Scientific Notebook - Secular Equilibrium Assumption Analysis

John Bradbury, 2010

Additional information was requested from DOE with regard to the assumption made in the DOE model of radionuclide transport in the saturated zone that the activity of some decay products can be set equal to that of their parents. The text of the Request for Additional Information (RAI) is given below:

> **RAI Volume 3, Chapter 2.2.1.3.9, First Set, Number 1:** Justify the assumption that setting the activity of non-simulated radionuclide decay products in the aqueous phase to be equal to the activity of aqueous-phase parent radionuclides does not underestimate aqueous-phase activity.
>
> Basis: In its saturated zone radionuclide transport model, the applicant simulates the transport of various radionuclide species in the aqueous phase. The radionuclides are subject to various processes, such as sorption, filtration, and matrix diffusion that attenuate their activity in groundwater. During transport simulations, these radionuclides are allowed to radiodecay and produce daughter products. Only a subset of the daughter products is directly simulated, however. The activities of the non-simulated daughter products are assumed, in the model, to be equivalent to the activity of the parent radionuclide in the aqueous phase. Sorption, along with filtration and matrix diffusion can result in accumulation of radionuclides in the alluvial aquifer. These accumulated radionuclides will also decay, in addition to those radionuclides in the aqueous phase, to produce daughter radionuclides. The radioactive decay of parents accumulated in the alluvium can produce daughters whose activity in the ground water can exceed those of the dissolved parents, depending upon their sorption coefficients relative to that of the parent. Furthermore, the applicant has acknowledged that sorption coefficient distributions have been biased to lesser values than suggested from experimental evidence. An underestimation of sorption coefficients could lead to smaller quantities of accumulated radionuclides and lower doses.
>
> The staff needs this information to determine whether radionuclide accumulation and decay products could result in an underprediction of radionuclide concentrations in groundwater. The staff needs information on the contribution to dose from accumulated radionuclides in the alluvial aquifer system to evaluate compliance with 10 CFR Part 63.114 (a)(3) and 63.311.

Background

DOE states that in the saturated-zone one-dimensional transport model (SAR 2.3.9.3.4.2.1),

> …the radionuclide decay chain analysis is simplified in a manner that overestimates the concentration of daughter product by calculating secular equilibrium between the final decay products and their parents in three of these chains (SNL 2008b, Section 6.5.1.2). ^{227}Ac is in secular equilibrium with ^{231}Pa in the actinium chain at the downstream end of the saturated zone analysis. ^{228}Ra is in secular equilibrium with ^{232}Th in the thorium series. ^{210}Pb is in secular

equilibrium with ^{226}Ra in the uranium series. [Note: reference above to "SNL, 2008b" is listed as SNL, 2007, in the reference list to this notebook]

Instead of simulating the transport of these daughter products through the saturated zone, DOE set their activities equal to the activities in the groundwater of their respective parents at the accessible environment boundary.

DOE applied this assumption not only to the three daughters described above, namely, ^{227}Ac, ^{228}Ra, and ^{210}Pb, but to all short-lived radionuclides in each decay chain in the biosphere model. DOE defined short-lived radionuclides as those with half-lives of 180 days or less. The dose contribution of short-lived decay products was included in the Biosphere Dose Conversion Factor (BDCF) for the primary radionuclide through the effective dose coefficients for external exposure, inhalation, and ingestion that were developed for primary radionuclides and used to calculate annual dose (Table 2.3.10-6 to 2.3.10-9) (SNL, 2007, Section 6.3.5). DOE defined primary radionuclides as those meeting the criteria of a radionuclide screening analysis (SAR 2.3.7.4.1.2). DOE stated that there would be greater than 100 radionuclides contained in the waste packages. However, "many of the radionuclides have short half-life, low solubility and/or strongly sorbing characteristics, or are present in small quantities. Therefore, such radionuclides cannot be significant contributors to estimated dose. As a result, only a small subset of radionuclides needs to be considered in the evaluation of repository post-closure performance, and calculation of risk from that subset of radionuclides will result in essentially the same risk as would a calculation that includes all radionuclides" (SAR 2.3.7.4.1.2). The small subset is comprised of the radionuclides that DOE terms "primary."

Table 1 is modified from Table 2.3.10-9 of the Biosphere chapter of the SAR dealing with dose from ingestion. There are comparable tables in the Biosphere chapter that list the dose conversion factors for the same radionuclides stemming from inhalation, and exposure to contaminated ground surface. The DOE simulated the transport of all the primary radionuclides listed in Table 1 except ^{227}Ac, ^{228}Ra, ^{210}Pb and ^{228}Th. Consequently, 27 radionuclides are transported through the saturated zone from beneath the repository to the accessible environment boundary. It is to these 27 radionuclides that sorption coefficients have been assigned by DOE, partitioning the radionuclides between solid and ground water in the saturated zone. There are 75 radionuclides listed in Table 1 to which the receptor can be exposed. Thus, sorption coefficients, partitioning radionuclides between solid and groundwater in the saturated zone are not assigned to (75 – 27) or 48 radionuclides.

In the response to the RAI, DOE described the effects of sorption coefficients on four parent-daughter pairs – $^{226}Ra/^{210}Pb$, $^{231}Pa/^{227}Ac$, $^{232}Th/^{228}Ra$, and $^{226}Ra/^{222}Rn$. DOE concluded that the effects were not risk significant for these four parent-daughter pairs. However, DOE did not describe the effects of sorption coefficients of other parent-daughter pairs in the decay series on radionuclide concentrations.

In the Biosphere model, DOE assumed that the concentration of primary radionuclides is 1 Bq/m^3 in the ground water (SAR 2.3.10, Table 2.3.10-10). Likewise, the concentration of every decay product of the primary radionuclide is also assumed to be 1 Bq/m^3 in the ground water. DOE adds the contribution of dose from the decay products to the dose from the primary radionuclide to yield an effective dose coefficient for each primary radionuclide. DOE accounts for the branching of certain decay product by multiplying the dose coefficient by the branching percentage before the summation. This approach does not consider the sorption enhancement factors (SEFs) of the decay products. The SEF is defined by DOE in the response to RAI as the ratio of the sorption coefficient of the parent to that of the daughter. Multiplying the concentration

of the long-lived parent radionuclide in ground water by the SEF yields the concentration of the short-lived daughter.

For example, the mass of plutonium that crosses the accessible environment boundary is but a small fraction of the mass that sorbs to the solids at the location of the receptor and at every point of the flow path. The plutonium retardation factor is the measure of the ratio of the mass of plutonium on the solid to that in the ground water in the aquifer, when the proportions of solids and liquids are considered. Given a plutonium Kd of 100 mL/g, bulk density of 2 g/cm^3 and a porosity of 0.2, the retardation factor is 1000. There is 1000 times more plutonium on the solid than is in the ground water. The decay of this additional mass can contribute to the production of daughters.

GoldSim, with its capability to simulate transport through the alluvium with sorption and radioactive decay and ingrowth, was used by DOE in the TSPA. DOE assumed that all daughters with half-lives shorter than 180 days were in secular equilibrium with their parents. Consequently, these short-lived daughters were not included in the transport simulations performed by DOE, nor were they assigned Kds.

The GoldSim pipe element does not handle solubility limits, or precipitation-dissolution reactions. The DOE provided evidence for excluding precipitation-dissolution reactions from the saturated zone in their performance assessment. Consequently, the use of the pipe element to simulate transport is appropriate. The DOE's performance assessment considered radionuclide flux through the saturated zone, i.e., g/yr input and g/yr output. Concentration of radionuclides in the pipe was not considered by DOE. Since there were not solubility limits, concentration was unimportant. Furthermore, DOE argued that linear sorption isotherms were an appropriate and conservative simplification in their model abstraction. With this assumption, concentration did not affect Kds. As long as the time it takes for water to travel from beneath the repository to the accessible environment is appropriate, the size of the pipe does not matter. For example, if two pipes, one large and one small have the same input flux of radionuclides, the concentrations in the smaller pipe are greater than those in the larger pipe, but the fluxes of radionuclides out the pipes are the same. If the Kds were dependent on concentration, the size of the pipe would have been important. In DOE's model there are 4 pipes, each with cross-sectional area of only 3.338 m^2, compared to the cross-sectional area of the plume, which DOE estimates would be 435,000 m^2, as described in the response to RAI 3.2.2.1.4.3-1 (DOE, 2009a). Consequently, the concentrations of radionuclides in the pipe elements are 435,000/(4*3.338) or about 33,000 times greater than in the plume. Given the conditions that precipitation-dissolution reactions do not occur and the Kds are constant, the pipe element is an appropriate tool in simulating transport.

In response to the RAI 3.2.2.1.3.9-1 (DOE, 2009b), DOE acknowledged that sorption affects radionuclide concentrations. For the 4 pairs, DOE compared the distributions of sorption coefficients for the parent and its daughter. The mean SEFs were calculated. For ^{226}Ra/^{210}Pb the mean SEF is 1.1; for ^{231}Pa/^{227}Ac, the mean SEF is 6.8; for ^{232}Th/^{228}Ra, the mean SEF is 14; and for ^{226}Ra/^{222}Rn, the mean SEF is 3500. DOE adjusted the SEF for ^{226}Ra/^{222}Rn by multiplying by an emanation factor whose mean value is 0.4. DOE determined that the resulting mean net enhancement factor for radon is 1406. The activity concentration of the parent is multiplied by the SEF, or NEF, in the case of radon, to give the activity concentration of the daughter.

Distributions of Sorption Coefficients

The DOE states in the SAR 2.3.9.3.2.3 that final Kd distributions used in TSPA, which were developed from the results of the batch experiments, are biased to values lower than expected in the saturated zone. The potential issue that biasing Kd to lower values might result in an underestimation of radionuclide concentrations was identified in RAI 3.2.2.1.3.9-1. The DOE response to the RAI did not include a discussion of biasing Kds.

The value of the net enhancement factor for ^{222}Rn provided by DOE, which depends upon the Kd for ^{226}Ra, is based on non site-specific conditions. However, concentrations of ^{226}Ra and ^{222}Rn measured in ground water in the Yucca Mountain vicinity can supply the NEF directly. La Camera and Westenburg (1994) describe ^{226}Ra concentrations and ^{222}Rn concentrations in waters in the Yucca Mountain vicinity sampled from 1990 to 1992. J-13 well water had an NEF of 10,000; J-12 well water had an NEF of 16500. The mean of all twenty-nine samples measured by La Camera and Westenburg (1994) which are located as far away as the springs in Death Valley is determined to be 7790, as compared with the DOE estimate of 1406.

Method

The effects of sorption coefficients on the concentrations and fluxes in the alluvial aquifer of parent-daughter pairs, to which the receptor could be exposed are evaluated in this study. In addition, the effect of biasing Kds to lower values on radionuclide concentrations is addressed in this notebook.

The conceptual model used in these analyses has the pipe element extend to the inlet to the receptor's well. The 1-D transport simulations include radionuclides whose half-lives are long enough to travel from the bottom of the receptor's well in the saturated zone of the alluvium to the receptor for ingestion and contribute to dose. Radionuclides with half-lives of greater than 1 hour that could potentially contribute to dose were considered in these 1-D simulations. Radionuclides with half-lives of 1 hour or less are screened from these analyses. This approach eliminates from consideration 25 radionuclides of the 75 radionuclides included in Table 1. Note that the radionuclide concentration the receptor can ingest depends not only on the half-life of the radionuclide, but also on its concentration at the end of the pipe. This, in turn, depends on the total mass of the parent at the end of the pipe and the Kd of the daughter.

Figure 1 shows the model used for simulating transport of radionuclides of the uranium series through the alluvial aquifer (File name: variable_input_U_ pipe.gsm). The processes included in the model are advection, sorption/desorption, and radioactive decay and ingrowth. The pipe is 7574 m long and has a cross-sectional area of 3.33387 m^2. The porosity of the pipe is 0.1497. The flow rate is 6.7184e-7 m^3/s. With these values for length, cross-sectional area, porosity and flow rate, comparable to values used in the TSPA, the time it takes for water to flow through the pipe is 178 years. Dispersivity in the pipe is 219.887 m.

The radionuclide input to the pipe comes from TSPA runs performed by DOE to address NRC request for additional analysis of postclosure groundwater impacts in its Supplemental Environmental Impact Statement. These runs were performed to generate information to be used by DOE's contractor, Jason Associates Corporation. This contractor

> … requested the mean, median, 95th percentile, and 5th percentile values of annual radionuclide mass release rate and cumulative release for the 300 realizations in TSPA–LA. The annual mass release rates and cumulative releases were requested for sum of the 1,000,000-year groundwater dose modeling cases (Drip Shield Early Failure, Waste Package Early Failure, Igneous

Intrusion, Seismic Ground Motion, and Seismic Fault Displacement) and for the 1,000,000-year Nominal Modeling case alone. This information was provided at the boundary between the unsaturated zone and the saturated zone and at the accessible environment for the 49 radionuclide species, including multiple colloidal forms, tracked in the TSPA-LA Model.

As the data at the unsaturated zone and saturated zone boundary were not saved when running the TSPA-LA Model for the license application documentation, the simulations had to be re-run for this analysis. The TSPA-LA Model v5.005 was updated to automatically export the unsaturated zone and saturated zone release information. Specifically, time history results elements that export calculated results to text files were added for the mass flux rates and cumulative releases from the Engineered Barrier System (EBS), unsaturated zone, and saturated zone. Time history elements were added for the 49 radionuclide species tracked in the TSPA-LA Model. In addition, release rates for dissolved and colloidal isotopes ("Ic," "If," and "Ifcp") were added together to yield one release history per isotope. For each of the five 1,000,000-yr groundwater dose modeling cases, the models were re-run to export the time history results. Dose comparisons were made to confirm that the calculations agree with the compliance runs. The results were then processed through EXDOC_LA v2.0 (Table 2) to yield expected quantities for each epistemic realization. Once the expected quantities for each epistemic realization were calculated, the values were summed together over all modeling cases to yield a total release history. The summation files are *Read_Histories_Calc_RN_Total_UZ_Flux_2021.gsm* and *Read_Histories_Calc_RN_Total_SZ_Flux_2021.gsm*. Mean, 5th percentile, median, and 95th percentile values were then reported at selected time steps for the annual mass release rates and cumulative releases at the unsaturated zone/saturated zone boundary and at the accessible environment. The Nominal Modeling Case was also re-run to export release histories at the unsaturated zone/saturated zone boundary and at the accessible environment. (Sandia, 2009, p 12; in DOE, 2009c).

Cumulative flux at the UZ/SZ boundary versus time was used as input to the pipe simulations. This data is contained in the MS Excel file, EIS_UZ_TimeStep_Resolution_Fractional_Basis.xls (DOE, 2009c; file path \Rad1\ EIS_UZ_TimeStep_Resolution_Fractional_Basis.xls).

Uranium Series

Although only five radionuclides (^{242}Pu, ^{238}U, ^{234}U, ^{230}Th and ^{226}Ra) enter the pipe at the upstream inlet, eleven radionuclides are included in the transport model. The cumulative masses of the five radionuclides entering the pipe for the 1 MY simulations are 169 kg ^{242}Pu, 198,000 kg ^{238}U, 28.9 kg ^{234}U, 7.45 kg ^{226}Ra, and 27.8 kg ^{230}Th. The additional radionuclides are ingrown from the decay of the parents. The additional radionuclides are ^{234}Th, ^{234}Pa, ^{222}Rn, ^{210}Pb, ^{210}Bi, and ^{210}Po. The input of the five radionuclides to the pipe varies over time. The mean of time-dependent flux from the unsaturated zone to saturated zone (Sandia, 2009) is used instead of the flux from the volcanic aquifer to the alluvial aquifer, which is not available from the TSPA simulations. The difference in flux at the two locations is considered insignificant, because there is relatively little attenuation capacity of the volcanic aquifer, as demonstrated by DOE.

Transport simulations were performed deterministically instead of stochastically to help understand the effects of varying parameter values on the system, which is complicated by multiple processes occurring at different spatial and temporal scales.

In the first simulation, Kd values consistent with the midrange values of the distributions in the TSPA were used for those primary radionuclides DOE transported. The Kd values are listed in Table 2.

The radionuclides DOE transported are ^{226}Ra, ^{230}Th, ^{234}U, ^{242}Pu, ^{238}U, ^{238}Pu. As illustrated in Figure 1, ^{238}Pu is not included as one of the cumulative inputs to the pipe. The short half life of ^{238}Pu coupled with its moderately large Kd causes a reduction of the mass of this radionuclide to insignificant amounts before exiting the pipe.

As an extreme of the sensitivity analysis Kd values for ^{222}Rn, ^{210}Bi, and ^{210}Po were chosen that reflect minimal sorption of these radionuclides on alluvial solids. The DOE did not determine the Kds for these radionuclides, nor did they utilize literature values of non-site-specific Kds for these radionuclides. Figure 2 illustrates the activity released per year as a function of time through the regulatory period up to 1MY. Dashed lines represent the time dependent output flux from the pipe of those radionuclides that entered into the pipe at the inlet. Solid lines are ingrown radionuclides considered in the transport simulation. One feature of this graph that should be noted is that there is a tendency for all of the radionuclide releases to approach a steady state over the first 100 to 200 Kyrs. Subsequently, the fluxes change little over the remaining 800 Kyrs at the receptor's location. Another feature of this graph is the positions of the flux curves strongly depend on the Kds. Small Kds of the ingrown radionuclides tend to yield high fluxes and large Kds tend to yield low fluxes. The order of radionuclides released from highest activity flux to lowest is ^{222}Rn, ^{210}Po, ^{210}Bi, ^{242}Pu, ^{234}U, ^{238}U, ^{210}Pb, ^{226}Ra, ^{230}Th, ^{234}Th, ^{234}Pa. In contrast, DOE determined that ^{242}Pu would be the greatest contributor to dose. The activity flux of ^{222}Rn is 46 times greater than that of ^{242}Pu; the activity flux of ^{210}Po is 20 times greater than ^{242}Pu; the activity released of ^{210}Bi is 3 times greater than ^{242}Pu. As the Kd of the daughter decreases by orders of magnitude toward zero, the daughter's activity flux increases by orders of magnitude. The limit is the activity flux of Rn, with its assumed Kd of zero. The significance of this observation is that small uncertainties in experimentally determining small Kds could produce large uncertainties in activity fluxes of ingrown daughters.

The dose per year from drinking contaminated water can be calculated using the equation below:

$$Dose\ \left(\frac{mrem}{yr}\right) = \left(Flux\ \left(\frac{Ci}{yr}\right)\right)\left(\frac{1e12pCi}{Ci}\right)\left(\frac{1Bq}{27pCi}\right)\left(\frac{1yr}{3.7e9L}\right)\left(\frac{730L}{yr}\right)\left(Dose\ Coefficient\ \left(\frac{Sv}{Bq}\right)\right)\left(\frac{1e5mrem}{Sv}\right)$$

The ingestion dose coefficient for ^{222}Rn of 3.5 nSv/Bq is provided in the DOE response to RAI 3.2.2.1.3.9-001 p. 28. Other dose coefficients come from Table 2.3.10-9 of the Biosphere Chapter of the SAR. The ingestion dose coefficient for ^{210}Po is 1.21 μSv/Bq. The ingestion dose coefficient for ^{242}Pu is 0.238 μSv/Bq. This equation converts the output of the simulation, flux in units of curies /year, into dose in units of mrem/year. On the right side of the equation, the second term converts curies to picocuries; the third term converts picocuries to bequerels; the fourth term introduces the condition that the radionuclides are dissolved in 3000 acre feet (=3.7e9 L) of water, the annual water demand; the fifth term represents that the RMEI drinks 2 L

per day or 730 L per year; the sixth term is the dose coefficient, whose source is described above; and the seventh term converts sieverts to mrem. This equation does not consider dose from ingesting contaminated material other than drinking water. Other ingestion pathways are considered to take longer for radionuclides to travel from the aquifer to the receptor's mouth. For this simulation the ingestion dose from ^{222}Rn is 0.068 mrem/yr; the dose from ^{210}Po is 10 mrem/yr; dose from ^{242}Pu is 0.099 mrem/yr. The order of the radionuclides ranked from highest to lowest in terms of dose, is ^{210}Po, ^{242}Pu, ^{222}Rn, ^{234}U, ^{238}U, ^{210}Pb, ^{210}Bi, ^{226}Ra, ^{230}Th, ^{234}Th, and ^{234}Pa.

Vandenhove et al (2009) provide new best estimates for the Kd values for the members of the uranium series. They state that "Kd values were generally about 10-fold higher for Ra, Pb and Th than for Po and U..." They conclude that "Whatever the classification system applied, Kd estimates are associated with large uncertainties. Proposed best estimates, mostly derived from the GM (geometric mean) values, may be suitable for screening assessments, but more site specific Kd values will be required for predicting effective impact." Table 3 lists the Kd values from Vandenhove et al 2009 which are used in the same 1D transport model as shown in Figure 1. The results are illustrated in Figure 3.

Note that the ^{242}Pu flux is still increasing at 1MY due to its larger Kd. However, it is not the ^{242}Pu that is controlling the flux of the other radionuclides. It is the ^{234}U and ^{238}U, which, because of their low Kds, have reached the outlet and supply a constant mass at that location. Their daughters can then ingrow and contribute to the activities released depending on their Kds.

Comparing Figure 3 with Figure 2 illustrates the importance of low Kd for daughters. The potential exists that the daughters can be the largest contributors of radioactivity released. By increasing the Kd of ^{210}Po to 100 mL/g, the flux of ^{210}Po decreases to a value comparable to that of ^{234}U, approximately 10^{-4} Ci/yr. At this level, ^{210}Po is relatively risk insignificant.

Sorption Heterogeneity

Alluvial pipe elements of the TSPA were up to 7500 m long. The pipe elements are considered homogeneous over that distance in terms of sorptive material. Each element transport through the pipe is assigned a single constant Kd. Heterogeneity of sorptive capacity in the alluvium might result in higher concentrations because of the local ingrowth of secondary radionuclides. The model described above and illustrated in Figure 1 was modified to include a second pipe element downstream of the first, which is 200 m long and contains alluvial solid material with Kds the same as listed in Table 2 except for the Kd for uranium which is increased to 200 mL/g. This value is within the range of effective Kds described for uranium in Appendix J of the Site-Scale Saturated Zone Transport AMR (SNL, 2008).

Results of the modified simulation (File name: variable_input_U_2_pipes.gsm) are displayed in Figure 4. The flux from the more sorptive pipe of the radionuclides ingrown from the decay of ^{234}U is 12 times greater than from the pipe segment with the smaller U Kd. Consequently, ^{222}Rn is 607 times greater than ^{242}Pu; ^{210}Po is 243 times greater; and ^{210}Bi is 41 times greater. The significance of this result is that increased fluxes of daughters can occur locally due to the increased sorption of parents. For this simulation the ingestion dose from ^{222}Rn is 0.864 mrem/yr; the dose from ^{210}Po is 120 mrem/yr; dose from ^{242}Pu is 0.099 mrem/yr.

Possible Natural Analog

Seiler (2010) describes ^{210}Po as a highly toxic alpha emitter whose concentration in groundwater rarely exceeds 1 pCi/L. However, Seiler 2010 has found ^{210}Po activity concentrations in groundwater in Lahontan Valley, near Fallon, Churchill County, Nevada that exceed the activity concentrations of its dissolved parents in the uranium series. The ^{210}Po activities range from 0.01± 0.005 to 178 ±16 pCi/L.

Appendix A describes an analysis of the groundwaters of Lahontan Valley to estimate sorption coefficients of uranium decay series radionuclides consistent with their activity concentrations. Sorption coefficients for ^{210}Po range from 0.4 to 1268 mL/g; sorption coefficients for ^{234}U range from 0.5 to 1620 mL/g.

Neptunium Series

The same simulations for the neptunium series were performed as for the uranium series. The GoldSim model for neptunium series transport is the same as in Figure 1, except the cumulative inputs are for the radionuclides, ^{241}Am, ^{237}Np, ^{233}U, and ^{229}Th. Table 4 lists the Kds for the radionuclides considered in this simulation. Radionuclides in this series with half-lives of an hour or less are not included in this simulation. Results of the modified simulation (File name: variable_input_Np_pipes.gsm) are displayed in Figure 5.

The relatively small Kds for ^{237}Np and ^{233}U result in high fluxes of these radionuclides. The high Kds for the ingrown daughters depress their fluxes. In this case, assuming secular equilibrium of the three daughters with ^{229}Th is nonconservative, but as illustrated in Figure 5, the fluxes of these radionuclides are significantly less than that of the ^{237}Np and ^{233}U and so contribute little to risk.

The simulation was modified to determine the effect of large local Kds for transported radionuclides. The Figure 6 shows the modifications of the model (Filename: variable_input_Np_2_pipes.gsm).

The downstream pipe is 200 m long and contains solids that more strongly sorb neptunium and uranium consistent with the range of effective Kds described for uranium in Appendix J of the Site-Scale Saturated Zone Transport AMR (SNL, 2007). Table 5 lists the sorption coefficients applied to the downstream pipe element.

Figure 7 illustrates that the daughter fluxes can become significant if their Kds are less than that of the transported parents. For comparison, ^{237}Np is the second largest contributor to dose in TSPA. The ^{225}Ra and ^{225}Ac curves, which lie on top of each other, slightly exceed the flux of ^{237}Np after 600 Kyrs.

Actinium Series

The same simulations for the actinium series were performed as for the uranium and neptunium series. The GoldSim model for actinium series transport is the same as in Figure 1, except the cumulative inputs are for the radionuclides, ^{243}Am, ^{239}Pu, ^{235}U, and ^{231}Pa. Table 6 lists the sorption coefficients applied to the pipe element.

As illustrated in Figure 8, the source of ^{239}Pu disappears after some time producing an outlet curve with a peak at 200 Kyrs. The large sorption coefficients for ^{243}Am and ^{231}Pa result in very small concentrations at the outlet.

One-dimensional transport was simulated in two pipes in series similar to the model illustrated in Figure 6. The downstream pipe is 200 m long and contains solid that is more sorptive for uranium (Kd =200 mL/g) and less sorptive for actinium (Kd = 100 mL/g). (Filename: variable_input_Ac_2_pipes.gsm)

Note that in Figure 9 the actinium concentration now exceeds that of ^{235}U, but only by a small amount. For comparison, ^{235}U is a relative minor contributor to dose in TSPA.

Thorium Series

The same simulations for the thorium series were performed as for the uranium, neptunium and actinium series. The GoldSim model for thorium series transport is the same as in Figure 1, except the cumulative inputs are for the radionuclides, ^{240}Pu, ^{236}U, and ^{232}Th. Although ^{240}Pu, ^{236}U, and ^{232}Th are input, it is only ^{236}U that reaches the outlet. In Figure 10, the radionuclides that exit the pipe other than ^{236}U are a result of decay of ^{236}U and ingrowth of the daughters.

The decay of ^{236}U near the outlet of the pipe results in the ingrowth of ^{232}Th. For comparison, ^{236}U is a minor contributor to dose in TSPA. Consequently, increasing the daughter activities which are six orders of magnitude less than ^{236}U is insignificant.

Figure 11 shows activity flux when ^{236}U Kd is 200 mL/g and ^{228}Ac and ^{228}Ra Kds are 100 mL/g. The activity flux of the daughters has increased by an order of magnitude over those in Figure 10, but is still insignificant.

References

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Tables

Table 1. Dose Coefficients and Effective Dose Coefficients for Ingestion				
Primary Radionuclide (Half-Life, yrs)	Fractional Uptake to blood	Decay Product (Branching fraction if not 100%, Half-Life)	Dose Coefficient (Sv/Bq)	Effective Dose Coefficient (Sv/Bq)
^{14}C (5730)	1.0	-	$5.81x10^{-10}$	$5.81x10^{-10}$
^{36}Cl ($3.01x10^{5}$)	1.0	-	$9.29x10^{-10}$	$9.29x10^{-10}$
^{79}Se ($1.13x10^{5}$)	$8.0x10^{-1}$	-	$2.89x10^{-9}$	$2.89x10^{-9}$
^{90}Sr (29.12)	$3x10^{-1}$ $1x10^{-4}$	- ^{90}Y(64.0 hrs)	$2.77x10^{-8}$ $2.69x10^{-9}$	$3.04x10^{-8}$
^{99}Tc ($2.13x10^{5}$)	$5x10^{-1}$	-	$6.42x10^{-10}$	$6.42x10^{-10}$
^{126}Sn ($1.0x10^{5}$)	$2x10^{-2}$ $1x10^{-1}$ $1x10^{-1}$	- ^{126m}Sb (19.0 min) ^{126}Sb(14%, 12.4 days)	$4.77x10^{-9}$ $3.60x10^{-11}$ $2.46x10^{-9}$	$5.15x10^{-9}$
^{129}I ($1.57x10^{7}$)	1.0	-	$1.06x10^{-7}$	$1.06x10^{-7}$
^{135}Cs ($2.3x10^{6}$)	1.0	-	$2.00x10^{-9}$	$2.00x10^{-9}$
^{137}Cs (30.0)	1.0 -	- ^{137m}Ba (94.6%, 2.552 min)	$1.36x10^{-8}$ 0	$1.36x10^{-8}$
^{242}Pu ($3.763x10^{5}$)	$5x10^{-4}$	-	$2.38x10^{-7}$	$2.38x10^{-7}$
^{238}U ($4.468x10^{9}$)	$2x10^{-2}$ $5x10^{-4}$ - $5x10^{-4}$	- ^{234}Th (24.10 days) ^{234m}Pa (99.80%, 1.17 min) ^{234}Pa (0.33%, 6.7 hrs)	$4.45x10^{-8}$ $3.40x10^{-9}$ 0 $5.25x10^{-10}$	$4.79x10^{-8}$
^{238}Pu (87.74)	$5x10^{-4}$	-	$2.28x10^{-10}$	$2.28x10^{-10}$
^{234}U ($2.445x10^{5}$)	$2x10^{-2}$	-	$4.95x10^{-8}$	$4.95x10^{-8}$
^{230}Th ($7.7x10^{4}$)	$5x10^{-4}$	-	$2.14x10^{-7}$	$2.14x10^{-7}$
^{226}Ra ($1.60x10^{3}$)	$2x10^{-1}$ - - $2x10^{-1}$ - $5x10^{-2}$ - -	- ^{222}Rn (3.8235 days) ^{218}Po (3.05 min) ^{214}Pb (99.98%, 26.8 min) ^{218}At (0.02%, 2 sec) ^{214}Bi (19.9 min) ^{214}Po (99.98%, $1.64x10^{-4}$ sec) ^{210}Tl (0.02%, 1.3 min)	$2.80x10^{-7}$ 0 0 $1.39x10^{-10}$ 0 $1.12x10^{-10}$ 0 0	$2.80x10^{-7}$
^{210}Pb (22.3)	$2x10^{-1}$ $5x10^{-2}$ $5x10^{-1}$	- ^{210}Bi (5.012 days) ^{210}Po (138.38 days)	$6.96x10^{-7}$ $1.31x10^{-9}$ $1.21x10^{-6}$	$1.91x10^{-6}$
^{240}Pu ($6.537x10^{3}$)	$5x10^{-4}$	-	$2.51x10^{-7}$	$2.51x10^{-7}$
^{236}U ($2.3415x10^{7}$)	$2x10^{-2}$	-	$4.69x10^{-8}$	$4.69x10^{-8}$
^{232}Th ($1.405x10^{10}$)	$5x10^{-4}$	-	$2.31x10^{-7}$	$2.31x10^{-7}$
^{228}Ra (5.75)	$2x10^{-1}$ $5x10^{-4}$	- ^{228}Ac (6.13 hrs)	$6.97x10^{-7}$ $4.01x10^{-10}$	$6.97x10^{-7}$
^{232}U (72)	$2x10^{-2}$	-	$3.36x10^{-7}$	$3.36x10^{-7}$
^{228}Th (1.9131)	$5x10^{-4}$ $2x10^{-1}$ - - $2x10^{-1}$ $5x10^{-2}$ - -	- ^{224}Ra (3.66 days) ^{220}Rn (55.6 sec) ^{216}Po (0.15 sec) ^{212}Pb (10.64 hrs) ^{212}Bi (60.55 min) ^{212}Po (64.07%, $3.05x10^{-7}$ sec) ^{208}Tl (35.93%, 3.07 min)	$7.20x10^{-8}$ $6.45x10^{-8}$ 0 0 $5.98x10^{-9}$ $2.59x10^{-10}$ 0 0	$1.43x10^{-7}$
^{243}Am ($7.38x10^{3}$)	$5x10^{-4}$ $5x10^{-4}$	- ^{239}Np (2.355 days)	$2.03x10^{-7}$ $7.99x10^{-10}$	$2.04x10^{-7}$
^{239}Pu ($2.4065x10^{4}$)	$5x10^{-4}$	-	$2.51x10^{-7}$	$2.51x10^{-7}$
^{235}U ($7.038x10^{8}$)	$2x10^{-2}$ $5x10^{-4}$	- ^{231}Th (25.52 hrs)	$4.67x10^{-8}$ $3.36x10^{-10}$	$4.70x10^{-8}$
^{231}Pa ($3.276x10^{4}$)	$5x10^{-4}$	-	$4.79x10^{-7}$	$4.79x10^{-7}$

Primary Radionuclide	Fractional Uptake to blood	Decay Product (Branching fraction if not 100%, Half-Life)	Dose Coefficient (Sv/Bq)	Effective Dose Coefficient (Sv/Bq)
^{227}Ac (21.773)	$5x10^{-4}$ $5x10^{-4}$ 1.0 $2x10^{-1}$ - - $2x10^{-1}$ - - -	- ^{227}Th (98.62%, 18.718 days) ^{223}Fr (1.38%, 21.8 min) ^{223}Ra (11.434 days) ^{219}Rn (3.96 sec) ^{215}Po ($1.78x10^{-3}$ sec) ^{211}Pb (36.1 min) ^{211}Bi (2.14 min) ^{207}Tl (99.72 %, 4.77 min) ^{211}Po (0.28%, 0.516 sec)	$3.23x10^{-7}$ $9.02x10^{-9}$ $2.36x10^{-9}$ $1.04x10^{-7}$ 0 0 $1.78x10^{-10}$ 0 0 0	$4.36x10^{-7}$
^{241}Am (432.2)	$5x10^{-4}$	-	$2.04x10^{-7}$	$2.04x10^{-7}$
^{237}Np ($2.14x10^{6}$)	$5x10^{-4}$ $5x10^{-4}$	- ^{233}Pa (27.0 days)	$1.07x10^{-7}$ $8.78x10^{-10}$	$1.08x10^{-7}$
^{233}U ($1.585x10^{5}$)	$2x10^{-2}$	-	$5.13x10^{-8}$	$5.13x10^{-8}$
^{229}Th ($7.34x10^{3}$)	$5x10^{-4}$ $2x10^{-1}$ $5x10^{-4}$ - - $5x10^{-2}$ - - $2x10^{-1}$	- ^{225}Ra (14.8 days) ^{225}Ac (10.0 days) ^{221}Fr (4.8 min) ^{217}At ($3.32x10^{-2}$ sec) ^{213}Bi (45.65 min) ^{213}Po (97.84%, $4.2x10^{-6}$ sec) ^{209}Tl (2.16%, 2.2 min) ^{209}Pb (3.253 hrs)	$5.00x10^{-7}$ $9.95x10^{-8}$ $3.89x10^{-8}$ 0 0 $1.98x10^{-10}$ 0 0 $5.67x10^{-11}$	$6.38x10^{-7}$

Table 2.
Sorption Coefficients in GoldSim Model

Radionuclide	Kd (mL/g)
^{226}Ra	550
^{222}Rn	0
^{210}Pb	270
^{230}Th	3008
^{234}U	8.7
^{242}Pu	100
^{238}U	8.7
^{238}Pu	100
^{210}Po	0.1
^{234}Th	3008
^{234}Pa	5500
^{210}Bi	1

Table 3.
Sorption Coefficients in GoldSim Model

Radionuclide	Kd (mL/g)
^{226}Ra	3100
^{222}Rn	0
^{210}Pb	220
^{230}Th	700
^{234}U	110
^{242}Pu	540
^{238}U	110
^{238}Pu	540
^{210}Po	100
^{234}Th	700
^{234}Pa	540
^{210}Bi	120

Table 4. Sorption Coefficients in GoldSim Model Neptunium Series

Radionuclide	Kd (mL/g)
^{237}Np	8.7
^{233}U	5
^{229}Th	3008
^{225}Ra	500
^{241}Am	5500
^{233}Pa	5500
^{225}Ac	1500
^{209}Pb	270

Table 5. Sorption Coefficients in GoldSim Model Neptunium Series

Radionuclide	Kd (mL/g)
^{237}Np	300
^{233}U	200
^{229}Th	3008
^{225}Ra	100
^{241}Am	5500
^{233}Pa	5500
^{225}Ac	100
^{209}Pb	270

Table 6. Sorption Coefficients in GoldSim Model Actinium Series

Radionuclide	Kd (mL/g)
^{239}Pu	100
^{235}U	10
^{231}Pa	5500
^{227}Ac	1500
^{223}Ra	500
^{243}Am	1000
^{239}Np	6
^{227}Th	5500

Figures

Figure 1. GoldSim Alluvial Pipe Model for Uranium Series

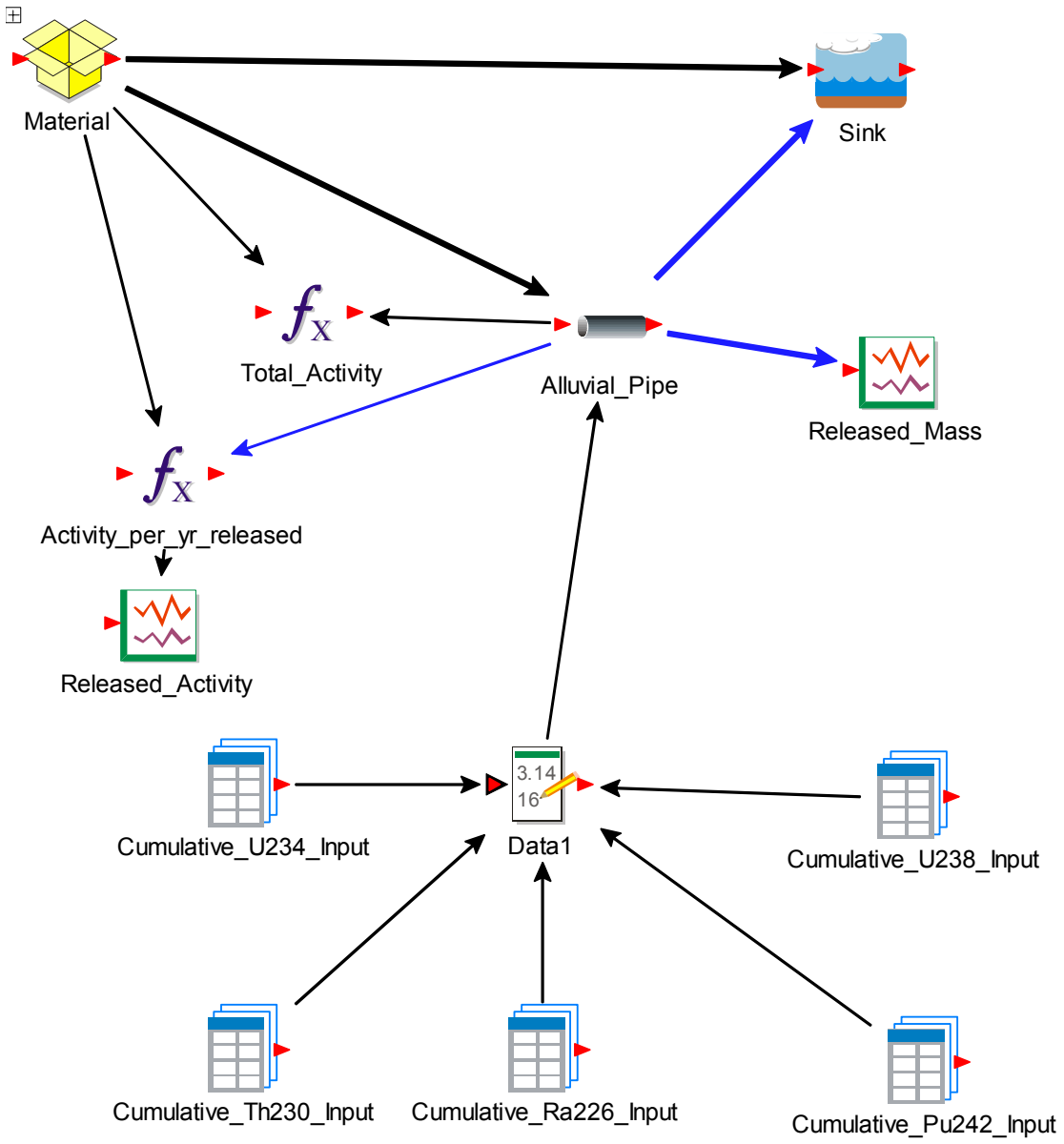
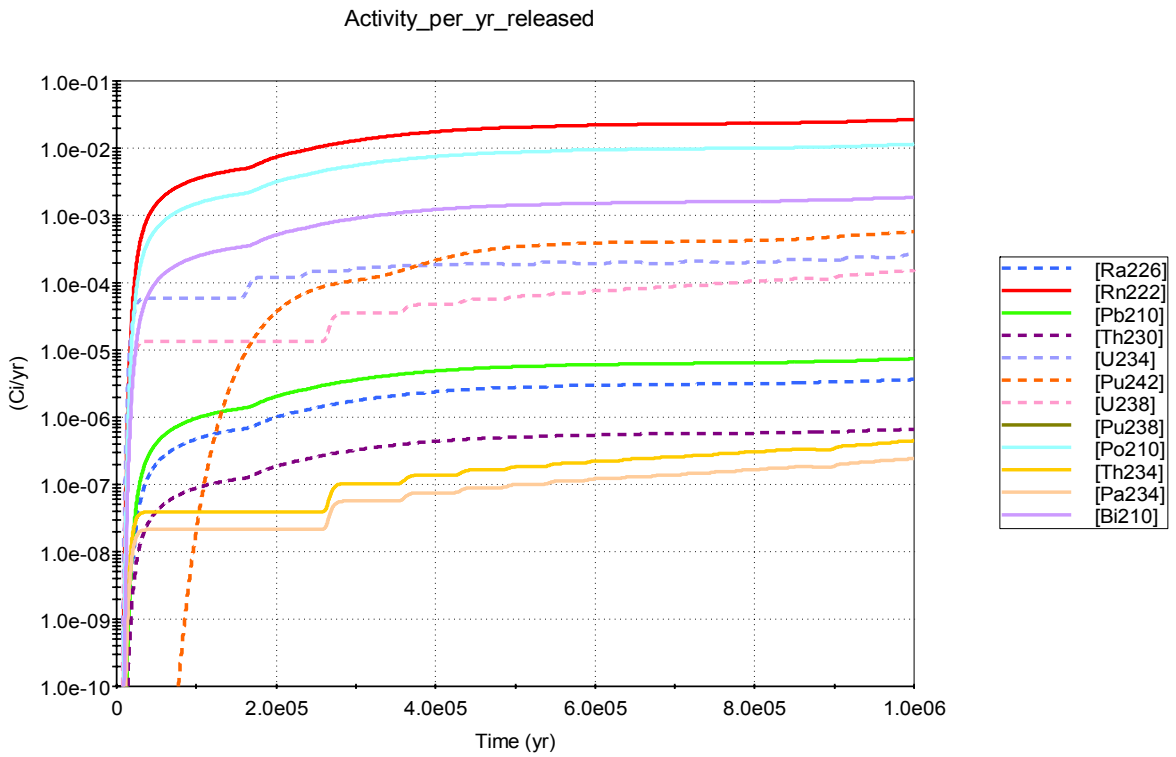


Figure 2.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1.0e-06
1.0e-07
1.0e-08
1.0e-09
1.0e-10
(Ci/yr)
0
2.0e05
4.0e05
6.0e05
8.0e05
1.0e06
Time (yr)
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[Rn222]
[Pb210]
[Th230]
[U234]
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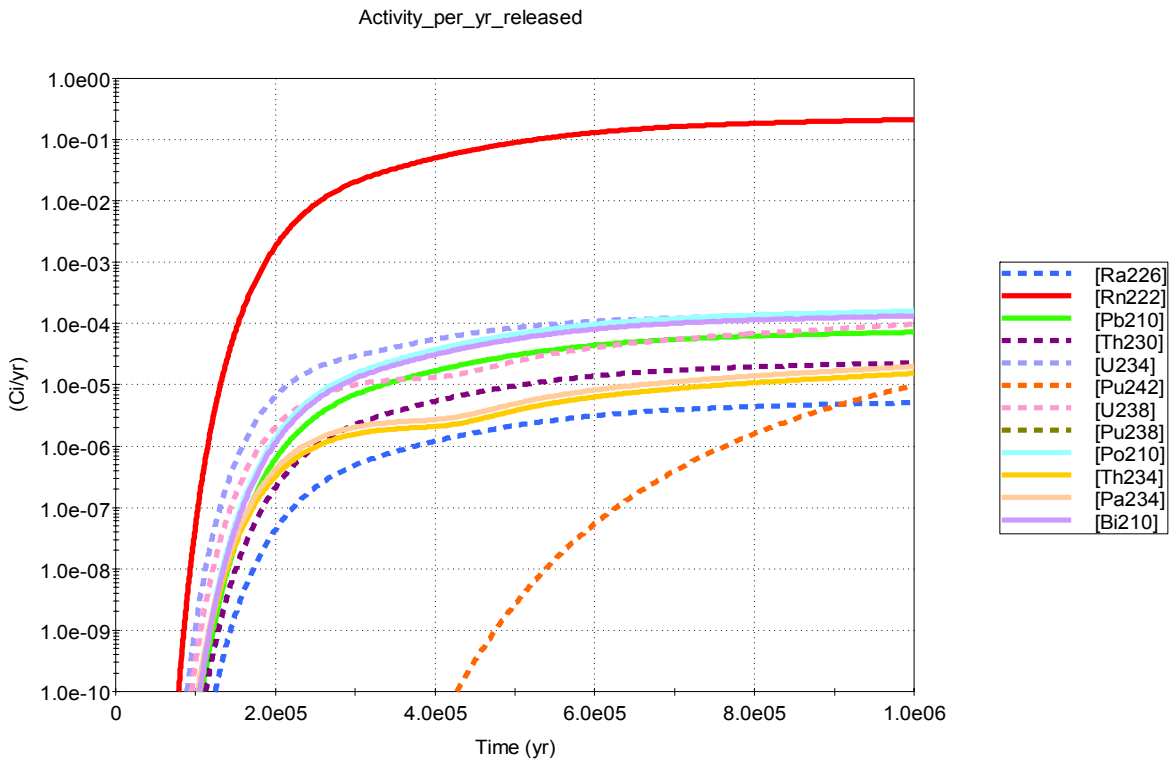
[U238]
[Pu238]
[Po210]
[Th234]
[Pa234]
[Bi210]

Figure 3.


Activity_per_yr_released
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1.0e-04
1.0e-05
1.0e-06
1.0e-07
1.0e-08
1.0e-09
1.0e-10
(Ci/yr)
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2.0e05
4.0e05
6.0e05
8.0e05
1.0e06
Time (yr)
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[Rn222]
[Pb210]
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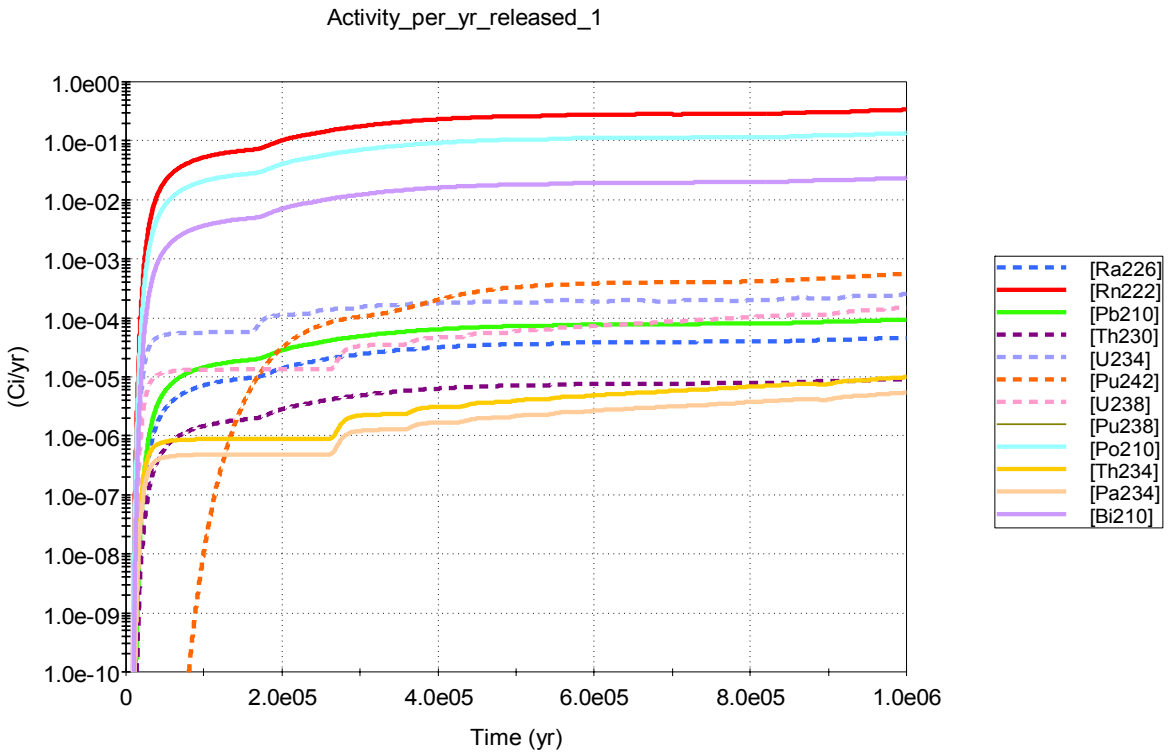
[U234]
[Pu242]
[U238]
[Pu238]
[Po210]
[Th234]
[Pa234]
[Bi210]

Figure 4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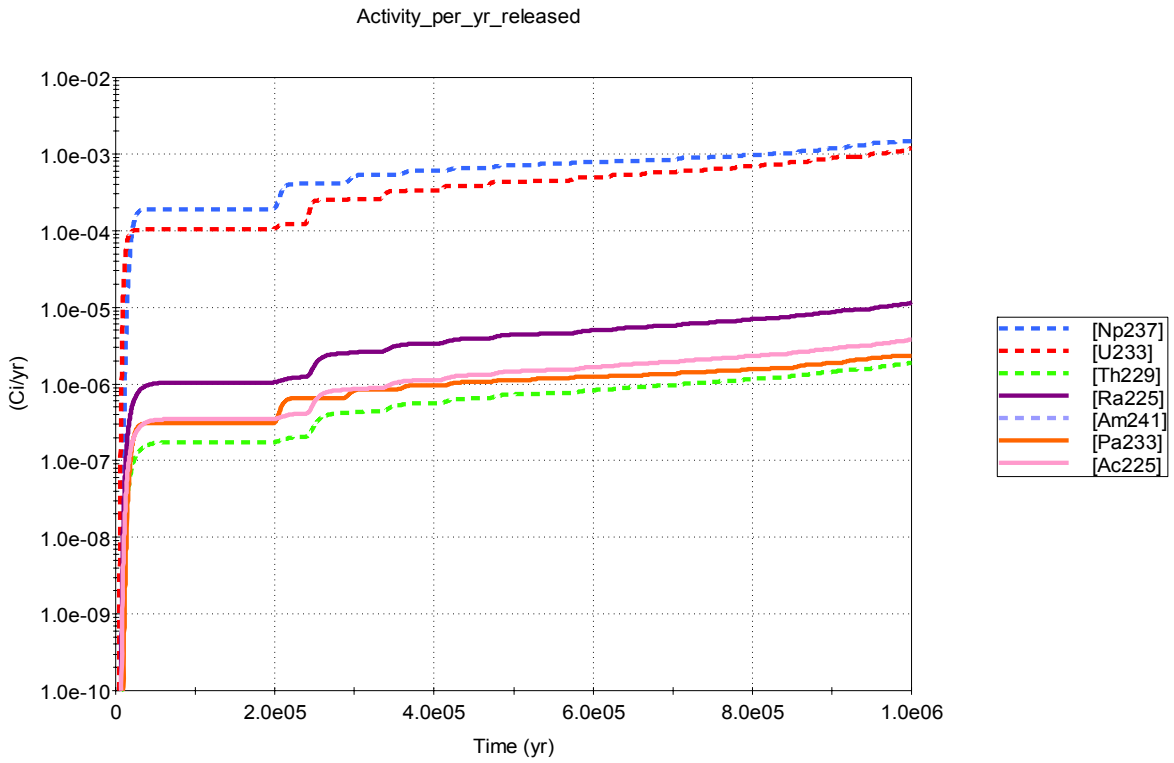
1.0e-03
1.0e-04
1.0e-05
1.0e-06
1.0e-07
1.0e-08
1.0e-09
1.0e-10
(Ci/yr)
0
2.0e05
4.0e05
6.0e05
8.0e05
1.0e06
Time (yr)
[Ra226]
[Rn222]
[Pb210]
[Th230]
[U234]
[Pu242]
[U238]
[Pu238]
[Po210]
[Th234]
[Pa234]
[Bi210]

Figure 5.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1.0e-04
1.0e-05
1.0e-06
1.0e-07
1.0e-08
1.0e-09
1.0e-10
(Ci/yr)
0
2.0e05
4.0e05
6.0e05
8.0e05
1.0e06
Time (yr)
[Np237]
[U233]
[Th229]
[Ra225]
[Am241]
[Pa233]
[Ac225]

Figure 6. Two Pipe GoldSim Model for Neptunium Series Transport

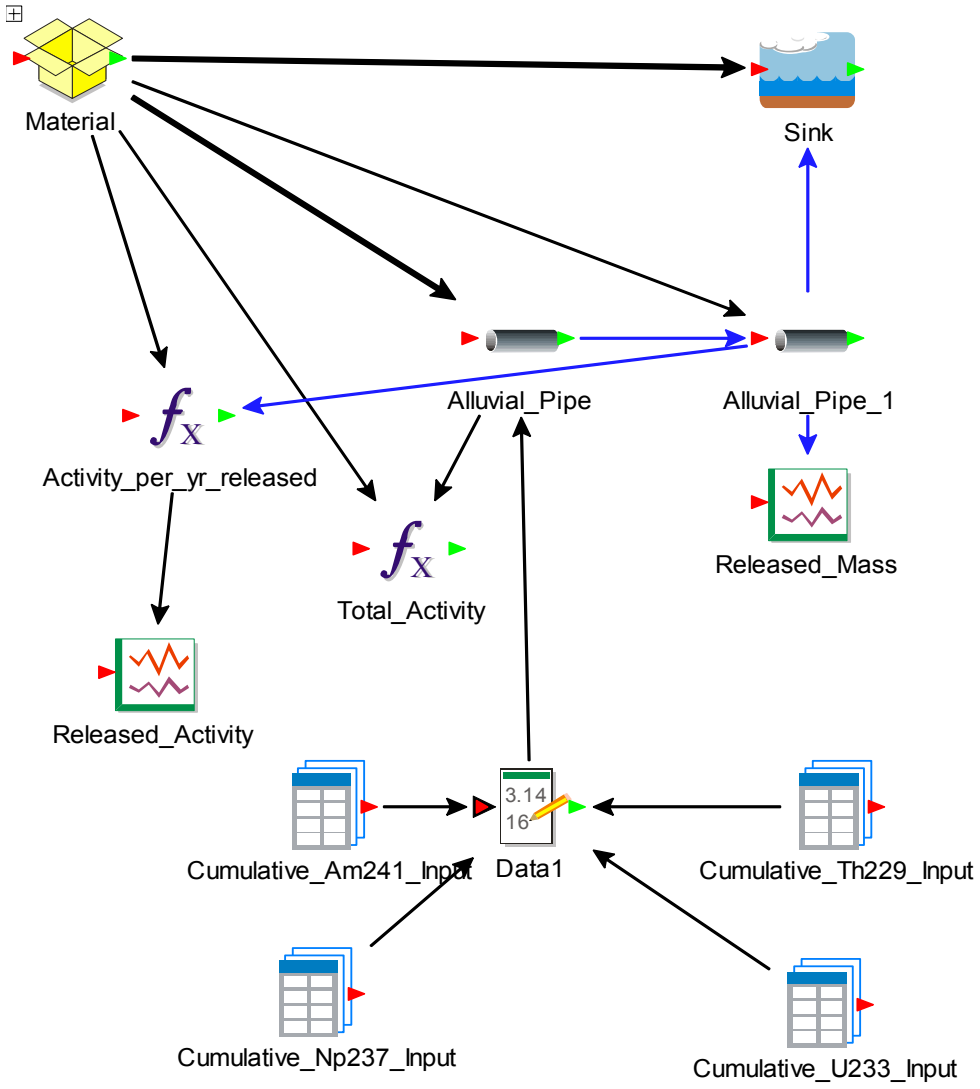
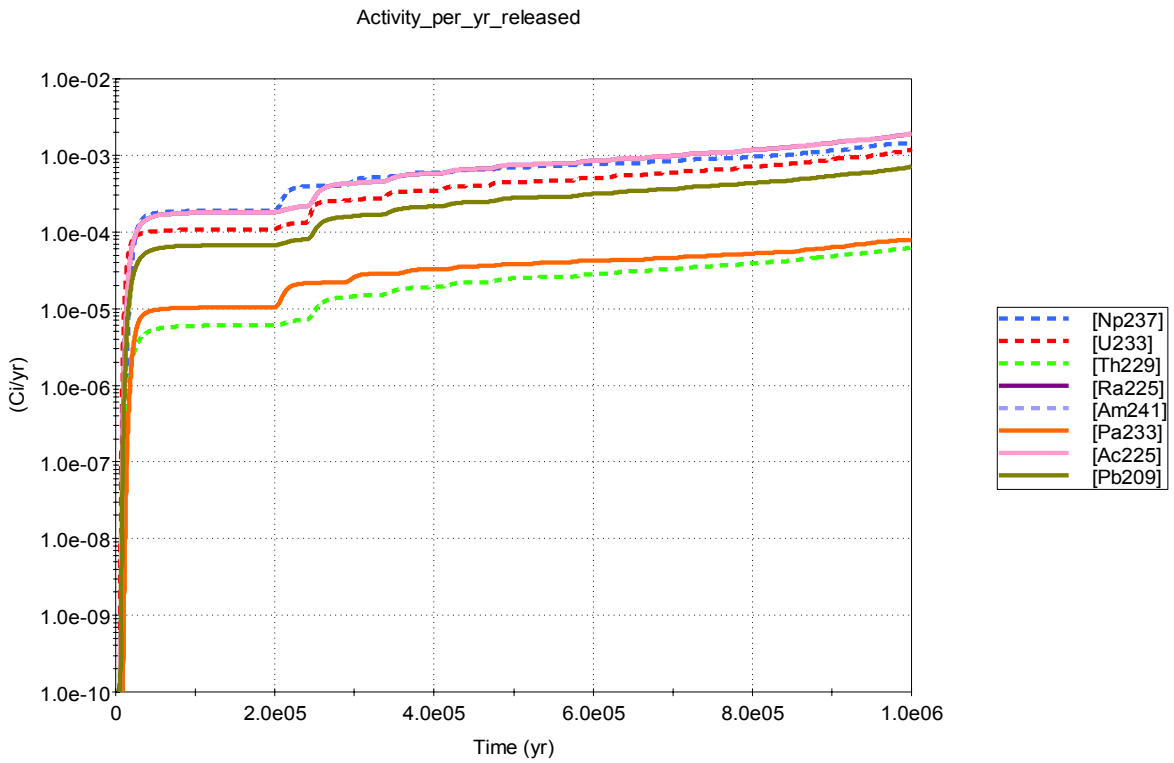


Figure 7.


Activity_per_yr_released
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1.0e-03
1.0e-04
1.0e-05
1.0e-06
1.0e-07
1.0e-08
1.0e-09
1.0e-10
(Ci/yr)
0
2.0e05
4.0e05
6.0e05
8.0e05
1.0e06
Time (yr)
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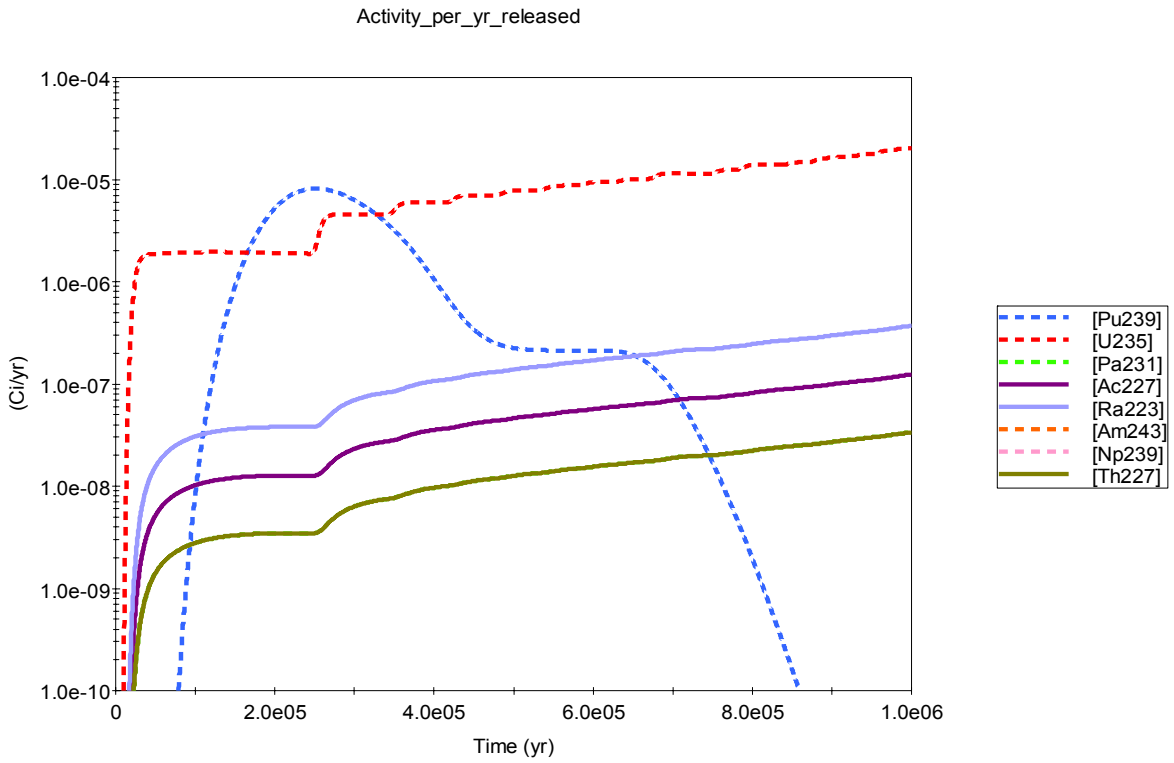
[U233]
[Th229]
[Ra225]
[Am241]
[Pa233]
[Ac225]
[Pb209]

Figure 8.


Activity_per_yr_released
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1.0e-05
1.0e-06
1.0e-07
1.0e-08
1.0e-09
1.0e-10
(Ci/yr)
0
2.0e05
4.0e05
6.0e05
8.0e05
1.0e06
Time (yr)
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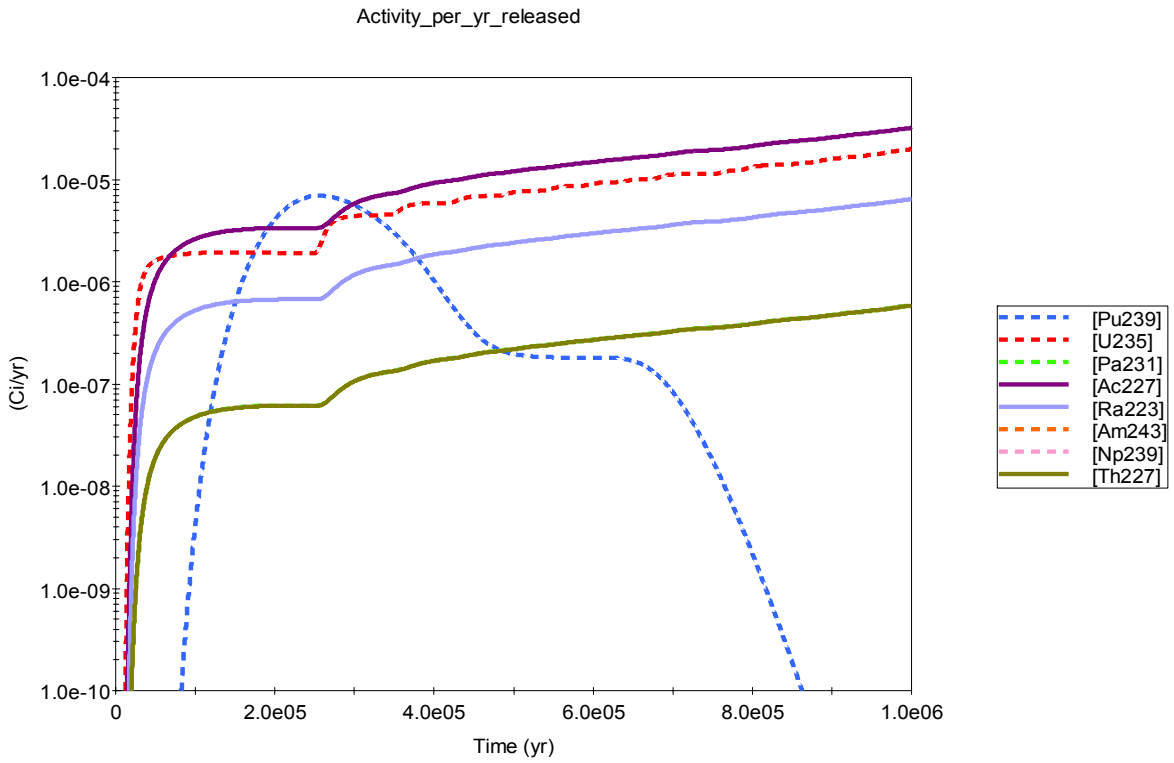
Figure 9.


Activity_per_yr_released
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1.0e-06
1.0e-07
1.0e-08
1.0e-09
1.0e-10
(Ci/yr)
0
2.0e05
4.0e05
6.0e05
8.0e05
1.0e06
Time (yr)
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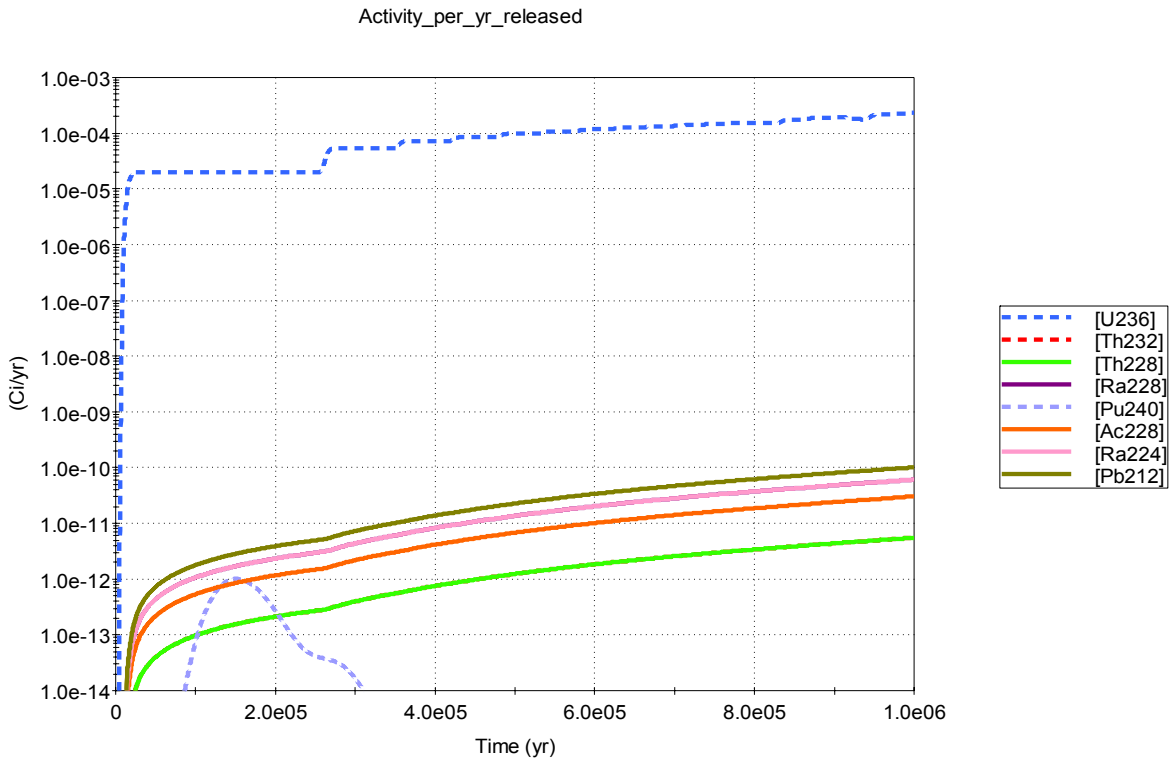
Figure 10.


Activity_per_yr_released
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1.0e-05
1.0e-06
1.0e-07
1.0e-08
1.0e-09
1.0e-10
1.0e-11
1.0e-12
1.0e-13
1.0e-14
(Ci/yr)
0
2.0e05
4.0e05
6.0e05
8.0e05
1.0e06
Time (yr)
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[Th232]
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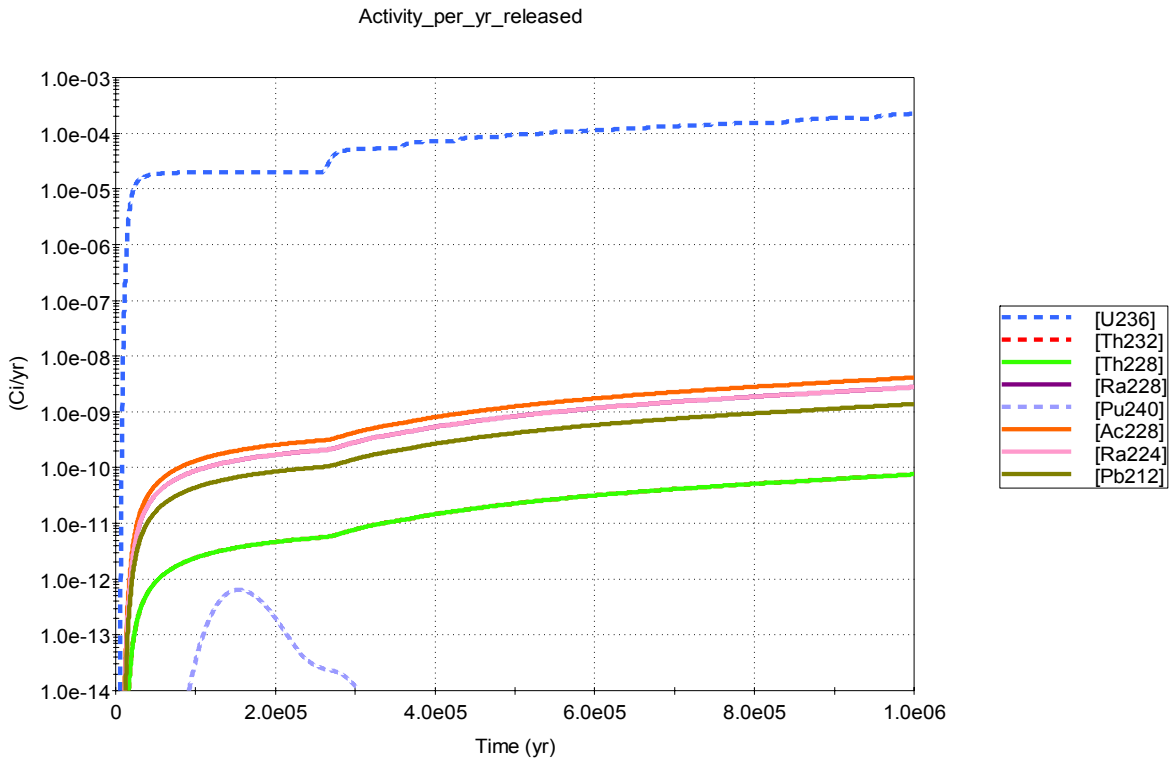
[Ra228]
[Pu240]
[Ac228]
[Ra224]
[Pb212]

Figure 11.


Activity_per_yr_released
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1.0e-04
1.0e-05
1.0e-06
1.0e-07
1.0e-08
1.0e-09
1.0e-10
1.0e-11
1.0e-12
1.0e-13
1.0e-14
(Ci/yr)
0
2.0e05
4.0e05
6.0e05
8.0e05
1.0e06
Time (yr)
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[Th232]
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Appendix A

Determination of Sorption Coefficients (K_ds)
Consistent with Fallon, Nevada Ground Water

Ground water in Lahontan Valley, near Fallon, Nevada (Churchill County), has been sampled and analyzed at several times as described in Seiler (2004; 2007; 2010). Different constituents may not have been analyzed in a given well at the same time. For this study, it is assumed that the concentrations of these constituents do not change over time. With this assumption, the constituent concentrations measured at different times can be used to calculate sorption coefficients.

It is assumed that ^{222}Rn does not sorb onto solids in the aquifer. Therefore, the K_d for ^{222}Rn is assumed to be zero. Furthermore, it is assumed that ^{222}Rn is in secular equilibrium with ^{226}Ra (both dissolved and sorbed). There are only 4 analyses that contain both ^{222}Rn and ^{226}Ra concentrations in the same well.

Well CDP-12 contains 126 pCi/L ^{222}Rn and <0.016 pCi/L ^{226}Ra. In a volume of aquifer that contains 1 L of ground water, there is assumed 126 pCi of ^{226}Ra. Under the assumption of secular equilibrium for ^{222}Rn/^{226}Ra, the activity of ^{226}Ra on the associated volume of solid is (126 - 0.016) = 125.084 pCi.

It is assumed that bulk density of the aquifer is 2 g/cm^3 and its porosity is 0.20. For a volume of ground water of 1 L, the volume of solid plus pores is 5,000 cm^3. The mass of the solid associated with the ground water is (2 g/cm^3)(5,000 cm^3) = 10,000 g. The K_d for ^{226}Ra is

$$Kd = \frac{\frac{125.084\ pCi}{10{,}000\ g\ solid}}{\frac{0.016\ pCi}{1000\ mL}} = 782\,\frac{mL}{g}$$

Because the ^{226}Ra activity is reported as a maximum value, the K_d above is a minimum. Calculations involving the three other wells at Fallon for which ^{226}Ra and ^{222}Rn were determined, produced K_ds listed in Table A-1.

Table A-1: K_d for ^{226}Ra

Well	K_d (mL/g)
FCL-56	1323
FCL-19	1341
FCL-50	746

It is assumed that the system is closed with respect to the uranium series from uranium down to polonium. Assuming that secular equilibrium applies here also, the approach described above is used to determine the K_ds of ^{234}U and ^{210}Po listed in Table A-2.

Table A-2: K_d for ^{234}U and ^{210}Po

Well	K_d (mL/g) of ^{234}U	K_d (mL/g) of ^{210}Po
Basalt Aquifer		
CDP-03	21	170
CDP-12	11	58
Shallow Aquifer		
FCL-30	0.5	1268
FCL-54	3.0	1224
FCL-56	2.9	639
Intermediate Aquifer		
CDP-11	322	1.9
CDP-16	1620	150
CDP-18	100	1.1
CDP-23	496	46.9
CDP-27	1240	0.8
CDP-28	251	1.0
CDP-29	383	0.4
CDP-30	49	0.8
CDP-39	3.7	2.5
FCL-03	9330	274
FCL-04	144	804
FCL-15	408	3.6
FCL-19	250	16.2
FCL-20	928	14.7
FCL-29	461	25.5
FCL-31	223	9.8
FCL-32	558	55.6
FCL-33	12.4	5.2
FCL-42	933	3.0
FCL-43	432	27.5
FCL-46	81.7	574
FCL-48	14.4	1264
FCL-50	40.8	0.5
FCL-51	125	1.6
FCL-59	315	1.0
FCL-60	616	146
FCL-61	616	81.4

There is some suggestion of a relationship between K_ds for ^{234}U and ^{210}Po. In some cases, a high K_d for ^{210}Po is associated with a low K_d for ^{234}U. Likewise, samples with a high calculated K_d for ^{234}U have a low calculated Kd for ^{210}Po. This relationship is not quantitatively supported for the existing data. There appears to be a lack of subequal Kds for the two elements in the well measurements. Figure A-1 shows the calculated K_ds for all of the samples, and Figure A-2 shows the calculated K_ds for only those samples from the intermediate aquifer, which contains

the elevated ^{210}Po activity. The analyses from sample FCL-03 are not plotted in these figures, as they appear to be anomalous.

Figure A-1: calculated K_ds for all samples

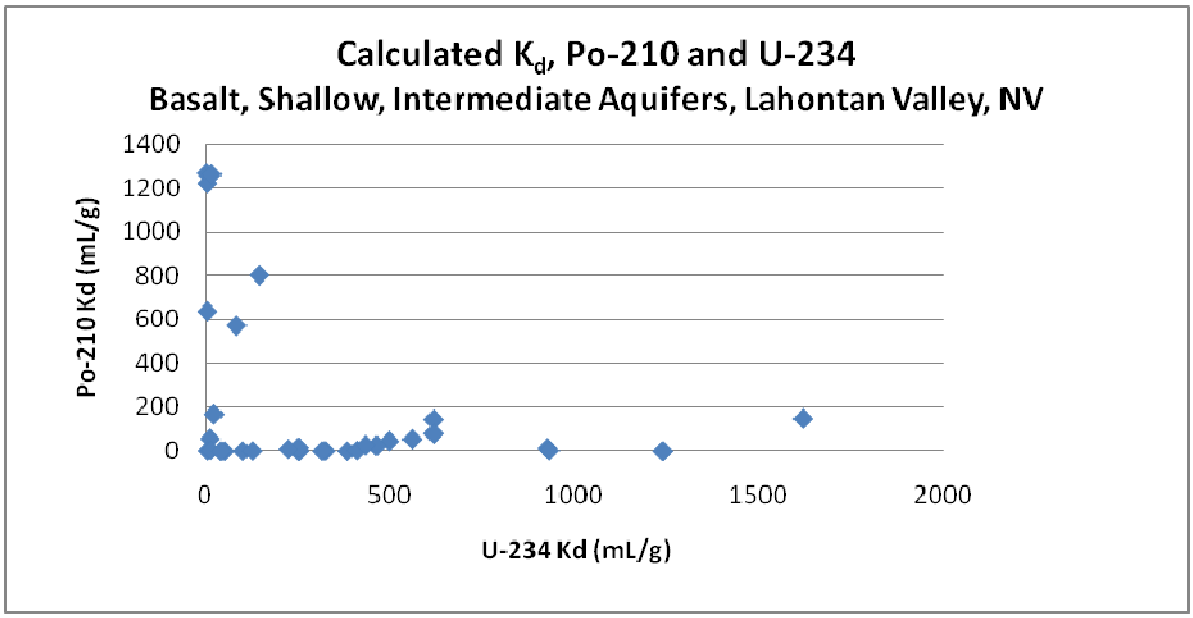
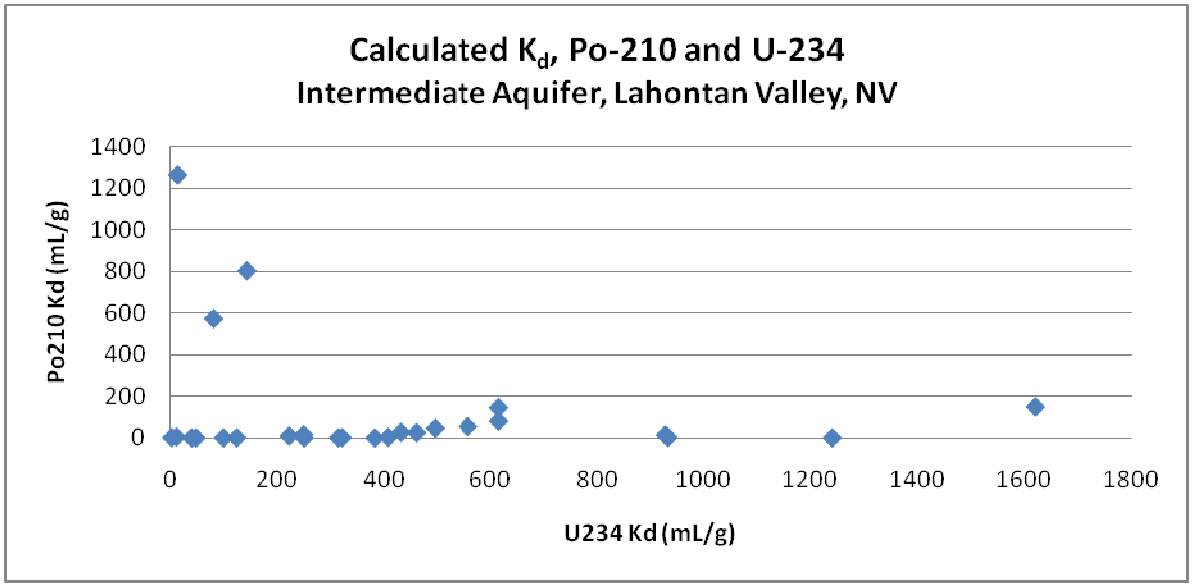


Figure A-2: calculated K_ds for samples from the intermediate aquifer



References

Seiler, R. L. 2007, Methods and Data Used to Investigate Polonium-210 as a Source of Excess Gross-Alpha Radioactivity in Ground Water, Churchill County, Nevada, Open-File Report 2007-1231, U.S. Geological Survey.

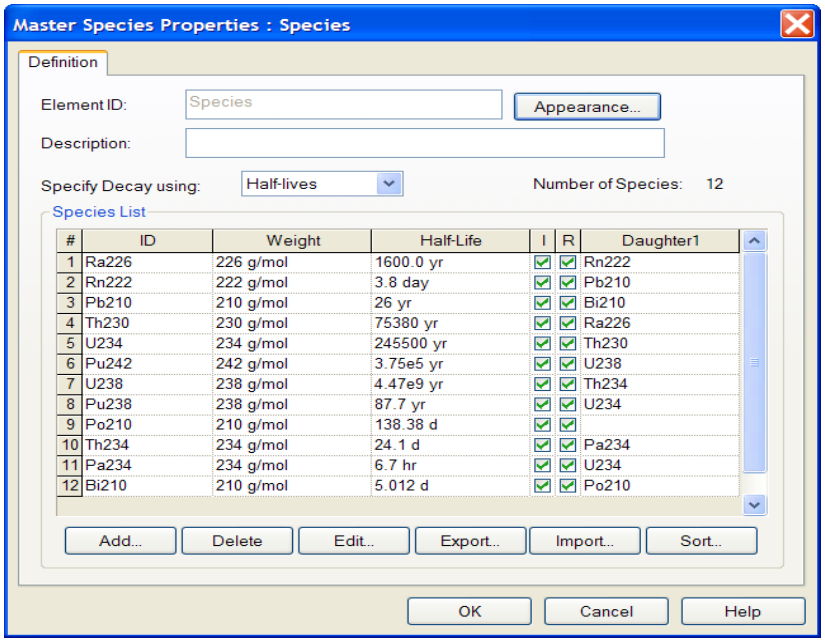
Seiler, R.L., 2010, ^{210}Po in Nevada Groundwater and Its Relation to Gross Alpha Radioactivity, Ground Water 49, 160-171, National Ground Water Association.

Seiler, R.L., 2004, Temporal Changes in Water Quality at a Childhood Leukemia Cluster, Ground Water 42, 446-455, National Ground Water Association.

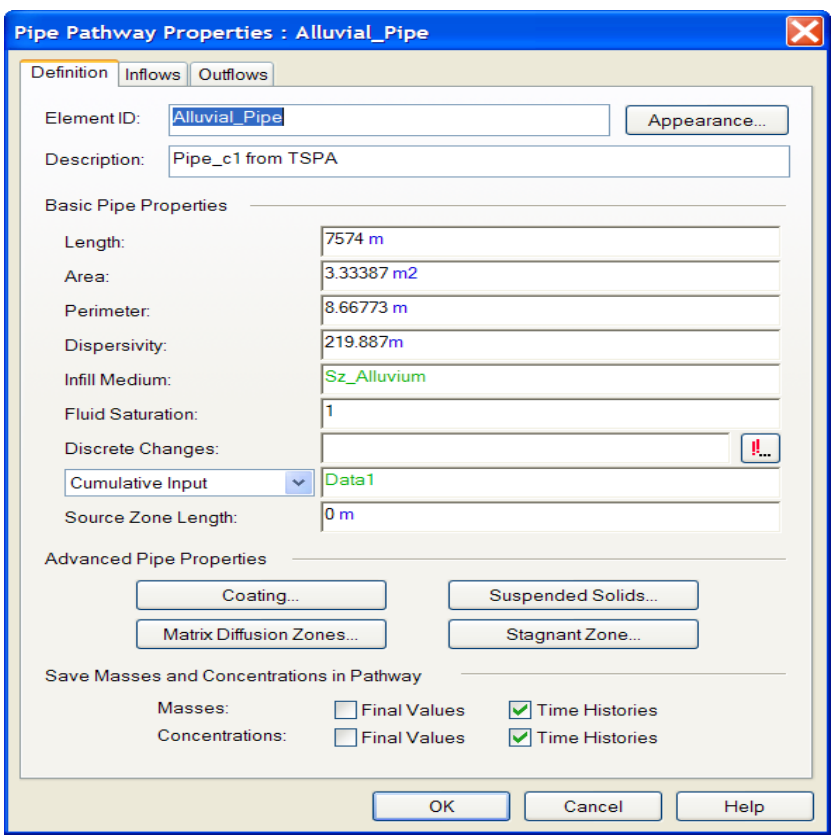
Appendix B

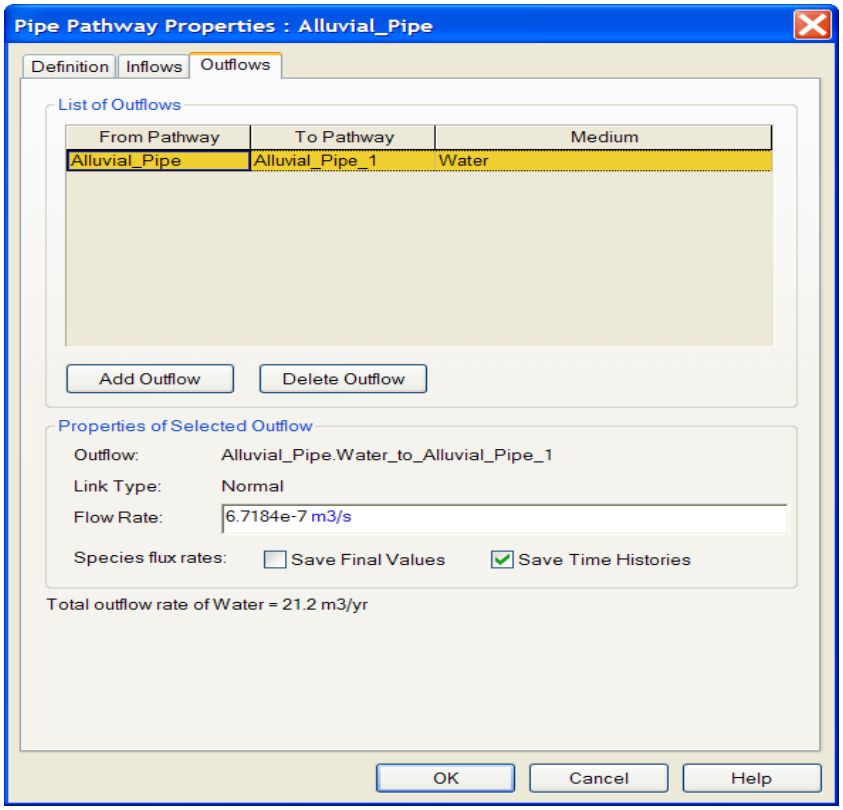
The figures in this Appendix provide details of the GoldSim elements used in the models.

Uranium Series GoldSim Elements

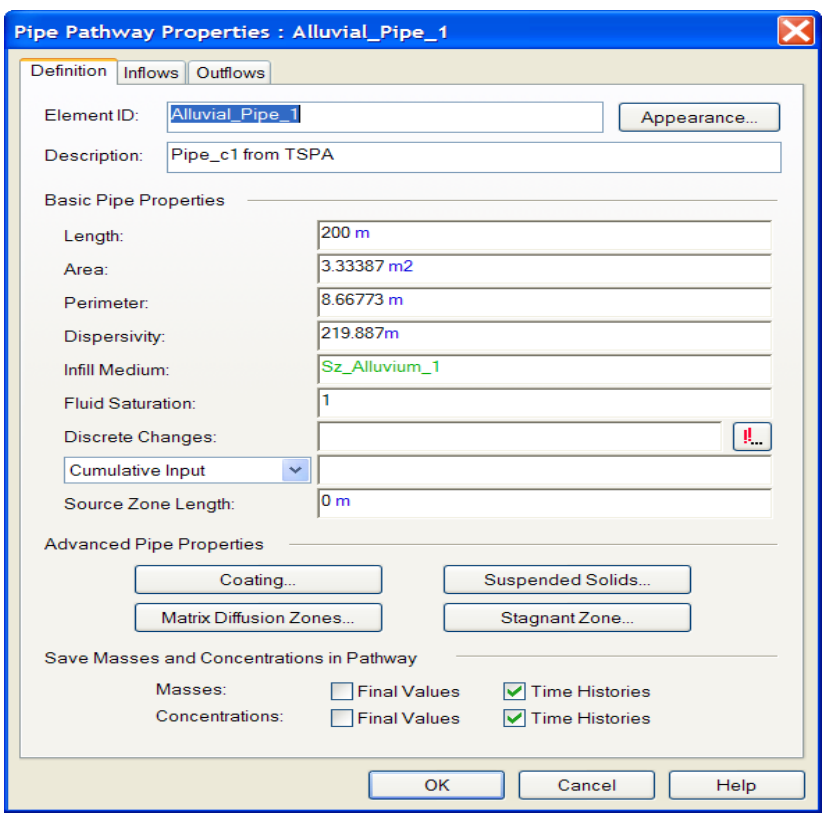


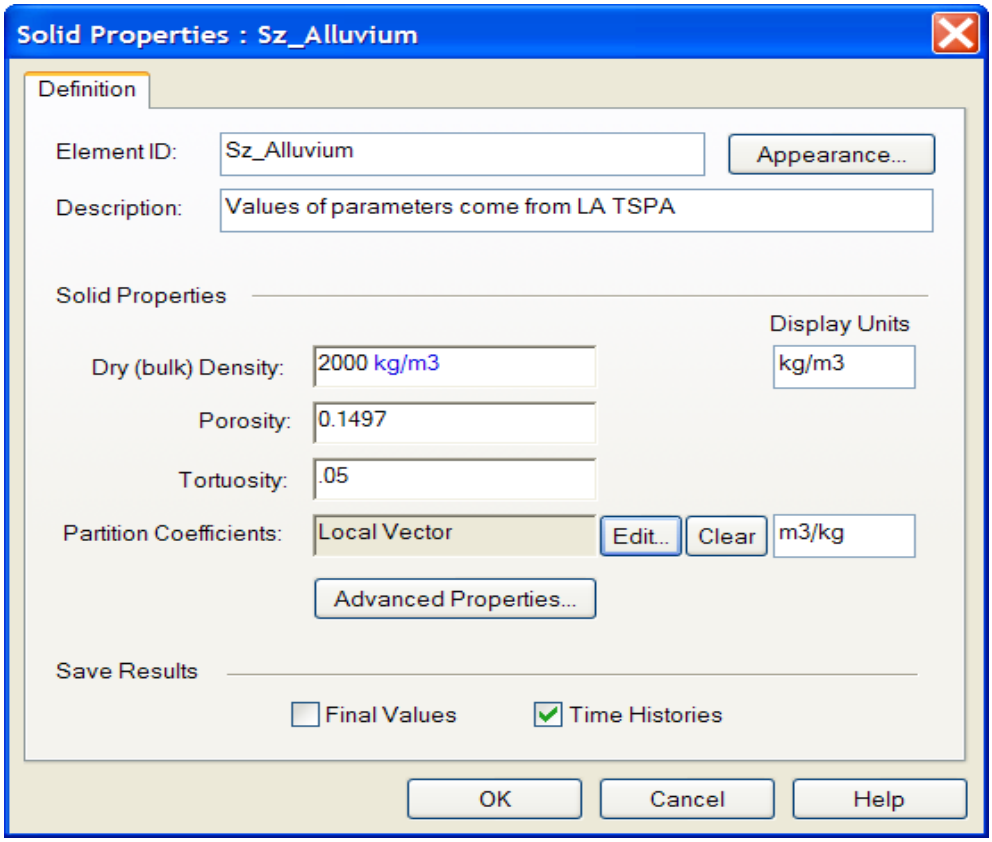
#	ID	Weight	Half-Life	I	R	Daughter1
1	Ra226	226 g/mol	1600.0 yr	✓	✓	Rn222
2	Rn222	222 g/mol	3.8 day	✓	✓	Pb210
3	Pb210	210 g/mol	26 yr	✓	✓	Bi210
4	Th230	230 g/mol	75380 yr	✓	✓	Ra226
5	U234	234 g/mol	245500 yr	✓	✓	Th230
6	Pu242	242 g/mol	3.75e5 yr	✓	✓	U238
7	U238	238 g/mol	4.47e9 yr	✓	✓	Th234
8	Pu238	238 g/mol	87.7 yr	✓	✓	U234
9	Po210	210 g/mol	138.38 d	✓	✓	
10	Th234	234 g/mol	24.1 d	✓	✓	Pa234
11	Pa234	234 g/mol	6.7 hr	✓	✓	U234
12	Bi210	210 g/mol	5.012 d	✓	✓	Po210

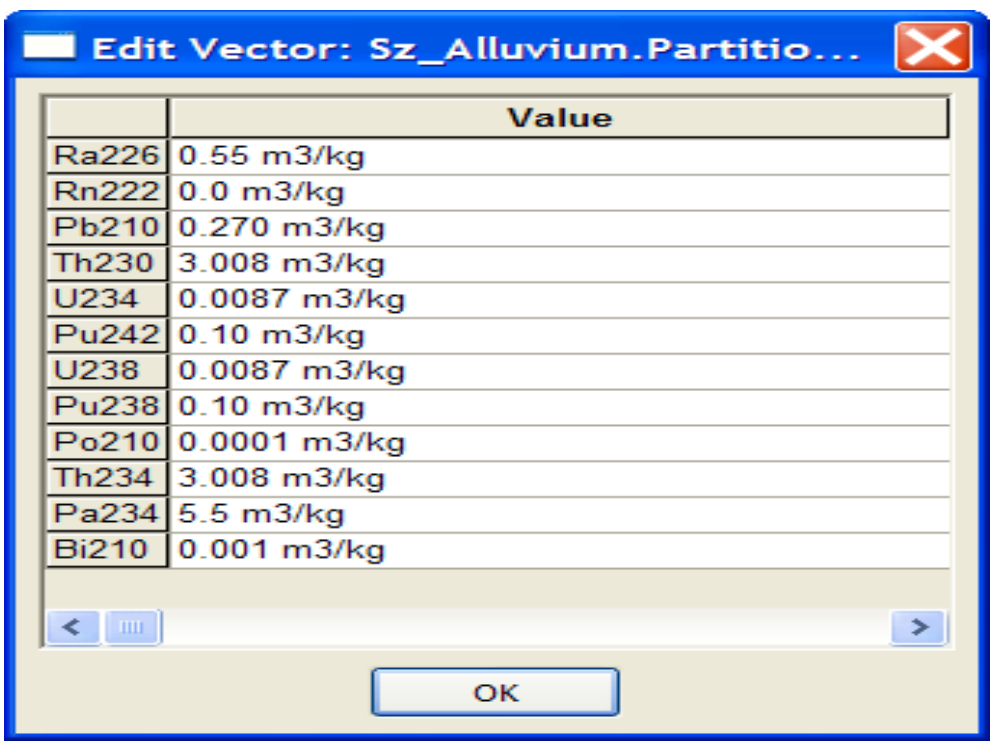




The figure above shows the flow rate used in all the simulations in this analysis.







	Value
Ra226	0.55 m3/kg
Rn222	0.0 m3/kg
Pb210	0.270 m3/kg
Th230	3.008 m3/kg
U234	0.0087 m3/kg
Pu242	0.10 m3/kg
U238	0.0087 m3/kg
Pu238	0.10 m3/kg
Po210	0.0001 m3/kg
Th234	3.008 m3/kg
Pa234	5.5 m3/kg
Bi210	0.001 m3/kg

The Solid Properties of Sz_Alluvium_1 are the same as Sz_Alluvium.

Edit Vector: Sz_Alluvium_1.Partiti...

	Value
Ra226	0.55 m3/kg
Rn222	0.0 m3/kg
Pb210	0.270 m3/kg
Th230	3.008 m3/kg
U234	0.200 m3/kg
Pu242	0.10 m3/kg
U238	0.200 m3/kg
Pu238	0.10 m3/kg
Po210	0.0001 m3/kg
Th234	3.008 m3/kg
Pa234	5.5 m3/kg
Bi210	0.001 m3/kg

OK

Edit 1-D Table

The table can be referenced in the model as:

Cumulative_U234_Input(row variable)

	Row Variable [yr]	Result [g]
1	0	0
2	250	0
3	145500	1440
4	216000	2880
5	273500	4320
6	324500	5760
7	372500	7210
8	418500	8650
9	463500	10100
10	508500	11500
11	552500	13000
12	596500	14400
13	640500	15900
14	684500	17300
15	728000	18800
16	770500	20200
17	812500	21600
18	853000	23100
19	892500	24500
20	930000	26000
21	966000	27400
22	1000000	28900

OK
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Edit 1-D Table

The table can be referenced in the model as:

Cumulative_Th230_Input(row variable)

	Row Variable [yr]	Result [g]
1	0	0
2	250	0
3	156000	1390
4	223500	2780
5	279000	4170
6	329000	5550
7	376500	6940
8	423000	8330
9	469000	9710
10	515000	11100
11	561500	12500
12	608000	13900
13	655000	15300
14	701500	16700
15	746500	18000
16	790500	19400
17	832500	20800
18	872000	22200
19	908000	23600
20	941500	25000
21	972000	26400
22	1000000	27800

OK
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Edit 1-D Table

The table can be referenced in the model as:

Cumulative_Ra226_Input(row variable)

	Row Variable [yr]	Result [g]
1	0	0
2	250	0
3	147500	372
4	231000	745
5	301000	1120
6	359500	1490
7	415500	1860
8	470000	2230
9	521500	2610
10	570000	2980
11	618500	3350
12	664500	3720
13	707500	4100
14	749000	4470
15	788500	4840
16	826000	5220
17	860500	5580
18	893000	5960
19	923000	6330
20	950500	6700
21	976500	7080
22	1000000	7450

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Help
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Edit 1-D Table

The table can be referenced in the model as:

Cumulative_Pu242_Input(row variable)

	Row Variable [yr]	Result [g]
1	0	0
2	250	0
3	176000	8400
4	245000	16800
5	304500	25300
6	360500	33700
7	414500	42200
8	467000	50600
9	519500	59000
10	571500	67400
11	622500	75900
12	670500	84300
13	713500	92800
14	753000	101000
15	790000	110000
16	825500	118000
17	858500	126000
18	889500	135000
19	919000	143000
20	946500	152000
21	973500	160000
22	1000000	169000

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Edit 1-D Table

The table can be referenced in the model as:

Cumulative_U238_Input(row variable)

	Row Variable [yr]	Result [g]
1	0	0
2	250	0
3	248000	9880000
4	342000	19800000
5	412500	29700000
6	471500	39600000
7	523500	49400000
8	571000	59400000
9	614500	69300000
10	655000	79200000
11	693000	89100000
12	729000	99000000
13	763000	109000000
14	795000	119000000
15	825500	129000000
16	854500	139000000
17	881500	148000000
18	907500	158000000
19	932500	168000000
20	956000	178000000
21	978500	188000000
22	1000000	198000000

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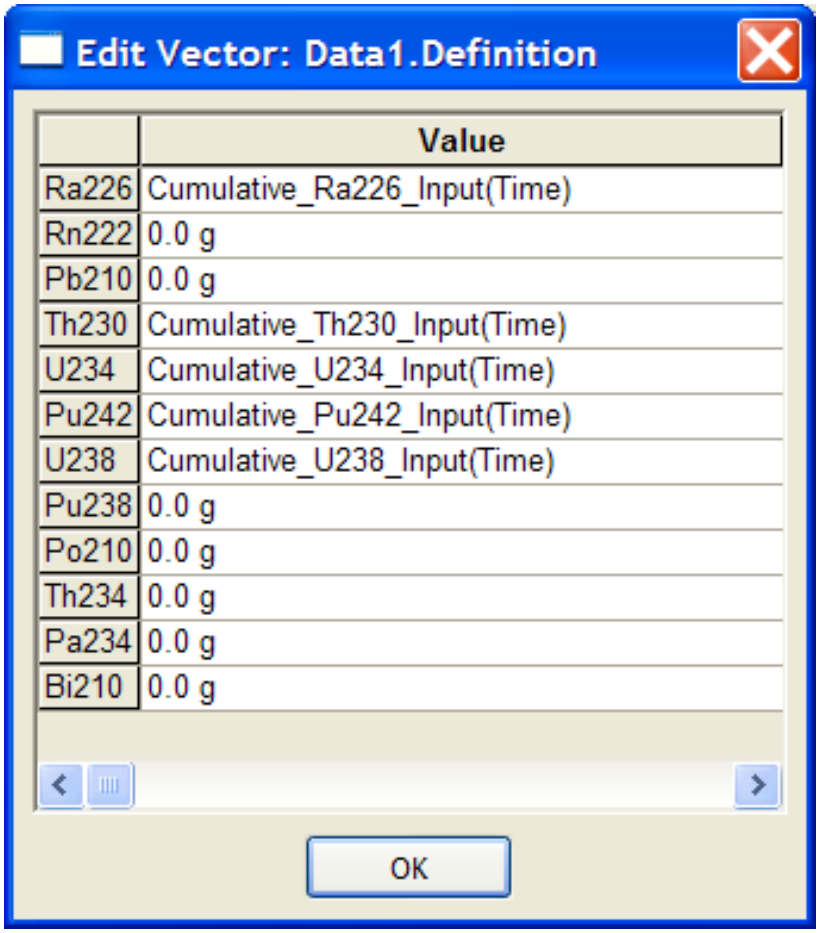
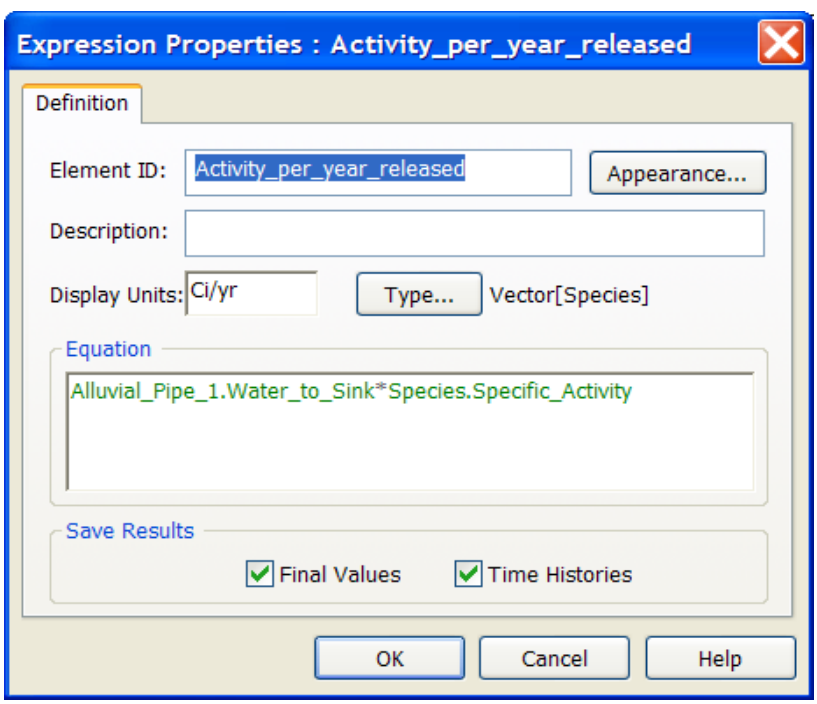
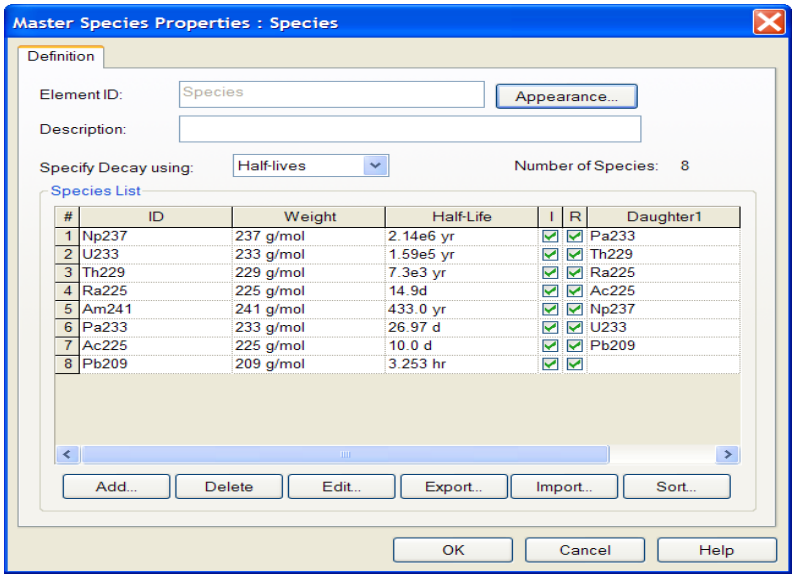

Edit Vector: Data1.Definition
Value
Ra226 Cumulative_Ra226_Input(Time)
Rn222 0.0 g
Pb210 0.0 g
Th230 Cumulative_Th230_Input(Time)
U234 Cumulative_U234_Input(Time)
Pu242 Cumulative_Pu242_Input(Time)
U238 Cumulative_U238_Input(Time)
Pu238 0.0 g
Po210 0.0 g
Th234 0.0 g
Pa234 0.0 g
Bi210 0.0 g
OK

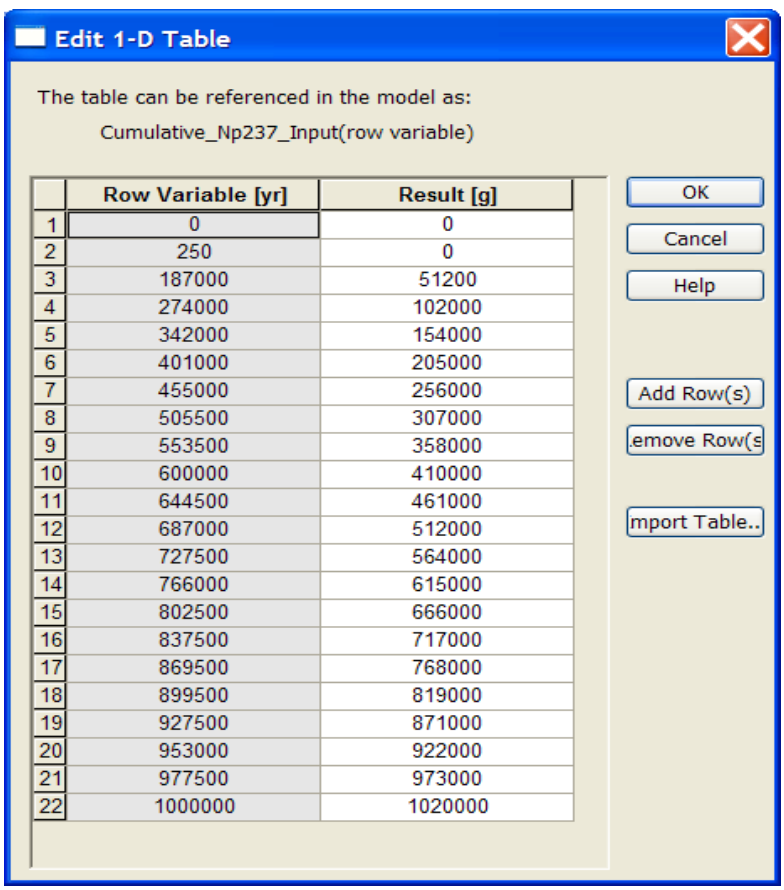

Expression Properties : Activity_per_year_released
Definition
Element ID: Activity_per_year_released
Appearance...
Description:
Display Units: Ci/yr
Type...
Vector[Species]
Equation
Alluvial_Pipe_1.Water_to_Sink*Species.Specific_Activity
Save Results
Final Values
Time Histories
OK
Cancel
Help

Neptunium Series GoldSim Elements

The figures for the neptunium series that are different from those of the uranium series are shown below. All the other elements are the same as those used in the uranium series simulations.



#	ID	Weight	Half-Life	I	R	Daughter1
1	Np237	237 g/mol	2.14e6 yr	✓	✓	Pa233
2	U233	233 g/mol	1.59e5 yr	✓	✓	Th229
3	Th229	229 g/mol	7.3e3 yr	✓	✓	Ra225
4	Ra225	225 g/mol	14.9d	✓	✓	Ac225
5	Am241	241 g/mol	433.0 yr	✓	✓	Np237
6	Pa233	233 g/mol	26.97 d	✓	✓	U233
7	Ac225	225 g/mol	10.0 d	✓	✓	Pb209
8	Pb209	209 g/mol	3.253 hr	✓	✓	



	Row Variable [yr]	Result [g]
1	0	0
2	250	0
3	187000	51200
4	274000	102000
5	342000	154000
6	401000	205000
7	455000	256000
8	505500	307000
9	553500	358000
10	600000	410000
11	644500	461000
12	687000	512000
13	727500	564000
14	766000	615000
15	802500	666000
16	837500	717000
17	869500	768000
18	899500	819000
19	927500	871000
20	953000	922000
21	977500	973000
22	1000000	1020000

Edit 1-D Table

The table can be referenced in the model as:

Cumulative_Am241_Input(row variable)

	Row Variable [yr]	Result [g]
1	0	0
2	250	0
3	1000	0.00599
4	1250	0.0182
5	1500	0.0318
6	1750	0.047
7	2000	0.0617
8	2250	0.076
9	2500	0.0901
10	2750	0.105
11	3000	0.116
12	3500	0.131
13	4000	0.14
14	4750	0.148
15	7500	0.157
16	97500	0.165
17	1000000	0.165

OK
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Edit 1-D Table

The table can be referenced in the model as:

Cumulative_U233_Input(row variable)

	Row Variable [yr]	Result [g]
1	0	0
2	250	0
3	232000	2190
4	326000	4380
5	398000	6570
6	459000	8750
7	514000	11000
8	564000	13100
9	611000	15300
10	654000	17500
11	694500	19700
12	732000	21900
13	767500	24100
14	800500	26300
15	832000	28500
16	861000	30700
17	888000	32900
18	913000	35100
19	936500	37200
20	959000	39400
21	980000	41600
22	1000000	43900

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Edit 1-D Table

The table can be referenced in the model as:

Cumulative_Th229_Input(row variable)

	Row Variable [yr]	Result [g]
1	0	0
2	250	0
3	219000	121
4	307500	242
5	374500	362
6	432000	484
7	483500	605
8	531000	726
9	576000	847
10	618500	968
11	659000	1090
12	698000	1210
13	735500	1330
14	771500	1450
15	806000	1570
16	839000	1690
17	870500	1810
18	900500	1940
19	928000	2060
20	953500	2180
21	977500	2300
22	1000000	2420

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Edit Vector: Sz_Alluvium.Partitio...

	Value
Np237	0.0087 m3/kg
U233	0.0050 m3/kg
Th229	3.008 m3/kg
Ra225	0.50 m3/kg
Am241	5.5 m3/kg
Pa233	5.5 m3/kg
Ac225	1.5 m3/kg
Pb209	0.270 m3/kg

OK

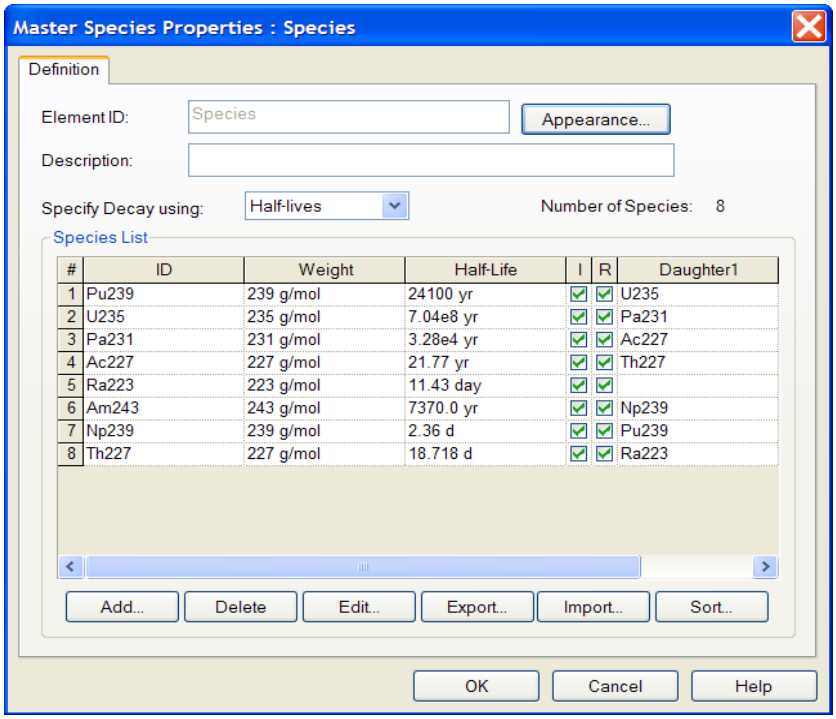
Edit Vector: Sz_Alluvium_1.Partiti...

	Value
Np237	0.3 m3/kg
U233	0.200 m3/kg
Th229	3.008 m3/kg
Ra225	0.1 m3/kg
Am241	5.5 m3/kg
Pa233	5.5 m3/kg
Ac225	0.1 m3/kg
Pb209	0.270 m3/kg

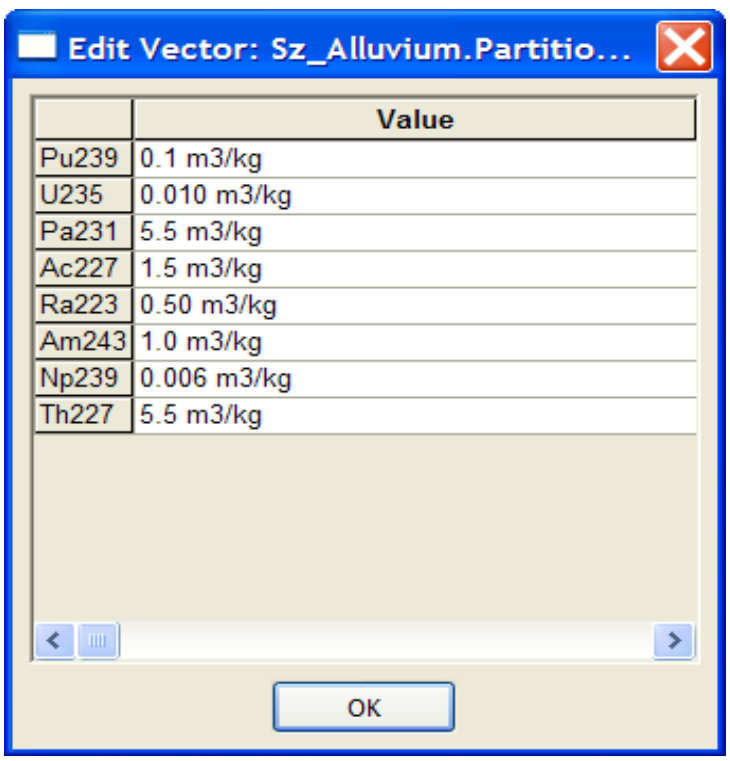
OK

Actinium Series GoldSim Elements

The figures for the actinium series that are different from those of the uranium series are shown below. All the other elements are the same as those used in the uranium series simulations.



#	ID	Weight	Half-Life	I	R	Daughter1
1	Pu239	239 g/mol	24100 yr	✓	✓	U235
2	U235	235 g/mol	7.04e8 yr	✓	✓	Pa231
3	Pa231	231 g/mol	3.28e4 yr	✓	✓	Ac227
4	Ac227	227 g/mol	21.77 yr	✓	✓	Th227
5	Ra223	223 g/mol	11.43 day	✓	✓	
6	Am243	243 g/mol	7370.0 yr	✓	✓	Np239
7	Np239	239 g/mol	2.36 d	✓	✓	Pu239
8	Th227	227 g/mol	18.718 d	✓	✓	Ra223



	Value
Pu239	0.1 m3/kg
U235	0.010 m3/kg
Pa231	5.5 m3/kg
Ac227	1.5 m3/kg
Ra223	0.50 m3/kg
Am243	1.0 m3/kg
Np239	0.006 m3/kg
Th227	5.5 m3/kg

Edit Vector: Sz_Alluvium_1.Partiti...

	Value
Pu239	0.1 m3/kg
U235	0.2 m3/kg
Pa231	5.5 m3/kg
Ac227	.1 m3/kg
Ra223	0.50 m3/kg
Am243	1.0 m3/kg
Np239	0.006 m3/kg
Th227	5.5 m3/kg

OK

Edit 1-D Table

The table can be referenced in the model as:

Cumulative_Am243_Input(row variable)

	Row Variable [yr]	Result [g]
1	0	0
2	250	0
3	6500	2.78
4	8500	5.46
5	10000	7.67
6	12000	10.7
7	13500	13.1
8	15500	16.5
9	17000	19.2
10	18500	21.9
11	20000	24.5
12	22000	27.8
13	23500	30.1
14	25500	33
15	28000	36.2
16	30000	38.6
17	33000	41.7
18	36000	44.4
19	40000	47.2
20	46500	50.2
21	60000	53
22	166000	55.9
23	1000000	55.9

OK
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Edit 1-D Table

The table can be referenced in the model as:

Cumulative_Pu239_Input(row variable)

	Row Variable [yr]	Result [g]
1	0	0
2	250	0
3	24500	355
4	34500	732
5	42500	1100
6	49500	1460
7	56000	1820
8	62500	2190
9	68500	2540
10	75000	2920
11	81500	3300
12	88000	3660
13	94500	4010
14	102000	4380
15	110000	4750
16	119000	5120
17	129500	5490
18	141500	5850
19	156500	6230
20	176000	6590
21	208000	6960
22	517500	7330
23	1000000	7330

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Edit 1-D Table

The table can be referenced in the model as:

Cumulative_U235_Input(row variable)

	Row Variable [yr]	Result [g]
1	0	0
2	250	0
3	233500	200000
4	329000	401000
5	402000	602000
6	463500	801000
7	518500	1000000
8	568000	1200000
9	613500	1400000
10	656000	1600000
11	695500	1810000
12	732000	2000000
13	766500	2200000
14	799000	2410000
15	829500	2610000
16	858500	2810000
17	885000	3010000
18	910500	3210000
19	935000	3410000
20	957500	3610000
21	979000	3810000
22	1000000	4010000

OK
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Edit 1-D Table

The table can be referenced in the model as:

Cumulative_Pa231_Input(row variable)

	Row Variable [yr]	Result [g]
1	0	0
2	250	0
3	254500	270
4	366000	540
5	453000	811
6	524500	1080
7	583000	1350
8	635500	1620
9	681000	1890
10	721000	2160
11	758000	2430
12	788500	2700
13	816000	2980
14	840500	3240
15	863500	3510
16	885500	3790
17	906500	4060
18	926500	4320
19	946000	4590
20	964500	4860
21	982500	5140
22	1000000	5410

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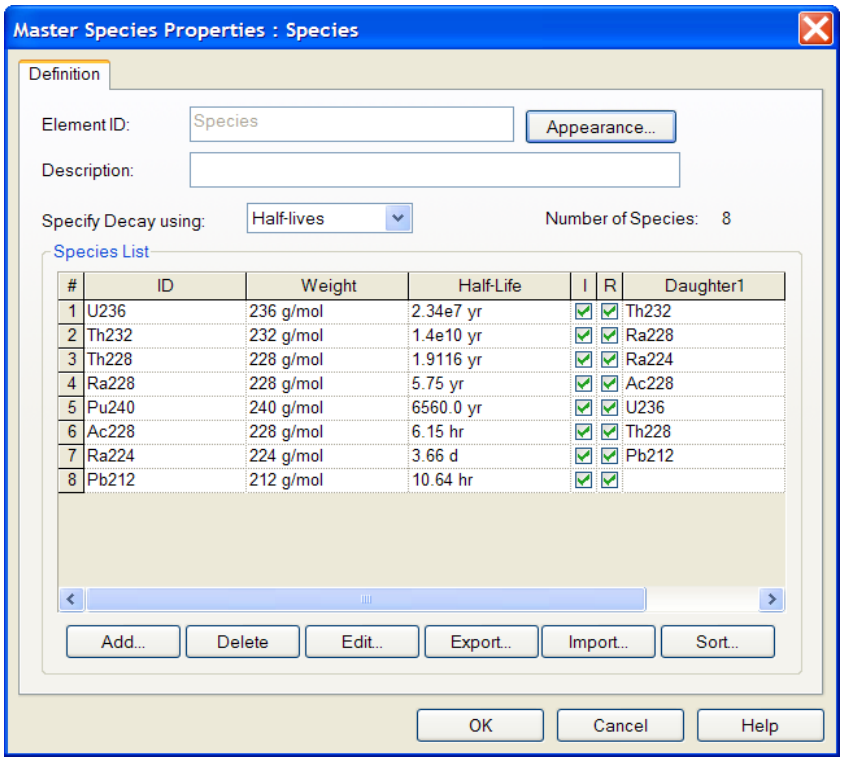
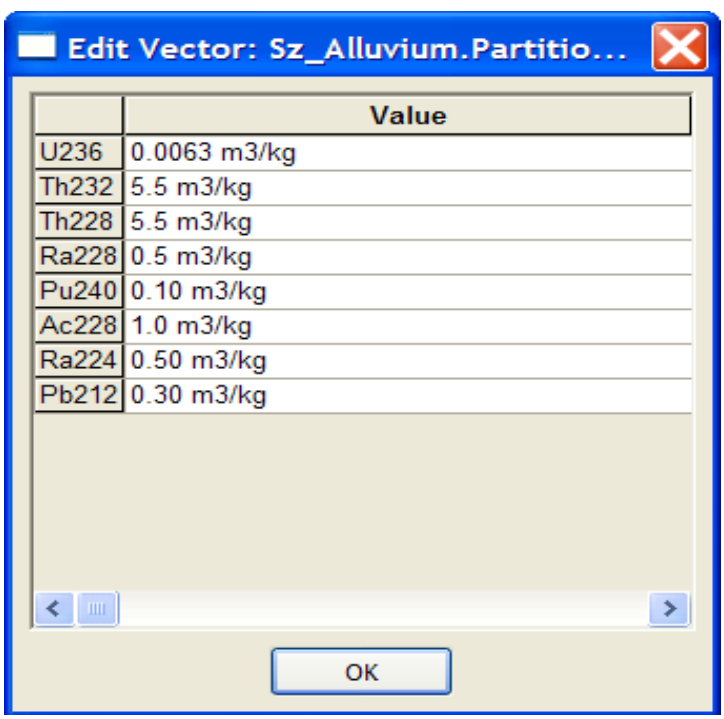
Thorium Series GoldSim Elements

The figures for the thoium series that are different from those of the uranium series are shown below. All the other elements are the same as those used in the uranium series simulations.



#	ID	Weight	Half-Life	I	R	Daughter1
1	U236	236 g/mol	2.34e7 yr	✓	✓	Th232
2	Th232	232 g/mol	1.4e10 yr	✓	✓	Ra228
3	Th228	228 g/mol	1.9116 yr	✓	✓	Ra224
4	Ra228	228 g/mol	5.75 yr	✓	✓	Ac228
5	Pu240	240 g/mol	6560.0 yr	✓	✓	U236
6	Ac228	228 g/mol	6.15 hr	✓	✓	Th228
7	Ra224	224 g/mol	3.66 d	✓	✓	Pb212
8	Pb212	212 g/mol	10.64 hr	✓	✓	



	Value
U236	0.0063 m3/kg
Th232	5.5 m3/kg
Th228	5.5 m3/kg
Ra228	0.5 m3/kg
Pu240	0.10 m3/kg
Ac228	1.0 m3/kg
Ra224	0.50 m3/kg
Pb212	0.30 m3/kg

Edit Vector: Sz_Alluvium_1.Partiti...

	Value
U236	0.2 m3/kg
Th232	5.5 m3/kg
Th228	5.5 m3/kg
Ra228	0.15 m3/kg
Pu240	0.10 m3/kg
Ac228	.10 m3/kg
Ra224	0.150 m3/kg
Pb212	0.30 m3/kg

OK

Edit 1-D Table

The table can be referenced in the model as:

Cumulative_Pu240_Input(row variable)

	Row Variable [yr]	Result [g]
1	0	0
2	250	0
3	12500	0.309
4	16500	0.675
5	19000	0.98
6	21500	1.33
7	23500	1.63
8	26000	2.01
9	28000	2.33
10	30000	2.65
11	32500	3.03
12	34500	3.34
13	37000	3.7
14	39500	4.04
15	42000	4.35
16	45000	4.69
17	48500	5.04
18	53000	5.41
19	58000	5.73
20	66000	6.09
21	79000	6.42
22	179000	6.77
23	1000000	6.77

OK
Cancel
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Add Row(s)
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Edit 1-D Table

The table can be referenced in the model as:

Cumulative_U236_Input(row variable)

	Row Variable [yr]	Result [g]
1	0	0
2	250	0
3	248500	77000
4	341000	154000
5	410500	232000
6	468500	309000
7	519500	386000
8	566000	463000
9	609500	541000
10	649500	618000
11	687500	696000
12	723000	772000
13	757000	850000
14	789500	927000
15	820500	1000000
16	850000	1080000
17	878000	1160000
18	905000	1240000
19	930500	1310000
20	954500	1390000
21	978000	1470000
22	1000000	1550000

OK
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Edit 1-D Table

The table can be referenced in the model as:

Cumulative_Th232_Input(row variable)

	Row Variable [yr]	Result [g]
1	0	0
2	250	0
3	275500	48900
4	387000	97500
5	473500	146000
6	547500	195000
7	611500	244000
8	665500	293000
9	709500	342000
10	746000	391000
11	776000	439000
12	801500	488000
13	825000	537000
14	847000	586000
15	869000	635000
16	890500	683000
17	911500	733000
18	931000	781000
19	949500	831000
20	967000	880000
21	983500	928000
22	1000000	978000

OK
Cancel
Help
Add Row(s)
emove Row(s
mport Table..