EXTERNAL DETECTION AND MEASUREMENT OF INHALED RADIONUCLIDES USING THERMOLUMINESCENT DOSIMETERS

A Thesis

by

CHRISTOPHER ALVIN PRAUSE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fullfillment to the requirements for the degree of

MASTER OF SCIENCE

December 2006

Major Subject: Health Physics

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Approved by:

Co-Chairs of Committee,	Ian S. Hamilton
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ABSTRACT

External Detection and Measurement of Inhaled Radionuclides

Using Thermoluminescent Dosimeters. (December 2006)

Christopher Alvin Prause, B.S., Texas A&M University

Co-Chairs of Advisory Committee: Dr. Ian S. Hamilton
Dr. John W. Poston, Sr.

Many radiation detection programs use bio-assays, whole-body counters, or air sampling to estimate internal doses. This study examines the possibility of using a common external thermoluminescent dosimeter (TLD) badge as a device for detecting inhaled radionuclides through radiation those radionuclides emit which escape the body. The three common radionuclides chosen for modeling due to their varying decay modes and use or production in the nuclear industry were Cs-137, U-238, and Sr-90. These three radionuclides were modeled for biological and radiological removal in the dynamic systems modeling program of STELLA II and modeled for TLD dose per organ in the geometry and radiation simulation program of MCNP.

The results show that none of the nuclides in the study can be detected at air concentrations below regulatory limits for acute inhalation exposures. To achieve a detectable dose from an 8-hour work exposure, with a 90-day wait until the TLD is read, the airborne concentrations for the inhalation classes that produced the most dose per Bq would be 37.9 kBq/m^3, 146 MBq/m^3, and 1.67 MBq/m^3 for Cs-137, U-238, and Sr-90, respectively.

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INTRODUCTION

Current US regulations on radiation protection are based on methods of determining intakes and internal doses outlined in ICRP Publications 23 and 30. ICRP Publication 23, released in 1975, defines a Reference Man designed to be used as a template for determining internal doses in an adult male (ICRP 1975). Physiological data are contained in the report and can be used to create models, both real-world phantoms and computer generated versions, for use in internal dosimetry. ICRP Publication 30, released in 1979, described mathematical models of important systems of the body, metabolic models for elements, and established dose and intake limits for individuals working with radioactive materials and the general public (ICRP 1979).

ICRP Publication 30 contains dosimetry models for the respiratory system and gastrointestinal (GI) tract. These models, which include deposition and clearance rates for wide spectrum of radionuclides, are used to create the methodology for and calculating internal doses and establishing intake limits. This methodology also is used to guide the creation of bioassay programs and interpret the results. Techniques used in a modern bioassay program have the ability to detect very low concentrations of radioactive materials either in the body or excreted from the body of a worker. According to a study conducted at Lawrence Livermore National Laboratories in 2005, whole body scans can detect Cs-137 intakes as low as 1 nCi, urine bioassay can detect Sr-90 concentrations of 11 pCi/L, and an array of high-purity germanium detectors (HPGe) placed over the lungs can detect depleted uranium activities as low as 1 nCi (ORAU 2005).

However, these detectors are expensive and, therefore, not every company will have access to them for regular monitoring of intakes in their employees. This study will examine the possibility of using regular thermoluminescence dosimeter (TLD) badges to detect inhaled internal doses. TLD use has grown due to its low cost, low fading, linear

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This thesis follows the style of Health Physics.

dose response, and near tissue equivalency (Knoll 2000). It is the primary choice for many radiation safety programs for record keeping of external exposures. Therefore, it could be a significant advantage for the employer and employees if it were also able to detect internal doses.

The purpose of this research is to determine the viability of using passive external TLD badge measurements for the estimation of inhalation intakes and internal doses. For these results to be considered viable for real-world application, they must show that the deposited radioactivity is not only detectable using the TLD but that the readings will be considered accurate enough to be included in the employee's permanent dose record.

The main research objective is to calculate the minimum activity of an inhaled radionuclide that will produce a measurable dose in a TLD badge. Knowing the minimum activity required will allow deductions to be made as to the viability of using TLDs to detect and/or estimate a worker's internal dose. Along with the main objective, this study will also attempt to identify which radionuclides could be detected and measured in this fashion. Some parameters for determining if other radionuclides would be relevant to this study will be: half-life, radiation type, decay energy, decay spectrum, yield, chance of exposure to the radionuclide, and biological retention. Both a general set of boundaries using the above parameters and specific examples of radionuclides within these boundaries will be used to determine which radionuclides are relevant and non-relevant to this study.

BACKGROUND

MCNP

The Monte Carlo N-Particle (MCNP) computer program is a powerful software program developed to study neutral particle and photon interactions with matter (Briesmeister 2000). Later versions of the computer program also allowed beta particle transport. The simulation can follow billions of particles and photons individually and provide estimates of absorbed dose, criticality, particle fluence, and generic energy deposition information in a user-defined volume and geometry.

With the advent of computers, it became less necessary to make generalizations in dosimetry problems for simplicity. Where one dosimetry calculation would have taken several hours or was difficult to complete by hand, a radiation transport code such as MCNP can now accomplish the task in a matter of minutes or hours. In addition to normal 3-dimensional volumes, such as boxes, spheres, cylinders and cones, the MCNP code also included considerations of ellipsoids, hyperboloids, paraboloids, elliptical and circular toroids (Thompson 1979). Entire libraries of neutron, photon, and beta interaction cross-sections could be accessed by the program without requiring the user to input the values manually or make estimations for brevity. This makes the MCNP transport code viable over a wide range of photon transport problems (Hendricks et al. 1991).

The MCNP code has been used to test a wide variety of real-world problems to ensure both the accuracy of the original results and the accuracy of the code (Harvey 1993). A code completely recreating a reference man phantom was eventually written. One of these phantom recreations was developed by White Rock Science. The Bodybuilder program was based on research conducted at the Oak Ridge National Laboratory by Cristy and Eckerman (1987) using data from Snyder, et al. (1974) and Cristy (1980). These researchers based their models on Reference Man as presented in ICRP Publication 23 (ICRP 1975).

The Bodybuilder program can be used to write MCNP code to create every organ volume specified in Reference Man and subsequent revisions for age and gender. A newer version allows consideration of a pregnant women and the embryo/fetus.

It has only been recently that have ordinary computers been capable of handling such a large MCNP computer program with a large number of starting particles in a time efficient way. However, there are still limitations to acquiring results with acceptable precision using this code. In merging Reference Man with the MCNP code, the cell geometries are complex, the dose target in this study is very small and the effective Z of the body is very low. This leads to low-energy photons interacting before reaching the target and low levels of bremsstrahlung emissions from beta particles, requiring larger numbers of histories to be followed to achieve coherent statistics. To overcome these limits there are several ways to induce the MCNP code to provide the same precise results, while using less computing time.

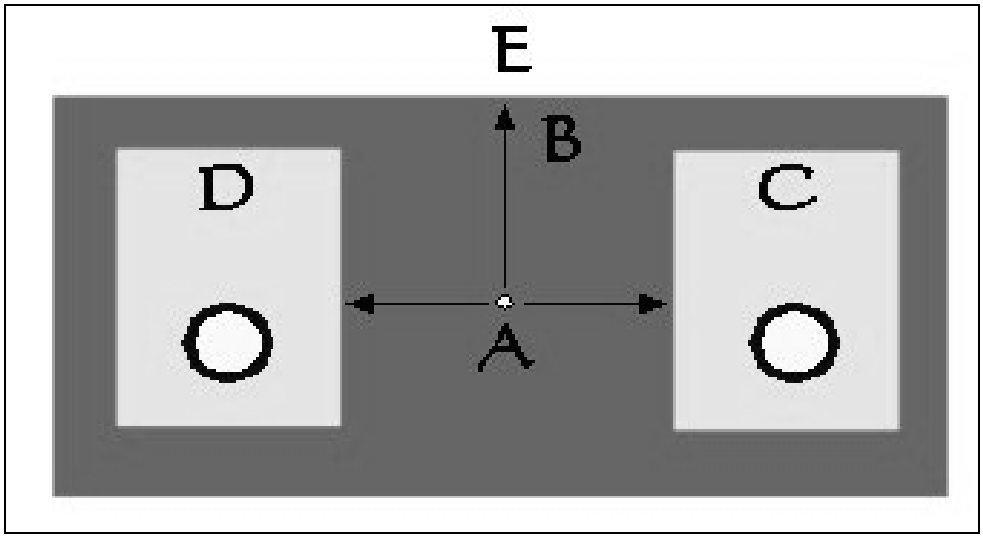

Fig. 1. Example of MCNP visualization. Point A is an isotropic radiation source, B is a diffuse transfer medium, C and D are air volumes containing spherical detectors (white), and E is the void outside the model.

MCNP has a variance reduction function called the importance function. It is used to increase the probability of incident radiation reaching a target volume. It is also used to "kill" (i.e., terminate) a radiation history reaching the edge of the model, saving on computing time. For example, if point A in Fig. 1 is the radiation source, volume B contains both point A and volumes C and D, volumes C and D contain spherical target

volumes, and volume E is the edge of the model, then the importances would be in order from B to E: 1, 2, 1, and 0.

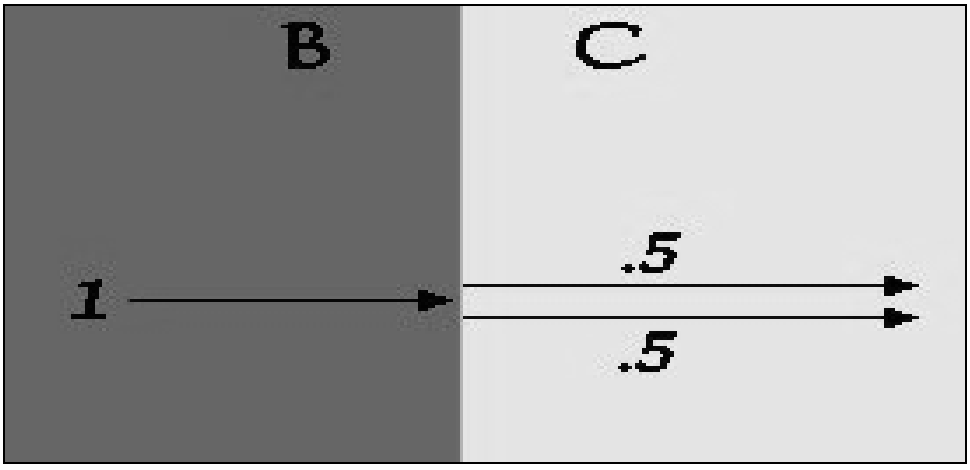

Fig. 2. Example of MCNP particle splitting. A particle entering a cell with twice the importance of the adjacent cell is split into 2 particles with half the statistical weight as the orignial particle.

At the border of B and C there is an increase in importance from 1 to 2. The MCNP code accounts for this increase in importance in volume C by increasing the number of photons entering volume C with the same direction and energy. The weight each particle contributes to the final tally is split evenly between the two particles at the border of C. In Fig. 2, the weight of the two particles is halved as it crosses the boundary, while the number of particles doubles. This allows each particle a higher probability of depositing energy in a desired region by creating more tracks but with less weight per track.

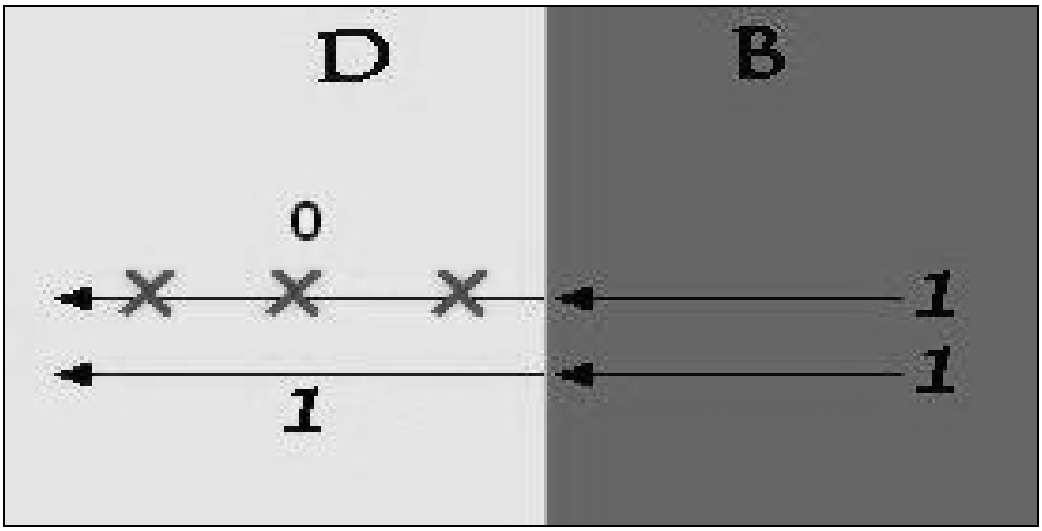

Fig. 3. Example of MCNP particle killing. A particle entering a cell with half the importance of the adjacent cell has a 50% chance of being "killed" by the MCNP

Conversely, Fig. 3 shows the Russian roulette style of particle killing that occurs when a particle moves from high to low importance. In this case, the importance decreases from 2 to 1 as the particle crosses from volume B to D. MCNP uses a random number generator to decide whether a particle track is killed or allowed to continue with the probability being 50% of the particle being killed. This is used to reduce computing time spent following particles in areas of the geometry that do not significantly alter the final result.

The MCNP code also has a variance reduction technique called direction biasing. The technique is used when a radioactive source is too far from the target volume of interest. The radiation can reach the target volume, but due to geometric effects, specifically the $1/r^2$ rule, the probability is extremely low and leads to poor statistics due to a small number of interactions in the target volume. Direction biasing increases the number of particles or photons emitted in the direction of a user specified bias cone, and decreases the number not emitted in that direction.

To create a direction bias, first a vector in the direction of interest is specified. This vector is most often from the center of the source volume to the center of the target volume. Next, an angle between the vector and a vector beginning at the same source is selected. Spinning this second vector about the first creates the direction bias cone. The cone should completely encompass the target volume when extended from the source

without regard to the creation point within the source volume. This cuts the emission possibilities from the source into 2 kinds: particles emitted within the direction bias cone and those outside of the cone. Fig. 4 illustrates the cone created about the direction bias vector. It is then appropriate to use the bias vector and move its origin to point b and find the smallest angle theta that encompasses the entire target volume. Moving the origin of the vector to the point on the source surface that demands the largest angle theta ensures the inclusion of the entirety of the target volume. Thus, it is certain that, for every point within the source volume, the direction bias cone includes the complete target volume.

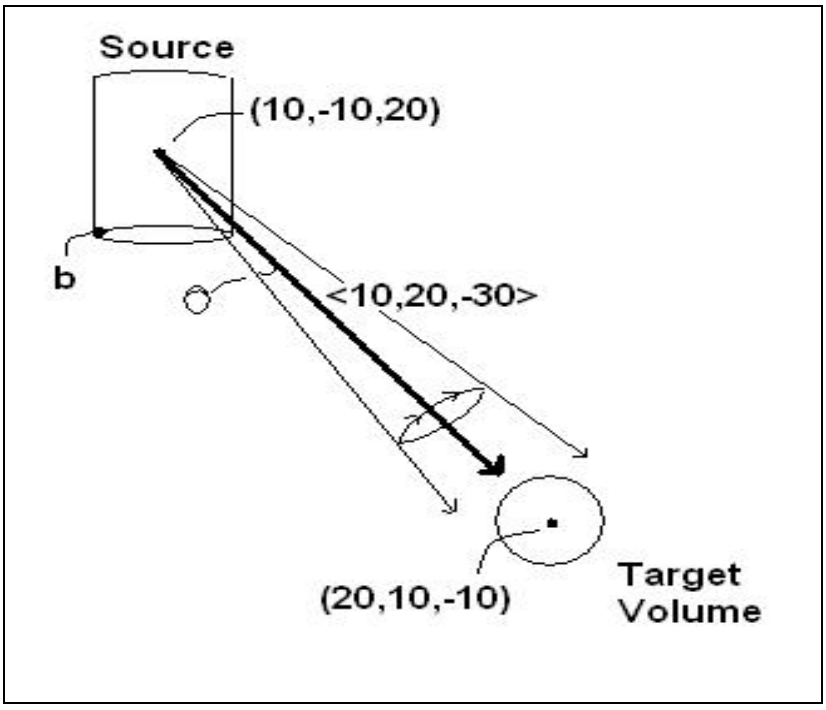

Fig. 4. Visual representation of a source bias cone in MCNP. It is created by rotating a vector about the bias vector at angle theta.

Once the cone is established, the amount of bias is entered. In Fig. 5, the amount of bias is proportional to the ratio between the biased number of particles started in the bias cone with the normal amount of particles started inside the cone without biasing. For example, from the “sp1” card, the normal distribution of particles between the outside and inside of the cone is 0.8 to 0.2. From the “sb1” card, the ratio is changed

from 0.2 to 0.8. The direction bias creates 4 times the number of particles that would normally be emitted in the direction of the target volume and decreases the chance of particles emitted outside the cone by 75%. The increase in directed particles increases the statistical probability of interaction in the target volume meaning that less particle histories are required to achieve similar statistical accuracy in the results.

```
sp1   -1    cos(theta)   1
si1    0     (1+cos(theta))/2    (1 – cos(theta))/2
sb2    0   (180° and theta bias)   (theta and 0° bias)

Input for theta=53.13°:
sp1  -1     .6     1
si1    0     .8     .2
sb1   0     .2     .8
```

Fig. 5. Sample input for the source card modifiers in the MCNP input code.

The MCNP code tracks the appropriate "weight" of each particle. In the previous example, the amount of the biasing is 4 times above normal. Each particle is therefore given a statistical weight of 0.25. If the particle achieves an interaction in the target volume, the energy information remains the same, but the amount of dose per photon created is reduced by a factor of 4 to keep correct statistics.

MCNP includes the ability to increase the amount of bremsstrahlung radiated during the slowing down of charged particles. This is very useful when the beta particles from an internally deposited radionuclide do not possess the necessary energy to escape the body. Their range is significantly shorter than the distance to the skin surface from the organ from which they are emitted. However, bremsstrahlung photons created as the beta particles slow have a better chance of escaping the body than do the particles themselves.

These photons are created following a normal spectral distribution over the possible energies as the particles slow. However, the low energy photons created have a low probability of escaping the body. The BREM function is used to artificially shift the amount of energy converted to bremsstrahlung photons to a larger fraction of the beta particle energy. This energetic photon produces a cascade of photons by creating higher

energy secondary electrons which then have a higher probability of producing photons and so on. This results in a greater number of photons, with greater energy, being radiated for each charged particle started.

The results from an MCNP calculation can take on many forms. For this study, the most important results were from the "F6" tally. The result created by this tally is the energy deposition averaged over a cell in terms of energy deposited per unit mass (MeV/g). This result is associated with an error that is one standard deviation given in fractional terms. An example output might read "4.00E-06 0.023" which means "the average energy deposited over this cell is $4.0 \times 10^{-6} \pm 0.092 \times 10^{-6}$ MeV/g." This allows the user to select the acceptable error in the problem and run the number of particles corresponding to that error target.

STELLA II

STELLA II is a system dynamic model originally developed by High Performance Systems, now ISEE Systems. STELLA II has been used to model systems from human blood flow to heavy metal transport by earthworms (Narayana et al. 1996; Johnston et al. 1995). Stella II uses reservoirs and flows with user generated flow rates to transport quantities through a system.

For a simple radioactive decay scheme involving an amount of radioactivity in a reservoir, which could be simulating a physical receptacle such as a dish or an organ, decaying into a stable daughter. Fig. 6 shows the graphical representation. "Activity 1" in Fig. 6 represents the location of the radioactivity, "Decay" represents the decay rate of the material in "Activity 1", and "Activity 2" represents the amount of activity that has decayed from "Activity 1". The initial amount of activity in "Activity 1" can be specified by the user or it can begin at zero and have a radioactive flow into it from another source, such as the stomach flowing into the small intestine, where "Activity 1" would be the small intestine. This activity can be removed through 1 of 2 flow connectors, either biological removal or radioactive decay removal. For the simple example, there is only radioactive decay removal.

The rate of decay of the activity is specified by the user and can be the quantity of the activity in "Activity 1" multiplied by the decay constant of the radionuclide being

modeled. The decay constant can have any units of reciprocal time that the user desires to use. The units must be kept constant for every flow in the model, however. A user may not have a flow rate in Bq/s for one flow and Bq/min in another or the results will be incorrect. Once the radionuclide has decayed for the desired amount of time, the resulting activity in "Activity 2" can be used to calculate the number of disintegrations of the radionuclide that occurred in "Activity 1" during that time. This number of disintegrations may be calculated using the STELLA II modifier feature which allows the user to modify a reservoir by a number of simple mathematical manipulations, similar to the tally multiplier used in MCNP. The result of this modification can then be displayed on the interface portion of the STELLA II program or the unmodified result of "Activity 2" may be shown.

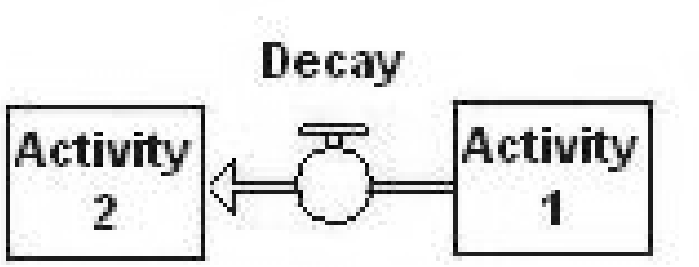

Fig. 6. Diagram of a simple decay scheme in STELLA II.

MATERIALS AND METHODS

First, a selection of some of the most common radionuclides with varying decay profiles was made. U-238, Cs-137, and Sr/Y-90 were chosen due to their many commercial uses and coinciding pathways to human exposure in the workplace and their differing decay spectra, radiation energies, and decay modes. U-238 was assumed to be a separated compound with none of its daughters in secular equilibrium. The two gamma rays associated with U-238 are of relatively low energy (0.04955 and 0.1135 MeV) compared to Cs-137 (0.667 MeV) or Co-60 (1.173 and 1.332 MeV). The probability of these low-energy gamma rays depositing energy in the TLD was lower due to higher interaction probabilities inside the body. U-238 was therefore chosen to represent low-energy gamma-emitting radionuclides.

Cs-137 is a radionuclide once commonly used in radiation therapy treatments at hospitals and is still in use at food irradiators and medical supply sterilizers around the world. Its moderately strong gamma ray and common uses made it an ideal candidate for study because unlike uranium, whose gamma rays are much lower in energy, the gamma rays associated with the decay of Cs-137 have an excellent chance of escaping the body.

Sr/Y-90 is a strong beta-emitting source. In the past it was used commonly as a heat source in radioisotope thermoelectric generators. It is also generated in all nuclear reactors, exists in nature as a result of fallout from atmospheric nuclear weapons testing, and can be released in nuclear power plant accidents or leak from radioactive waste storage sites (NCRP, 1991). Although there are no gamma rays generated by the decay of either strontium or its daughter yttrium-90, the energetic beta particles emitted by the yttrium-90 have the ability to create bremsstrahlung x rays, which could escape the body. Strontium is also a bone seeker, which places more of the beta particles being emitted closer to heavier elements such as calcium in bones. These heavier materials also increase the chances of bremsstrahlung being created.

The computer code STELLA II was chosen to model physiological dynamics of compartments in the human body. STELLA II is a powerful systems and population modeling tool. By recreating the flow of radioactive material through the human body,

important results are easily obtained. The most important results from the model were the number of nuclear transformations in the individual compartments and organs.

It was assumed that the inhalation intake was acute and that the integrated dose from uptake to evaluation of the TLD badge would be divided by 3 to simulate an 8-hour workday. Depending on when during the day the intake took place, the dose to the TLD could be significantly different. An intake could occur at the end of the day and the TLD would not be exposed until 15 hours later when the worker returned to work, or it could occur before a weekend. The intake could also be due to a chronic exposure over several work days. However, there are so many variables to consider when determining initial uptake, it was assumed that the error involved with these two assumptions will not greatly affect the overall conclusions of this study.

Physiological System Model – STELLA II

The internal deposition, retention, and decay of the radionuclides were modeled using the code STELLA II. The model used the ICRP Publication 30 compartmental models and metabolic data. Implicit in all of the programs used were all 10 lung compartments, the stomach, small intestine, upper large intestine and lower large intestine (considered the colon later in MCNP), and the bladder.

The tissue retention functions and f_1 values were unique to each element and each program in the study. The inhalation class of the aerosol was input as 1 = Class D, 2 = Class W, and 3 = Class Y. The simulation was such that any inhalation intake was assumed to be acute and immediately split into the appropriate lung compartments, where radiological and biological removal began. Although there was an input for "Inhalation_Activity_(in_Bq)", the value was always 1 Bq so the results provided by the simulation were already normalized.

An overall picture of the entire STELLA II program is provided in appendix A. Unfortunately, there were so many connections and lines between each compartment that it is difficult to distinguish what is happening so there are close-up graphical representations of each of the compartments and organs included in the text below.

Lung Compartments

The lung compartments were modeled after ICRP Publication 30 (ICRP 1979) design specifications. All 10 compartments had initial activity values set to the deposition fraction in their region times the fraction entering the compartment in question. For example, as shown in Fig. 7, a class D deposition would give an initial activity in compartment "e" of:

$$I = D_P \, x \, F_{e\,\mathrm{ClassD}} \qquad (1)$$

$$0.2 \text{ Bq} = 0.25 \text{ x } 0.8$$

Region	Compartment	Class D T day	D F	Class W T day	W F	Class Y T day	Y F
N–P (D_{N-P} = 0.30)	a	0.01	0.5	0.01	0.1	0.01	0.01
	b	0.01	0.5	0.40	0.9	0.40	0.99
T–B (D_{T-B} = 0.08)	c	0.01	0.95	0.01	0.5	0.01	0.01
	d	0.2	0.05	0.2	0.5	0.2	0.99
P (D_P = 0.25)	e	0.5	0.8	50	0.15	500	0.05
	f	n.a.	n.a.	1.0	0.4	1.0	0.4
	g	n.a.	n.a.	50	0.4	500	0.4
	h	0.5	0.2	50	0.05	500	0.15
L	i	0.5	1.0	50	1.0	1000	0.9
	j	n.a.	n.a.	n.a.	n.a.	∞	0.1

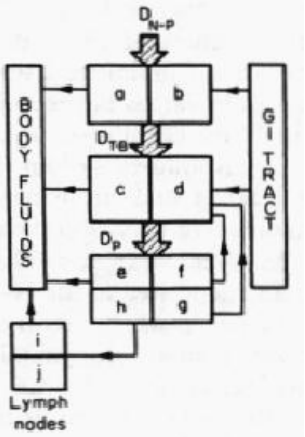

Fig. 7. ICRP-30 lung model. On the left is a chart of deposition fractions and biological half-lives in each of the 10 lung compartments. On the right is a diagram showing how materials flow out of each of the lung compartments. Taken from ICRP Publication 30 (ICRP 1979).

Each inhalation class for each radionuclide had "IF" statements used to change the initial activity in the lung compartments. If the "Inhalation Class" was input to be "2" on the user interface level of STELLA II, then each of the compartments would use the initial activity indicated by the "(IF Inhalation Class=2)THEN" statements on the formula level corresponding to class W fractions and biological half-lives. This way, instead of having three models for uranium and two for strontium, the inhalation class was input and all the necessary changes were made automatically on the formula level.

There were at least two outflows from every lung compartment except “j”, which has only one. One of the outflows was always “Decay in ‘compartment’”; this took activity out of the compartment at the radioactive decay rate. The other flow rate related to the biological half-life in Fig. 7. Note that, since “j” retains the nuclide indefinitely, there is no biological outflow from that compartment. The instantaneous outflow rates from radioactive decay and biological removal for each lung compartment were set to be:

$$\textit{(Activity in compartment) x (}0.693\textit{/(Radioactive Half-life)) = Flow rate in } \text{Bq d}^{-1} \quad (2)$$

$$\textit{(Activity in compartment) x (}0.693\textit{/(Biological Half-life)) = Flow rate in } \text{Bq d}^{-1} \quad (3)$$

respectively.

Compartments b and d flowed into the gastrointestinal tract (GI tract) starting at the stomach. This meant all of the activity entering the GI tract from the lungs had to pass through the stomach first providing for a chance to decay in the stomach even though this was an inhalation and not an ingestion intake. Compartments f and g flowed back into compartment d with different biological half-lives, where the material was cleared into the GI tract or decayed.

Compartments a, c, e, and i, however, had different outflows, which depended on the radionuclide being studied. Their outflow in Fig. 7 shows clearance into the body fluids, or blood, only.

Stomach

As mentioned, the stomach was the pathway for the activity being removed from lung compartments b and d. For the purposes of this study, each model, except for cesium-137, had the contents of the stomach empty through two outflows. One outflow was straight into the Small Intestine (SI) as seen in Fig. 8. The activity entering the stomach had a mean residence time of $1/24^{th}$ of a day. Meaning it took about an hour for contents to clear the stomach via the biological exit pathway. The other outflow was for radioactive decay.

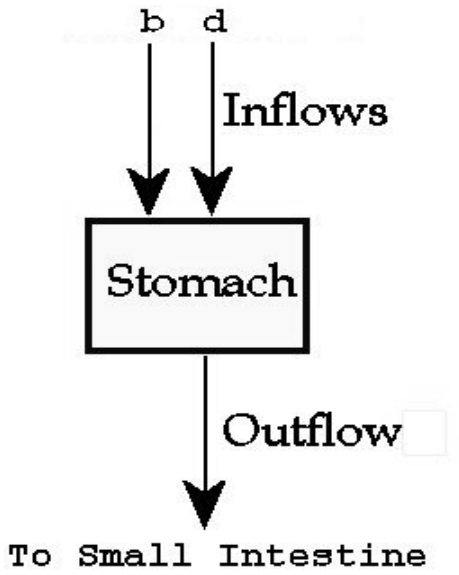

Fig. 8. Stomach model in STELLA II. Diagrams the flow of radioactive material into and out of the stomach.

Small Intestine

Lung compartments b and d feed the small intestine through the stomach. The outflow from the small intestine included radioactive decay, biological removal to the Upper Large Intestine (ULI), and biological removal to body fluids as seen in Fig. 9. The activity in the small intestine has a mean residence time of $4/24^{th}$ of a day. The activity entering the small intestine is not immediately absorbed into other body compartments, but flows out at a rate comparable to the fraction going to a particular compartment. The flow rate of 6 d^{-1} times the activity present in the small intestine is split among the biological removals by multiplying by the fraction that goes down the pathway. This concept is explained in greater detail in the individual radionuclide section below.

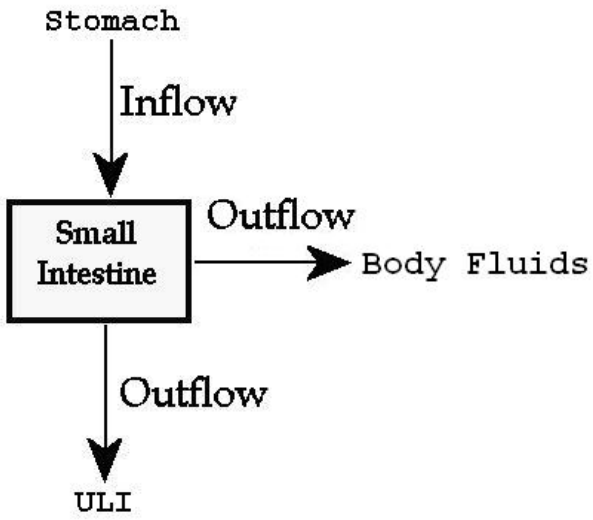

Fig. 9. Small intestine model in STELLA II. Diagrams the flow of radioactive material into and out of the small intestine.

Upper Large Intestine (ULI) and Lower Large Intestine (LLI)

These organs had only two outflows at any time and never changed their mean residence time with any radionuclide or inhalation class, as seen in Fig. 10. The ULI received its activity from the small intestine and retained it with a mean residence time of 13/24th of a day. What activity wasn't lost to decay proceeded into the Lower Large Intestine (LLI).

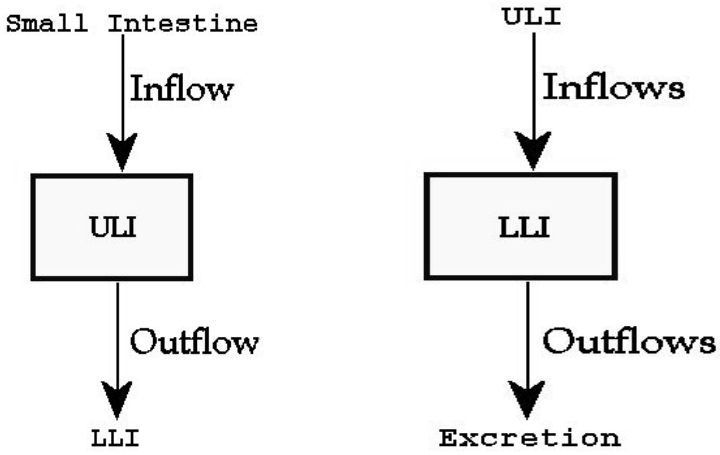

Fig. 10. ULI and LLI models in STELLA II. Diagrams the flows into and out of the Upper Large Intestine and Lower Large Intestine.

Once in the LLI, the activity had a mean residence time of 1 day. The activity not following the decay flow was assumed to flow out of the body with the feces. For clarity and cohesiveness, in the section on MCNP, the ULI and LLI are assumed to be combined to form the colon.

Bladder

The bladder was the final organ that activity entering the transfer compartment, organs in which the material was retained, or skeleton, which did not decay, passed through before excretion. A small number of transformations do occur in the bladder and activity leaving the above three compartments usually is assumed to go straight to excretion in the ICRP-30 metabolic model. However, its location in the lower torso and the anterior side of the body was assumed to produce high energy deposition per starting particle in the TLD target compared with other organs.

Since the ICRP-30 metabolic models assumed direct excretion from the transfer compartment, organs in which the material was retained, and skeleton, it did not include a metabolic model for the bladder. Discrete voiding of the bladder could cause large variations in the amount of dose reported in the first day of uptake, so a mean residence time of 4 hours (Cloutier, et. al, 1973) was used to continuously drain the bladder in place of discrete voiding.

Calculating Transformations

For each lung compartment, there was an outflow of activity into a decay reservoir. Once the activity reached the reservoir, it stayed there for the remainder of the simulation. All of the activity, in each of the lung decay compartments, was summed to give the activity that decayed completely within the lungs. The activity was in units of becquerels, so a simple formula was used to calculate the number of transformations that occurred.

$$N = A / \lambda_{radioactive} \qquad (4)$$

N was the number of transformations in this case since all of the atoms in the decay compartment are assumed to have undergone radioactive decay. The yield of the radiation was taken into account individually and explained in the results section.

Cs-137

This was the simplest model to create. All of the previously mentioned compartments were created, and two transfer compartments were added to the model. Although the body retains the radionuclide in the same physical tissues, two compartments were needed to allow for the separate biological half-lives in one compartment, as seen in Fig. 11. Each transfer compartment corresponded to a separate retention time, and all of the activity entering it is assumed to be retained. There is no immediate excretion of cesium through the urine. The single retention equation from ICRP Publication 30 was:

$$R(t) = 0.1\, e^{-0.693t/T_1} + 0.9\, e^{-0.693t/T_2} \qquad (5)$$

t = time passed since activity in question entered the transfer compartment in days

T_1 = 2 days, and is the biological half-life of 1/10th of the activity entering the transfer compartment, and

T_2 = 110 days, and is the biological half-life of 9/10ths of the activity entering the transfer compartment.

Lung compartments a, c, e, and i flowed directly into the transfer compartments with the same fractions entering each as shown in Eq. 5. The initial cesium activities in these lung compartments are listed in Table 1.

Table 1. Lung compartment initial activities for Cs-137. Activities present in each lung compartment for a class D, 1Bq, Cs-137 acute inhalation model in STELLA II.

	Initial Radioactivity (in Bq out of 1 Bq)
Lung Compartments	Class D f1 = 1
a	0.15
b	0.15
c	0.076
d	0.004
e	0.2
f	0
g	0
h	0.05
i	0
j	0

The absorption of cesium is complete and the f_1 value is 1.0. Therefore, the model simply had two outflows from the stomach cleared at the standard 24 d^{-1} rate as seen in Table 1 and there was no need to create "IF" statements in the formula level to account for inhalation classes. The radionuclide was assumed to be absorbed immediately into the TC once it reached the GI tract and thus have no residence time at all in the small intestine, so this will be the only model to take material straight from the stomach into the transfer compartment due to the f_1 value being 1.

The inflows into the transfer compartment from the stomach are obtained from Eq. 3. Using the data from Eq. 4, the inflow for transfer compartments 1 and 2 became:

$$(0.1) \times (\textit{Activity in Stomach}) \times (24\ d^{-1}) = \textit{Flow rate into TC1 in}\ Bqd^{-1} \qquad (6)$$

$$(0.9) \times (\textit{Activity in Stomach}) \times (24\ d^{-1}) = \textit{Flow rate into TC2 in}\ Bqd^{-1} \qquad (7)$$

This meant that the outflows from the transfer compartment were simple. One of the outflows was for the radioactive decay in the compartment and one for biological removal to the bladder. The decay from both compartments flowed into a single reservoir so that the transformations calculated from it would be for the entire transfer compartment, as seen in Fig. 12.

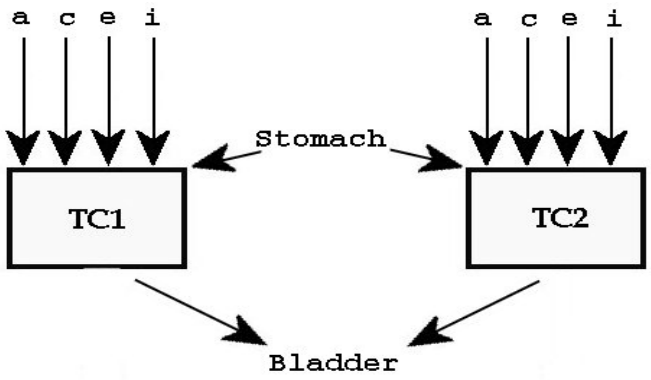

Fig. 11. Transfer compartment models in STELLA II. Inflows and outflows of the two transfer compartments for Cs-137.

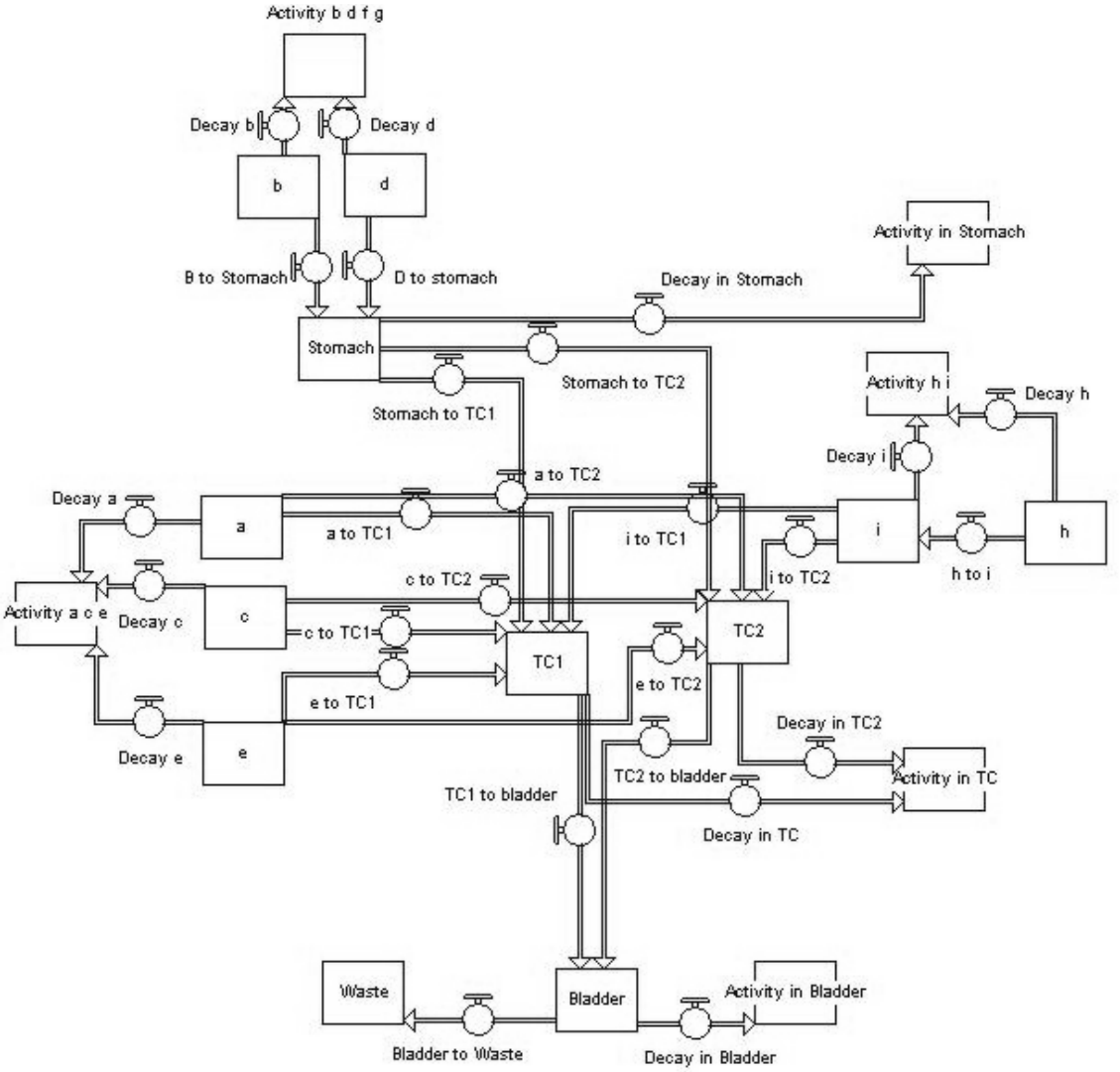

Fig. 12. Schematic from STELLA II for Cs-137. Organ and compartmental model based on ICRP-30 metabolic rates and lung model.

U-238

The model for uranium contained several more compartments than the cesium model. While cesium was only retained in the body tissues and uniformly distributed throughout them, uranium was also retained in the kidneys and skeleton. Each of these retention equations involved splitting the incoming activity among the two separate biological half-lives. Below are the retention equations for body tissues, bones, and kidneys for activity reaching the transfer compartment from ICRP Publication 30 (ICRP 1979).

$$R_{BONE}(t) = 0.2\, e^{-0.693t/20} + 0.023\, e^{-0.693t/5000} \quad (8)$$

$$R_{KIDNEY}(t) = 0.12\, e^{-0.693t/6} + 0.00052\, e^{-0.693t/1500} \quad (9)$$

$$R_{TISSUE}(t) = 0.12\, e^{-0.693t/6} + 0.00052\, e^{-0.693t/1500} \quad (10)$$

The remaining 0.53596 fraction of activity entering the transfer compartment is assumed to go directly to the bladder for excretion. Thus, there were six distribution compartments created in the model, two for each retention equation above. Fig. 13 shows the connections made on the graphical interface portion of the STELLA II program. The outflow rate for each compartment was determined using Eq. 3.

Lung compartments a, c, e, and i had a total of seven outflows each. One for radioactive decay and the rest for biological removal to the bladder, two kidney compartments, two bone compartments, and two transfer compartments. The small intestine also had each of those seven outflows, and it had an additional outflow into the ULI.

There were three separate inhalation classes, and therefore three initial activities for each lung compartment. Table 2 shows the initial activities in units of becquerels in the lung compartments for each inhalation class for a 1Bq inhalation of U-238. The program toggled between the initial activities using “IF” statements in the formula level and the user input the inhalation class on the interface level.

Table 2. Lung compartment initial activities for U-238. The initial activities present in each lung compartment for each inhalation class and its corresponding f_1 value.

	Initial Radioactivity (in Bq out of 1 inhaled Bq)		
Lung Compartment	Class D f1 = .05	Class W f1 = .05	Class Y f1 = .002
a	0.15	0.03	0.003
b	0.15	0.27	0.297
c	0.076	0.04	0.0008
d	0.004	0.04	0.0792
e	0.2	0.0375	0.0125
f	0	0.1	0.1
g	0	0.1	0.1
h	0.05	0.0125	0.0375
i	0	0	0
j	0	0	0

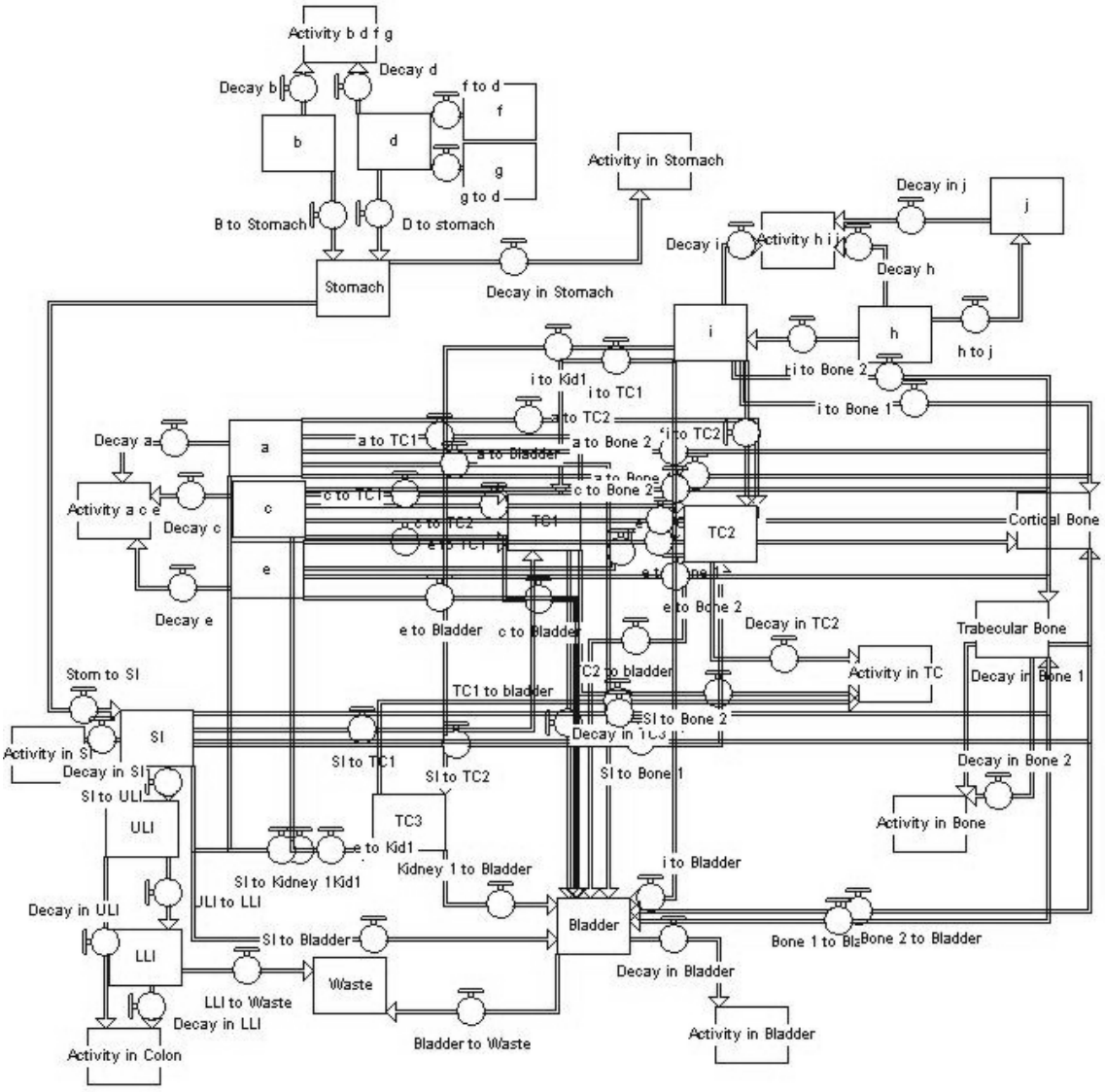

Fig. 13. Schematic from STELLA II for U-238. Organ and compartmental model based on ICRP-30 metabolic rates and lung model.

Sr-90

Strontium-90 is rapidly absorbed from the gastrointestinal tract or the lung into the bloodstream and is subsequently deposited in bone (Hobbs and McClellan, 1986). The two inhalation classes for strontium, class D and class Y, had initial activities for each lung compartment as shown in Table 3. The inhalation is assumed by this study to have yttrium-90 in secular equilibrium with its parent strontium-90 (NCRP, 1991). Therefore, the number of transformations calculated was for strontium only, but due to secular equilibrium, the same number of yttrium atoms decayed during that time and in

the same compartment. The retention equations for strontium activity reaching the transfer compartment are taken from ICRP Publication 30 (ICRP, 1979).

$$R_{TISSUE}(t) = (0.85)\ x\ (0.8\ e^{-0.693t/2} + 0.15\ e^{-0.693t/30} + 0.05\ e^{-0.693t/200}) \quad (11)$$

$$R_{CORTICAL\ BONE}(t) = 0.06\ e^{-0.693t/8431.5} \quad (12)$$

$$R_{TRABECULAR\ BONE}(t) = 0.09\ e^{-0.693t/1405.25} \quad (13)$$

Of the activity entering the transfer compartment, 85% is retained with the three tissue compartments with half-lives of 2, 30, and 200 days. The other 15% was split between cortical bone and trabecular bone with half-lives of 8431.5 and 1405.25 days, respectively. The lung compartments a, c, e, and i each had 5 outflows into these compartments and 1 each for radioactive decay. The small intestine had an extra outflow, relative to these lung compartments, to the ULI in addition to the outflows to the bones. These connections can be seen in Fig. 14. None of the activity was assumed to go straight to excretion after entering the transfer compartments; it was all retained to some degree.

Table 3. Lung compartment initial activities for Sr-90. The initial activities present in each lung compartment for each inhalation class and its corresponding f_1 value.

	Initial Radioactivity (in Bq out of 1 Bq)	
Lung Compartment	Class D f1 = .3	Class Y f1 = .01
a	0.15	0.003
b	0.15	0.297
c	0.076	0.0008
d	0.004	0.0792
e	0.2	0.0125
f	0	0.1
g	0	0.1
h	0.05	0.0375
i	0	0
j	0	0

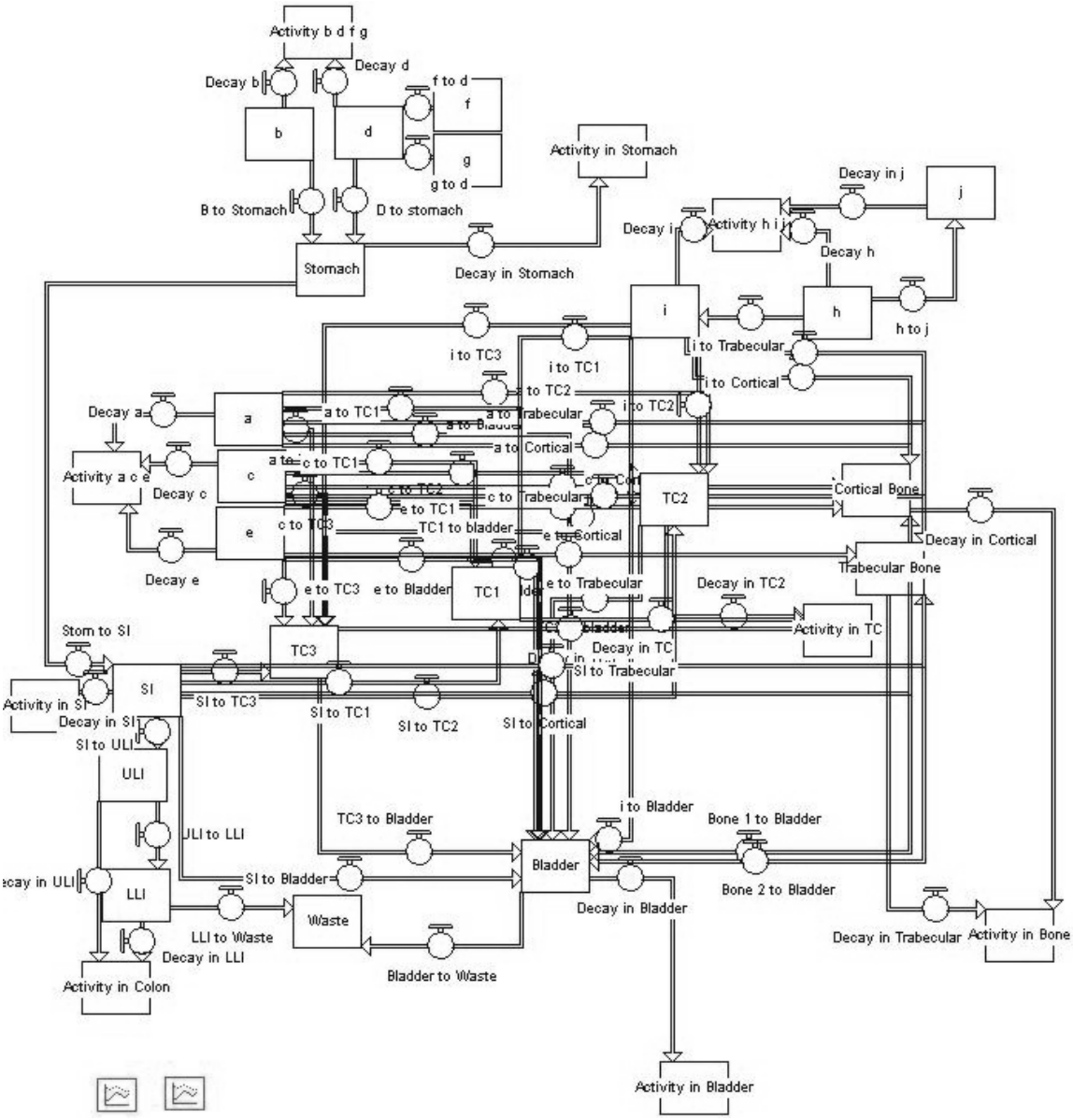

Fig. 14. Schematic from STELLA II for Sr-90. Organ and compartmental model based on ICRP-30 metabolic rates and lung model.

MCNP

To create the initial human model for use in MCNP, the program BodyBuilder by White Rock Science was used. This program could be used to create an MCNP input file that represented the models described by Cristy and Eckerman (1987). These models were based on the research of Snyder and his colleagues (Snyder, et al, 1974) and Cristy (1980). The program allowed the user to select which organs to include in the final

MCNP code. Since all of the models required many of the same organs to be present, the initial MCNP file generated would have every organ present used in all of the simulations. Then, organs not needed in a particular simulation were combined into the soft tissue and not considered further. The main reason for this approach was that the BodyBuilder program could not be used to create a program that could be used directly by MCNP. The input file it created was full of extra characters that were removed before the program could be included in the MCNP simulation. The process of removing the unneeded organs took a long time, so it was much easier to simply "comment out" an unneeded organ for a MCNP simulation.

Fig. 15 is from the BodyBuilder user interface. The organs checked means they were included in the initial program and used as sources for every nuclide studied. These included the lungs, stomach, and bladder. Ordinary body tissue was also a source for all of the nuclides studied, but this region is not listed as an organ and required modification to the code. This modification is explained in the *body tissue* section below. Each of the models, other than the cesium model, also used the small intestine, ascending colon, transverse colon, descending colon, and sigmoid colon as sources of radioactivity. The uranium and strontium models also required the skeleton as a source, though the skeleton was present in the cesium model for correct geometry. The skin was used in every model for variance reduction. The size, weight and location of the organs were comparable to those listed in ICRP Publication 30 (ICRP, 1979).

The age of 21 years represents a full-grown, adult male. The height of 1.79 m is 9 cm taller than the recommended height for Reference Man used in ICRP dose calculations (ICRP 1975), and the mass of 72.94 kg represents an increase of 2.94 kg over the same Reference Man. The extra mass was due to the model being taller. The model being 5% taller than the ICRP Publication 23 model was not expected to alter the results significantly since the organs in the same regions and the geometry of the model were not changed significantly. Therefore, the results were assumed to be applicable to situations in which a Reference Man model was supposed to be used.

Composition of body tissues (and organs excluding lungs), skeleton, lungs, and air are listed in Table 4. The TLD was composed of lithium and fluorine at natural isotopic abundances.

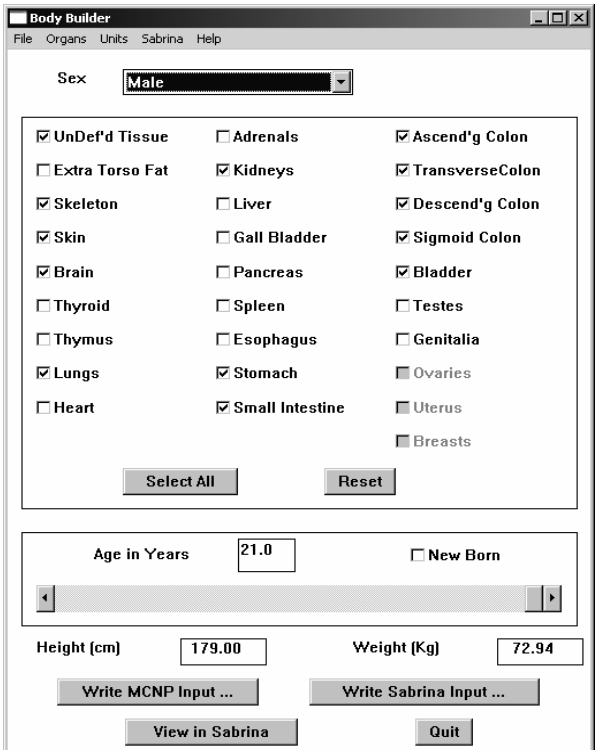

Fig. 15. Body Builder user interface. Used for creating MCNP input files. The output is a text file.

Table 4. Elemental composition of regions of the body in percent weight.

	Materials Inside the Body (% Weight)			
Element	Body Tissues	Skeleton	Lungs	Air
hydrogen	10.454	7.337	10.134	0
carbon	22.663	25.475	10.238	0.012
nitrogen	2.490	3.057	2.866	75.527
oxygen	63.525	47.893	75.752	23.178
fluorine	0	0.025	0	0
sodium	0.112	0.326	0.184	0
magnesium	0.013	0.112	0.007	0
silicon	0.03	0.002	0	0
phosphorous	0.134	5.095	0.08	0
sulfur	0.204	0.173	0.225	0
chlorine	0.133	0.143	0.266	0
argon	0	0	0	1.283
potassium	0.208	0.153	0.194	0
calcium	0.024	10.19	0.009	0
iron	0.005	0.008	0.037	0
zinc	0.003	0.005	0.001	0
rubidium	0.001	0.005	0.001	0
zirconium	0.001	0	0	0
lead	0	0.001	0	0

Source cards were written for the lungs, bladder, and each part of the body that had a retention equation for the radionuclide. In MCNP, to make a cell a source, the entire source must be enclosed inside of a virtual source volume, typically a sphere or cylinder. The computer uses random number generators to select points at random inside the virtual source volume. If the point selected is within the actual source volume, a particle was created at that point and tracked until it is lost or it has dissipated all its energy. If the point selected was within the virtual source volume, but outside the actual source, it was discarded and a new point was selected. Shrinking the virtual source volume to be just slightly larger than the actual source volume reduced computing time by increasing the efficiency by which random numbers were used in the model. A model in which 80% of the points selected were used would run faster than one in which only 2% are used. Direction biasing also occurred in the source cards for sources that were too far to obtain accurate data from unbiased runs.

Every computer simulation used some variance reduction. The most common method was the importance function. Cells with little or no bearing on the outcome of the results were given low importances while cells that were in the direction of the TLD from the source organ were given higher importances. For example, the skin was on the outside of the body. Therefore, any photon reaching the skin had a better chance of reaching the TLD because it had already traversed body tissue and perhaps the skeleton, so the skin was given a higher importance than any of the body tissues. The air in the –y direction from the y = 0 plane enclosed the TLD, so any photons reaching that air volume had a higher importance than ones leaving the body in the +y direction. Thus, the air in the –y direction was given a higher importance. For some simulations, it was enough to make the entire air sphere around the body the same importance rather than splitting it into –y and +y hemispheres and assigning separate importances. The hemisphere splitting was only employed when proper statistics could not be achieved through simple source biasing and importance functions or the simulation took too long and the simulation time needed to be shortened.

Body Tissues

For each of the radionuclides studied, there was some retention of each in the body tissues. Body tissues included muscle, connective tissue, and all organs, excluding the digestive tract, skeleton, and respiratory organs, which did not have separate retention equations. The BodyBuilder program could be used to create a model that broke up these tissues into the head, neck, outer trunk---arms and scapulae, upper trunk---above ribs, high chest organs, chest---liver level, lower trunk and legs. Any radionuclide distributed throughout the body would need eight programs to simulate each of the regions that would act as source regions. Then, those regions would have to be weighted according to their masses; which were not always calculated as part of the MCNP simulation

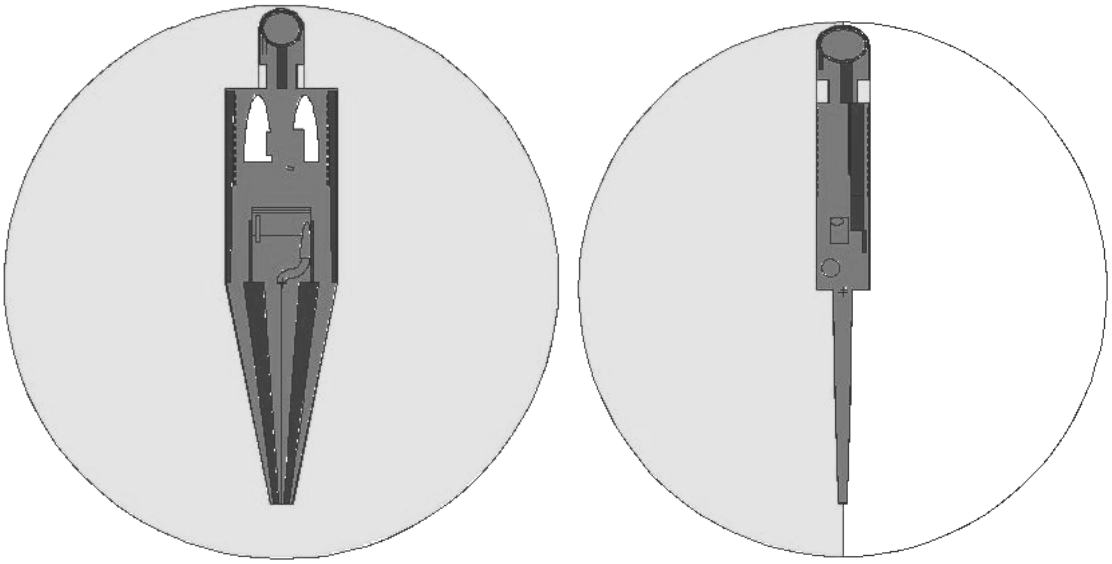

Fig. 16. Whole body view from MCNP. The figure on the left shows a view through the ZX-plane at y=0. The light grey around the body is the surrounding air. The view through the ZY-plane (right) shows the variance reduction technique of importances. On the left side of the figure is the –y direction and the direction the model is facing, so it contains the TLD. On the right side it is white because any photon reaching this area is considered lost because the probability of a recoil in air that could traverse the body is remote.

and were difficult to obtain by hand calculations. To simplify this calculation, all eight of these regions were combined into one cell card in MCNP as seen in Fig. 16. So, only one program was needed to simulate radionuclides retained in body tissues instead of eight

individual programs. This also reduced the time required to model body tissue retention to approximately $1/8^{th}$ the computing time required to simulate all 8 regions separately.

The TLD chip was very close to the torso of the model, so direction biasing of the source was not required to achieve good statistics. For the beta-radiation emitter, the bremsstrahlung photons created would tend to be produced with energies less than 300 keV and at such low probabilities that obtaining accurate statistics required additional variance reduction. A separate cell of air was created around the TLD to enable a higher importance to photons reaching the vicinity. The air box was 3.12 x 0.35 x 3.4 cm centered at (9.66, -9.625, 2.7).

The sampling volume for the body tissue source card was a right circular cylinder that started at -80 cm centered on the xy-axis and extended in the +z direction to 98.61cm. The difference in height from the total height of 179 cm to the body tissue height of 178.61 cm is the thickness of two layers of skin, one of the head and one on the bottom of the legs, which were not considered soft tissue. The radius of the source cylinder was 20 cm, and encompassed the outer extent of the arm tissue. Every part of the soft tissue fell within this source cylinder while some of the skin on the legs and head were outside of it.

Lungs

The lungs were assumed to include the disintegrations occurring in the nasal passages (N-P), trachea-bronchial trees (T-B), pulmonary parenchyma (P), and lymph nodes. This assumption was made because the nasal passages have very short biological half-lives and, therefore, contribute very little to the dose per photon coming from the respiratory tract. This would result in only a slight overestimate of the dose received by the TLD from the lungs in the first two days, and that overestimate would decrease significantly as days passed as the pulmonary region would continue to be the largest contributor to the dose per photon due to the long biological half-lives of its compartments as compared to the N-P region.

The lungs were enclosed by a virtual cylinder for source sampling that began at the bottom of the lungs at (0, 0, 43.5 cm) and extended 24 cm in the positive z direction. The radius of 13.5 cm for the source cylinder was tight around the outermost parts of the

lungs, and enclosed all of the points within cell 330. The sections that appeared to be cut out of the lungs were intended to simulate the space occupied by the heart. In Fig. 17, the right side of each picture represents the left side of the body; therefore, more volume is taken up by the heart on that side.

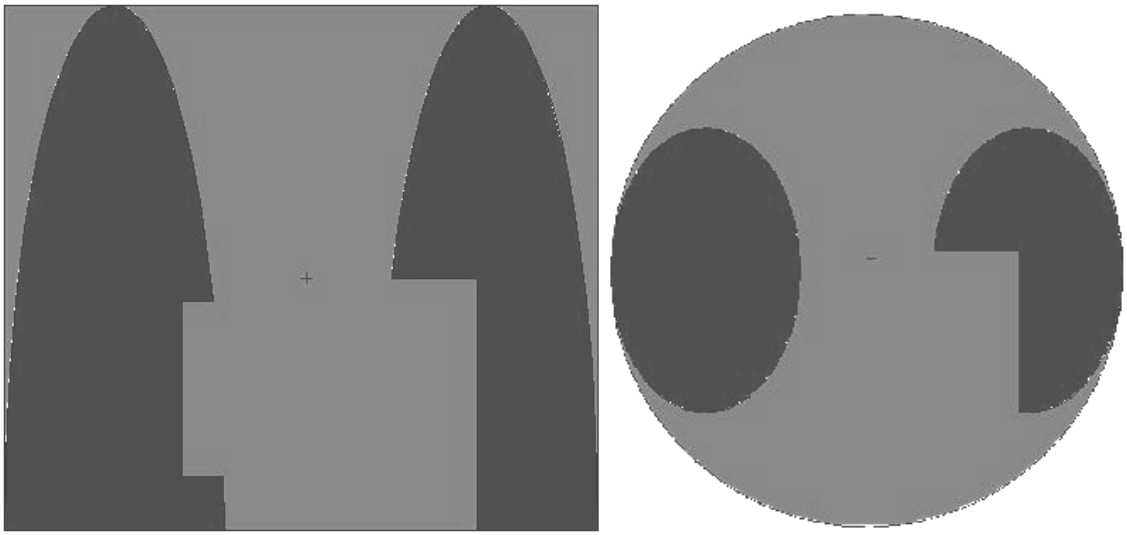

Fig. 17. Lungs view from MCNP. Left, cutaway view of the lungs through the zx-plane, from z=43.5 to 67.5 and x=-13.5 to +13.5. Right, view of the lungs through the xy-plane at z=43.5 from x=-13.5 to +13.5 and y=-13.5 to +13.5. The dark grey represents the volume within the outer lung tissue and the light grey is tissue within the sampling volume that is not used.

The distance between the lungs and the TLD required additional variance reduction to ensure enough photons reached the TLD sampling volume. The source bias referred to the "VEC" and "DIR" entries in the source definition card and the si3, sp3, and sb3 entries below it, as seen in Fig. 18. The "VEC" entry referred to the direction vector about which solid angles could be selected. In this case, the photons needed to be biased to be emitted in the direction of the TLD. The vector specified was from the bottom center of the virtual source sampling cylinder (0, 0, 43.5) pointing directly at the center of the TLD at (9.62, -9.525, 2.7). To decide how large to make the solid angle, two points on opposite sides of the organ were used with the point at the center of the TLD to form an angle in 2-D space from the resulting vectors to the center of the TLD.

This angle was found to be 34.5^{o} and was rounded up to 35^{o} to ensure all of the points sampled in the cylinder contained the TLD within their direction bias cone. Then, 80% of the photons created in the source began in the directions contained within the cone, while the other 20% had directions outside of the cone.

```
SDEF  POS=0 0 43.5  CEL=330  AXS=0 0 1  RAD=d1 EXT=d2
      VEC=9.62 -9.525 -40.8 DIR=d3
si1 0  13.5
sp1 -21  1
si2 0  24
sp2 -21  0
si3 -1 .743145 1
sp3 0 .8716 .1283
sb3 0 .2 .8
```

Fig. 18. MCNP source definition card for the lung model.

Stomach

Each simulation also used the stomach as a source organ. In MCNP, the stomach was described by a simple hyperboloid. The virtual sampling volume that included the least amount of dead sampling space was a sphere of radius 8.1 cm centered at the same coordinates as the center as the stomach center, (8, -4, 35).

The stomach was far enough away from the TLD to require direction biasing. The direction vector from the center of the stomach volume (8, -4, 35) to the center of the TLD was <1.62, -5.525, -32.3>. The angle about the vector was found to be 30^{o} to enclose the TLD in the bias cone for all points in the source volume.

Small Intestine

The small intestine was defined as an ellipsoid in the xy-plane, extended on the z-axis to create a volume. It was bounded by z = 27 cm and z =17 cm on the z-axis, and by y = 2.2 and y = -4.86. This volume included the colon, which was then subtracted out.

The small intestine was enclosed inside a sampling cylinder. The bottom of this cylinder was at (0, -3.5, 17) and extended 10 cm on the +z-axis and was 11.7 cm in radius. The small intestine source was biased about the vector from the center of the sampling volume (0, -3.5, 22) to the center of the TLD defining the vector <9.62, -6.025, -19.3>.

Upper Large Intestine and Lower Large Intestine

The Upper and Lower Large Intestines were combined into a single source volume called “colon” for use with the MCNP code. The colon contains the ascending, transverse, descending and sigmoid colons parts. The volume contained within these four parts of the colon was set as the source using an ambiguous volume source definition with a cylindrical sampling volume centered at (0, 0, 15) with a length along the z-axis of 30cm, and a radius of 12cm. No direction biasing was required for any of the models for this organ.

Bladder

The bladder was defined as a hyperboloid centered at (0, -4.5, 8.53) and the sampling source volume that surrounded it was a sphere with the same center and 5.2 cm in radius. Due to its position near the anterior of the body and in the lower trunk, direction biasing was not required; however, it was employed to expedite results. A bias cone about vector <9.62, -5.025, -5.83> with an angle of 32^{o} was applied.

RESULTS

The results from STELLA II gave the total number of transformations from the intake until the selected end day. Since workers do not wear their badges 24 hours each day, the final number of transformations needed to represent an 8-hour workday. This was achieved by dividing the number of transformations each day by 3. Errors caused by the use of this assumption are discussed in the conclusions section. A sample of the full STELLA II results from Appendix A is given in Table 5.

Table 5. Transformations per compartment for Sr-90.

Compartment	Transformation per Compartment for Sr-90				
	Day 1	Day 7	Day 30	Day 90	Day 365
Lungs	13509	19266	19269	19269	19269
Stomach	554	554	554	554	554
Small Intestine	2205	2218	2218	2218	2218
Colon	6344	14462	14487	14487	14487
TC	7004	37934	79630	135860	218979
Skeleton	1394	13299	59664	178661	689961
Bladder	2329	3335	3476	3542	3595

For each day, the total number of transformations was calculated using STELLA II for each organ and/or compartment of interest. All calculations were normalized to an intake of 1 Bq. The number of transformations in an organ or compartment was multiplied by the MNCP-result after converting the result from units of MeV/g-photon to units of J/kg-photon. This result, when corrected for yield, represented the absorbed dose, in Gy per Bq intake, deposited in the TLD since the initial intake. Typical results are given in Table 6. A complete listing of all the results is provided in Appendix B.

For U-238, the MCNP simulation did not provide statistically significant results for activity deposited in the lungs. Therefore, it was assumed to contribute a trivial amount of dose to the TLD. Several of the other compartments had large errors associated with their dose contribution to the TLD. Each of these was typically farther away from the TLD, involved low-energy photons and, therefore, did not contribute significantly to the overall results.

Table 6. Total average dose per unit of inhalation intake to the TLD. Dose is cummulative over the specified period, in Gy/Bq.

	Dose to TLD in Gy/Bq				
Nuclide	1 Day	7 Days	30 Days	90 Days	365 Days
U-238 Class D	9.1×10^{-17}	3.2×10^{-16}	5.6×10^{-16}	7.1×10^{-16}	1.0×10^{-15}
U-238 Class W	5.95×10^{-17}	2.86×10^{-16}	3.58×10^{-16}	4.34×10^{-16}	5.6×10^{-16}
U-238 Class Y	6.28×10^{-17}	2.92×10^{-16}	3.00×10^{-16}	3.07×10^{-16}	3.35×10^{-16}
Cs-137 Class D	3.31×10^{-12}	2.74×10^{-11}	1.10×10^{-10}	2.75×10^{-10}	5.53×10^{-10}
Sr/Y-90 Class D	5.70×10^{-15}	1.75×10^{-14}	3.35×10^{-14}	6.21×10^{-14}	1.47×10^{-13}
Sr/Y-90 Class Y	3.96×10^{-15}	1.72×10^{-14}	1.77×10^{-14}	1.85×10^{-14}	2.1510^{-14}

Due to the distribution of the skeleton throughout the body, and the nature of bremsstrahlung production over a spectrum of energies, the MCNP results for Sr/Y-90 had significant error for the skeletal simulation despite taking 5.3 days to complete. This affected the results for Class D Sr/Y-90, at 90 days after intake and after, since most of the radioactivity is located in the bone this radiation made significant contributions to the total dose measured by the TLD.

CONCLUSIONS

Assuming the minimum sensitivity of 100 µGy (10 mrad) for typical dosimeters has been met by background radiation over the monitoring period and assuming a resolution of 1µGy (0.1 mrad), a TLD could receive detectable levels of dose by receiving 1 µGy or more during the monitoring period (Knoll, 2000). The intakes (in MBq) required to achieve this dose for each of the radionuclides over discrete time periods are listed in Table 7.

Table 7. Minimum inhaled activity (MBq) required to produce a detectable dose in the TLD.

	Minimum Inhaled Activity in MBq				
Nuclide	1 Day	7 Days	30 Days	90 Days	365 Days
U-238 Class D	10989	3125	1785	1408	1000
U-238 Class W	16807	3497	2793	2304	1786
U-238 Class Y	15924	3425	3333	3257	2985
Cs-137 Class D	0.302	0.0365	9.09×10^{-3}	3.64×10^{-3}	1.81×10^{-3}
Sr/Y-90 Class D	175.4	57.1	29.9	16.1	6.8
Sr/Y-90 Class Y	252.5	58.1	56.5	54.1	46.5

If an intake occurs before 100 µGy (10 mrad) of dose is acquired in the TLD from background or other known sources, then Table 7 may be used to quantify the amount of the nuclide required to bring the dose up to the minimum level of sensitivity before it can be detected accurately. To distinguish between dose to the TLD from internal and external sources, typical doses estimated from previous radiation surveys or from stationary monitors would be subtracted from the initial TLD reading.

Cs-137

Cs-137 intake per day is estimated at 10 µg/day from a diet of typical fluids and foods (ICRP, 1975). From Table 7, the inhalation intake required to produce a measurable dose in the TLD is 0.167µg for a single day, acute inhalation. Therefore, chemical toxicity is not an issue when dealing with low-level exposure to Cs-137 as it is present in greater amounts in a normal diet.

An inhalation intake of Cs-137 producing a detectable dose in the TLD could be significantly lower than the Annual Limit on Intake (ALI) of 6 MBq recommended in

ICRP Publication 30. However, the 1-hour DAC for the required inhalation in Table 7 would still be greater than the ICRP Publication 30 DAC of 2 kBq/m^3 for all of the time periods studied except for the 365 day period.

It is therefore unlikely that an acute occupational inhalation intake would be large enough to register on the TLD, but small enough to elude a facility's continuous air monitoring system set to alarm before the ICRP Publication 30 DAC is reached.

U-238

For all inhalation classes of U-238, chemical toxicity took precedence over TLD radiation detection. Toxic effects in the kidneys begin at concentrations of uranium of 3 µg-U/g-kidneys (Leggett, 1989; Fisher et al. 1994). The values observed in the kidneys are 7 orders of magnitude above the lower limit for toxic effects. Additionally, it would take 80 kg of U-238 to accumulate an activity of 1,000 MBq. It is unlikely that someone would consume that quantity of material in any setting.

This conclusion also applies to naturally-occurring uranium. Activity in natural uranium is split mostly between U-235 and U-238. Both have similar energy photons, similar yields, and have roughly the same activity per gram in a sample of natural uranium. Therefore, even if natural uranium were used instead of U-238, the intake required to provide a measurable dose in the TLD would be reduced by half since the addition of U-235 would effectively double the activity and number of photons emitted by U-238. This would not be enough to make TLD monitoring or discovery of a uranium uptake feasible because the amount of uranium required would still be approximately 40 kg.

Sr-90

Since there are no data available on the chemical toxicity of inhaled strontium, and only chronic ingestion reference doses are available, it will be assumed that radiation effects take precedence over deleterious health effects caused by chemical toxicity. Based on the intake requirements from Table 5 and a strontium-90 half-life of 28.79 years, Table 7 shows the activity of strontium-90 necessary to that meet the MDI.

From Table 7, it takes 34.33 µg of Class D strontium-90 to produce a detectable dose in the TLD in one day. This could be achieved by a "short" 1-hour exposure at a derived air concentration (DAC) of 144.7 MBq/m^3. This concentration is several orders of magnitude above the DACs recommended in ICRP Publication 30 for Sr/Y-90. These values are 300 Bq/m^3 for Class D and 60Bq/m^3 for Class Y. If the area in which possible exposure to Sr/Y-90 has a continuous air monitoring system set to alarm before these ICRP limits are reached, it is highly unlikely that an intake of significance to this study could occur during a worker's TLD-badged occupational days.

It can be inferred from these results that less energetic beta emitters would also not produce enough dose in an external measuring detector. A less energetic (<2 MeV maximum energy) beta emitter with a specific activity comparable to that of a Sr/Y-90 source and similar biological retentions and pathways would not be detectable below certain large calculable threshold intakes.

It is also likely that low-energy (<100 keV) gamma-emitters would effect the TLD in a similar manner if their specific activity was similar to that of Sr/Y-90 and their biological retentions and pathways were comparable. Roughly 60% of the dose to the TLD came from photons below 100 keV in the Sr/Y-90 trials. This result combined with a maximum beta range of ~1 cm in tissue (Turner, 1995) suggests that most of the bremsstrahlung were created either within the organ, or in the adjacent tissue. This is similar to how a low-energy gamma emitter would appear to the TLD and, therefore, the dose would be related.

Future Research

These calculations can also be used to consider other radionuclides with varying specific activities, energies, and biological retentions. Models can be constructed for site specific radiological hazards, ingestions, chronic ingestions, and chronic inhalations. To study chronic exposure scenarios using the STELLA II program, the experimenter will need more than just a passing knowledge of the program. Whereas changing the energy or type of the radiation or location of the TLD in MCNP will require only basic knowledge of the program.

The data from the Cs-137 results indicate that a chronic inhalation exposure to a nuclide such as Co-60 with a higher specific activity and more energetic gamma rays could possibly be detected at intakes lower than those recommended in ICRP Publication 30. The more energetic gamma rays would have a greater chance of escaping the body and the shorter half-life and high photon yield would produce more gamma rays per unit intake. The data from Cs-137 also suggests that an ingestion intake well below the ALI recommended by ICRP Publication 30, for nuclides of similar energy, specific activity and biological retentions to Cs-137 may be detected or proven to have not occurred using this method.

In addition, the use of an alternative thermoluminescent dosimeter material with much greater sensitivity to low-energy photons could also lower the required intake by a factor of 5 in the case of CsSO4 : Mn (Knoll, 2000).

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APPENDIX A

STELLA II

STELLA II Formula Section – Cs-137

a(t) = a(t - dt) + (- a_to_TC2 - a_to_TC1 - Decay_a) * dt
INIT a = .15
OUTFLOWS:
a_to_TC2 = a*(.693/.01)*.9
a_to_TC1 = a*(.693/.01)*.1
Decay_a = a*(.693/Halflife_in_days)

Activity_a_c_e(t) = Activity_a_c_e(t - dt) + (Decay_a + Decay_c + Decay_e) * dt
INIT Activity_a_c_e = 0
INFLOWS:
Decay_a = a*(.693/Halflife_in_days)
Decay_c = c*(.693/Halflife_in_days)
Decay_e = e*(.693/Halflife_in_days)

Activity_b_d_f_g(t) = Activity_b_d_f_g(t - dt) + (Decay_b + Decay_d) * dt
INIT Activity_b_d_f_g = 0
INFLOWS:
Decay_b = b*(.693/Halflife_in_days)
Decay_d = d*(.693/Halflife_in_days)

Activity_h_i(t) = Activity_h_i(t - dt) + (Decay_i + Decay_h) * dt
INIT Activity_h_i = 0
INFLOWS:
Decay_i = i*(.693/Halflife_in_days)
Decay_h = h*(.693/Halflife_in_days)

Activity_in_Bladder(t) = Activity_in_Bladder(t - dt) + (Decay_in_Bladder) * dt
INIT Activity_in_Bladder = 0
INFLOWS:
Decay_in_Bladder = Bladder*(.693/Halflife_in_days)

Activity_in_Stomach(t) = Activity_in_Stomach(t - dt) + (Decay_in_Stomach) * dt
INIT Activity_in_Stomach = 0
INFLOWS:
Decay_in_Stomach = Stomach*(.693/Halflife_in_days)

Activity_in_TC(t) = Activity_in_TC(t - dt) + (Decay_in_TC + Decay_in_TC2) * dt
INIT Activity_in_TC = 0
INFLOWS:
Decay_in_TC = TC1*(.693/Halflife_in_days)
Decay_in_TC2 = TC2*(.693/Halflife_in_days)

b(t) = b(t - dt) + (- B_to_Stomach - Decay_b) * dt
INIT b = .15
OUTFLOWS:
B_to_Stomach = b*(.693/.01)
Decay_b = b*(.693/Halflife_in_days)

```
Bladder(t) = Bladder(t - dt) + (TC1_to_bladder + TC2_to_bladder - Decay_in_Bladder -
Bladder_to_Waste) * dt
INIT Bladder = 0
INFLOWS:
TC1_to_bladder = TC1*(.693/2)
TC2_to_bladder = TC2*(.693/110)
OUTFLOWS:
Decay_in_Bladder = Bladder*(.693/Halflife_in_days)
Bladder_to_Waste = Bladder*12

c(t) = c(t - dt) + (- c_to_TC2 - c_to_TC1 - Decay_c) * dt
INIT c = .076
OUTFLOWS:
c_to_TC2 = c*(.693/.01)*.9
c_to_TC1 = c*(.693/.01)*.1
Decay_c = c*(.693/Halflife_in_days)

d(t) = d(t - dt) + (- D_to_stomach - Decay_d) * dt
INIT d = .004
OUTFLOWS:
D_to_stomach = d*(.693/.2)
Decay_d = d*(.693/Halflife_in_days)

e(t) = e(t - dt) + (- e_to_TC1 - e_to_TC2 - Decay_e) * dt
INIT e = .2
OUTFLOWS:
e_to_TC1 = e*(.693/.5)*.1
e_to_TC2 = e*(.693/.5)*.9
Decay_e = e*(.693/Halflife_in_days)

h(t) = h(t - dt) + (- h_to_i - Decay_h) * dt
INIT h = .05
OUTFLOWS:
h_to_i = h*(.693/.5)
Decay_h = h*(.693/Halflife_in_days)

i(t) = i(t - dt) + (h_to_i - i_to_TC2 - i_to_TC1 - Decay_i) * dt
INIT i = 0
INFLOWS:
h_to_i = h*(.693/.5)
OUTFLOWS:
i_to_TC2 = i*(.693/.5)*.9
i_to_TC1 = i*(.693/.5)*.1
Decay_i = i*(.693/Halflife_in_days)

Stomach(t) = Stomach(t - dt) + (D_to_stomach + B_to_Stomach - Decay_in_Stomach - Stomach_to_TC1 -
Stomach_to_TC2) * dt
INIT Stomach = 0
INFLOWS:
D_to_stomach = d*(.693/.2)
B_to_Stomach = b*(.693/.01)
OUTFLOWS:
Decay_in_Stomach = Stomach*(.693/Halflife_in_days)
Stomach_to_TC1 = IF(F1>0)THEN(Stomach*24*.1)ELSE(0)
Stomach_to_TC2 = IF(F1>0)THEN(Stomach*24*.9)ELSE(0)
```

```
TC1(t) = TC1(t - dt) + (Stomach_to_TC1 + a_to_TC1 + c_to_TC1 + e_to_TC1 + i_to_TC1 - Decay_in_TC
- TC1_to_bladder) * dt
INIT TC1 = 0
INFLOWS:
Stomach_to_TC1 = IF(F1>0)THEN(Stomach*24*.1)ELSE(0)
a_to_TC1 = a*(.693/.01)*.1
c_to_TC1 = c*(.693/.01)*.1
e_to_TC1 = e*(.693/.5)*.1
i_to_TC1 = i*(.693/.5)*.1
OUTFLOWS:
Decay_in_TC = TC1*(.693/Halflife_in_days)
TC1_to_bladder = TC1*(.693/2)

TC2(t) = TC2(t - dt) + (Stomach_to_TC2 + a_to_TC2 + c_to_TC2 + e_to_TC2 + i_to_TC2 -
TC2_to_bladder - Decay_in_TC2) * dt
INIT TC2 = 0
INFLOWS:
Stomach_to_TC2 = IF(F1>0)THEN(Stomach*24*.9)ELSE(0)
a_to_TC2 = a*(.693/.01)*.9
c_to_TC2 = c*(.693/.01)*.9
e_to_TC2 = e*(.693/.5)*.9
i_to_TC2 = i*(.693/.5)*.9
OUTFLOWS:
TC2_to_bladder = TC2*(.693/110)
Decay_in_TC2 = TC2*(.693/Halflife_in_days)

Waste(t) = Waste(t - dt) + (Bladder_to_Waste) * dt
INIT Waste = 0
INFLOWS:
Bladder_to_Waste = Bladder*12


F1 = 1
Halflife_in_days = 0
INTAKE_in_Bq = 0
TC_Transformations = Activity_in_TC/(.693/(Halflife_in_days*24*3600))
Transformations_in_Bladder = Activity_in_Bladder/(.693/(Halflife_in_days*24*3600))
Transformations_in_Lungs =
(Activity_a_c_e/(.693/(Halflife_in_days*24*3600)))+(Activity_b_d_f_g/(.693/(Halflife_in_days*24*3600)
))+(Activity_h_i/(.693/(Halflife_in_days*24*3600)))
Transformations_in_Stomach = Activity_in_Stomach/(.693/(Halflife_in_days*24*3600))
```

STELLA II Formula Section – U-238

a(t) = a(t - dt) + (- a_to_TC2 - a_to_TC1 - Decay_a - a_to_Kid1 - a_to_Bone_1 - a_to_Bone_2 - a_to_Bladder) * dt

INIT a = IF(Inhalation_Class=1)THEN(.5*Dnp*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=2)THEN(.1*Dnp*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=3)THEN(.01*Dnp*Inhalation_in_Bq)ELSE(0)
OUTFLOWS:
a_to_TC2 = a*69.3*.00052
a_to_TC1 = a*69.3*.12
Decay_a = a*(.693/Halflife_in_days)
a_to_Kid1 = a*69.3*.12
a_to_Bone_1 = a*69.3*.2
a_to_Bone_2 = a*69.3*.023
a_to_Bladder = a*69.3*.53596

Activity_a_c_e(t) = Activity_a_c_e(t - dt) + (Decay_a + Decay_c + Decay_e) * dt
INIT Activity_a_c_e = 0
INFLOWS:
Decay_a = a*(.693/Halflife_in_days)
Decay_c = c*(.693/Halflife_in_days)
Decay_e = e*(.693/Halflife_in_days)

Activity_b_d_f_g(t) = Activity_b_d_f_g(t - dt) + (Decay_b + Decay_d) * dt
INIT Activity_b_d_f_g = 0
INFLOWS:
Decay_b = b*(.693/Halflife_in_days)
Decay_d = d*(.693/Halflife_in_days)

Activity_h_i_j(t) = Activity_h_i_j(t - dt) + (Decay_i + Decay_h + Decay_in_j) * dt
INIT Activity_h_i_j = 0
INFLOWS:
Decay_i = i*(.693/Halflife_in_days)
Decay_h = h*(.693/Halflife_in_days)
Decay_in_j = j*(.693/Halflife_in_days)

Activity_in_Bladder(t) = Activity_in_Bladder(t - dt) + (Decay_in_Bladder) * dt
INIT Activity_in_Bladder = 0
INFLOWS:
Decay_in_Bladder = Bladder*(.693/Halflife_in_days)

Activity_in_Bone(t) = Activity_in_Bone(t - dt) + (Decay_in_Bone_2 + Decay_in_Bone_1) * dt
INIT Activity_in_Bone = 0
INFLOWS:
Decay_in_Bone_2 = Trabecular_Bone*(.693/Halflife_in_days)
Decay_in_Bone_1 = Cortical_Bone*(.693/Halflife_in_days)

Activity_in_Colon(t) = Activity_in_Colon(t - dt) + (Decay_in_ULI + Decay_in_LLI) * dt
INIT Activity_in_Colon = 0
INFLOWS:
Decay_in_ULI = ULI*(.693/Halflife_in_days)
Decay_in_LLI = LLI*(.693/Halflife_in_days)

```
Activity_in_SI(t) = Activity_in_SI(t - dt) + (Decay_in_SI) * dt
INIT Activity_in_SI = 0
INFLOWS:
Decay_in_SI = SI*(.693/Halflife_in_days)

Activity_in_Stomach(t) = Activity_in_Stomach(t - dt) + (Decay_in_Stomach) * dt
INIT Activity_in_Stomach = 0
INFLOWS:
Decay_in_Stomach = Stomach*(.693/Halflife_in_days)

Activity_in_TC(t) = Activity_in_TC(t - dt) + (Decay_in_TC + Decay_in_TC2 + Decay_in_TC3) * dt
INIT Activity_in_TC = 0
INFLOWS:
Decay_in_TC = TC1*(.693/Halflife_in_days)
Decay_in_TC2 = TC2*(.693/Halflife_in_days)
Decay_in_TC3 = TC3*(.693/Halflife_in_days)

b(t) = b(t - dt) + (- B_to_Stomach - Decay_b) * dt
INIT b = IF(Inhalation_Class=1)THEN(.5*Dnp*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=2)THEN(.9*Dnp*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=3)THEN(.99*Dnp*Inhalation_in_Bq)ELSE(0)
OUTFLOWS:
B_to_Stomach = IF(Inhalation_Class=1)THEN(b*(.693/.01))ELSE
IF(Inhalation_Class=2)THEN(b*(.693/.4))ELSE
IF(Inhalation_Class=3)THEN(b*(.693/.4))ELSE(0)
Decay_b = b*(.693/Halflife_in_days)

Bladder(t) = Bladder(t - dt) + (TC1_to_bladder + TC2_to_bladder + Kidney_1_to_Bladder +
SI_to_Bladder + Bone_1_to_Bladder + Bone_2_to_Bladder + i_to_Bladder + e_to_Bladder +
c_to_Bladder + a_to_Bladder - Decay_in_Bladder - Bladder_to_Waste) * dt
INIT Bladder = 0
INFLOWS:
TC1_to_bladder = TC1*(.693/6)
TC2_to_bladder = TC2*(.693/1500)
Kidney_1_to_Bladder = TC3*(.693/6)
SI_to_Bladder =
IF(Inhalation_Class=1)THEN(SI*6*.05*.53596)ELSE
IF(Inhalation_Class=2)THEN(SI*6*.05*.53596)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.002*.53596)ELSE(0)
Bone_1_to_Bladder = Cortical_Bone*(.693/20)
Bone_2_to_Bladder = Trabecular_Bone*(.693/5000)
i_to_Bladder =
IF(Inhalation_Class=1)THEN(i*(.693/.5)*.53596)ELSE
IF(Inhalation_Class=2)THEN(i*(.693/50)*.53596)ELSE
IF(Inhalation_Class=3)THEN(i*(.693/1000)*.53596)ELSE(0)
e_to_Bladder =
IF(Inhalation_Class=1)THEN(e*(.693/.5)*.53596)ELSE
IF(Inhalation_Class=2)THEN(e*(.693/50)*.53596)ELSE
IF(Inhalation_Class=3)THEN(e*(.693/500)*.53596)ELSE(0)
c_to_Bladder = c*69.3*.53596
a_to_Bladder = a*69.3*.53596
OUTFLOWS:
Decay_in_Bladder = Bladder*(.693/Halflife_in_days)
Bladder_to_Waste = Bladder*12
```

c(t) = c(t - dt) + (- c_to_TC2 - c_to_TC1 - Decay_c - c_to_Kid1 - c_to_Bone_1 - c_to_Bone_2 - c_to_Bladder) * dt
INIT c = IF(Inhalation_Class=1)THEN(.95*Dtb*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=2)THEN(.5*Dtb*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=3)THEN(.01*Dtb*Inhalation_in_Bq)ELSE(0)
OUTFLOWS:
c_to_TC2 = c*(.693/.01)*.00052
c_to_TC1 = c*(.693/.01)*.12
Decay_c = c*(.693/Halflife_in_days)
c_to_Kid1 = c*69.3*.12
c_to_Bone_1 = c*69.3*.2
c_to_Bone_2 = c*69.3*.023
c_to_Bladder = c*69.3*.53596

Cortical_Bone(t) = Cortical_Bone(t - dt) + (e_to_Bone_1 + c_to_Bone_1 + a_to_Bone_1 + i_to_Bone_1 + SI_to_Bone_1 - Decay_in_Bone_1 - Bone_1_to_Bladder) * dt
INIT Cortical_Bone = 0
INFLOWS:
e_to_Bone_1 =
IF(Inhalation_Class=1)THEN(e*(.693/.5)*.2)ELSE
IF(Inhalation_Class=2)THEN(e*(.693/50)*.2)ELSE
IF(Inhalation_Class=3)THEN(e*(.693/500)*.2)ELSE(0)
c_to_Bone_1 = c*69.3*.2
a_to_Bone_1 = a*69.3*.2
i_to_Bone_1 =
IF(Inhalation_Class=1)THEN(i*(.693/.5)*.2)ELSE
IF(Inhalation_Class=2)THEN(i*(.693/50)*.2)ELSE
IF(Inhalation_Class=3)THEN(i*(.693/1000)*.2)ELSE(0)
SI_to_Bone_1 =
IF(Inhalation_Class=1)THEN(SI*6*.05*.2)ELSE
IF(Inhalation_Class=2)THEN(SI*6*.05*.2)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.002*.2)ELSE(0)
OUTFLOWS:
Decay_in_Bone_1 = Cortical_Bone*(.693/Halflife_in_days)
Bone_1_to_Bladder = Cortical_Bone*(.693/20)

d(t) = d(t - dt) + (g_to_d + f_to_d - D_to_stomach - Decay_d) * dt
INIT d = IF(Inhalation_Class=1)THEN(.05*Dtb*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=2)THEN(.5*Dtb*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=3)THEN(.99*Dtb*Inhalation_in_Bq)ELSE(0)
INFLOWS:
g_to_d =
IF(Inhalation_Class=2)THEN(g*(.693/50))ELSE
IF(Inhalation_Class=3)THEN(g*(.693/500))ELSE(0)
f_to_d = f*.693
OUTFLOWS:
D_to_stomach = d*(.693/.2)
Decay_d = d*(.693/Halflife_in_days)

e(t) = e(t - dt) + (- e_to_TC1 - e_to_TC2 - Decay_e - e_to_Kid1 - e_to_Bone_1 - e_to_Bone_2 - e_to_Bladder) * dt
INIT e = IF(Inhalation_Class=1)THEN(.8*Dp*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=2)THEN(.15*Dp*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=3)THEN(.05*Dp*Inhalation_in_Bq)ELSE(0)
OUTFLOWS:
e_to_TC1 =

```
IF(Inhalation_Class=1)THEN(e*(.693/.5)*.12)ELSE
IF(Inhalation_Class=2)THEN(e*(.693/50)*.12)ELSE
IF(Inhalation_Class=3)THEN(e*(.693/500)*.12)ELSE(0)
e_to_TC2 =
IF(Inhalation_Class=1)THEN(e*(.693/.5)*.00052)ELSE
IF(Inhalation_Class=2)THEN(e*(.693/50)*.00052)ELSE
IF(Inhalation_Class=3)THEN(e*(.693/500)*.00052)ELSE(0)
Decay_e = e*(.693/Halflife_in_days)
e_to_Kid1 =
IF(Inhalation_Class=1)THEN(e*(.693/.5)*.12)ELSE
IF(Inhalation_Class=2)THEN(e*(.693/50)*.12)ELSE
IF(Inhalation_Class=3)THEN(e*(.693/500)*.12)ELSE(0)
e_to_Bone_1 =
IF(Inhalation_Class=1)THEN(e*(.693/.5)*.2)ELSE
IF(Inhalation_Class=2)THEN(e*(.693/50)*.2)ELSE
IF(Inhalation_Class=3)THEN(e*(.693/500)*.2)ELSE(0)
e_to_Bone_2 =
IF(Inhalation_Class=1)THEN(e*(.693/.5)*.023)ELSE
IF(Inhalation_Class=2)THEN(e*(.693/50)*.023)ELSE
IF(Inhalation_Class=3)THEN(e*(.693/500)*.023)ELSE(0)
e_to_Bladder =
IF(Inhalation_Class=1)THEN(e*(.693/.5)*.53596)ELSE
IF(Inhalation_Class=2)THEN(e*(.693/50)*.53596)ELSE
IF(Inhalation_Class=3)THEN(e*(.693/500)*.53596)ELSE(0)

f(t) = f(t - dt) + (- f_to_d) * dt
INIT f = IF(Inhalation_Class=1)THEN(0)ELSE
IF(Inhalation_Class=2)THEN(.4*Dp*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=3)THEN(.4*Dp*Inhalation_in_Bq)ELSE(0)
OUTFLOWS:
f_to_d = f*.693

g(t) = g(t - dt) + (- g_to_d) * dt
INIT g = IF(Inhalation_Class=1)THEN(0)ELSE
IF(Inhalation_Class=2)THEN(.4*Dp*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=3)THEN(.4*Dp*Inhalation_in_Bq)ELSE(0)
OUTFLOWS:
g_to_d =
IF(Inhalation_Class=2)THEN(g*(.693/50))ELSE
IF(Inhalation_Class=3)THEN(g*(.693/500))ELSE(0)

h(t) = h(t - dt) + (- h_to_i - Decay_h - h_to_j) * dt
INIT h = IF(Inhalation_Class=1)THEN(.2*Dp*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=2)THEN(.05*Dp*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=3)THEN(.15*Dp*Inhalation_in_Bq)ELSE(0)
OUTFLOWS:
h_to_i =
IF(Inhalation_Class=1)THEN(h*(.693/.5))ELSE
IF(Inhalation_Class=2)THEN(h*(.693/50))ELSE
IF(Inhalation_Class=3)THEN(h*(.693/500)*.9)ELSE(0)
Decay_h = h*(.693/Halflife_in_days)
h_to_j = IF(Inhalation_Class=3)THEN(h*(.693/500)*.1)ELSE(0)

i(t) = i(t - dt) + (h_to_i - i_to_TC2 - i_to_TC1 - Decay_i - i_to_Kid1 - i_to_Bone_1 - i_to_Bone_2 -
i_to_Bladder) * dt
INIT i = 0
```

INFLOWS:
h_to_i =
IF(Inhalation_Class=1)THEN(h*(.693/.5))ELSE
IF(Inhalation_Class=2)THEN(h*(.693/50))ELSE
IF(Inhalation_Class=3)THEN(h*(.693/500)*.9)ELSE(0)
OUTFLOWS:
i_to_TC2 =
IF(Inhalation_Class=1)THEN(i*(.693/.5)*.00052)ELSE
IF(Inhalation_Class=2)THEN(i*(.693/50)*.00052)ELSE
IF(Inhalation_Class=3)THEN(i*(.693/1000)*.00052)ELSE(0)
i_to_TC1 =
IF(Inhalation_Class=1)THEN(i*(.693/.5)*.12)ELSE
IF(Inhalation_Class=2)THEN(i*(.693/50)*.12)ELSE
IF(Inhalation_Class=3)THEN(i*(.693/1000)*.12)ELSE(0)
Decay_i = i*(.693/Halflife_in_days)
i_to_Kid1 =
IF(Inhalation_Class=1)THEN(i*(.693/.5)*.12)ELSE
IF(Inhalation_Class=2)THEN(i*(.693/50)*.12)ELSE
IF(Inhalation_Class=3)THEN(i*(.693/1000)*.12)ELSE(0)
i_to_Bone_1 =
IF(Inhalation_Class=1)THEN(i*(.693/.5)*.2)ELSE
IF(Inhalation_Class=2)THEN(i*(.693/50)*.2)ELSE
IF(Inhalation_Class=3)THEN(i*(.693/1000)*.2)ELSE(0)
i_to_Bone_2 =
IF(Inhalation_Class=1)THEN(i*(.693/.5)*.023)ELSE
IF(Inhalation_Class=2)THEN(i*(.693/50)*.023)ELSE
IF(Inhalation_Class=3)THEN(i*(.693/1000)*.023)ELSE(0)
i_to_Bladder =
IF(Inhalation_Class=1)THEN(i*(.693/.5)*.53596)ELSE
IF(Inhalation_Class=2)THEN(i*(.693/50)*.53596)ELSE
IF(Inhalation_Class=3)THEN(i*(.693/1000)*.53596)ELSE(0)

j(t) = j(t - dt) + (h_to_j - Decay_in_j) * dt
INIT j = 0
INFLOWS:
h_to_j = IF(Inhalation_Class=3)THEN(h*(.693/500)*.1)ELSE(0)
OUTFLOWS:
Decay_in_j = j*(.693/Halflife_in_days)

LLI(t) = LLI(t - dt) + (ULI_to_LLI - LLI_to_Waste - Decay_in_LLI) * dt
INIT LLI = 0
INFLOWS:
ULI_to_LLI = ULI*1.8
OUTFLOWS:
LLI_to_Waste = LLI
Decay_in_LLI = LLI*(.693/Halflife_in_days)

SI(t) = SI(t - dt) + (Stom_to_SI - SI_to_ULI - Decay_in_SI - SI_to_Kidney_1 - SI_to_Bladder - SI_to_TC2 - SI_to_Bone_1 - SI_to_Bone_2 - SI_to_TC1) * dt
INIT SI = 0
INFLOWS:
Stom_to_SI = Stomach*24
OUTFLOWS:
SI_to_ULI =
IF(Inhalation_Class=1)THEN(SI*6*.95)ELSE

IF(Inhalation_Class=2)THEN(SI*6*.95)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.998)ELSE(0)
Decay_in_SI = SI*(.693/Halflife_in_days)
SI_to_Kidney_1 =
IF(Inhalation_Class=1)THEN(SI*6*.05*.12)ELSE
IF(Inhalation_Class=2)THEN(SI*6*.05*.12)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.002*.12)ELSE(0)
SI_to_Bladder =
IF(Inhalation_Class=1)THEN(SI*6*.05*.53596)ELSE
IF(Inhalation_Class=2)THEN(SI*6*.05*.53596)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.002*.53596)ELSE(0)
SI_to_TC2 =
IF(Inhalation_Class=1)THEN(SI*6*.05*.00052)ELSE
IF(Inhalation_Class=2)THEN(SI*6*.05*.00052)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.002*.00052)ELSE(0)
SI_to_Bone_1 =
IF(Inhalation_Class=1)THEN(SI*6*.05*.2)ELSE
IF(Inhalation_Class=2)THEN(SI*6*.05*.2)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.002*.2)ELSE(0)
SI_to_Bone_2 =
IF(Inhalation_Class=1)THEN(SI*6*.05*.023)ELSE
IF(Inhalation_Class=2)THEN(SI*6*.05*.023)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.002*.023)ELSE(0)
SI_to_TC1 =
IF(Inhalation_Class=1)THEN(SI*6*.05*.12)ELSE
IF(Inhalation_Class=2)THEN(SI*6*.05*.12)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.002*.12)ELSE(0)

Stomach(t) = Stomach(t - dt) + (D_to_stomach + B_to_Stomach - Decay_in_Stomach - Stom_to_SI) * dt
INIT Stomach = 0
INFLOWS:
D_to_stomach = d*(.693/.2)
B_to_Stomach = IF(Inhalation_Class=1)THEN(b*(.693/.01))ELSE
IF(Inhalation_Class=2)THEN(b*(.693/.4))ELSE
IF(Inhalation_Class=3)THEN(b*(.693/.4))ELSE(0)
OUTFLOWS:
Decay_in_Stomach = Stomach*(.693/Halflife_in_days)
Stom_to_SI = Stomach*24

TC1(t) = TC1(t - dt) + (a_to_TC1 + c_to_TC1 + e_to_TC1 + i_to_TC1 + SI_to_TC1 - Decay_in_TC - TC1_to_bladder) * dt
INIT TC1 = 0
INFLOWS:
a_to_TC1 = a*69.3*.12
c_to_TC1 = c*(.693/.01)*.12
e_to_TC1 =
IF(Inhalation_Class=1)THEN(e*(.693/.5)*.12)ELSE
IF(Inhalation_Class=2)THEN(e*(.693/50)*.12)ELSE
IF(Inhalation_Class=3)THEN(e*(.693/500)*.12)ELSE(0)
i_to_TC1 =
IF(Inhalation_Class=1)THEN(i*(.693/.5)*.12)ELSE
IF(Inhalation_Class=2)THEN(i*(.693/50)*.12)ELSE
IF(Inhalation_Class=3)THEN(i*(.693/1000)*.12)ELSE(0)
SI_to_TC1 =
IF(Inhalation_Class=1)THEN(SI*6*.05*.12)ELSE

IF(Inhalation_Class=2)THEN(SI*6*.05*.12)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.002*.12)ELSE(0)
OUTFLOWS:
Decay_in_TC = TC1*(.693/Halflife_in_days)
TC1_to_bladder = TC1*(.693/6)

TC2(t) = TC2(t - dt) + (a_to_TC2 + c_to_TC2 + e_to_TC2 + i_to_TC2 + SI_to_TC2 - TC2_to_bladder - Decay_in_TC2) * dt
INIT TC2 = 0
INFLOWS:
a_to_TC2 = a*69.3*.00052
c_to_TC2 = c*(.693/.01)*.00052
e_to_TC2 =
IF(Inhalation_Class=1)THEN(e*(.693/.5)*.00052)ELSE
IF(Inhalation_Class=2)THEN(e*(.693/50)*.00052)ELSE
IF(Inhalation_Class=3)THEN(e*(.693/500)*.00052)ELSE(0)
i_to_TC2 =
IF(Inhalation_Class=1)THEN(i*(.693/.5)*.00052)ELSE
IF(Inhalation_Class=2)THEN(i*(.693/50)*.00052)ELSE
IF(Inhalation_Class=3)THEN(i*(.693/1000)*.00052)ELSE(0)
SI_to_TC2 =
IF(Inhalation_Class=1)THEN(SI*6*.05*.00052)ELSE
IF(Inhalation_Class=2)THEN(SI*6*.05*.00052)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.002*.00052)ELSE(0)
OUTFLOWS:
TC2_to_bladder = TC2*(.693/1500)
Decay_in_TC2 = TC2*(.693/Halflife_in_days)

TC3(t) = TC3(t - dt) + (SI_to_Kidney_1 + e_to_Kid1 + c_to_Kid1 + a_to_Kid1 + i_to_Kid1 - Kidney_1_to_Bladder - Decay_in_TC3) * dt
INIT TC3 = 0
INFLOWS:
SI_to_Kidney_1 =
IF(Inhalation_Class=1)THEN(SI*6*.05*.12)ELSE
IF(Inhalation_Class=2)THEN(SI*6*.05*.12)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.002*.12)ELSE(0)
e_to_Kid1 =
IF(Inhalation_Class=1)THEN(e*(.693/.5)*.12)ELSE
IF(Inhalation_Class=2)THEN(e*(.693/50)*.12)ELSE
IF(Inhalation_Class=3)THEN(e*(.693/500)*.12)ELSE(0)
c_to_Kid1 = c*69.3*.12
a_to_Kid1 = a*69.3*.12
i_to_Kid1 =
IF(Inhalation_Class=1)THEN(i*(.693/.5)*.12)ELSE
IF(Inhalation_Class=2)THEN(i*(.693/50)*.12)ELSE
IF(Inhalation_Class=3)THEN(i*(.693/1000)*.12)ELSE(0)
OUTFLOWS:
Kidney_1_to_Bladder = TC3*(.693/6)
Decay_in_TC3 = TC3*(.693/Halflife_in_days)

Trabecular_Bone(t) = Trabecular_Bone(t - dt) + (e_to_Bone_2 + c_to_Bone_2 + a_to_Bone_2 + i_to_Bone_2 + SI_to_Bone_2 - Decay_in_Bone_2 - Bone_2_to_Bladder) * dt
INIT Trabecular_Bone = 0
INFLOWS:
e_to_Bone_2 =
IF(Inhalation_Class=1)THEN(e*(.693/.5)*.023)ELSE

IF(Inhalation_Class=2)THEN(e*(.693/50)*.023)ELSE
IF(Inhalation_Class=3)THEN(e*(.693/500)*.023)ELSE(0)
c_to_Bone_2 = c*69.3*.023
a_to_Bone_2 = a*69.3*.023
i_to_Bone_2 =
IF(Inhalation_Class=1)THEN(i*(.693/.5)*.023)ELSE
IF(Inhalation_Class=2)THEN(i*(.693/50)*.023)ELSE
IF(Inhalation_Class=3)THEN(i*(.693/1000)*.023)ELSE(0)
SI_to_Bone_2 =
IF(Inhalation_Class=1)THEN(SI*6*.05*.023)ELSE
IF(Inhalation_Class=2)THEN(SI*6*.05*.023)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.002*.023)ELSE(0)
OUTFLOWS:
Decay_in_Bone_2 = Trabecular_Bone*(.693/Halflife_in_days)
Bone_2_to_Bladder = Trabecular_Bone*(.693/5000)

ULI(t) = ULI(t - dt) + (SI_to_ULI - ULI_to_LLI - Decay_in_ULI) * dt
INIT ULI = 0
INFLOWS:
SI_to_ULI =
IF(Inhalation_Class=1)THEN(SI*6*.95)ELSE
IF(Inhalation_Class=2)THEN(SI*6*.95)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.998)ELSE(0)
OUTFLOWS:
ULI_to_LLI = ULI*1.8
Decay_in_ULI = ULI*(.693/Halflife_in_days)

Waste(t) = Waste(t - dt) + (Bladder_to_Waste + LLI_to_Waste) * dt
INIT Waste = 0
INFLOWS:
Bladder_to_Waste = Bladder*12
LLI_to_Waste = LLI

Dnp = .3
Dp = .25
Dtb = .08
Halflife_in_days = 1.63082E12
Inhalation_Class = 1
Inhalation_in_Bq = 0
TC_Transformations = Activity_in_TC/(.693/(Halflife_in_days*24*3600))
Transformations_in_Bladder = Activity_in_Bladder/(.693/(Halflife_in_days*24*3600))
Transformations_in_Lungs =
(Activity_a_c_e/(.693/(Halflife_in_days*24*3600)))+(Activity_b_d_f_g/(.693/(Halflife_in_days*24*3600)
))+(Activity_h_i_j/(.693/(Halflife_in_days*24*3600)))
Transformations_in_Stomach = Activity_in_Stomach/(.693/(Halflife_in_days*24*3600))
Trans_in_Bone = Activity_in_Bone/(.693/(Halflife_in_days*24*3600))
Trans_in_Colon = Activity_in_Colon/(.693/(Halflife_in_days*24*3600))
Trans_in_SI = Activity_in_SI/(.693/(Halflife_in_days*24*3600))

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a(t) = a(t - dt) + (- a_to_TC2 - a_to_TC1 - Decay_a - a_to_TC3 - a_to_Cortical - a_to_Trabecular - a_to_Bladder) * dt
INIT a = IF(Inhalation_Class=1)THEN(.5*Dnp*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=2)THEN(.1*Dnp*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=3)THEN(.01*Dnp*Inhalation_in_Bq)ELSE(0)
OUTFLOWS:
a_to_TC2 = a*69.3*.03825
a_to_TC1 = a*69.3*.204
Decay_a = a*(.693/Halflife_in_days)
a_to_TC3 = a*69.3*.01275
a_to_Cortical = a*69.3*.018
a_to_Trabecular = a*69.3*.027
a_to_Bladder = a*69.3*.7

Activity_a_c_e(t) = Activity_a_c_e(t - dt) + (Decay_a + Decay_c + Decay_e) * dt
INIT Activity_a_c_e = 0
INFLOWS:
Decay_a = a*(.693/Halflife_in_days)
Decay_c = c*(.693/Halflife_in_days)
Decay_e = e*(.693/Halflife_in_days)
Activity_b_d_f_g(t) = Activity_b_d_f_g(t - dt) + (Decay_b + Decay_d) * dt
INIT Activity_b_d_f_g = 0
INFLOWS:
Decay_b = b*(.693/Halflife_in_days)
Decay_d = d*(.693/Halflife_in_days)

Activity_h_i_j(t) = Activity_h_i_j(t - dt) + (Decay_i + Decay_h + Decay_in_j) * dt
INIT Activity_h_i_j = 0
INFLOWS:
Decay_i = i*(.693/Halflife_in_days)
Decay_h = h*(.693/Halflife_in_days)
Decay_in_j = j*(.693/Halflife_in_days)

Activity_in_Bladder(t) = Activity_in_Bladder(t - dt) + (Decay_in_Bladder) * dt
INIT Activity_in_Bladder = 0
INFLOWS:
Decay_in_Bladder = Bladder*(.693/Halflife_in_days)

Activity_in_Bone(t) = Activity_in_Bone(t - dt) + (Decay_in_Trabecular + Decay_in_Cortical) * dt
INIT Activity_in_Bone = 0
INFLOWS:
Decay_in_Trabecular = Trabecular_Bone*(.693/Halflife_in_days)
Decay_in_Cortical = Cortical_Bone*(.693/Halflife_in_days)

Activity_in_Colon(t) = Activity_in_Colon(t - dt) + (Decay_in_ULI + Decay_in_LLI) * dt
INIT Activity_in_Colon = 0
INFLOWS:
Decay_in_ULI = ULI*(.693/Halflife_in_days)
Decay_in_LLI = LLI*(.693/Halflife_in_days)

Activity_in_SI(t) = Activity_in_SI(t - dt) + (Decay_in_SI) * dt
INIT Activity_in_SI = 0

INFLOWS:
Decay_in_SI = SI*(.693/Halflife_in_days)

Activity_in_Stomach(t) = Activity_in_Stomach(t - dt) + (Decay_in_Stomach) * dt
INIT Activity_in_Stomach = 0
INFLOWS:
Decay_in_Stomach = Stomach*(.693/Halflife_in_days)

Activity_in_TC(t) = Activity_in_TC(t - dt) + (Decay_in_TC + Decay_in_TC2 + Decay_in_TC3) * dt
INIT Activity_in_TC = 0
INFLOWS:
Decay_in_TC = TC1*(.693/Halflife_in_days)
Decay_in_TC2 = TC2*(.693/Halflife_in_days)
Decay_in_TC3 = TC3*(.693/Halflife_in_days)

b(t) = b(t - dt) + (- B_to_Stomach - Decay_b) * dt
INIT b = IF(Inhalation_Class=1)THEN(.5*Dnp*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=2)THEN(.9*Dnp*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=3)THEN(.99*Dnp*Inhalation_in_Bq)ELSE(0)
OUTFLOWS:
B_to_Stomach = IF(Inhalation_Class=1)THEN(b*(.693/.01))ELSE
IF(Inhalation_Class=3)THEN(b*(.693/.4))ELSE(0)
Decay_b = b*(.693/Halflife_in_days)

Bladder(t) = Bladder(t - dt) + (TC1_to_bladder + TC2_to_bladder + TC3_to_Bladder + SI_to_Bladder + Bone_1_to_Bladder + Bone_2_to_Bladder + i_to_Bladder + e_to_Bladder + c_to_Bladder + a_to_Bladder - Decay_in_Bladder - Bladder_to_Waste) * dt
INIT Bladder = 0
INFLOWS:
TC1_to_bladder = TC1*(.693/2)
TC2_to_bladder = TC2*(.693/30)
TC3_to_Bladder = TC3*(.693/200)
SI_to_Bladder =
IF(Inhalation_Class=1)THEN(SI*6*.3*.7)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.01*.7)ELSE(0)
Bone_1_to_Bladder = Cortical_Bone*.00008219
Bone_2_to_Bladder = Trabecular_Bone*.00049315
i_to_Bladder =
IF(Inhalation_Class=1)THEN(i*(.693/.5)*.7)ELSE
IF(Inhalation_Class=3)THEN(i*(.693/1000)*.7)ELSE(0)
e_to_Bladder =
IF(Inhalation_Class=1)THEN(e*(.693/.5)*.7)ELSE
IF(Inhalation_Class=3)THEN(e*(.693/500)*.7)ELSE(0)
c_to_Bladder = c*69.3*.7
a_to_Bladder = a*69.3*.7
OUTFLOWS:
Decay_in_Bladder = Bladder*(.693/Halflife_in_days)
Bladder_to_Waste = Bladder*12

c(t) = c(t - dt) + (- c_to_TC2 - c_to_TC1 - Decay_c - c_to_TC3 - c_to_Cortical - c_to_Trabecular - c_to_Bladder) * dt
INIT c = IF(Inhalation_Class=1)THEN(.95*Dtb*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=2)THEN(.5*Dtb*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=3)THEN(.01*Dtb*Inhalation_in_Bq)ELSE(0)
OUTFLOWS:
c_to_TC2 = c*(.693/.01)*.03825

```
c_to_TC1 = c*(.693/.01)*.204
Decay_c = c*(.693/Halflife_in_days)
c_to_TC3 = c*69.3*.01275
c_to_Cortical = c*69.3*.018
c_to_Trabecular = c*69.3*.027
c_to_Bladder = c*69.3*.7

Cortical_Bone(t) = Cortical_Bone(t - dt) + (e_to_Cortical + c_to_Cortical + a_to_Cortical + i_to_Cortical
+ SI_to_Cortical - Decay_in_Cortical - Bone_1_to_Bladder) * dt
INIT Cortical_Bone = 0
INFLOWS:
e_to_Cortical =
IF(Inhalation_Class=1)THEN(e*(.693/.5)*.018)ELSE
IF(Inhalation_Class=2)THEN(e*(.693/50)*.018)ELSE
IF(Inhalation_Class=3)THEN(e*(.693/500)*.018)ELSE(0)
c_to_Cortical = c*69.3*.018
a_to_Cortical = a*69.3*.018
i_to_Cortical =
IF(Inhalation_Class=1)THEN(i*(.693/.5)*.018)ELSE
IF(Inhalation_Class=2)THEN(i*(.693/50)*.018)ELSE
IF(Inhalation_Class=3)THEN(i*(.693/1000)*.018)ELSE(0)
SI_to_Cortical =
IF(Inhalation_Class=1)THEN(SI*6*.3*.018)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.01*.018)ELSE(0)
OUTFLOWS:
Decay_in_Cortical = Cortical_Bone*(.693/Halflife_in_days)
Bone_1_to_Bladder = Cortical_Bone*.00008219

d(t) = d(t - dt) + (g_to_d + f_to_d - D_to_stomach - Decay_d) * dt
INIT d = IF(Inhalation_Class=1)THEN(.05*Dtb*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=2)THEN(.5*Dtb*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=3)THEN(.99*Dtb*Inhalation_in_Bq)ELSE(0)
INFLOWS:
g_to_d =
IF(Inhalation_Class=2)THEN(g*(.693/50))ELSE
IF(Inhalation_Class=3)THEN(g*(.693/500))ELSE(0)
f_to_d = f*.693
OUTFLOWS:
D_to_stomach = d*(.693/.2)
Decay_d = d*(.693/Halflife_in_days)

e(t) = e(t - dt) + (- e_to_TC1 - e_to_TC2 - Decay_e - e_to_TC3 - e_to_Cortical - e_to_Trabecular -
e_to_Bladder) * dt
INIT e = IF(Inhalation_Class=1)THEN(.8*Dp*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=2)THEN(.15*Dp*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=3)THEN(.05*Dp*Inhalation_in_Bq)ELSE(0)
OUTFLOWS:
e_to_TC1 =
IF(Inhalation_Class=1)THEN(e*(.693/.5)*.204)ELSE
IF(Inhalation_Class=3)THEN(e*(.693/500)*.204)ELSE(0)
e_to_TC2 =
IF(Inhalation_Class=1)THEN(e*(.693/.5)*.03825)ELSE
IF(Inhalation_Class=3)THEN(e*(.693/500)*.03825)ELSE(0)
Decay_e = e*(.693/Halflife_in_days)
e_to_TC3 =
IF(Inhalation_Class=1)THEN(e*(.693/.5)*.01275)ELSE
```

IF(Inhalation_Class=3)THEN(e*(.693/500)*.01275)ELSE(0)
e_to_Cortical =
IF(Inhalation_Class=1)THEN(e*(.693/.5)*.018)ELSE
IF(Inhalation_Class=2)THEN(e*(.693/50)*.018)ELSE
IF(Inhalation_Class=3)THEN(e*(.693/500)*.018)ELSE(0)
e_to_Trabecular =
IF(Inhalation_Class=1)THEN(e*(.693/.5)*.027)ELSE
IF(Inhalation_Class=3)THEN(e*(.693/500)*.027)ELSE(0)
e_to_Bladder =
IF(Inhalation_Class=1)THEN(e*(.693/.5)*.7)ELSE
IF(Inhalation_Class=3)THEN(e*(.693/500)*.7)ELSE(0)

f(t) = f(t - dt) + (- f_to_d) * dt
INIT f = IF(Inhalation_Class=1)THEN(0)ELSE
IF(Inhalation_Class=2)THEN(.4*Dp*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=3)THEN(.4*Dp*Inhalation_in_Bq)ELSE(0)
OUTFLOWS:
f_to_d = f*.693

g(t) = g(t - dt) + (- g_to_d) * dt
INIT g = IF(Inhalation_Class=1)THEN(0)ELSE
IF(Inhalation_Class=2)THEN(.4*Dp*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=3)THEN(.4*Dp*Inhalation_in_Bq)ELSE(0)
OUTFLOWS:
g_to_d =
IF(Inhalation_Class=2)THEN(g*(.693/50))ELSE
IF(Inhalation_Class=3)THEN(g*(.693/500))ELSE(0)

h(t) = h(t - dt) + (- h_to_i - Decay_h - h_to_j) * dt
INIT h = IF(Inhalation_Class=1)THEN(.2*Dp*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=2)THEN(.05*Dp*Inhalation_in_Bq)ELSE
IF(Inhalation_Class=3)THEN(.15*Dp*Inhalation_in_Bq)ELSE(0)
OUTFLOWS:
h_to_i =
IF(Inhalation_Class=1)THEN(h*(.693/.5))ELSE
IF(Inhalation_Class=2)THEN(h*(.693/50))ELSE
IF(Inhalation_Class=3)THEN(h*(.693/500)*.9)ELSE(0)
Decay_h = h*(.693/Halflife_in_days)
h_to_j = IF(Inhalation_Class=3)THEN(h*(.693/500)*.1)ELSE(0)

i(t) = i(t - dt) + (h_to_i - i_to_TC2 - i_to_TC1 - Decay_i - i_to_TC3 - i_to_Cortical - i_to_Trabecular - i_to_Bladder) * dt
INIT i = 0
INFLOWS:
h_to_i =
IF(Inhalation_Class=1)THEN(h*(.693/.5))ELSE
IF(Inhalation_Class=2)THEN(h*(.693/50))ELSE
IF(Inhalation_Class=3)THEN(h*(.693/500)*.9)ELSE(0)
OUTFLOWS:
i_to_TC2 =
IF(Inhalation_Class=1)THEN(i*(.693/.5)*.03825)ELSE
IF(Inhalation_Class=3)THEN(i*(.693/1000)*.03825)ELSE(0)
i_to_TC1 =
IF(Inhalation_Class=1)THEN(i*(.693/.5)*.204)ELSE

IF(Inhalation_Class=3)THEN(i*(.693/1000)*.204)ELSE(0)
Decay_i = i*(.693/Halflife_in_days)
i_to_TC3 =
IF(Inhalation_Class=1)THEN(i*(.693/.5)*.01275)ELSE
IF(Inhalation_Class=3)THEN(i*(.693/1000)*.01275)ELSE(0)
i_to_Cortical =
IF(Inhalation_Class=1)THEN(i*(.693/.5)*.018)ELSE
IF(Inhalation_Class=2)THEN(i*(.693/50)*.018)ELSE
IF(Inhalation_Class=3)THEN(i*(.693/1000)*.018)ELSE(0)
i_to_Trabecular =
IF(Inhalation_Class=1)THEN(i*(.693/.5)*.027)ELSE
IF(Inhalation_Class=3)THEN(i*(.693/1000)*.027)ELSE(0)
i_to_Bladder =
IF(Inhalation_Class=1)THEN(i*(.693/.5)*.7)ELSE
IF(Inhalation_Class=3)THEN(i*(.693/1000)*.7)ELSE(0)

j(t) = j(t - dt) + (h_to_j - Decay_in_j) * dt
INIT j = 0
INFLOWS:
h_to_j = IF(Inhalation_Class=3)THEN(h*(.693/500)*.1)ELSE(0)
OUTFLOWS:
Decay_in_j = j*(.693/Halflife_in_days)

LLI(t) = LLI(t - dt) + (ULI_to_LLI - LLI_to_Waste - Decay_in_LLI) * dt
INIT LLI = 0
INFLOWS:
ULI_to_LLI = ULI*1.8
OUTFLOWS:
LLI_to_Waste = LLI
Decay_in_LLI = LLI*(.693/Halflife_in_days)

SI(t) = SI(t - dt) + (Stom_to_SI - SI_to_ULI - Decay_in_SI - SI_to_TC3 - SI_to_Bladder - SI_to_TC2 - SI_to_Cortical - SI_to_Trabecular - SI_to_TC1) * dt
INIT SI = 0
INFLOWS:
Stom_to_SI = Stomach*24
OUTFLOWS:
SI_to_ULI =
IF(Inhalation_Class=1)THEN(SI*6*.7)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.99)ELSE(0)
Decay_in_SI = SI*(.693/Halflife_in_days)
SI_to_TC3 =
IF(Inhalation_Class=1)THEN(SI*6*.3*.01275)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.01*.01275)ELSE(0)
SI_to_Bladder =
IF(Inhalation_Class=1)THEN(SI*6*.3*.7)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.01*.7)ELSE(0)
SI_to_TC2 =
IF(Inhalation_Class=1)THEN(SI*6*.3*.03825)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.01*.03825)ELSE(0)
SI_to_Cortical =
IF(Inhalation_Class=1)THEN(SI*6*.3*.018)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.01*.018)ELSE(0)
SI_to_Trabecular =
IF(Inhalation_Class=1)THEN(SI*6*.3*.027)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.01*.027)ELSE(0)

```
SI_to_TC1 =
IF(Inhalation_Class=1)THEN(SI*6*.3*.204)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.01*.204)ELSE(0)

Stomach(t) = Stomach(t - dt) + (D_to_stomach + B_to_Stomach - Decay_in_Stomach - Stom_to_SI) * dt
INIT Stomach = 0
INFLOWS:
D_to_stomach = d*(.693/.2)
B_to_Stomach = IF(Inhalation_Class=1)THEN(b*(.693/.01))ELSE
IF(Inhalation_Class=3)THEN(b*(.693/.4))ELSE(0)
OUTFLOWS:
Decay_in_Stomach = Stomach*(.693/Halflife_in_days)
Stom_to_SI = Stomach*24

TC1(t) = TC1(t - dt) + (a_to_TC1 + c_to_TC1 + e_to_TC1 + i_to_TC1 + SI_to_TC1 - Decay_in_TC -
TC1_to_bladder) * dt
INIT TC1 = 0
INFLOWS:
a_to_TC1 = a*69.3*.204
c_to_TC1 = c*(.693/.01)*.204
e_to_TC1 =
IF(Inhalation_Class=1)THEN(e*(.693/.5)*.204)ELSE
IF(Inhalation_Class=3)THEN(e*(.693/500)*.204)ELSE(0)
i_to_TC1 =
IF(Inhalation_Class=1)THEN(i*(.693/.5)*.204)ELSE
IF(Inhalation_Class=3)THEN(i*(.693/1000)*.204)ELSE(0)
SI_to_TC1 =
IF(Inhalation_Class=1)THEN(SI*6*.3*.204)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.01*.204)ELSE(0)
OUTFLOWS:
Decay_in_TC = TC1*(.693/Halflife_in_days)
TC1_to_bladder = TC1*(.693/2)

TC2(t) = TC2(t - dt) + (a_to_TC2 + c_to_TC2 + e_to_TC2 + i_to_TC2 + SI_to_TC2 - TC2_to_bladder -
Decay_in_TC2) * dt
INIT TC2 = 0
INFLOWS:
a_to_TC2 = a*69.3*.03825
c_to_TC2 = c*(.693/.01)*.03825
e_to_TC2 =
IF(Inhalation_Class=1)THEN(e*(.693/.5)*.03825)ELSE
IF(Inhalation_Class=3)THEN(e*(.693/500)*.03825)ELSE(0)
i_to_TC2 =
IF(Inhalation_Class=1)THEN(i*(.693/.5)*.03825)ELSE
IF(Inhalation_Class=3)THEN(i*(.693/1000)*.03825)ELSE(0)
SI_to_TC2 =
IF(Inhalation_Class=1)THEN(SI*6*.3*.03825)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.01*.03825)ELSE(0)
OUTFLOWS:
TC2_to_bladder = TC2*(.693/30)
Decay_in_TC2 = TC2*(.693/Halflife_in_days)

TC3(t) = TC3(t - dt) + (SI_to_TC3 + e_to_TC3 + c_to_TC3 + a_to_TC3 + i_to_TC3 - TC3_to_Bladder -
Decay_in_TC3) * dt
INIT TC3 = 0
INFLOWS:
```

```
SI_to_TC3 =
IF(Inhalation_Class=1)THEN(SI*6*.3*.01275)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.01*.01275)ELSE(0)
e_to_TC3 =
IF(Inhalation_Class=1)THEN(e*(.693/.5)*.01275)ELSE
IF(Inhalation_Class=3)THEN(e*(.693/500)*.01275)ELSE(0)
c_to_TC3 = c*69.3*.01275
a_to_TC3 = a*69.3*.01275
i_to_TC3 =
IF(Inhalation_Class=1)THEN(i*(.693/.5)*.01275)ELSE
IF(Inhalation_Class=3)THEN(i*(.693/1000)*.01275)ELSE(0)
OUTFLOWS:
TC3_to_Bladder = TC3*(.693/200)
Decay_in_TC3 = TC3*(.693/Halflife_in_days)

Trabecular_Bone(t) = Trabecular_Bone(t - dt) + (e_to_Trabecular + c_to_Trabecular + a_to_Trabecular +
i_to_Trabecular + SI_to_Trabecular - Decay_in_Trabecular - Bone_2_to_Bladder) * dt
INIT Trabecular_Bone = 0
INFLOWS:
e_to_Trabecular =
IF(Inhalation_Class=1)THEN(e*(.693/.5)*.027)ELSE
IF(Inhalation_Class=3)THEN(e*(.693/500)*.027)ELSE(0)
c_to_Trabecular = c*69.3*.027
a_to_Trabecular = a*69.3*.027
i_to_Trabecular =
IF(Inhalation_Class=1)THEN(i*(.693/.5)*.027)ELSE
IF(Inhalation_Class=3)THEN(i*(.693/1000)*.027)ELSE(0)
SI_to_Trabecular =
IF(Inhalation_Class=1)THEN(SI*6*.3*.027)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.01*.027)ELSE(0)
OUTFLOWS:
Decay_in_Trabecular = Trabecular_Bone*(.693/Halflife_in_days)
Bone_2_to_Bladder = Trabecular_Bone*.00049315

ULI(t) = ULI(t - dt) + (SI_to_ULI - ULI_to_LLI - Decay_in_ULI) * dt
INIT ULI = 0
INFLOWS:
SI_to_ULI =
IF(Inhalation_Class=1)THEN(SI*6*.7)ELSE
IF(Inhalation_Class=3)THEN(SI*6*.99)ELSE(0)
OUTFLOWS:
ULI_to_LLI = ULI*1.8
Decay_in_ULI = ULI*(.693/Halflife_in_days)

Waste(t) = Waste(t - dt) + (Bladder_to_Waste + LLI_to_Waste) * dt
INIT Waste = 0
INFLOWS:
Bladder_to_Waste = Bladder*12
LLI_to_Waste = LLI

Dnp = .3
Dp = .25
Dtb = .08
Halflife_in_days = 1.63082E12
Inhalation_Class = 1
Inhalation_in_Bq = 0
```

```
TC_Transformations = Activity_in_TC/(.693/(Halflife_in_days*24*3600))
Transformations_in_Bladder = Activity_in_Bladder/(.693/(Halflife_in_days*24*3600))
Transformations_in_Lungs =
(Activity_a_c_e/(.693/(Halflife_in_days*24*3600)))+(Activity_b_d_f_g/(.693/(Halflife_in_days*24*3600)
))+(Activity_h_i_j/(.693/(Halflife_in_days*24*3600)))
Transformations_in_Stomach = Activity_in_Stomach/(.693/(Halflife_in_days*24*3600))
Trans_in_Bone = Activity_in_Bone/(.693/(Halflife_in_days*24*3600))
Trans_in_Colon = Activity_in_Colon/(.693/(Halflife_in_days*24*3600))
```

STELLA II Results – Cs-137 (Class D)

		Dose		TLD Dose		Y								
		per Photor	Error	per transformation	Error	0.851								
		MeV/g	%	J/(kg*dis)	J/(kg*dis)									
	Lungs	4.15E-08	5.17	5.64E-18	2.92E-19									
Cs-137	TC	1.80E-06	3.04	2.45E-16	7.45E-18									
Class D	Bladder	7.35E-06	1.6	1.00E-15	1.60E-17									
	Stomach	3.28E-07	4.36	4.46E-17	1.95E-18									
		1	2	3	4	5	7	14	21	30	60	90	120	365
	Lungs	13509	17559	18774	19128	19229	19266	19270	19270	19270	19270	19270	19270	19270
	TC	39686	87913	137675	187237	236198	332317	655327	962977	1338769	2446735	3362164	4118517	6759552
	Bladder	108	227	327	407	472	570	783	949	1146	1728	2209	2606	4111
	Stomach	554	554	554	554	554	554	554	554	554	554	554	554	554
Total Dose (Gy) =		3.31E-12	7.30E-12	1.14E-11	1.55E-11	1.95E-11	2.74E-11	5.38E-11	7.90E-11	1.10E-10	2.00E-10	2.75E-10	3.37E-10	5.53E-10
Dose Rate (Gy/day) =		3.31E-12	3.99E-12	4.1E-12	4.07E-12	4.02E-12	3.94E-12	3.78E-12	3.6E-12	3.42E-12	3.02E-12	2.5E-12	2.06E-12	8.82E-13
Dose TLD 1µGy (Bq) =		3.02E+05	1.37E+05	8.78E+04	6.46E+04	5.13E+04	3.65E+04	1.86E+04	1.27E+04	9.11E+03	4.99E+03	3.63E+03	2.97E+03	1.81E+03
Dose TLD 1µGy (g) =		1.63E-07	7.41E-08	4.75E-08	3.50E-08	2.77E-08	1.98E-08	1.00E-08	6.85E-09	4.93E-09	2.70E-09	1.96E-09	1.60E-09	9.77E-10

STELLA II Results – U-238 (Class D)

		Dose per Photon MeV/g	Error %	TLD Dose per transformation J/(kg*dis)	Error J/(kg*dis)	Y 0.000742
	Lungs					
	Stomach	3.39E-09	19.69	4.02E-22	7.91E-23	
U-238	Small Intestin	2.59E-08	11.22	3.08E-21	3.45E-22	
Class D	Colon	1.13E-07	7.69	1.34E-20	1.03E-21	
	TC	1.45E-07	4.54	1.72E-20	7.83E-22	
	Skeleton	2.42E-08	11.49	2.88E-21	3.31E-22	
	Kidneys	1.37E-09	25.99	1.63E-22	4.23E-23	
	Bladder	4.07E-07	4.93	4.84E-20	2.38E-21	

		1	2	3	4	5	7	14	21	30	60	90	120	365
	Lungs	13510	17560	18775	19129	19230	19267	19270	19270	19270	19270	19270	19270	19270
	Stomach	554	554	554	554	554	554	554	554	554	554	554	554	554
	Small Intestin	2205	2217	2218	2218	2218	2218	2218	2218	2218	2218	2218	2218	2218
	Colon	8610	15114	17910	19005	19419	19630	19663	19663	19663	19663	19663	19663	19663
	TC	3253	7202	11041	14561	17728	23087	34591	39800	42620	44651	45325	45947	50711
	Skeleton	6248	14348	22821	31226	39432	55148	103296	142515	182863	267560	315917	351346	582917
	Kidneys	2960	6554	10047	13250	16132	21009	31478	36218	38784	40633	41245	41812	46147
	Bladder	1596	1929	2098	2210	2298	2444	2785	2977	3120	3310	3369	3389	3403
Total Dose (Gy) =		9.1E-17	1.6E-16	2.0E-16	2.4E-16	2.7E-16	3.2E-16	4.3E-16	5.1E-16	5.6E-16	6.6E-16	7.1E-16	7.5E-16	1.0E-15
Dose Rate (Gy/day) =		9.14E-17	6.5E-17	4.56E-17	3.51E-17	2.95E-17	2.47E-17	1.69E-17	1.01E-17	6.37E-18	3.2E-18	1.71E-18	1.26E-18	1.02E-18
To Dose TLD 1µGy (B		1.09E+10	6.39E+09	4.95E+09	4.22E+09	3.75E+09	3.17E+09	2.30E+09	1.98E+09	1.78E+09	1.52E+09	1.41E+09	1.34E+09	1.00E+09
To Dose TLD 1µGy (g)		8.80E+05	5.14E+05	3.98E+05	3.39E+05	3.01E+05	2.54E+05	1.85E+05	1.59E+05	1.43E+05	1.22E+05	1.13E+05	1.07E+05	8.05E+04

STELLA II Results – U-238 (Class W)

		Dose		TLD Dose		Y								
		per Photon	Error	per transformation	Error	0.000742								
		MeV/g	%	J/(kg*dis)	J/(kg*dis)									
	Lungs													
	Stomach	3.39E-09	19.69	4.02E-22	7.91E-23									
U-238	Small Intestin	2.59E-08	11.22	3.08E-21	3.45E-22									
Class W	Colon	1.13E-07	7.69	1.34E-20	1.03E-21									
	TC	1.45E-07	4.54	1.72E-20	7.83E-22									
	Skeleton	2.42E-08	11.49	2.88E-21	3.31E-22									
	Kidneys	1.37E-09	25.99	1.63E-22	4.23E-23									
	Bladder	4.07E-07	4.93	4.84E-20	2.38E-21									

	1	2	3	4	5	7	14	21	30	60	90	120	365
Lungs	17414	24451	29431	33885	38148	46403	73739	99101	129048	210229	268591	310266	404152
Stomach	1060	1336	1425	1464	1484	1504	1538	1566	1597	1679	1732	1767	1834
Small Intestin	3813	5225	5658	5835	5925	6012	6150	6260	6387	6713	6927	7069	7335
Colon	9925	28018	40227	46777	50037	52596	54346	55345	56491	59425	61362	62639	65034
TC	748	1523	2246	2905	3502	4529	6870	8110	9006	10502	11478	12231	14991
Skeleton	1439	3046	4666	6266	7835	10872	20490	28760	37841	60067	75781	88552	165653
Kidneys	680	1386	2044	2644	3187	4121	6252	7380	8196	9557	10445	11130	13641
Bladder	336	379	405	426	445	477	561	618	671	786	858	907	1018
Total Dose (Gy) =	5.95E-17	1.49E-16	2.10E-16	2.45E-16	2.65E-16	2.86E-16	3.18E-16	3.38E-16	3.58E-16	4.04E-16	4.34E-16	4.58E-16	5.60E-16
Ave. Dose Rate (Gy/da	5.95E-17	8.9E-17	6.11E-17	3.51E-17	1.99E-17	1.04E-17	4.58E-18	2.94E-18	2.22E-18	1.51E-18	1.03E-18	7.75E-19	4.19E-19
To Dose TLD 1µGy (Bq	1.68E+10	6.73E+09	4.77E+09	4.08E+09	3.78E+09	3.50E+09	3.15E+09	2.96E+09	2.79E+09	2.48E+09	2.30E+09	2.19E+09	1.78E+09
To Dose TLD 1µGy (g)	1.35E+06	5.41E+05	3.83E+05	3.28E+05	3.04E+05	2.81E+05	2.53E+05	2.38E+05	2.24E+05	1.99E+05	1.85E+05	1.76E+05	1.43E+05

STELLA II Results – U-238 (Class Y)

		Dose		TLD Dose		Y								
		per Photon	Error	per transformation	Error	0.000742								
		MeV/g	%	J/(kg*dis)	J/(kg*dis)									
	Lungs													
	Stomach	3.39E-09	19.69	4.02E-22	7.91E-23									
U-238	Small Intestin	2.59E-08	11.22	3.08E-21	3.45E-22									
Class Y	Colon	1.13E-07	7.69	1.34E-20	1.03E-21									
	TC	1.45E-07	4.54	1.72E-20	7.83E-22									
	Skeleton	2.42E-08	11.49	2.88E-21	3.31E-22									
	Kidneys	1.37E-09	25.99	1.63E-22	4.23E-23									
	Bladder	4.07E-07	4.93	4.84E-20	2.38E-21									

		1	2	3	4	5	7	14	21	30	60	90	120	365
	Lungs	19386	26683	31775	36356	40782	49486	79664	109744	148308	275964	402233	527103	1493390
	Stomach	1272	1563	1651	1686	1702	1714	1721	1724	1729	1743	1756	1769	1857
	Small Intestin	4607	6131	6564	6727	6800	6854	6884	6898	6915	6971	7025	7077	7428
	Colon	12824	35136	49630	57138	60748	63255	64095	64227	64389	64915	65418	65902	69180
	TC	40	81	119	153	184	236	354	413	454	522	579	637	1139
	Skeleton	77	162	247	330	412	569	1059	1474	1922	3005	3806	4529	11191
	Kidneys	37	74	108	139	167	215	322	376	413	475	527	580	1037
	Bladder	18	20	21	22	23	25	29	31	34	39	43	47	80
Total Dose (Gy) =		6.28E-17	1.64E-16	2.30E-16	2.64E-16	2.80E-16	2.92E-16	2.97E-16	2.98E-16	3.00E-16	3.04E-16	3.07E-16	3.11E-16	3.35E-16
Ave. Dose Rate (Gy/da		6.28E-17	1.02E-16	6.55E-17	3.4E-17	1.65E-17	5.87E-18	7.14E-19	1.97E-19	1.62E-19	1.31E-19	1.16E-19	1.1E-19	1.01E-19
To Dose TLD 1µGy (Bo		1.59E+10	6.08E+09	4.35E+09	3.79E+09	3.57E+09	3.42E+09	3.37E+09	3.35E+09	3.33E+09	3.29E+09	3.25E+09	3.22E+09	2.98E+09
To Dose TLD 1µGy (g)		1.28E+06	4.89E+05	3.50E+05	3.04E+05	2.87E+05	2.75E+05	2.70E+05	2.69E+05	2.68E+05	2.64E+05	2.61E+05	2.59E+05	2.40E+05

STELLA II Results – Sr-90 (Class D)

		Dose		TLD Dose		Y	$T_{1/2}$	
		per Photon	Error	per transformation	Error	2	28.79	years
		MeV/g	%	J/(kg*dis)	J/(kg*dis)			
	Lungs	1.60E-10	70.84	5.12E-20	3.63E-20			
	Stomach	8.11E-11	32.67	2.60E-20	8.49E-21			
Sr-90	Small Intestin	8.16E-10	10.65	2.61E-19	2.78E-20			
Class D	Colon	2.40E-09	11.61	7.70E-19	8.94E-20			
	TC	2.25E-09	13.71	7.21E-19	9.88E-20			
	Skeleton	8.76E-10	18.49	2.81E-19	5.19E-20			
	Bladder	7.17E-09	8.15	2.30E-18	1.87E-19			

Transformations/Bq Intake

	Days	1	2	3	4	5	7	14	21	30	60	90	120	365
	Lungs	13509	17559	18774	19128	19229	19266	19269	19269	19269	19269	19269	19269	19269
	Stomach	554	554	554	554	554	554	554	554	554	554	554	554	554
	Small Intestin	2205	2217	2218	2218	2218	2218	2218	2218	2218	2218	2218	2218	2218
	Colon	6344	11136	13196	14002	14307	14462	14487	14487	14487	14487	14487	14487	14487
	TC	7004	14562	21086	26477	30938	37934	53994	66161	79630	113200	135860	152483	218979
	Skeleton	1394	3241	5215	7227	9249	13299	27454	41571	59664	119512	178661	237119	689961
	Bladder	2329	2805	3033	3161	3242	3335	3433	3457	3476	3518	3542	3556	3595
Total Dose (Gy) =		5.65E-15	9.24E-15	1.17E-14	1.35E-14	1.49E-14	1.71E-14	2.23E-14	2.66E-14	3.15E-14	4.52E-14	5.62E-14	6.57E-14	1.24E-13
Ave. Dose Rate (Gy/da		5.65E-15	3.59E-15	2.46E-15	1.79E-15	1.4E-15	1.09E-15	7.52E-16	6.09E-16	5.5E-16	4.57E-16	3.67E-16	3.16E-16	2.38E-16
To Dose TLD 1µGy (Bq		1.77E+08	1.08E+08	8.55E+07	7.42E+07	6.72E+07	5.86E+07	4.48E+07	3.76E+07	3.17E+07	2.21E+07	1.78E+07	1.52E+07	8.05E+06
To Dose TLD 1µGy (g)		3.46E-05	2.12E-05	1.67E-05	1.45E-05	1.32E-05	1.15E-05	8.77E-06	7.36E-06	6.21E-06	4.33E-06	3.48E-06	2.98E-06	1.58E-06

STELLA II Results – Sr-90 (Class Y)

		Dose		TLD Dose		Y	$T_{1/2}$							
		per Photon	Error	per transformation	Error	2	28.79	years						
		MeV/g	%	J/(kg*dis)	J/(kg*dis)									
	Lungs	1.60E-10	70.84	5.12E-20	3.63E-20									
	Stomach	8.11E-11	32.67	2.60E-20	8.49E-21									
Sr-90	Small Intesti	8.16E-10	10.65	2.61E-19	2.78E-20									
Class Y	Colon	2.40E-09	11.61	7.70E-19	8.94E-20									
	TC	2.25E-09	13.71	7.21E-19	9.88E-20									
	Skeleton	8.76E-10	18.49	2.81E-19	5.19E-20									
	Bladder	7.17E-09	8.15	2.30E-18	1.87E-19									
						Length in Days Since Uptake								
		1	2	3	4	5	7	14	21	30	60	90	120	365
	Lungs	19386	26682	31774	36353	40778	49479	79636	109681	148180	275458	401105	525115	1476218
	Stomach	1272	1563	1651	1686	1702	1714	1721	1724	1729	1743	1756	1769	1857
	Small Intesti	4607	6131	6564	6727	6799	6853	6884	6897	6915	6971	7025	7077	7428
	Colon	12721	34852	49228	56674	60254	62741	63574	63705	63865	64386	64886	65365	68617
	TC	105	229	337	427	502	621	900	1115	1360	2018	2526	2957	5768
	Skeleton	21	51	83	116	149	216	454	694	1007	2086	3218	4405	16016
	Bladder	37	45	49	52	53	55	58	59	61	65	69	73	106
Total Dose (Gy) =		3.96E-15	9.82E-15	1.36E-14	1.55E-14	1.65E-14	1.72E-14	1.75E-14	1.76E-14	1.77E-14	1.81E-14	1.85E-14	1.88E-14	2.15E-14
Ave. Dose Rate (Gy/da		3.96E-15	5.85E-15	3.76E-15	1.95E-15	9.47E-16	3.4E-16	4.4E-17	1.57E-17	1.47E-17	1.34E-17	1.21E-17	1.15E-17	1.08E-17
To Dose TLD 1µGy (B		2.52E+08	1.02E+08	7.37E+07	6.44E+07	6.07E+07	5.83E+07	5.73E+07	5.69E+07	5.65E+07	5.52E+07	5.41E+07	5.31E+07	4.66E+07
To Dose TLD 1µGy (g)		4.94E-05	1.99E-05	1.44E-05	1.26E-05	1.19E-05	1.14E-05	1.12E-05	1.11E-05	1.11E-05	1.08E-05	1.06E-05	1.04E-05	9.12E-06

APPENDIX B

MCNP

MCNP Input Deck – Cs-137

```
Male Phantom at  21.0 Years
c ++++++++++++++++++++++++++++++++++++++++
c
c   File Prepared by Body Builder
c   CopyRight 1996-1998, White Rock Science
c
c   This input file is for the use of
c   BodyBuilder License holder only.
c   Distribution is Prohibited.
c
c ++++++++++++++++++++++++++++++++++++++++
c
c ++++++++++++++++++++++++++++++++++++++++++++++
c         CELLS
c ++++++++++++++++++++++++++++++++++++++++++++++
c SkeletonVolume = 7218.700000, skel_vol = 7142.857143
c
c       LEG BONES
50     2 -1.40    -4 53 (-51:-52)
            vol=  2800.00 imp:n,p,e = 1
c
c       ARM BONES
70     2 -1.40     4 -73 (-71:-72)
            vol=   956.00 imp:n,p,e = 1
c
c       PELVIS
90     2 -1.40     91 -92 93 4 -101 (95:-94)
            vol=   606.00 imp:n,p,e = 1
c
c       SPINE
100    2 -1.40   -100 -98 101 imp:n,p,e = 1
101    2 -1.40   -100 -8   98 imp:n,p,e = 1
102    2 -1.40   -105 -102 8   imp:n,p,e = 1
c           Total Spine vol=   983.00
c
c       SKULL & FACE
110    2 -1.40   (111 -110):(121 -120 122 -1 -123 110)
            vol=   923.00 imp:n,p,e = 1
c
c       RIBS
130    2 -1.40    132 -131 ((134 -133):(136 -135):(138 -137):(74 -139):
            (76 -75):(78 -77):(80 -79):(82 -81):(332 -83):
            (86 -85):(88 -87):(98 -89))
            vol=   694.00 imp:n,p,e = 1
c
c       CLAVICLES
140    2 -1.40    -140 ((141 -143):(-142 144))
            vol=    54.70 imp:n,p,e = 1
c
```

```
c        SCAPULAE
150    2 -1.40     131 -156 154 -155 ((150 -152):(-151 153))
             vol=   202.00 imp:n,p,e = 1
c
c        BRAIN
180     1 -1.04    -111
             vol=  1370.00 imp:n,p,e = 1
c
c        ESOPHAGUS
212   1 -1.04       (213 -212 322 -8 100) :
                (-216 217 -218 210 100)
             vol=   44.70 imp:n,p,e = 1
c          Air in Upper Esophagus
213   4 -0.001293   -213 322 -8
                     imp:n,p,e = 1
c
c        STOMACH
210   1 -1.04       -210
             vol=   402.00 imp:n,p,e = 1
c
c        SMALL INTESTINE
220   1 -1.04       -91 221 -222 223 -7
C              exclude         Ascending Colon
                    (232:230:-223)
c              exclude         Transverse Colon
                    (240 :241 :-242 )
c              exclude         Descending Colon
                    (232:250:-223)
              vol=  1060.00 imp:n,p,e = 1
c
c        ASCENDING COLON
230   1 -1.04       -230 231 -232
              vol=   187.50 imp:n,p,e = 1
c
c        TRANSVERSE COLON
240   1 -1.04       -240 -241 242
           vol=   248.00 imp:n,p,e = 1
c
c        DESCENDING COLON
250   1 -1.04       -250 251 -232
           vol=  191.90 imp:n,p,e = 1
c
c        SIGMOID COLON
280   1 -1.04       (-280 312 -251):(-281 -312 4)
           vol=  106.00 imp:n,p,e = 1
c
c
c        LUNGS
330     3 -0.296   332 ((-331 (-335:336:334:-333)):
                    (-330 ( 339:338:337)))
              vol=  3380.00 imp:n,p,e = 1
c
c
c        URINARY BLADDER
410   1 -1.04       -410
           vol=  248.70 imp:n,p,e = 1
```

```
c
c       SKIN
c
c           Head & Neck Skin
22    1 -1.04       ((-21 22 9):(-20 23 -9 12))
                imp:n,p,e = 1
28    1 -1.04       28 -27 8 -12
          vol=  318.00 imp:n,p,e = 1
c          (Above Volume for Head + Neck Skin Combined
c
c         Trunk Skin
17    1 -1.04       (-8 18 20 -10)
                : (4 -18 -10 11)
          vol= 1440.00 imp:n,p,e = 2
c       Legs Skin
34    1 -1.04      (-4 34 -31 36 32):(-31 33 -36 32)
          vol=  605.00 imp:n,p,e = 2
35    1 -1.04      (-4 35 -32 36 31):(-32 33 -36 31)
          vol=  605.00 imp:n,p,e = 2
c
c
c
c       Body Tissues
c
11    1 -1.04  ((-18 -131 133):(-8 18 -20 -10):(-132 -133 332):
           (-132 -332 98):(-131 -98 7):(-131 4 -7):(-4 (-34:-35) 36):
           (-28 8 -12):(4 131 -18 -11):(-22 9):(-23 -9 12):
           (-131 132 79 -133):(-131 132 -79 98))
c             exclude         Lungs
c                   (330:133:-332:(-339 -338 -337))
c                   (331:133:-332:(335 -336 -334 333))
                  #330
c             exclude         Esophagus
                   #212 #213
c             exclude        Spine
                  (100:8:-133)(100:133:-332)
                  (100:332:-7)(100:-101:7)(105:-8:12)
                  (105:-8:102)
c             exclude        Clavicles
                   (140:-141:143) (140:142:-144)
c             exclude        Upper Lungs
c                   (-133:330) (-133:331)
c             exclude        Stomach and Pelvis
                   210 #90
c             exclude          Small Intestine
                    (91:-221:222:-223:7)
c             exclude          Ascending Colon
                    (232:230:-231)
c             exclude          Descending Colon
                    (232:250:-251)
c             exclude          Sigmoid Colon
                    (280:-312:251) (281:312:-4)
c             exclude          Urinary Bladder
                    410
c             exclude          Leg Bones
                    (4:51:-53) (4:52:-53)
```

```
c              exclude        Scapulae
                   (-131:156:-150:152:-154:155)
                   (-131:156:151:-153:-154:155)
c              exclude        Arm Bones
                   (-4:71:73) (-4:72:73)
c              exclude        Skull
                   110
c              exclude        Face Bones
                   (-121:120:-122:1:123:-110)
c              exclude        Ribs 1-9
               (131:-132:133:-134) (131:-132:135:-136) (131:-132:137:-138)
               (131:-132:139:-74) (131:-132:75:-76) (131:-132:77:-78)
c              exclude        Ribs 10-12
               (131:-132:85:-86) (131:-132:87:-88) (131:-132:89:-98)
               (131:-132:79:-80) (131:-132:81:-82) (131:-132:83:-332)
              imp:n,p,e = 1
c
c
c       UPPER RIB CAGE
c
c 12    1 -1.04       -131 132 79 -133
c              exclude        Ribs 1-9
c                (131:-132:133:-134) (131:-132:135:-136) (131:-132:137:-138)
c                (131:-132:139:-74) (131:-132:75:-76) (131:-132:77:-78)
c               imp:n,p,e = 1
c
c       LOWER RIB CAGE
c
c 13    1 -1.04       -131 132 -79 98
c              exclude        Ribs 10-12
c                (131:-132:85:-86) (131:-132:87:-88) (131:-132:89:-98)
c                (131:-132:79:-80) (131:-132:81:-82) (131:-132:83:-332)
c               imp:n,p,e = 1
c
c
c
c      TLD
61    5 -2.6        -66
          imp:n,p,e = 16
c
c
c      Air Box Around TLD (variance reduction)
62     4 -0.001293   -69 66
c      Exclude        trunk skin, lower trunk, legs skin, legs
c             #17 #10 #16 #34 #35 #30
              imp:n,p,e = 8
c
c
c       SURROUNDING AIR (-y direction)
600    4 -0.001293   -600 -1
c           exclude        HEAD & NECK
                    (21:-9)  (20:9:-8)
c           exclude        TRUNK
                    (-4:10:8)
c           exclude        LEGS
                    (4:-33:(31 32))
```

```
c          exclude        TLD CHIP
                  #61 #62
          imp:n,p,e = 4
c
c       SURROUNDING AIR (+y direction)
601    0   -600 1
c          exclude        HEAD & NECK
                 (21:-9)  (20:9:-8)
c          exclude        TRUNK
                  (-4:10:8)
c          exclude        LEGS
                  (4:-33:(31 32))
          imp:n,p,e = 1
c          air           OUTSIDE of NECK
602    4 -0.001293   -20 27 8 -12
          imp:n,p,e = 1
c
c       VOID
700   0             600
          imp:n,p,e = 0

c ++++++++++++++++++++++++++++++++++++++++++++++
c          SURFACES
c ++++++++++++++++++++++++++++++++++++++++++++++
c TLD
66 RPP   9.5  9.82    -9.55  -9.5    2.54  2.86
c
c       Air Sphere around TLD
c
c 67   s    9.62 -9.525 2.7 5.5
c 68   C/Z  2.6     15        25.2
69 RPP   8.1   11.22      -9.8 -9.45         1   4.4
c
c Planes used in several places
c
1     py 0
4     pz 0
332   pz    43.5000
7     pz    27.0000
8     pz    70.0000
9     pz    91.4500
12    pz    78.4000
c
c       BODY SURFACE
c
c          HEAD
21    sq  5620.5009  3632.4729  6995.6496 0 0 0 -377922.4805 0 0     91.450
22    sq  5112.2500  3271.8400  6400.0000 0 0 0 -327184.0000 0 0     91.450
20    sq   104.0400    67.2400 0 0 0 0 -6995.649600 0 0 0
23    sq   100.0000    64.0000 0 0 0 0 -6400.000000 0 0 0
c
c
c          NECK
27    cz     5.6000
28    cz     5.4000
c
```

```
c
c           TORSO
10    sq   104.0400   408.0400 0 0 0 0 -42452.481600 0 0 0
11    sq   100.0000   400.0000 0 0 0 0 -40000.000000 0 0 0
18    pz    69.8000
c
c           LEGS
c     left
31    gq 1 1 0 0 0  -0.2000   -20.2000 0 0 0
32    gq 1 1 0 0 0   0.2000    20.2000 0 0 0
33    pz  -80.200
34    gq 1 1 0 0 0  -0.2000   -20.0000 0 0 0
35    gq 1 1 0 0 0   0.2000    20.0000 0 0 0
36    pz  -80.000
c
c    SKELETON
c
c
c        LEG BONES
51    gq   1 1  0.009069 0 0  -0.200501   -20.000000
         0   1.785714      87.7500
52    gq   1 1  0.009069 0 0   0.200501    20.000000
         0   1.785714      87.7500
53    pz   -79.8000
c
c        ARM BONES ( left/right)
71     gq   0.510204     0.137174 0 0 0     0.010352
          -19.489796 0    -0.204969   185.877551
72    gq   0.510204   0.137174 0 0 0    -0.010352
          19.489796 0    -0.204969     185.877551
73    pz     69.0000
c
c        PELVIS
91    sq   127.6900   127.6900 0 0 0 0 -16304.7361
      0    -3.8000 0
92    sq   144.0000   144.0000 0 0 0 0 -20736.0000 0    -3.0000 0
93    py    -3.0000
94    py     5.0000
95    pz    14.0000
c
c        SPINE
100      sq      6.2500     4.0000 0 0 0 0   -25.0000 0     5.5000 0
105      sq      6.2500     4.0000 0 0 0 0   -25.0000 0     1.4500 0
101      pz    22.0000
102      pz    84.8000
c
c    SKELETON
c
c
c           SKULL (head)
c
c
c           CRANIUM
110    sq  3991.0806  2487.5156  5076.5625 0 0 0
    -224498.2852 0 0    91.4500
111    sq   2445.3025  1440.2025  3221.6976 0 0 0
```

```
      -106517.3769 0 0    91.4500
c
c       FACIAL
120     sq     81.0000    49.0000 0 0 0 0 -3969.0000 0 0 0
121     sq     57.7600    31.3600 0 0 0 0 -1811.3536 0 0 0
c
122     pz    82.4000
123     pz    93.1300
c
c       RIBS
131     sq     96.0400   289.0000 0 0 0 0 -27755.5600 0 0 0
132     sq     86.4900   272.2500 0 0 0 0 -23546.9025 0 0 0
133     pz    67.3000
134     pz    65.9000
135     pz    64.5000
136     pz    63.1000
137     pz    61.7000
138     pz    60.3000
139     pz    58.9000
74      pz    57.5000
75      pz    56.1000
76      pz    54.7000
77      pz    53.3000
78      pz    51.9000
79      pz    50.5000
80      pz    49.1000
81      pz    47.7000
82      pz    46.3000
83      pz    44.9000
85      pz    42.1000
86      pz    40.7000
87      pz    39.3000
88      pz    37.9000
89      pz    36.5000
98      pz    35.1000
c
c       CLAVICLES
140     tz    0    11.1000    68.2500
        20.0000   0.788300   0.788300
141     p   7.034200 1 0     11.100
142     p   7.034200 -1 0    -11.100
143     p   0.894150 1 0     11.100
144     p   0.894150 -1 0    -11.100
c
c       SCAPULAE
156     sq    96.0400   361.0000 0 0 0 0 -34670.4400
        0 0 0
150   p      0.2500 1 0 0
151   p      0.2500 -1 0 0
152   p      0.8000 1 0 0
153   p      0.8000 -1 0 0
154   pz    50.9000
155   pz    67.3010
c
c       ESOPAHGUS
212     sq     0.1764     1.3689 0  0 0 0    -0.2415 0     2.5750 0
```

```
213   sq     0.0144     0.7569 0  0 0 0    -0.0109 0     2.5750 0
216 6  cx     0.7000
217 6  px     0.1000
218 6  px     7.8000
c
c        STOMACH
210   sq   576.0000  1024.0000   144.0000 0 0 0 -9216.0000
          8.0000    -4.0000    35.0000
c extent     4.0000    12.0000    -7.0000    -1.0000    27.0000    43.0000
c
c        SMALL INTESTINE
221   py    -4.8600
222   py     2.2000
223   pz    17.0000
c
c        ASCENDING COLON
230   sq     6.2500     6.2500 0 0 0 0   -39.0625    -8.5000    -2.3600 0
231   pz    14.4500
232   pz    24.0000
c
c        TRANSVERSE COLON
240   sq  0   2.250000     6.2500 0 0 0   -14.0625 0    -2.3600    25.5000
241   px    10.5000
242   px   -10.5000
c
c
c        DESCENDING COLON
251    pz     8.7200
250   gq   4.536900   3.534400     0.106435 0     1.156545    -0.463191
         -72.816057     -10.085068       2.067006   283.328636
c
c
c        SIGMOID COLON
280   ty     3.0000 0     8.7200     5.7200     1.5700     1.5700
281   ty      3.000 0 0      3.000     1.5700     1.5700
c
c        KIDNEYS
312   px     3.0000
c
c        LIVER
322   pz    43.0000
c
c
c        LUNGS
330   sq      32.4000      14.4000       1.4062 0 0 0
            -810.0000     8.5000 0    43.5000
331   sq      32.4000      14.4000       1.4062 0 0 0
           -810.0000    -8.5000 0    43.5000
333   px    -5.4000
334   py     1.5000
335   pz    46.0000
336   pz    54.0000
337   px     8.0000
338   py     1.0000
339   pz    55.0000
c
```

```
c
c           THYROID
c 390    c/z 0    -3.1500     2.2000
c 391    c/z 0    -3.1500     1.0000
c 392    py    -3.1500
c 393    pz    75.0000
c
c        URINARY BLADDER
410    sq   142.9881   293.9429   293.9429 0 0 0 -3514.9002 0
          -4.5000     8.0000
c extent    -4.9580     4.9580    -7.9580    -1.0420     4.5420    11.4580
c      Void
600    so 100
c
c     STATISTICS
c  Weight =    72.94 kg ( =   160.79 pounds)
c  Height =   179.00 cm ( =    70.47 inches)
c

c        ESOPHAGUS
tr6      0.000      2.575     42.300
       0.736084  -0.604969  -0.303634
       0.634945   0.772557   0.000000
       0.234575  -0.192791       0.953
c
c ++++++++++++++++++++++++++++++++++++++++++++++++
c      MATERIALS
c      Compositions from ORNL Report TM-8381
c ++++++++++++++++++++++++++++++++++++++++++++++++
c      Adult Tissues (Density = 1.04 g/cc)
m1       1001  -0.10454
         6012  -0.22663
         7014  -0.02490
         8016  -0.63525
        11023  -0.00112
        12000  -0.00013
        14000  -0.00030
        15031  -0.00134
        16000  -0.00204
        17000  -0.00133
        19000  -0.00208
        20000  -0.00024
        26000  -0.00005
        30000  -0.00003
        37085  -0.00001
        40000  -0.00001
c
c       Skeleton (Density = 1.4 g/cc)
m2       1001  -0.07337
         6012  -0.25475
         7014  -0.03057
         8016  -0.47893
         9019  -0.00025
        11023  -0.00326
        12000  -0.00112
        14000  -0.00002
```

```
       15031  -0.05095
       16000  -0.00173
       17000  -0.00143
       19000  -0.00153
       20000  -0.10190
       26000  -0.00008
       30000  -0.00005
       37085  -0.00005
       82000  -0.00001
c
c      Lung (Density = 0.296 g/cc)
m3       1001  -0.10134
         6012  -0.10238
         7014  -0.02866
         8016  -0.75752
        11023  -0.00184
        12000  -0.00007
        14000  -0.00006
        15031  -0.00080
        16000  -0.00225
        17000  -0.00266
        19000  -0.00194
        20000  -0.00009
        26000  -0.00037
        30000  -0.00001
        37085  -0.00001
c
c      Air (Density = 0.001020 g/cc)
m4       6012  -0.00012
         7014  -0.75527
         8016  -0.23178
        18000  -0.01283
c
c     TLD (Density = 2.64 g/cc)
m5       3006    .0375
        3007    .4625
        9019    .5
c
c +++++++++++++++++++++++++++++++++++++++++++++++
c   User Supplied Cards
c +++++++++++++++++++++++++++++++++++++++++++++++
c Number of Histories to Run
f6:p 61
e6:p 0 .03 .04 .05 .06 .07 .08 .09 .1 .2 .3 .4 .5 .6 .7
```

MCNP Source Cards – Cs-137

Whole Body (TC)

```
c Source Definition
SDEF  POS=0 0 -80  CEL=11  AXS=0 0 1  RAD=d1  EXT=d2  ERG=d3
si1 0  20
sp1 -21  1
si2 0  178.61
sp2 -21  0
```

Lungs

```
c Source Definition
SDEF  POS=0 0 43.5  CEL=330  AXS=0 0 1  RAD=d1  EXT=d2  ERG=.661657
     VEC=9.62 -9.525 -40.8 DIR=d3
si1 0  13.5
sp1 -21  1
si2 0  24
sp2 -21  0
si3 -1 .743145 1
sp3 0 .8716 .1283
sb3 0 .2 .8
```

Stomach

```
c Source Definition
SDEF  POS=8 -4 35  CEL=210 RAD=d1 ERG=.661657
      VEC=1.62 -5.525 -32.3  DIR=d3
si1 0  8.1
sp1 -21  2
si3 -1 .866 1
sp3 0 .933 .067
sb3 0 .3 .7
```

Bladder

```
c Source Definition
SDEF POS=0 -4.5 8.53 CEL=410 RAD=d1 ERG=.661657 VEC=9.62 -5.025 -5.83 DIR=d3
si1 0  5.2
sp1 -21  2
si3 -1 .848 1
sp3 0 .924 .076
sb3 0 .2 .8
```

MCNP Tally Results – Cs-137

Whole Body

	tally 6				
nps	mean	error	vov	slope	fom
16384000	1.4944E-06	0.1149	0.0712	0.0	8.9E-01
32768000	1.6542E-06	0.0760	0.0290	0.0	1.0E+00
49152000	1.7668E-06	0.0631	0.0297	3.2	9.9E-01
65536000	1.7573E-06	0.0560	0.0201	10.0	9.4E-01
81920000	1.7254E-06	0.0494	0.0155	10.0	9.7E-01
98304000	1.7396E-06	0.0447	0.0119	8.9	9.8E-01
114688000	1.7585E-06	0.0408	0.0096	6.4	1.0E+00
131072000	1.7772E-06	0.0376	0.0079	5.4	1.0E+00
147456000	1.7867E-06	0.0350	0.0068	4.2	1.1E+00
163840000	1.7830E-06	0.0333	0.0060	4.1	1.1E+00
180224000	1.7949E-06	0.0314	0.0051	4.5	1.1E+00
190000000	1.8002E-06	0.0304	0.0048	4.8	1.1E+00

Lungs

	tally 6				
nps	mean	error	vov	slope	fom
65536000	3.0373E-08	0.1760	0.1078	0.0	2.4E-01
131072000	3.6868E-08	0.1268	0.0560	0.0	2.3E-01
196608000	3.5931E-08	0.1194	0.1500	0.0	1.8E-01
262144000	3.6800E-08	0.0974	0.1005	0.0	2.0E-01
327680000	3.8423E-08	0.0884	0.0764	0.0	1.9E-01
393216000	3.9101E-08	0.0823	0.0602	2.7	1.8E-01
458752000	4.0381E-08	0.0733	0.0466	2.6	2.0E-01
524288000	4.0089E-08	0.0679	0.0388	2.8	2.0E-01
589824000	3.9296E-08	0.0635	0.0347	2.8	2.1E-01
655360000	3.9831E-08	0.0599	0.0286	3.3	2.1E-01
720896000	4.0122E-08	0.0595	0.0332	3.1	1.9E-01
786432000	4.0174E-08	0.0581	0.0309	3.1	1.9E-01
851968000	4.0805E-08	0.0558	0.0281	2.9	1.9E-01
917504000	4.0827E-08	0.0530	0.0256	3.1	1.9E-01
983040000	4.1570E-08	0.0523	0.0279	3.0	1.8E-01
1000000000	4.1451E-08	0.0517	0.0275	2.8	1.8E-01

Stomach

	tally 6				
nps	mean	error	vov	slope	fom
32768000	3.3647E-07	0.1237	0.3534	2.0	7.5E-01
65536000	3.7827E-07	0.1010	0.1096	1.7	5.5E-01
98304000	3.6563E-07	0.0797	0.0743	1.7	5.8E-01
131072000	3.4304E-07	0.0673	0.0610	1.8	6.1E-01
163840000	3.3882E-07	0.0580	0.0492	1.9	6.6E-01
196608000	3.2902E-07	0.0522	0.0439	2.0	6.9E-01
229376000	3.3281E-07	0.0521	0.0734	1.9	5.9E-01
262144000	3.4208E-07	0.0559	0.1312	1.9	4.5E-01
294912000	3.3820E-07	0.0516	0.1184	1.8	4.7E-01

327680000	3.3008E-07	0.0481	0.1130	1.9	4.8E-01
360448000	3.2611E-07	0.0449	0.1070	1.9	5.1E-01
393216000	3.2654E-07	0.0436	0.0900	1.9	4.9E-01
400000000	3.2763E-07	0.0436	0.0848	1.9	4.9E-01

Bladder

tally 6

nps	mean	error	vov	slope	fom
8192000	6.8212E-06	0.0495	0.0914	1.9	2.5E+00
16384000	6.8435E-06	0.0368	0.1326	1.9	2.3E+00
24576000	7.1124E-06	0.0320	0.0592	1.7	2.0E+00
32768000	7.3739E-06	0.0291	0.0441	2.1	1.8E+00
40960000	7.4029E-06	0.0254	0.0329	3.0	1.9E+00
49152000	7.4455E-06	0.0231	0.0250	4.5	1.9E+00
57344000	7.4203E-06	0.0214	0.0205	4.8	1.9E+00
65536000	7.3858E-06	0.0197	0.0180	5.4	2.0E+00
73728000	7.3649E-06	0.0186	0.0153	6.1	2.0E+00
81920000	7.3796E-06	0.0176	0.0134	9.5	2.0E+00
90112000	7.3703E-06	0.0167	0.0121	10.0	2.0E+00
98304000	7.3638E-06	0.0161	0.0111	10.0	2.0E+00
100000000	7.3574E-06	0.0160	0.0109	10.0	2.0E+00

MCNP Input Deck – U-238

See Cs-137 input deck….

For simulating the bone as the source, all bones were consolidated into a single cell card numbered 50.

```
c        ALL BONES
50   2 -1.40   (-4 53 (-51:-52)):(4 -73 (-71:-72)):(91 -92 93 4 -101 (95:-94)):
          (-100 -98 101):(-100 -8   98):(-105 -102 8):((111 -110):
          (121 -120 122 -1 -123 110)):(132 -131 ((134 -133):(136 -135):
          (138 -137):(74 -139):(76 -75):(78 -77):(80 -79):(82 -81):(332 -83):
          (86 -85):(88 -87):(98 -89))):(-140 ((141 -143):(-142 144))):
          (131 -156 154 -155 ((150 -152):(-151 153)))
             imp:n,p,e = 1
```

MCNP Source Cards – U-238

Stomach

```
c Source Definition
SDEF  POS=8 -4 35  CEL=210 RAD=d1 ERG=d4
      VEC=1.62 -5.525 -32.3  DIR=d3
si1 0  8.1
sp1 -21  2
si3 -1 .866 1
sp3 0 .933 .067
sb3 0 .3 .7
si4 0 .04955 .1135
sp4 0 .8625  .1375
```

Small Intestine

```
c Source Definition
SDEF  POS=0 -3.5 17  CEL=220  AXS=0 0 1  RAD=d1  EXT=d2  ERG=d4
     VEC=9.62 -6.025 -15.3 DIR=d3
si1 0  11.7
sp1 -21  1
si2 0  10
sp2 -21  0
si3 -1 .9522 1
sp3 0 .9761 .0239
sb3 0 .2 .8
si4 0 .04955 .1135
sp4 0 .8625  .1375
```

Colon

```
c Source Definition
SDEF  POS=0 0 0  CEL=230  AXS=0 0 1  RAD=d1  EXT=d2  ERG=d3
si1 0  12
```

```
sp1 -21  1
si2 0  30
sp2 -21  0
si3 0 .04955 .1135
sp3 0 .8625  .1375
```

Whole Body (TC)

```
c Source Definition
SDEF  POS=0 0 -79.8  CEL=11  AXS=0 0 1  RAD=d1  EXT=d2  ERG=d3
si1 0  20
sp1 -21  1
si2 0  158.2
sp2 -21  0
si3 0 .04955 .1135
sp3 0 .8625  .1375
```

Skeleton

```
c Source Definition
SDEF  POS=0 0 -80  CEL=50  AXS=0 0 1  RAD=d1  EXT=d2  ERG=d3
      VEC=0 -1 0  DIR=d4
si1 0  22
sp1 -21  1
si2 0  180
sp2 -21  0
si3 0 .04955 .1135
sp3 0 .8625  .1375
```

Kidneys

```
c Source Definition
SDEF  POS=0 6 26  CEL=310  AXS=0 0 1  RAD=d1  EXT=d2  ERG=d3
si1 0  11
sp1 -21  1
si2 0  13
sp2 -21  0
si3 0 .04955 .1135
sp3 0 .8625  .1375
```

Bladder

```
c Source Definition
SDEF POS=0 -4.5 8.53 CEL=410 RAD=d1 ERG=d4 VEC=9.62 -5.025 -5.83 DIR=d3
si1 0  5.2
sp1 -21  2
si3 -1 .848 1
sp3 0 .924 .076
sb3 0 .2 .8
si4 0 .04955 .1135
sp4 0 .8625  .1375
```

MCNP Tally Results – U-238

Stomach

	tally 6				
nps	mean	error	vov	slope	fom
65536000	7.5173E-09	0.4605	0.3450	0.0	6.2E-02
131072000	6.1081E-09	0.4214	0.3690	0.0	3.7E-02
196608000	4.3935E-09	0.3913	0.3662	0.0	2.9E-02
262144000	4.1776E-09	0.3331	0.2853	0.0	3.0E-02
327680000	3.5705E-09	0.3122	0.2841	0.0	2.7E-02
393216000	3.6177E-09	0.2798	0.2145	0.0	2.8E-02
458752000	3.8568E-09	0.2601	0.1716	0.0	2.8E-02
524288000	3.5568E-09	0.2472	0.1703	0.0	2.7E-02
589824000	3.5649E-09	0.2314	0.1470	0.0	2.7E-02
655360000	3.5319E-09	0.2159	0.1337	0.0	2.8E-02
720896000	3.2820E-09	0.2113	0.1334	0.0	2.7E-02
786432000	3.4258E-09	0.1979	0.1138	0.0	2.8E-02
800000000	3.3855E-09	0.1969	0.1137	0.0	2.8E-02

Small Intestine

	tally 6				
nps	mean	error	vov	slope	fom
32768000	1.0725E-08	0.5223	0.7694	0.0	1.2E-01
65536000	1.7377E-08	0.3006	0.1901	0.0	1.7E-01
98304000	1.4831E-08	0.2453	0.1623	0.0	1.7E-01
131072000	1.9024E-08	0.2228	0.1309	0.0	1.6E-01
163840000	2.1211E-08	0.1860	0.0850	10.0	1.8E-01
196608000	2.0454E-08	0.1669	0.0748	10.0	1.9E-01
229376000	2.1326E-08	0.1511	0.0600	10.0	2.0E-01
262144000	2.3033E-08	0.1447	0.0666	10.0	1.9E-01
294912000	2.2148E-08	0.1400	0.0597	10.0	1.8E-01
327680000	2.7632E-08	0.1370	0.0668	10.0	1.7E-01
360448000	2.8859E-08	0.1297	0.0551	10.0	1.7E-01
393216000	2.7581E-08	0.1257	0.0531	10.0	1.7E-01
425984000	2.6928E-08	0.1206	0.0503	10.0	1.7E-01
458752000	2.5677E-08	0.1179	0.0495	10.0	1.6E-01
491520000	2.5650E-08	0.1128	0.0456	10.0	1.6E-01
500000000	2.5911E-08	0.1122	0.0436	10.0	1.6E-01

Colon

	tally 6				
nps	mean	error	vov	slope	fom
4096000	1.2633E-07	0.2884	0.1305	0.0	2.2E+00
8192000	9.1066E-08	0.2487	0.1221	0.0	1.5E+00
12288000	1.2608E-07	0.2310	0.3273	0.0	1.2E+00
16384000	1.1466E-07	0.1996	0.2737	0.0	1.2E+00
20480000	1.0799E-07	0.1755	0.2393	0.0	1.2E+00
24576000	1.0348E-07	0.1610	0.1960	0.0	1.2E+00
28672000	1.0607E-07	0.1434	0.1545	0.0	1.3E+00
32768000	1.0896E-07	0.1319	0.1189	0.0	1.3E+00
36864000	1.0952E-07	0.1210	0.1034	0.0	1.4E+00

nps	mean	error	vov	slope	fom
40960000	1.1031E-07	0.1134	0.0878	0.0	1.4E+00
45056000	1.1527E-07	0.1047	0.0714	0.0	1.5E+00
49152000	1.1123E-07	0.1007	0.0678	0.0	1.5E+00
53248000	1.0992E-07	0.0968	0.0612	0.0	1.5E+00
57344000	1.1147E-07	0.0939	0.0527	0.0	1.5E+00
61440000	1.1270E-07	0.0893	0.0473	0.0	1.6E+00
65536000	1.1324E-07	0.0858	0.0425	0.0	1.6E+00
69632000	1.1471E-07	0.0826	0.0377	0.0	1.6E+00
73728000	1.1416E-07	0.0804	0.0350	0.0	1.6E+00
77824000	1.1458E-07	0.0778	0.0321	0.0	1.6E+00
80000000	1.1323E-07	0.0769	0.0315	0.0	1.6E+00

Whole Body (TC)

	tally 6				
nps	mean	error	vov	slope	fom
32768000	1.4541E-07	0.1287	0.0477	0.0	8.8E-01
65536000	1.2121E-07	0.0961	0.0390	0.0	7.9E-01
98304000	1.2484E-07	0.0782	0.0243	0.0	8.0E-01
131072000	1.2086E-07	0.0706	0.0211	0.0	7.3E-01
163840000	1.2458E-07	0.0607	0.0153	10.0	7.9E-01
196608000	1.2451E-07	0.0550	0.0122	10.0	8.0E-01
229376000	1.2524E-07	0.0500	0.0098	10.0	8.3E-01
262144000	1.2780E-07	0.0459	0.0080	10.0	8.7E-01
294912000	1.2487E-07	0.0436	0.0072	10.0	8.5E-01
327680000	1.2670E-07	0.0409	0.0062	10.0	8.7E-01
360448000	1.2804E-07	0.0397	0.0059	10.0	8.4E-01
393216000	1.3057E-07	0.0378	0.0052	10.0	8.5E-01
425984000	1.2932E-07	0.0365	0.0048	10.0	8.5E-01
458752000	1.2933E-07	0.0358	0.0059	10.0	8.1E-01
491520000	1.2936E-07	0.0348	0.0057	10.0	8.0E-01
524288000	1.3082E-07	0.0335	0.0052	10.0	8.1E-01
550000000	1.3263E-07	0.0326	0.0047	7.2	8.2E-01

Skeleton

	tally 6				
nps	mean	error	vov	slope	fom
16384000	2.4286E-08	0.4175	0.7371	0.0	8.4E-02
32768000	3.9794E-08	0.3908	0.5526	0.0	4.8E-02
49152000	3.5511E-08	0.3004	0.4934	0.0	5.3E-02
65536000	3.5305E-08	0.2490	0.3513	0.0	5.8E-02
81920000	3.0687E-08	0.2310	0.3406	0.0	5.4E-02
98304000	2.9844E-08	0.2026	0.3109	0.0	5.9E-02
114688000	2.8288E-08	0.1854	0.2966	0.0	6.0E-02
131072000	2.7161E-08	0.1705	0.2860	0.0	6.2E-02
147456000	2.6896E-08	0.1576	0.2554	0.0	6.5E-02
163840000	2.7009E-08	0.1440	0.2364	0.0	7.0E-02
180224000	2.5780E-08	0.1386	0.2270	0.0	6.9E-02
196608000	2.5389E-08	0.1303	0.2180	0.0	7.2E-02
212992000	2.5097E-08	0.1232	0.2073	0.0	7.4E-02
229376000	2.4463E-08	0.1184	0.2008	0.0	7.4E-02
240000000	2.4241E-08	0.1149	0.1954	0.0	7.5E-02

Kidneys

	tally 6				
nps	mean	error	vov	slope	fom
65536000	1.6756E-10	1.0000	1.0000	0.0	1.2E-02
131072000	1.4789E-09	0.4938	0.3693	0.0	2.4E-02
196608000	1.5474E-09	0.3599	0.2315	0.0	3.1E-02
262144000	1.5992E-09	0.3787	0.3274	0.0	2.1E-02
327680000	1.2793E-09	0.3787	0.3274	0.0	1.7E-02
393216000	1.0924E-09	0.3702	0.3253	0.0	1.4E-02
458752000	1.2526E-09	0.3183	0.2157	0.0	1.7E-02
524288000	1.3332E-09	0.3164	0.2009	0.0	1.5E-02
589824000	1.5665E-09	0.2678	0.1416	0.0	1.8E-02
655360000	1.4175E-09	0.2664	0.1415	0.0	1.7E-02
700000000	1.3699E-09	0.2599	0.1376	0.0	1.6E-02

Bladder

	tally 6				
nps	mean	error	vov	slope	fom
16384000	3.9243E-07	0.1602	0.1239	1.4	2.9E+00
32768000	3.3779E-07	0.1056	0.0803	1.5	3.4E+00
49152000	3.3548E-07	0.0822	0.0510	1.5	3.7E+00
65536000	3.3410E-07	0.0694	0.0383	1.5	3.9E+00
81920000	3.5073E-07	0.0655	0.0275	1.5	3.5E+00
98304000	3.5060E-07	0.0593	0.0225	1.6	3.5E+00
114688000	3.5753E-07	0.0573	0.0230	3.2	3.3E+00
131072000	3.6137E-07	0.0581	0.0325	4.8	2.8E+00
147456000	3.7196E-07	0.0557	0.0264	10.0	2.7E+00
163840000	3.7283E-07	0.0534	0.0235	10.0	2.6E+00
180224000	3.7525E-07	0.0509	0.0210	10.0	2.6E+00
196608000	3.9382E-07	0.0567	0.0864	10.0	1.9E+00
212992000	4.0171E-07	0.0531	0.0755	6.5	2.0E+00
229376000	4.1228E-07	0.0510	0.0612	6.3	2.1E+00
245760000	4.0978E-07	0.0498	0.0556	4.8	2.0E+00
250000000	4.0747E-07	0.0493	0.0552	5.0	2.0E+00

MCNP Input Deck – Sr-90

See Cs-137 and U-238 input decks…

MCNP Source Cards – Sr-90

Lungs

```
SDEF  POS=0 0 43.5  CEL=330  AXS=0 0 1  RAD=d1  EXT=d2  ERG=d4 PAR=3
si1 0  13.5
sp1 -21  1
si2 0  24
sp2 -21  0
si4 0 .05  .1  .2  .3  .4  .5  1  1.5  2  2.2
sp4 0 .1640 .2148 .2031 .1641 .0938 .0594 .0469 .0359 .0141 .0039
BBREM 1 1. 10I 2. 20I 25. 10I 125. 250. 500. 1000. 2000. 1 2
CUT:E 1E6 .042
CUT:P 1E6 .03
```

Stomach

```
c Source Definition
SDEF  POS=8 -4 35  CEL=210 RAD=d1 ERG=d4 PAR=3
si1 0  8.1
sp1 -21  2
si4 0 .05  .1  .2  .3  .4  .5  1  1.5  2  2.2
sp4 0 .1640 .2148 .2031 .1641 .0938 .0594 .0469 .0359 .0141 .0039
BBREM 1 1. 10I 2. 20I 50. 10I 100. 200. 250. 1000. 4000. 1 2
CUT:E 1E6 .042
CUT:P 1E6 .03
```

Small Intestine

```
c Source Definition
SDEF  POS=0 -3.5 17  CEL=220  AXS=0 0 1  RAD=d1  EXT=d2  ERG=d4
          PAR=3
si1 0  11.7
sp1 -21  1
si2 0  10
sp2 -21  0
si4 0 .05  .1  .2  .3  .4  .5  1  1.5  2  2.2
sp4 0 .1640 .2148 .2031 .1641 .0938 .0594 .0469 .0359 .0141 .0039
BBREM 1 1. 10I 2. 20I 50. 10I 100. 200. 250. 1000. 4000. 1 2
CUT:E 1E6 .042
CUT:P 1E6 .03
```

Colon

```
c Source Definition
SDEF  POS=0 0 0  CEL=230  AXS=0 0 1  RAD=d1  EXT=d2  ERG=d3 PAR=3
si1 0  12
sp1 -21  1
si2 0  30
sp2 -21  0
si3 0 .05  .1  .2  .3  .4  .5  1  1.5  2  2.2
sp3 0 .1640 .2148 .2031 .1641 .0938 .0594 .0469 .0359 .0141 .0039
BBREM 1 1. 10I 2. 20I 50. 10I 100. 200. 250. 1000. 3000. 1 2
CUT:E 1E6 .042
CUT:P 1E6 .03
```

Whole Body (TC)

```
c Source Definition
SDEF  POS=0 0 -79.8  CEL=11  AXS=0 0 1  RAD=d1  EXT=d2  ERG=d3 PAR=3
si1 0  20
sp1 -21  1
si2 0  158.2
sp2 -21  0
si3 0 .05  .1  .2  .3  .4  .5  1  1.5  2  2.2
sp3 0 .1640 .2148 .2031 .1641 .0938 .0594 .0469 .0359 .0141 .0039
BBREM 1 1. 10I 2. 20I 50. 10I 100. 200. 250. 1000. 4000. 1 2
CUT:E 1E6 .042
CUT:P 1E6 .03
```

Skeleton

```
c Source Definition
SDEF  POS=0 0 -79.8  CEL=50  AXS=0 0 1  RAD=d1  EXT=d2  ERG=d3 PAR=3
si1 0  19.8
sp1 -21  1
si2 0  177.9
sp2 -21  0
si3 0 .05  .1  .2  .3  .4  .5  1  1.5  2  2.2
sp3 0 .1640 .2148 .2031 .1641 .0938 .0594 .0469 .0359 .0141 .0039
BBREM 1 1. 5I 20. 15I 100. 10I 400. 11I 2000. 10000. 50000. 1 2
CUT:E 1E6 .049
CUT:P 1E6 .02
```

Bladder

```
c Source Definition
SDEF POS=0 -4.5 8.53 CEL=410 RAD=d1 ERG=d4 PAR=3
si1 0  5.2
sp1 -21  2
si4 0 .05  .1  .2  .3  .4  .5  1  1.5  2  2.2
sp4 0 .1640 .2148 .2031 .1641 .0938 .0594 .0469 .0359 .0141 .0039
BBREM 1 1. 10I 2. 20I 50. 10I 100. 200. 250. 1000. 4000. 1 2
CUT:E 1E6 .041
CUT:P 1E6 .03
```

MCNP Tally Results – Sr-90

Lungs

	tally 6				
nps	mean	error	vov	slope	fom
32768000	0.0000E+00	0.0000	0.0000	0.0	0.0E+00
65536000	3.7839E-10	1.0000	1.0000	0.0	4.9E-03
98304000	6.3757E-10	0.7223	0.5800	0.0	6.3E-03
131072000	4.7818E-10	0.7223	0.5800	0.0	4.7E-03
163840000	3.8254E-10	0.7223	0.5800	0.0	3.8E-03
196608000	3.1879E-10	0.7223	0.5800	0.0	3.2E-03
229376000	2.7325E-10	0.7223	0.5800	0.0	2.7E-03
262144000	2.3909E-10	0.7223	0.5800	0.0	2.4E-03
294912000	2.1337E-10	0.7195	0.5800	0.0	2.1E-03
327680000	1.9509E-10	0.7084	0.5794	0.0	2.0E-03
360448000	1.7736E-10	0.7084	0.5794	0.0	1.8E-03
393216000	1.6258E-10	0.7084	0.5794	0.0	1.6E-03
400000000	1.5982E-10	0.7084	0.5794	0.0	1.6E-03

Stomach

	tally 6				
nps	mean	error	vov	slope	fom
65536000	0.0000E+00	0.0000	0.0000	0.0	0.0E+00
131072000	2.4061E-11	0.6726	0.7568	0.0	1.1E-02
196608000	4.0183E-11	0.4482	0.2724	0.0	1.7E-02
262144000	3.4040E-11	0.4131	0.2379	0.0	1.5E-02
327680000	2.7232E-11	0.4131	0.2379	0.0	1.2E-02
393216000	4.8546E-11	0.3903	0.3315	0.0	1.1E-02
458752000	5.3109E-11	0.3529	0.2409	0.0	1.2E-02
524288000	4.7514E-11	0.3459	0.2390	0.0	1.1E-02
589824000	6.2557E-11	0.3935	0.4487	0.0	7.2E-03
655360000	9.0438E-11	0.3531	0.2385	0.0	8.1E-03
720896000	8.6853E-11	0.3368	0.2316	0.0	8.1E-03
786432000	8.2528E-11	0.3267	0.2268	0.0	7.9E-03
800000000	8.1128E-11	0.3267	0.2268	0.0	7.7E-03

Small Intestine

	tally 6				
nps	mean	error	vov	slope	fom
32768000	1.4037E-09	0.9347	0.9981	0.0	1.2E-02
65536000	7.6498E-10	0.8580	0.9961	0.0	7.0E-03
98304000	5.9262E-10	0.7433	0.9700	0.0	6.2E-03
131072000	5.6987E-10	0.5991	0.8535	0.0	7.2E-03
163840000	7.3868E-10	0.4320	0.4982	0.0	1.1E-02
196608000	8.8601E-10	0.3819	0.3168	0.0	1.2E-02
229376000	7.9647E-10	0.3668	0.3079	0.0	1.1E-02
262144000	8.2052E-10	0.3300	0.2523	0.0	1.2E-02
294912000	7.3648E-10	0.3268	0.2522	0.0	1.1E-02
327680000	6.7091E-10	0.3229	0.2521	0.0	9.9E-03
360448000	6.9731E-10	0.3005	0.2101	0.0	1.0E-02
393216000	1.5300E-09	0.5548	0.8937	0.0	2.8E-03
425984000	1.4231E-09	0.5506	0.8937	0.0	2.6E-03
430000000	1.4099E-09	0.5506	0.8937	0.0	2.6E-03

Colon

	tally 6				
nps	mean	error	vov	slope	fom
32768000	1.4661E-09	0.4168	0.2932	0.0	4.9E-02
65536000	3.5413E-09	0.5831	0.9282	0.0	1.2E-02
98304000	3.2797E-09	0.4321	0.8282	0.0	1.5E-02
131072000	3.2552E-09	0.3326	0.7694	0.0	1.9E-02
163840000	3.2935E-09	0.2701	0.6921	0.0	2.3E-02
196608000	3.2056E-09	0.2346	0.6535	0.0	2.6E-02
229376000	3.0001E-09	0.2161	0.6395	0.0	2.6E-02
262144000	2.8013E-09	0.2033	0.6292	0.0	2.5E-02
294912000	2.6570E-09	0.1916	0.6155	0.0	2.6E-02
327680000	2.5527E-09	0.1804	0.6031	0.0	2.6E-02
360448000	2.5111E-09	0.1685	0.5777	0.0	2.7E-02
393216000	2.4245E-09	0.1609	0.5643	0.0	2.7E-02
425984000	2.4311E-09	0.1498	0.5399	0.0	2.9E-02
458752000	2.4095E-09	0.1415	0.5218	0.0	3.0E-02
491520000	2.4091E-09	0.1338	0.4965	0.0	3.1E-02
524288000	2.3272E-09	0.1303	0.4894	0.0	3.1E-02
557056000	2.4578E-09	0.1213	0.4146	0.0	3.4E-02
589824000	2.4150E-09	0.1172	0.4058	0.0	3.4E-02
600000000	2.4040E-09	0.1161	0.4014	0.0	3.4E-02

Whole Body (TC)

	tally 6				
nps	mean	error	vov	slope	fom
8192000	4.5379E-09	0.4218	0.5736	0.0	1.0E-02
16384000	2.8801E-09	0.3436	0.5028	0.0	8.9E-03
24576000	2.0351E-09	0.3258	0.4931	0.0	7.0E-03
32768000	2.7790E-09	0.2482	0.1961	0.0	9.2E-03
40960000	2.7266E-09	0.2159	0.1574	0.0	9.9E-03
49152000	2.5060E-09	0.2020	0.1412	0.0	9.5E-03
57344000	2.3384E-09	0.1878	0.1347	0.0	9.5E-03
65536000	2.3936E-09	0.1771	0.1050	0.0	9.4E-03
73728000	2.3411E-09	0.1649	0.0961	0.0	9.7E-03
81920000	2.3395E-09	0.1577	0.0814	0.0	9.6E-03
90112000	2.1809E-09	0.1541	0.0806	0.0	9.1E-03
98304000	2.2690E-09	0.1453	0.0665	0.0	9.4E-03
106496000	2.1962E-09	0.1411	0.0626	0.0	9.3E-03
110000000	2.2490E-09	0.1371	0.0581	0.0	9.5E-03

Skeleton

	tally 6				
nps	mean	error	vov	slope	fom
32768000	1.3021E-09	0.4084	0.2811	0.0	1.1E-02
65536000	1.6659E-09	0.4342	0.6204	0.0	5.1E-03
98304000	1.2516E-09	0.3916	0.5821	0.0	4.1E-03
131072000	1.2065E-09	0.3214	0.4752	0.0	4.1E-03
163840000	1.0269E-09	0.3056	0.4545	0.0	3.7E-03
196608000	1.0088E-09	0.2713	0.3831	0.0	4.0E-03
229376000	1.0780E-09	0.2482	0.2525	0.0	4.1E-03

nps	mean	error	vov	slope	fom
262144000	1.0219E-09	0.2327	0.2376	0.0	4.1E-03
294912000	1.1060E-09	0.2217	0.1873	0.0	4.1E-03
327680000	1.0185E-09	0.2170	0.1860	0.0	3.8E-03
360448000	9.7496E-10	0.2076	0.1807	0.0	3.8E-03
393216000	9.3336E-10	0.1996	0.1779	0.0	3.8E-03
425984000	9.2197E-10	0.1891	0.1685	0.0	3.9E-03
458752000	8.7851E-10	0.1849	0.1666	0.0	3.8E-03
460000000	8.7613E-10	0.1849	0.1666	0.0	3.8E-03

Bladder

	tally 6				
nps	mean	error	vov	slope	fom
65536000	4.4418E-09	0.2199	0.1647	0.0	2.7E-01
131072000	4.1625E-09	0.1500	0.0883	0.0	2.9E-01
196608000	6.0624E-09	0.1429	0.0843	10.0	2.1E-01
262144000	7.2709E-09	0.1366	0.0760	10.0	1.7E-01
327680000	6.9160E-09	0.1185	0.0674	6.8	1.8E-01
393216000	6.5687E-09	0.1093	0.0591	5.6	1.8E-01
458752000	6.5560E-09	0.1037	0.0579	5.0	1.7E-01
524288000	6.3948E-09	0.0959	0.0517	5.3	1.7E-01
589824000	6.5236E-09	0.0900	0.0420	6.0	1.8E-01
655360000	7.0423E-09	0.0974	0.1006	4.3	1.4E-01
720896000	7.4625E-09	0.0935	0.0773	4.2	1.3E-01
786432000	7.4216E-09	0.0889	0.0693	4.4	1.4E-01
851968000	7.3732E-09	0.0844	0.0640	4.6	1.4E-01
915000000	7.1687E-09	0.0815	0.0619	4.4	1.4E-01

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