g_{\mathrm{Th}})(\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}})} P\left[1 - e^{-(\lambda_{\mathrm{Ra}} + g_{\mathrm{Ra}})t}\right]. \qquad \text{(A-25)}$$

The differential equation for the $FF_{Ra}(t)$ compartment is

$$\frac{dFF_{\mathrm{Ra}}(t)}{dt} = g_{\mathrm{Ra}}\, NF_{\mathrm{Ra}}(t) + \lambda_{\mathrm{Th}} FF_{\mathrm{Th}}(t) - (\lambda_{\mathrm{Ra}} + h_{\mathrm{Ra}})\, FF_{\mathrm{Ra}}(t). \qquad \text{(A-26)}$$

Eqs. (A-23) and (A-25) are substituted into Eq. (A-26) and arranged into the general form of the differential equation and its solution in Eqs. (A-2) and (A-3) to yield

$$FF_{\mathrm{Ra}}(t)\, e^{\int(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})dt} = \frac{g_{\mathrm{Ra}}\,\lambda_{\mathrm{Th}}\,P}{(\lambda_{\mathrm{Th}}+g_{\mathrm{Th}})(\lambda_{\mathrm{Ra}}+g_{\mathrm{Ra}})}\int\left[1-e^{-(\lambda_{\mathrm{Ra}}+g_{\mathrm{Ra}})t}\right]e^{\int(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})dt}\,dt + \frac{g_{\mathrm{Th}}\,\lambda_{\mathrm{Th}}\,P}{(\lambda_{\mathrm{Th}}+g_{\mathrm{Th}})(\lambda_{\mathrm{Th}}+h_{\mathrm{Th}})}\int\left[1-e^{-(\lambda_{\mathrm{Th}}+h_{\mathrm{Th}})t}\right]e^{\int(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})dt}\,dt \quad \text{(A-27)}$$

and partially integrated to obtain

$$FF_{\mathrm{Ra}}(t)\, e^{(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})t} = \frac{g_{\mathrm{Ra}}\,\lambda_{\mathrm{Th}}\,P}{(\lambda_{\mathrm{Th}}+g_{\mathrm{Th}})(\lambda_{\mathrm{Ra}}+g_{\mathrm{Ra}})}\int\left[e^{(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})t}-e^{(h_{\mathrm{Ra}}-g_{\mathrm{Ra}})t}\right]dt + \frac{g_{\mathrm{Th}}\,\lambda_{\mathrm{Th}}\,P}{(\lambda_{\mathrm{Th}}+g_{\mathrm{Th}})(\lambda_{\mathrm{Th}}+h_{\mathrm{Th}})}\int\left[e^{(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})t}-e^{(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}-\lambda_{\mathrm{Th}}-h_{\mathrm{Th}})t}\right]dt. \quad \text{(A-28)}$$

Completing the integration yields

$$FF_{\mathrm{Ra}}(t)e^{(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})t} = \frac{g_{\mathrm{Ra}}\,\lambda_{\mathrm{Th}}\,P}{(\lambda_{\mathrm{Th}}+g_{\mathrm{Th}})(\lambda_{\mathrm{Ra}}+g_{\mathrm{Ra}})}\left[\frac{e^{(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})t}}{\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}}-\frac{e^{(h_{\mathrm{Ra}}-g_{\mathrm{Ra}})t}}{h_{\mathrm{Ra}}-g_{\mathrm{Ra}}}\right] + \frac{g_{\mathrm{Th}}\,\lambda_{\mathrm{Th}}\,P}{(\lambda_{\mathrm{Th}}+g_{\mathrm{Th}})(\lambda_{\mathrm{Th}}+h_{\mathrm{Th}})}\left[\frac{e^{(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})t}}{\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}}-\frac{e^{(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}-\lambda_{\mathrm{Th}}-h_{\mathrm{Th}})t}}{\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}-\lambda_{\mathrm{Th}}-h_{\mathrm{Th}}}\right]+C. \quad \text{(A-29)}$$

The boundary condition, $FF_{\mathrm{Ra}}(t) = 0$ at $t = 0$, is applied to solve for C,

$$C = \frac{g_{\mathrm{Ra}}\,\lambda_{\mathrm{Th}}\,P}{(\lambda_{\mathrm{Th}}+g_{\mathrm{Th}})(\lambda_{\mathrm{Ra}}+g_{\mathrm{Ra}})}\left[\frac{-1}{\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}}-\frac{-1}{h_{\mathrm{Ra}}-g_{\mathrm{Ra}}}\right] + \frac{g_{\mathrm{Th}}\,\lambda_{\mathrm{Th}}\,P}{(\lambda_{\mathrm{Th}}+g_{\mathrm{Th}})(\lambda_{\mathrm{Th}}+h_{\mathrm{Th}})}\left[\frac{-1}{\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}}-\frac{-1}{\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}-\lambda_{\mathrm{Th}}-h_{\mathrm{Th}}}\right]. \quad \text{(A-30)}$$

The combination of Eqs. (A-29) and (A-30) results in

$$FF_{\mathrm{Ra}}(t)e^{(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})t} = \frac{g_{\mathrm{Ra}}\,\lambda_{\mathrm{Th}}\,P}{(\lambda_{\mathrm{Th}}+g_{\mathrm{Th}})(\lambda_{\mathrm{Ra}}+g_{\mathrm{Ra}})}\left[\frac{e^{(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})t}-1}{\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}}-\frac{e^{(h_{\mathrm{Ra}}-g_{\mathrm{Ra}})t}-1}{h_{\mathrm{Ra}}-g_{\mathrm{Ra}}}\right] + \frac{g_{\mathrm{Th}}\,\lambda_{\mathrm{Th}}\,P}{(\lambda_{\mathrm{Th}}+g_{\mathrm{Th}})(\lambda_{\mathrm{Th}}+h_{\mathrm{Th}})}\left[\frac{e^{(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})t}-1}{\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}}-\frac{e^{(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}-\lambda_{\mathrm{Th}}-h_{\mathrm{Th}})t}-1}{\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}-\lambda_{\mathrm{Th}}-h_{\mathrm{Th}}}\right]. \quad \text{(A-31)}$$

The solution for the amount of ^{226}Ra in the far field over time for Model 2 is

$$FF_{\mathrm{Ra}}(t) = \frac{g_{\mathrm{Ra}}\,\lambda_{\mathrm{Th}}\,P}{(\lambda_{\mathrm{Th}}+g_{\mathrm{Th}})(\lambda_{\mathrm{Ra}}+g_{\mathrm{Ra}})}\left[\frac{1-e^{-(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})t}}{\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}}-\frac{e^{-(\lambda_{\mathrm{Ra}}+g_{\mathrm{Ra}})t}-e^{-(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})t}}{h_{\mathrm{Ra}}-g_{\mathrm{Ra}}}\right] + \frac{g_{\mathrm{Th}}\,\lambda_{\mathrm{Th}}\,P}{(\lambda_{\mathrm{Th}}+g_{\mathrm{Th}})(\lambda_{\mathrm{Th}}+h_{\mathrm{Th}})}\left[\frac{1-e^{-(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})t}}{\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}}-\frac{e^{-(\lambda_{\mathrm{Th}}+h_{\mathrm{Th}})t}-e^{-(\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}})t}}{\lambda_{\mathrm{Ra}}+h_{\mathrm{Ra}}-\lambda_{\mathrm{Th}}-h_{\mathrm{Th}}}\right]. \quad \text{(A-32)}$$

Comparison of Model Results for Long Timeframes

Steady-state behaviour was used to model the long-term build-up within the model compartments. Steady state is reached as t increases. Times required to reach steady state depend on the exponential terms in the solutions. For the comparisons presented in this report, state steady is reached well within 1 million years, the simulation time used for demonstrating repository performance. The steady-state solution for the flux of ^{226}Ra into the biosphere for Model 1 was calculated by multiplying h_{Ra} with $FF_{Ra}(t)$ in Eq. (A-21) as t approaches infinity:

$$\text{Model 1 Steady-State } ^{226}\text{Ra Flux into Biosphere} = \frac{g_{Ra}\, h_{Ra}\, P}{(\lambda_{Ra} + g_{Ra})(\lambda_{Ra} + h_{Ra})}. \quad \text{(A-33)}$$

The steady-state solution for the flux of ^{226}Ra into the biosphere for Model 2 was calculated by multiplying h_{Ra} with $FF_{Ra}(t)$ in Eq. (A-32) as t approaches infinity:

$$\text{Model 2 Steady-State } ^{226}\text{Ra Flux into Biosphere} = \frac{h_{Ra}\, \lambda_{Th}\, P}{(\lambda_{Ra} + h_{Ra})(\lambda_{Th} + g_{Th})}\left[\frac{g_{Ra}}{(\lambda_{Ra} + g_{Ra})} + \frac{g_{Th}}{(\lambda_{Th} + h_{Th})}\right]. \quad \text{(A-34)}$$

The ratio of steady-state solutions for ^{226}Ra flux into the biosphere is used to compare the results of the models:

$$\frac{\text{Model 2 Steady-State } ^{226}\text{Ra Flux into Biosphere}}{\text{Model 1 Steady-State } ^{226}\text{Ra Flux into Biosphere}} = \frac{\lambda_{Th}}{(\lambda_{Th} + g_{Th})}\left[1 + \frac{(\lambda_{Ra} + g_{Ra})g_{Th}}{g_{Ra}(\lambda_{Th} + h_{Th})}\right]. \quad \text{(A-35)}$$

Figure A-1. Compartment diagram for model without thorium transport (Model 1)

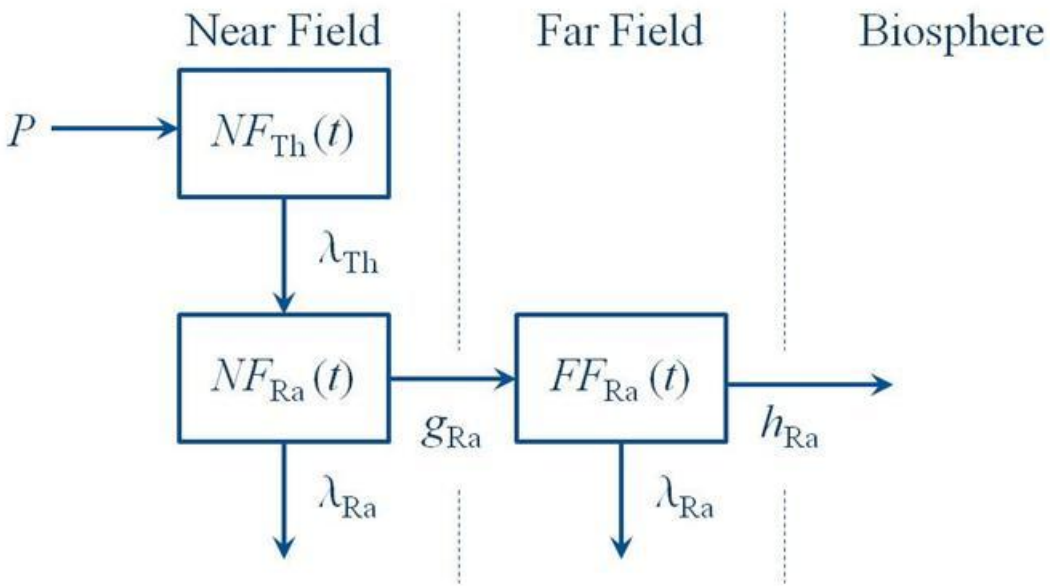
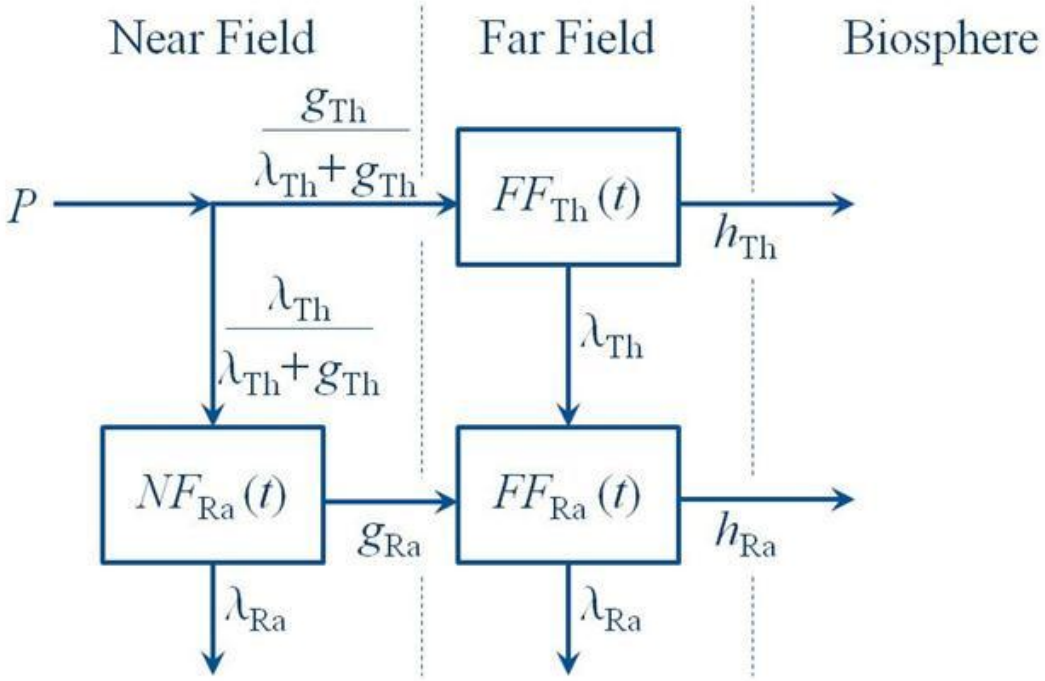


Figure A-2. Compartment diagram for model with thorium transport (Model 2)



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T he Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 270 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

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