To the Graduate Council:

I am submitting herewith a thesis written by Alfred Rybka entitled "A Technique of Dose Estimation and Reconstruction of Acute and Chronic Intakes of Pu-241 and Am-241 by Inhalation". I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment for the degree of Master of Science, with a major in Nuclear Engineering.

Dr. Rafael B. Perez, Major Professor

We have read this thesis and
recommend its acceptance:

Dr. Keith F. Eckerman, Nuclear Engineering

Dr. Laurence F. Miller, Nuclear Engineering

Accepted for the Council:

Associate Vice Chancellor and
Dean of the Graduate School

A Technique of Dose Estimation and Reconstruction of Acute and Chronic Intakes of Pu-241 and Am-241 by Inhalation

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Alfred Rybka

August 1997

Acknowledgements

I would like to thank my major thesis professor, Dr. Rafael B. Perez, for his guidance, encouragement, support, and friendship throughout this project, and for his willingness to meet at his home at times which were convenient for me. I would also like to thank Dr. Keith Eckerman for suggesting this project for a thesis. Dr. Eckerman not only introduced me to Internal Dosimetry and biokinetic modeling, but also provided the transfer parameters for the model used in this project. I would like to thank Dr. Laurence Miller for the many skills he taught me, in many classes, which I used to successfully complete the project. I am also thankful to my coworkers at EG&G ORTEC, for their support and for bearing with me during the project. I am very thankful to my parents, Herbert and Waltraut Rybka, living in Germany, for their love, support and their encouragement in all of my endeavors throughout my life. But most important I need to thank my wife Janice, for her love, support, encouragement, understanding, coffee making, and much more. I also would like to thank my children, Samantha and Jonathan, for their understanding during the project and studies.

Abstract

The estimation of the time and the level of intake of Pu-241 and Am-241 is the focal point of this study. The computer program Stella II simulates a biokinetic model, the mathematical representation of the behavior of these radionuclides in the human body, and these results are further analyzed. The research performed for the thesis is the critical examination of the biokinetic model for the Pu-241 and the Am-241 nuclide and the validation/verification through comparison with established models for the same initial conditions. The simulations, represented through pulses, allow the study of the behavior of the radionuclides in regard to various intakes and provide more realistic intake situations. The intake scenarios here include acute single intakes of varying strengths, and long term chronic intakes of varying strengths. Observations of the simulations show that the activities in the compartments of the models are unique functions of time and that the ratios of the activities in various bioassay compartments are also unique functions of time. These characteristics of the unique curves are the basis for the study and provide information about the time the intake occurred, as well as the strength of the intake.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

ALI	Annual Limit on Intake
AMAD	Activity Median Aerodynamic Diameter
DIL	Decision Investigation Level
EPA	Environmental Protection Agency
IAEA	International Atomic Energy Agency
ICRP	International Committee on Radiological Protection
MDA	Minimum Detectable Activity/Amount
MIRD	Medical Internal Radiation Dose

Glossary

activity median aerodynamic diameter (AMAD): The diameter of a sphere having a density of 1 g cm-3 and the same terminal settling velocity in air as that of the aerosol particle whose activity is the median for the entire aerosol.

alpha: The probability (not to be confused with an alpha particle) of a Type I error or false positive. Also called the false positive probability.

analyte: The material to be detected in a quantitative analysis.

annual limit on intake (ALI): The derived limit for the amount of radioactive material taken into the body of an adult worker by inhalation or ingestion in a year. ALI is the smaller value of intake of either: 1) a given radionuclide in a year by the Reference Man (ICRP Publication 23) that would result in a committed effective dose equivalent of 5 rems (0.05 Sievert); or 2) a committed dose equivalent of 50 rems (0.5 Sievert) to any individual organ or tissue. ALI values for intake by ingestion and inhalation of selected radionuclides are based on Table 1 of U.S. Environmental Protection Agency (EPA), EPA-520/1-88-020, "Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion," Federal Guidance Report No. 11 (EPA, 1988).

baseline bioassay: An appropriate bioassay measurement obtained from a bioassay program participant prior to beginning or resuming work with radioactive material.

beta: The probability (not to be confused with a beta particle) of a Type II error or false negative. Also called the non-detection probability.

bioassay: The determination of kinds, quantities, or concentrations, and, in some cases, locations of radioactive material in the human body, whether by direct (in-vivo) measurement or by analysis and evaluation of radioactive materials excreted or removed from the human body (in-vitro). Examples of bioassay are: (1) measurement of radionuclides in urine, feces, hair, blood, or sputum; and (2) direct counting of the whole body or portions of the body (chest, abdomen, neck, wound) using external detectors.

biokinetic model: A series of often empirically determined mathematical relationships formulated to describe the intake, deposition in respiratory tract (if applicable), uptakes by the transfer compartment from intake compartment(s), uptakes by tissues or organs from the transfer compartment, translocation, retention, and elimination of a radionuclide from the body.

compartment: The smallest element in a biokinetic model for which a mathematical representation of a retained quantity is given. Compartments may be organs (e.g., lung, liver), tissues (e.g., bone marrow), or systemic (e.g., the transfer compartment).

confirmed intake: An intake confirmed by follow-up bioassay, by association with a known incident, or by investigation.

direct (in vivo) bioassay: The assessment of radionuclides in the body by detection of radiations emitted using external detector and analyzer systems.

elimination: The biological removal of a radionuclide from the body by excretion, perspiration, exhalation, secretion (e.g., breast milk), exfoliation (sloughing of dead tissue), or excision.

evaluation: The process of arriving at a value for intake or dose that uses, among other inputs, measurement results.

excretion: The biological removal of a radionuclide from the body via one or more excretion pathways: urine and feces.

exposure: The general condition of being subjected to ionizing radiation, such as by exposure to ionizing radiation from external sources or to ionizing radiation sources inside the body. In this document, exposure does not refer to the radiological physics concept of charge liberated per unit mass of air.

false negative: A Type II (beta) error, that is, concluding that analyte is not present when in fact it is.

false positive: A Type I (alpha) error that is, concluding that there is analyte present when it is not.

gastrointestinal (GI) tract model: A mathematical representation of the behavior of radionuclides in the contents of the human gastrointestinal tract.

group of radionuclides: Two or more radionuclides that are contained in a matrix such that an individual could not have an intake of one without simultaneously having an intake of all of the radionuclides in that matrix.

indirect (in vitro) bioassay: The measurement or analysis of radionuclides in excreta or other biological samples removed from the body.

intake: The amount of radionuclide taken into the body by inhalation, absorption through intact skin, injection, ingestion, or through wounds. Depending on the radionuclide involved, intakes may be reported in mass (e.g., micro-g, mg) or activity (e.g., micro-Ci, Bq) units.

intake compartment: One of four compartments from which systemic uptake can occur: the respiratory tract; the GI tract; a wound; or intact skin.

intake retention fraction: The fraction of an intake present in the systemic body or excreta at some time after intake.

intake route: A pathway by which radioactive material enters the body. The main intake routes are inhalation, ingestion, absorption through the skin, and entry through injection or a cut or wound in the skin.

minimum detectable amount/activity (MDA): The smallest amount/activity of a radionuclide in a sample that will yield a result above the decision level with a beta probability of non-detection (Type II error) while accepting an alpha probability of erroneously detecting that radionuclide in an appropriate blank sample (Type I error). The MDA is computed using the same value of alpha as used for the DL. The MDA depends on both alpha and beta. Measurement results are compared to the DL, not the MDA; the MDA is used to determine whether a program has adequate detection capability. The MDA will be greater than or equal to the DL.

occupational exposure: An individual's exposure to ionizing radiation (external and internal) as a result of that individual's work assignment. Occupational exposure does not include planned special exposures, exposure received as a medical patient, background radiation, or voluntary participation in medical research programs.

radiological worker: A general employee whose job assignment involves operation of radiation producing devices or working with radioactive materials, or who is likely to be routinely occupationally exposed above 0.1 rem (0.001 Sv) per year total effective dose equivalent.

Reference Man: A reference human model with the anatomical and physiological characteristics defined in the International Commission on Radiological Protection (ICRP) Publication 23, "Report of the Task Group on Reference Man," ICRP 23 (ICRP, 1975). The ICRP Reference Man includes parameters for males and females of various ages.

respiratory tract model: A mathematical representation of the behavior of particles and gases in the human respiratory tract.

retained quantity: The amount of material which, after being taken into the body by inhalation, ingestion, entry through an open wound, or absorption through the skin, exists in the whole body, a compartment, an organ, or a tissue at a specified time.

routine bioassay monitoring: Any bioassay measurement made on a predetermined, periodic schedule, to establish a worker's internal exposure status relative to previous periods of time.

special bioassay monitoring: Any bioassay measurement that is not required for routine bioassay, but that is required for confirmation of a suspected intake of radionuclides, or is required for follow-up evaluation of confirmed intakes.

state-of-the-art: The most advanced technology that is commercially available and successfully field tested.

Type I error: Incorrectly concluding from a result that there is analyte present; the probability (alpha) of a Type I error is usually taken as 0.05. The decision level is determined on the basis of an acceptable level of Type I errors.

Type II error: Incorrectly concluding from a result that there is no analyte present; its probability (beta) is usually taken as 0.05.

whole body: For the purposes of external exposure, head, trunk (including male gonads), arms above and including the elbow, or legs above and including the knee.

1.0 Introduction

1.1 Objective

The goal of this study is to examine the possibly estimating both the time and level of intake of Pu-241 and Am-241, when only a limited set of isolated measurements are available to the analyst. The study involves the use of the state-of-the-art biokinetic model for Pu-241 and Am-241. The kinetics of these materials is investigated by pulses that simulate radioactive intakes at different times, for different lengths of time, and of varying strengths. Several intake scenarios are examined to relate the activity in bioassay compartments to the time and magnitude of the intake.

The initial modeling used biokinetic models from published material (e.g. ICRP 67 [1] and the ACTACAL [2] program). The first step was the reproduction of an accepted model, and to examine the algorithms used to solve the rather large set of coupled differential equations. Equations describing the biokinetic model, were coded in STELLA [3] and the solutions were verified against the ACTACAL data.

In the early stage of the project, several software programs were used, to model or simulate the intake of radionuclides, their distribution within and removal from the body. The results data set of the ACTACAL was labeled as scenario #1. The other software programs used included: ACSL™[4] (Advanced Continuous Simulation Language), which was used through the University of Tennessee Computing Center by telecommunication, Scientist™[5] and STELLA®. All programs verified the values

obtained for the initial conditions of the ACTACAL © program. Since the results of the software programs were in agreement to the ACTACAL© data and Stella was somewhat more user friendly, the simulation software Stella®, selected for use in this work was on the basis of availability and ease of coding. The ease of coding was particular important in the examining the "What if" questions in this work.

1.2 Motivation

Many individuals are exposed to radioactive materials or radiation sources in the work environment. Occupational radiation exposures are monitored in the work environment for the purpose of controlling doses to individuals and demonstrating compliance with occupational exposure limits [6]. Increased attention is directed toward the need for data on the pattern of those dose accumulations over a person's work lifetime, especially for those occupations where higher level of exposure are encountered.[6]. Clearly a need exists for a reliable estimate of the level of intake of the radionuclides into the body. The primary function of monitoring in the work environment is to provide information for the control and further reduction of exposures, where possible, and to ensure satisfactory work conditions. This includes providing information necessary for estimating the exposures of personnel. The dosimetric quantities of interest (e.g. the equivalent dose in a tissue or organ, the effective dose and the intake of a radionuclide), in practice can not be measured, and must be computed on the basis of other measured quantities. The measured quantities are inferred from personal monitoring devices or measurements of activity of the radionuclides retained or excreted from the body [6]. Mathematical

simulations serve as the tools to obtain information to enable a better assessment of the time the intakes occurred, as well as the strengths of the intakes

The nature and type of the measurements conducted, and the relationship between the quantities found are the central focuses of this study. The modeling of various types of intake patterns should provide a better estimate of the assessment of intakes. The estimation of time and level of an intake is the main objective of this study. Even though an exact determination of an intake cannot always be made, it should be possible to establish the domain (or bounds) on the time and magnitude of the intake, by asking the question; What possible intake scenarios would result in the activity distribution values at the time of measurement? Reconstructing and assessment of intakes is the motivation for this work.

1.3 Report Structure

The organization of the work presented is as follows. Section 1 of this work is the introduction. In Section 2 a general theory of the compartmental/biokinetic modeling is presented, including an example of a simplified model, which is analytically evaluated for several segments of the time interval (before, during, and after the intake). Following a brief review of the physical characteristics of plutonium and americium, the lung and gastrointestinal tract model are introduced, and the systemic compartmental model is discussed. The analysis of various intake scenarios is performed in section 4, where acute and chronic intake scenarios are investigated. Section 5 includes a sensitivity analysis as

it relates to bioassay considerations. The concluding Section 6 provides the conclusions and recommendations regarding future directions in this work.

2.0 General Theory

This section contains the theoretical background for the biokinetic modeling.

2.1 Compartmental Models and Biokinetic Modeling

Biokinetic modeling provides a mathematical representation of the behavior of a substance within the human body, the transfer from one organ or compartment to the other, and the rates of removal from the body (complemented being the retained material) through excretion.[8] The coefficients describing the transfer rates between the compartments of the model for specific nuclides are derived from measurements of exposed personnel and analysis of experimental data obtained in animal studies. The coefficients for transfer rates between compartments and the radiological decay are expressed in mathematical terms to define a coupled set of differential equations. Often single organs are mathematically subdivided into parallel compartments to express the behavior of the nuclide within the organ or its compartment(s) in a more accurate manner. The lung, for example, is subdivided into 10 compartments, but not all compartments are included when assessing the intake or a particular chemical form. The general differential equations for a system of n compartments is of the form [8]:

$$\frac{d}{dt}q_i(t) = \sum_{\substack{k=1 \\ k\neq i}}^{n} \lambda_{ik} q_k(t) + \sum_{\substack{k=1 \\ k\neq i}}^{n} \lambda_{ki} q_i(t) \dot{I}_i(t) \qquad (i,k|=1.....n) \qquad (2\text{-}1)$$

where $q_i(t)$ is the activity in compartment i at time t, λ_{ki} is the transfer coefficient from compartment k to i and $\dot{I}_i(t)$ is the rate of the intake compartment I from outside the system. This type of kinetics is referred to as first order kinetics since the flow of materials leaving a compartment at any time is directly proportional to the activity within the compartment.

2.2 Two compartment model

The schematic of Figure 2-1 illustrates the flow of nuclides between compartments. The horizontal arrows represent the transfer of the nuclide through the compartment, and the vertical arrows represent the radioactive decay of the nuclide from the compartments. To clarify the terms used in the modeling a brief explanation of the terms used is given below:

$q_A(t)$ = activity in compartment A at any time t,

$q_B(t)$ = activity in compartment B at time t

$\dot{I}_A(t)$ = rate of intake in compartment A from outside the system

λ_R = decay rate of the nuclide

λ_A = transfer rate from compartment A to compartment B

λ_B = transfer rate out compartment B

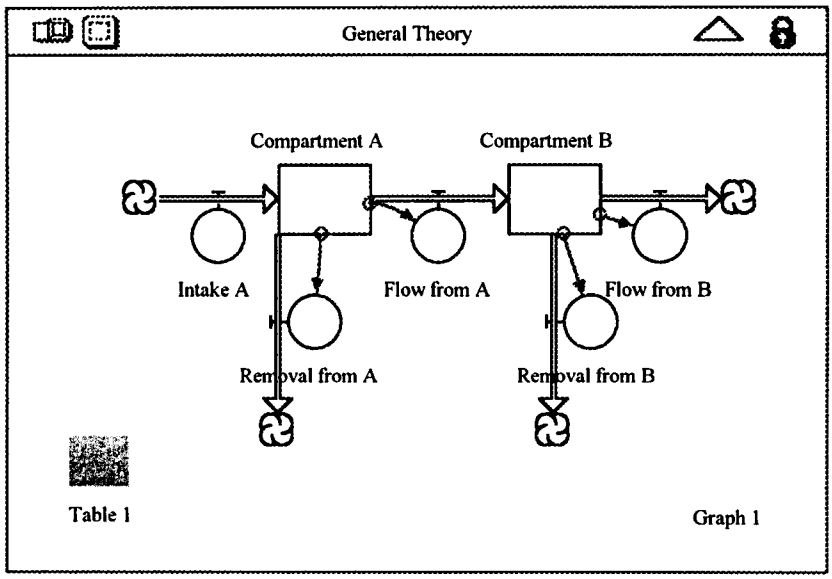


Figure 2-1 STELLA® generated block flow diagram for a 2 compartment system.

The set of coupled differential equations describe the activities as a function of time in each of the compartments are:

$$\frac{d}{dt}q_A(t) = \dot{I}(t) - (\lambda_A + \lambda_R)q_B(t) \qquad (2\text{-}2)$$

for compartment A and

$$\frac{d}{dt}q_B(t) = \lambda_A q_A(t) - (\lambda_B + \lambda_R)q_B(t) \qquad (2\text{-}3)$$

for compartment B.

2.3 Analytical treatment of a two compartment model

In this section a simple two compartment model is analyzed to provide insight into the structure and dynamics of the biokinetic model. The analytical treatment of the simplified compartmental model provides additional support for the analysis of the curve characteristics within certain segments of the time interval. The following intake function is considered (see Figure 2-2):

$$\dot{I}(t) = \begin{cases} 0 & 0 < t < T_1 \\ I_0 & T_1 \le t \le T_2 \\ 0 & t > T_2 \end{cases} \qquad (2\text{-}4)$$

The intake begins at T_1, is constant over the period T_1 to T_2 and ends at T_2.

Figure 2-2 Illustration of an intake pulse starting at T_1 and ending at T_2.

The following conditions apply:

$q_A(0) = 0$ and $q_B(0) = 0$

For the system we have the following set of equations:

Let $\lambda_1 = \lambda_A + \lambda_R$ and $\lambda_2 = \lambda_B + \lambda_R$

$$\frac{d}{dt}q_A(t) = \dot{I}(t) - \lambda_1 q_A(t) \qquad (2\text{-}5)$$

$$\frac{d}{dt}q_B(t) = \lambda_A q_A(t) - \lambda_2 q_B(t) \qquad (2\text{-}6)$$

The differential equations can be solved by elementary methods; e.g. using separation of variables or the integrating factor method. The solutions are given for each of the time intervals. For compartment A the solutions are:

For $0 < t < T_1$: $q_A(t) = 0$, (2-7)

for $T_1 < t < T_2$: $q_A(t) = \frac{I_0}{\lambda_1}(1 - e^{-\lambda_1(t - T_1)})$, (2-8)

for $t > T_2$: $q_A(t) = \frac{I_0}{\lambda_1}[(1 - e)^{-\lambda_1(T_2 - T_1)}]e^{-\lambda_1(t - T_2)}$ (2-9)

and for compartment B:

For $0 < t < T_1$: $q_B(t) = 0$ (2-10)

for $T_1 < t < T_2$:

$$q_B(t) = \frac{\lambda_A I_0}{\lambda_1}\{\frac{1}{\lambda_2}(1 - e^{-\lambda_1(t - T_1)}) - \frac{1}{\lambda_2 - \lambda_1}(e^{-\lambda_1(t - T_1)} - e^{-\lambda_2(t - T_1)})\} \qquad (2\text{-}11)$$

and for $T_2 < t < T_3$:

$$q_B(t)=\frac{\lambda_A I_0}{\lambda_1}\{[\frac{1}{\lambda_2}(1-e^{-\lambda_2(T_2-T_1)})-\frac{1}{\lambda_2-\lambda_1}(e^{-\lambda_1(T_2-t)}-e^{-\lambda_2(T_2-t)})]e^{-\lambda_2(t-T_2)}$$
$$+\frac{1}{\lambda_2-\lambda_1}(1-e^{\lambda_1(T_2-T_1)})(e^{-\lambda_1(t-T_1)}-e^{-\lambda_2(t-T_2)-\lambda_1(T_2-T_1)})\} \quad (2\text{-}12)$$

The ratios of the activities in compartments B and A are:

$0 < t < T_1$: N/A

$T_1 < t < T_2$:

$$\frac{q_B(t)}{q_A(t)}=\frac{\lambda_A}{1-e^{-\lambda_1(T_2-T_1)}}\{e^{-(\lambda_2-\lambda_1)(t-T_2)}[\frac{1}{\lambda_2}(1-e^{-\lambda_2(T_2-T_1)})-\frac{1}{\lambda_2-\lambda_1}(e^{\lambda_1(T_2-T_1)}-e^{-\lambda_2(T_2-T_1)})$$
$$+\frac{1}{\lambda_2-\lambda_1}(1-e^{\lambda_1(T_2-T_1)})e^{-\lambda_2(T_2-T_1)}]+\frac{1}{\lambda_2-\lambda_1}(1-e^{\lambda_1(T_2-T_1)})e^{-\lambda_2(T_2-T_1)}\} \quad (2\text{-}13)$$

$T_2 < t < T_3$:

$$\frac{q_B(t)}{q_A(t)}=\frac{\lambda_A}{1-e^{-\lambda_1(T_2-T_1)}}\{e^{-(\lambda_2-\lambda_1)(t-T_2)}[\frac{1}{\lambda_2}(1-e^{-\lambda_2(T_2-T_1)})-\frac{1}{\lambda_2-\lambda_1}(e^{\lambda_1(T_2-T_1)}-e^{-\lambda_2(T_2-T_1)})$$
$$+\frac{1}{\lambda_2-\lambda_1}(1-e^{\lambda_1(T_2-T_1)})e^{-\lambda_2(T_2-T_1)}]+\frac{1}{\lambda_2-\lambda_1}(1-e^{\lambda_1(T_2-T_1)})e^{-\lambda_2(T_2-T_1)}\} \quad (2\text{-}14)$$

The ratio of the activity between compartments $\frac{q_B(t)}{q_A(t)}$ is independent of the strength of the intake rate I_0 and is only functions of time. In every instance, the solution for the activity is a product of two factors, the initial intake rate, I_0, and a function of time after either the initiation of the pulse for the chronic intake scenario or after the end of the pulse for acute irradiation scenarios. The timing of the intakes simply shifts the activity curves in both compartments. The ratio of measured activities in compartments A and B

should therefore be independent of intake and a universal function of time. The behavior of the activity profiles as a function of intake is shown in Fig. 2-3, where proportionality with the intake strength is clearly seen as well as the invariance of shape versus time.

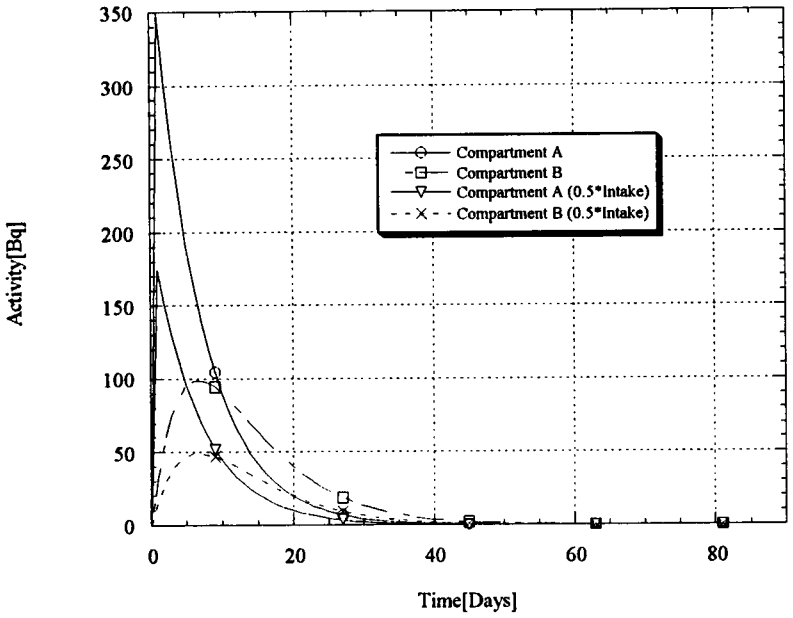


Figure 2-3 Effects of decreasing the intake by a factor of 2 compared to a normal intake.

Figure 2-4 shows that the ratio the compartment activities is invariant with intake. Figure 2-5 shows the ratio of the activity profile of compartment A with respect to compartment B for the same intake function except it is displaced in time. As expected, the ratio of the activity profiles for the time delayed intake is simply shifted by 30 days as shown in Figure 2-6.

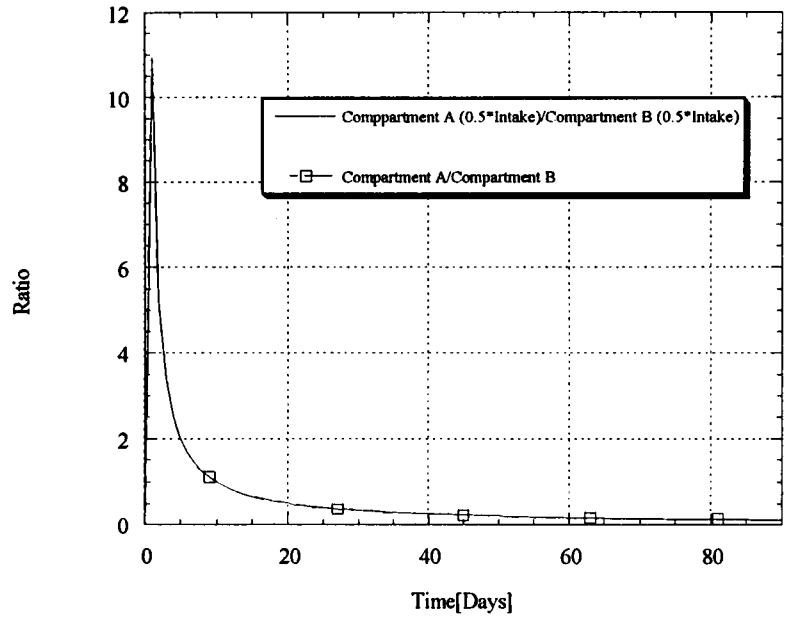


Figure 2-4 Ratio of activities of compartment A to compartment B for two different intakes doses.

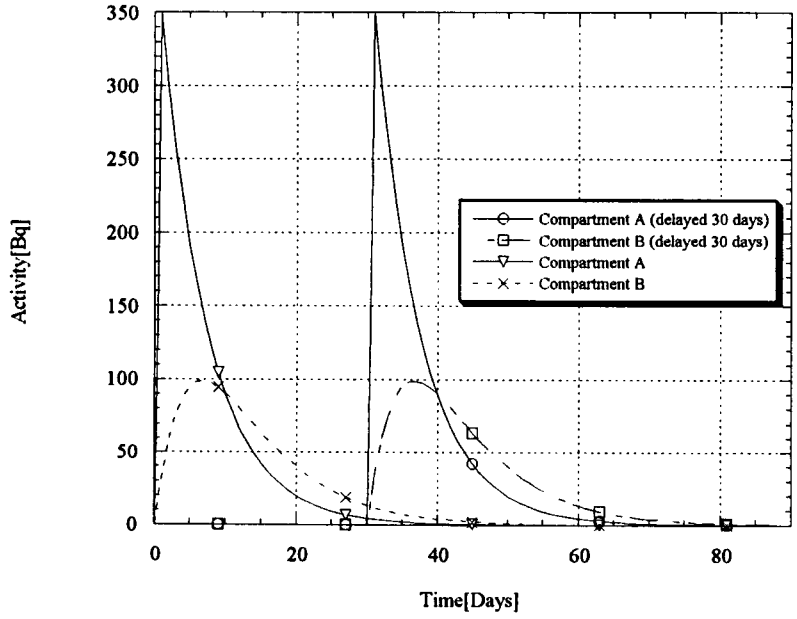


Figure 2-5 Effect of a 30 days time-delayed intake.

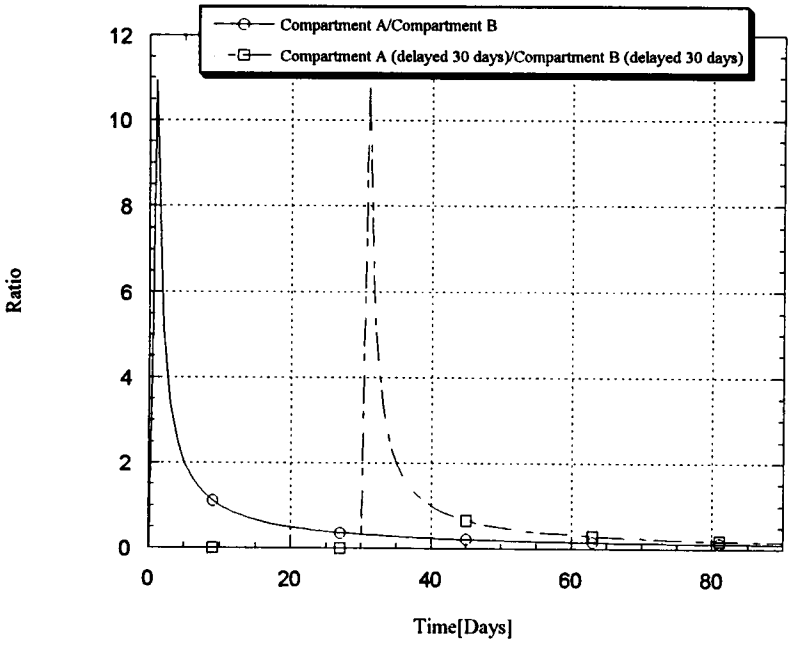


Figure 2-6 Ratios of the activities of compartment A to compartment B for a normal and a time-delayed intake.

In this section, it was shown that the time-dependent profile of the intake was found to be invariant with respect to the intake but it was displaced by any displacement in intake. These two insights are the basis for the work performed in this project.

3.0 Biokinetic Development of the Pu-241 / Am-241 Model

In the previous section, the focus was on the general development of the compartmental/biokinetic model. The analytical treatment of a simple two-compartment model provided some insights regarding the characteristic behaviors of the activities within the compartments, and their corresponding ratios. In this section a specific model for the Pu-241 and Am-241 nuclides is used. The specification of the model was in terms of the transfer rates between the systemic compartments of the body as used in the ACTACAL program. The transfer rates define a coupled set of differential equations as discussed in Section 2 and presented later. The Stella® II source program code for the model and various intake scenarios is listed in appendix A3.

3.1 Physical Characteristics of Pu-241 and Am-241

The physical characteristics of these nuclides is reviewed in this section. Both nuclides have very long half-lives, from an internal dosimetry viewpoint. Pu-241 (half-life of 14.4 y) decays by beta decay to Am-241 (half-life 432.2 y). Am-241 decays by alpha decay to the extremely long-lived Np-237 (half-life of $2.14\ 10^6$ y). The dose following an intake of Pu-241 is largely due to the alpha emission of Am-241 formed by Pu-241. For sources of typical age (10-20 years), the intake of both Pu-241 and Am-241 must be considered.

3.1.1 Radiological Characteristics of Pu-241 and Am-241

The radiological characteristics of the Pu-241 and Am-241 are summarized in Table 3-1.

Table 3-1 Radiological Characteristics of Pu-241 and Am-241.[2]

Pu-241	Am-241
Half-life: 14.4 years Decay product:Am-241	Half-life: 432.4 years Decay product:Np-237
Decay paths: alpha ($2.45*10^{-5}$) beta (1.0)	Decay path: gamma: 59 keV (90) alpha(1.0)

3.1.2 Chemical Characteristics of Pu-241 and Am-241

Plutonium has a varied chemistry and hence various compounds are possible. The most common compounds are the oxides and nitrates. In this work inhalation intakes are considered and it is assumed that the aerosol is characterized by an activity median aerodynamic diameter (AMAD) of 1 μm.

3.2 Annual Limits on Intake for Pu-241 and Am-241

The Annual Limit on Intake (ALI) for personnel established by the ICRP are given in Table 3-2. These values are mainly determined by the clearance rate of the compounds, within the lung compartments and the fractional absorption to blood from the gastrointestinal tract. For this project the compounds were assumed to be in Class W.

Table 3-2 Annual Limits on Intake for Pu-241 and Am-241.[9]

Annual Limit of Intake Pu-241		Annual Limit of Intake Am-241	
Class W	10000 Bq	Class W	200 Bq
Class Y	30000 Bq		

3.3 Detectability of Pu-241 and Am-241

Measurements of Pu-241 and Am-241 in the body are potentially possible only within certain organs (lung and liver) but generally must be inferred by analysis of excretions (fecal and urinal) and blood. The limit of detection differs of these nuclides significally between externally obtained in vivo measurements (lung scan or liver scan), to in vitro measurements (assay of blood and excreta). The differences in the limit of detection are several orders of magnitude. It should be also noted that he counting times differ for in vivo measurements (approximately 20-30 minutes) and for in vitro counting (1000 min. or almost 17 hours).[10]

3.3.1 In vivo Measurements

The detection of Am-241 in the lung and in the liver, due to the emission of a 59 keV gamma ray, gives the analyst information regarding the distribution of the nuclide in the these particular compartments of the human body. "The minimum detectable activity for the measurement of ^{241}Am in the lung of an 'average man' subject is 0.129 nCi based on the method of Altshuler and Pasternak for the conditions 1) an accurately known subject background count 2) a 0.05 risk of making either a Type I or a Type II error, and 3) a counting time of 2000 seconds."[11]. The limit expressed for the delectability of Am-241 in the lung is 4.77 Bq.

"Another measure of the measurement capability is the relative uncertainty in the measured amount. A relative standard deviation of 60 percent is obtained for the measurements of 0.073 nCi ^{241}Am and of 1.55 nCi Plutonium at 1000 PPM of the Am-241, calculated by the method of Falk."[12]. Myint Thein's MDA calculations [10] state that the MDA for in vivo measurements of Am-241 in the lung as 0.18 nCi (6.66 Bq). The MDA for a liver scan is about 1.5 times that of a lung scan.[14]. The minimum detectable activities are listed in Table 3-3.

Table 3-3 Minimum Detectable Activities (MDA).[Reference indicated]

Compartment measured	MDA Am-241[Bq]	MDA Pu-241{Bq]
Lung scan	4.77 [10]	N/A
Liver scan	6.66 [13]	N/A
Bioassay measurement	0.00033 [10]	0.0005 [10]
Blood (20 cc)	0.1425 [10]	0.1425 [10]

3.3.2 In vitro minimum detectable activity of Pu-241 and Am-241 in blood, urine and feces

For the measurement of Americium and Plutonium, alpha spectrometers are employed. For measurements of bioassay (feces and urine), MDA is 0.03 dpm/sample (0.0005 Bq/sample) when counted for 1000 min. [10]

3.4 Model of the Respiratory Tract and the Gastrointestinal Tract

Inhaled nuclides are deposited in various regions of the lung and are subsequently transferred to blood (absorbed) or into the gastrointestinal tract. To allow a better overview of the model and to have a better understanding of how the transfer rates are applied in the model, the submodel of the respiratory tract and gastrointestinal tract are presented in this section.

3.4.1 Lung model (ICRP)

The model of the lung, illustrated in Figure 3-1, consists of 10 compartments labeled a through j. The transfer rates (or halftimes) to blood and to the gastrointestinal tract are given in Table 3-4. The table also lists the fraction of the regional deposition that enters each compartment and the clearance halftime of the compartments for Class W compound materials. Table 3-5 clarifies the role of the compartments or pathways in the lung.

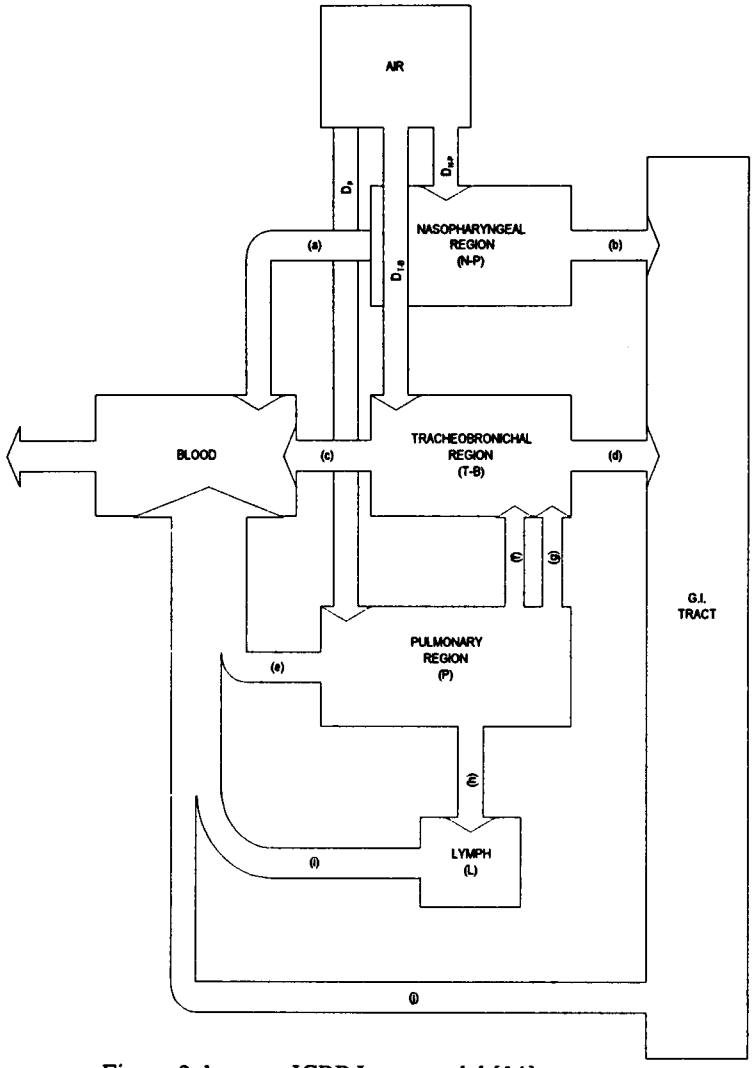


Figure 3-1 ICRP Lung model.[14]

Table 3-4 ICRP Lung model grouped in lung region. The fraction is the fraction inhaled that leaves the compartment with the corresponding clearance rate (Class W) indicated.[14]

REGION	PATHWAY	FRACTION	CLEARANCE days
N-P (NASOPHARYNGEAL REGION)	a	0.1	0.01
$D_{N-P} = 0.3$	b	0.9	0.4
T-B (TRACHEOBRONICHIAL REGION)	c	0.5	0.01
$D_{T-B} = 0.08$	d	0.5	0.2
P (PULMONARY REGION)	e	0.15	50
$D_P = 0.25$	f	0.4	1
	g	0.4	50
	h	0.05	50
L (LYMPH)	i	1.0	50

Table 3-5 Description of pathways of the lung ICRP model. The descriptions are to be taken literary, but the format was changed.[14]

Pathway	Description
a	Rapid uptake of material deposited in the nasopharynx region directly into the systemic blood.
b	Rapid clearance of all dusts from the nasopharynx region by ciliary-mucus transport.
c	Rapid absorption of dust deposited in the tracheobronchial compartment into systemic circulation.
d	Analogous to b and represents the rapid ciliary clearance of the tracheobronchial region.; the dust cleared by (d) goes quantitatively to the gastrointestinal tract.
e	Direct translocation of dust from the pulmonary region to blood.
f	Relatively rapid clearance phase of the pulmonary region, which presumably depends on recruitable macrophages, and this in turn is coupled to the ciliary-mucus transport process; therefore the dust cleared by (f) goes to the gastrointestinal tract via the tracheobronchial tree.
g	Second pulmonary clearance process that is typically much slower than (f) but still depends on endocytosis and ciliary-mucus transport; the cleared dust goes via the gastrointestinal tract (the important distinction is that the clearance is apparently rate-limited in the pulmonary region by the nature of the dust per se).
h	Process describing the slow removal of dust from the pulmonary compartment via the lymphatic system; this process can be regarded as qualitatively similar to (g) with the exception that the lymph transport replaces the ciliary-mucus transport.
i	Secondary pathway in which dust is cleared by the lymphatic system (h) is introduced into the systemic blood; this pathway obviously depends on the ability of the cleared material to penetrate the lymph tissue, especially the lymph nodes (this implies partial or complete dissolution of the dust particles, but the turnover of lymphocytes may contribute).

When information is not available in regard to a particle's size, the aerosol is assumed to be characterized by an AMAD (activity median aerodynamic diameter) of 1 μm. For a different work environment this value may be different and these differences would result in a change of the distribution of activity within the regions of the lung (N-P, TB,L). Simply stated, the smaller the size of the particle is, the deeper it will be deposited in the lung as shown in Figure 3-2.

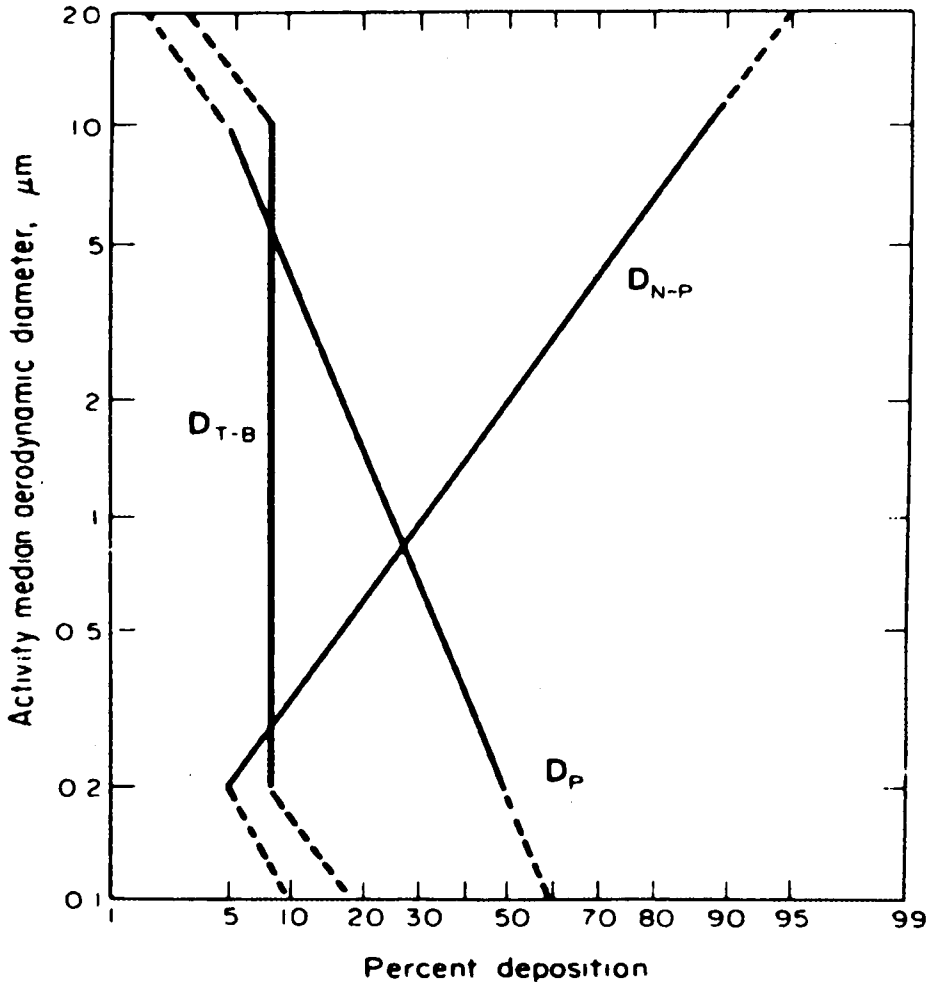


Figure 3-2 Percentage deposition as a function of activity median aerodynamic diameter.

3.4.2 Gastrointestinal Tract (GI) Model

After the nuclide is deposited in the lung, it may be transferred to the blood (transfer compartment) and/or gastrointestinal tract. From the gastrointestinal tract it may be excreted or absorbed by blood. The corresponding flows are illustrated in Figure 3-3. Data in regard to the sections of the GI tract are given in Table 3-6.

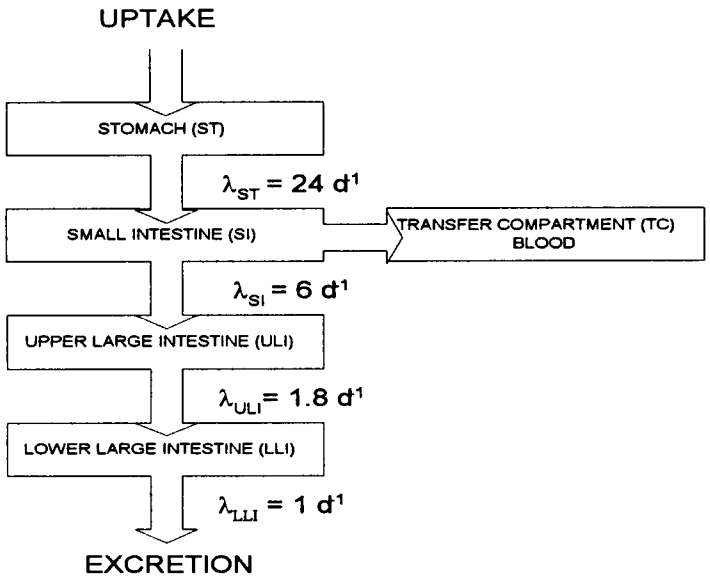


Figure 3-3 ICRP Model of the Gastrointestinal Tract.[14]

Table 3-6 Gastrointestinal tract: masses of the walls and contents and the mean residence times of the substance in the GI section, and the inverse in the last column.[14]

Section of GI tract	Mass of walls [g]	Mass of contents [g]	Mean residence time [d]	λ [d^{-1}]
Stomach	150	250	1/24	24
Small intestine	640	400	4/24	6
Upper large intestine	210	220	13/24	1.8
Lower large intestine	160	135	24/24	1

3.5 Biokinetic Model of Pu-241 / Am-241

The values of the transfer parameters between systemic compartments are the most important parameters, since the decay or formation of these nuclides are almost negligible. The transfer rates of the nuclide from the lung and gastrointestinal tract are the driving functions of the model. The definition of the kinetics was obtained in the format used by the ACTACAL program. The transfer coefficients among the compartments are listed in Table 3-8 for the Pu-241 and in Table 3-10 for the Am-241 nuclide. The mapping of the biokinetic compartments to specific organs, as required by the dosimetry are given in Table 3-7 and Table 3-9.

3.5.1 Transfer Values for Pu-241

Table 3-7 shows the compartments contributing to the activities in organs, note that for dosimetric purposes not all compartments of the lung are summed. For an example, Table 3-7 shows that the contribution to the activity content "the lung", 'lng_cont', is derived from compartments c, d, e, f, g, h, and i, but it does not include compartments a, b and j (applicable to Class Y compounds), although all compartments are included in the kinetic evaluation. Also the activity within the liver comes in a major part from compartment liver_1 and has a only a minor contribution from compartment liver_2. In Table 3-8 the transfer values for Pu-241, from the source compartment to the target compartment, are given in inverse days.

Table 3-7 Relationships between biokinetic compartments and body organs.[2].

Pu-241								
Compartment/Organ		Compartment sections contributing to activity in organ						
lng_cont	<-	lng_cont_c	lng_cont_d	lng_cont_e	lng_cont_f	lng_cont_g	lng_cont_h	lng_cont_i
st_cont	<-	st_cont						
si_cont	<-	si_cont						
uli_cont	<-	uli_cont						
lli_cont	<-	lli_cont						
blood	<-	blood						
liver	<-	liver_1	liver_2					
c_bone-s	<-	c_bone-s	c_bone-s_1					
t_bone-s	<-	t_bone-s						
ub_cont	<-	ub_cont						
kidneys	<-	kidneys_1	kidneys_2					
testes	<-	testes						
ovaries	<-	ovaries						
other	<-	other_0	other_1	other_2				
c_bone-v	<-	c_bone-v						
r_marrow	<-	r_marrow						
t_bone-v	<-	t_bone-v						

Table 3-8 Transfer rates for Pu-241 nuclide.[2].

Pu-241			
Source	compartment	target	rate
	number		[1/d]
lng_cont_a	(1)-->	blood	6.93E+01
lng_cont_b	(2)-->	st_cont	1.73E+00
lng_cont_c	(3)-->	blood	6.93E+01
lng_cont_d	(4)-->	st_cont	3.47E+00
lng_cont_e	(5)-->	blood	1.39E-02
lng_cont_f	(6)-->	lng_cont_d(4)	6.93E-01
lng_cont_g	(7)-->	lng_cont_d(4)	1.39E-02
lng_cont_h	(8)-->	lng_cont_i(9)	1.39E-02
lng_cont_i	(9)-->	blood	1.39E-02
st_cont	(10)-->	si_cont	2.40E+01
si_cont	(11)-->	uli_cont	6.00E+00
si_cont	(11)-->	blood	6.01E-03
uli_cont	(12)-->	lli_cont	1.80E+00
lli_cont	(13)-->	feces	1.00E+00
blood	(14)-->	uli_cont	1.29E-02
blood	(14)-->	liver_1	1.94E-01
blood	(14)-->	c_bone-s	1.29E-01
blood	(14)-->	t_bone-s	1.94E-01
blood	(14)-->	ub_cont	1.29E-02
blood	(14)-->	kidneys_1	6.47E-03
blood	(14)-->	kidneys_2	3.23E-03
blood	(14)-->	testes	2.30E-04
blood	(14)-->	ovaries	7.10E-05
blood	(14)-->	other_0	2.77E-01
blood	(14)-->	other_1	8.06E-02
blood	(14)-->	other_2	1.29E-02
liver_1	(15)-->	si_cont	1.33E-04
liver_1	(15)-->	liver_2	1.77E-03
c_bone-s	(16)-->	c_bone-s_1	8.21E-05
c_bone-s	(16)-->	c_bone-v	4.11E-05
t_bone-s	(17)-->	r_marrow	4.93E-04
t_bone-s	(17)-->	t_bone-v	2.47E-04
ub_cont	(18)-->	urine	1.20E+01
kidneys_1	(19)-->	ub_cont	1.39E-02
kidneys_2	(20)-->	blood	1.39E-03
testes	(21)-->	blood	1.90E-04
ovaries	(22)-->	blood	1.90E-04
other_0	(23)-->	blood	6.93E-01
other_1	(24)-->	blood	4.75E-04
other_1	(24)-->	ub_cont	4.75E-04
other_2	(25)-->	blood	1.90E-05
liver_2	(26)-->	blood	2.11E-04
c_bone-s_1	(27)-->	blood	7.60E-03
c_bone-v	(28)-->	c_bone-s_1	8.21E-05
r_marrow	(29)-->	blood	7.60E-03
t_bone-v	(30)-->	r_marrow	4.93E-04

3.5.2 Transfer values for the Am-241 nuclide

Table 3-9 Relationships between biokinetic compartments and body organs.[2].

Am-241								
Compartment/Organ		Compartment contributing to activity in organ						
lng_cont	<-	lng_cont_c	lng_cont_d	lng_cont_e	lng_cont_f	lng_cont_g	lng_cont_h	lng_cont_i
st_cont	<-	st_cont						
si_cont	<-	si_cont						
uli_cont	<-	uli_cont						
lli_cont	<-	lli_cont						
blood	<-	blood						
liver	<-	liver_1						
other	<-	other_0	other_1	other_2				
c_bone-s	<-	c_bone-s	c_bone-s_1					
t_bone-s	<-	t_bone-s						
kidneys	<-	kidneys_0	kidneys_1					
testes	<-	testes						
ovaries	<-	ovaries						
ub_cont	<-	ub_cont						
c_bone-v	<-	c_bone-v						
r_marrow	<-	r_marrow						
t_bone-v	<-	t_bone-v						

Table 3-10 Transfer rates for the Am-241 nuclide[2].

Am-241			
source	compartment	target	rate
	number		[1/d]
lng_cont_a	(1)-->	blood	6.93E+01
lng_cont_b	(2)-->	st_cont	1.73E+00
lng_cont_c	(3)-->	blood	6.93E+01
lng_cont_d	(4)-->	st_cont	3.47E+00
lng_cont_e	(5)-->	blood	1.39E-02
lng_cont_f	(6)-->	lng_cont_d(4)	6.93E-01
lng_cont_g	(7)-->	lng_cont_d(4)	1.39E-02
lng_cont_h	(8)-->	lng_cont_i(9)	1.39E-02
lng_cont_i	(9)-->	blood	1.39E-02
st_cont	(10)-->	si_cont	2.40E+01
si_cont	(11)-->	uli_cont	6.00E+00
si_cont	(11)-->	blood	6.01E-03
uli_cont	(12)-->	lli_cont	1.80E+00
lli_cont	(13)-->	feces	1.00E+00
blood	(14)-->	uli_cont	3.03E-01
blood	(14)-->	liver_1	1.16E+01
blood	(14)-->	other_0	1.00E+01
blood	(14)-->	other_1	1.67E+00
blood	(14)-->	other_2	4.66E-01
blood	(14)-->	c_bone-s	3.49E+00
blood	(14)-->	t_bone-s	3.49E+00
blood	(14)-->	kidneys_0	4.66E-01
blood	(14)-->	kidneys_1	1.16E-01
blood	(14)-->	testes	8.20E-03
blood	(14)-->	ovaries	2.60E-03
blood	(14)-->	ub_cont	1.63E+00
liver_1	(15)-->	si_cont	4.90E-05
liver_1	(15)-->	blood	1.85E-03
other_0	(16)-->	blood	1.39E+00
other_1	(17)-->	blood	1.39E-02
other_2	(18)-->	blood	1.90E-05
c_bone-s	(19)-->	c_bone-s_1(26)	8.21E-05
c_bone-s	(19)-->	c_bone-v	4.11E-05
t_bone-s	(20)-->	r_marrow	4.93E-04
t_bone-s	(20)-->	t_bone-v	2.47E-04
kidneys_0	(21)-->	ub_cont	9.90E-02
kidneys_1	(22)-->	blood	1.39E-03
testes	(23)-->	blood	1.90E-04
ovaries	(24)-->	blood	1.90E-04
ub_cont	(25)-->	urine	1.20E+01
c_bone-s_1	(26)-->	blood	7.60E-03
c_bone-v	(27)-->	c_bone-s_1(26)	8.21E-05
r_marrow	(28)-->	blood	7.60E-03

The compartments contributing to the Am-241 activities within the organ are listed in Table 3-9. The transfer rates of Am-241 are shown in Table 3-10 with the transfer rates given in inverse days. Although the Table 3-7 and Table 3-9 and also Table 3-8 and Table 3-10 look almost identical, the biokinetics of the nuclides are different in their compartmental makeup, their transfer rates, and in those compartments involved that contribute to the activity within a compartment or organ. Tables 3-7 through 3-10 are the framework for the model used in this work.

3.6 Biokinetic Model of Pu-241 and Am-241

The model can be expressed in for m of the Stella program. The transfer rates of Tables 3-8 and 3-10 do not include the decay or formation of the radionuclides. These considerations must be included in the differential equations that are solved by using the Stella program.

3.6.1 STELLA® Model of Pu-241 / Am-241 intakes

The differential equations were coded into the STELLA® program. The differential equations were discretized in the form of difference equations, and solved by a fourth order Runge-Kutta algorithm. The visual building blocks of the STELLA® program are found in Figure 3-3. A listing of the STELLA® code is given in Appendix A3.

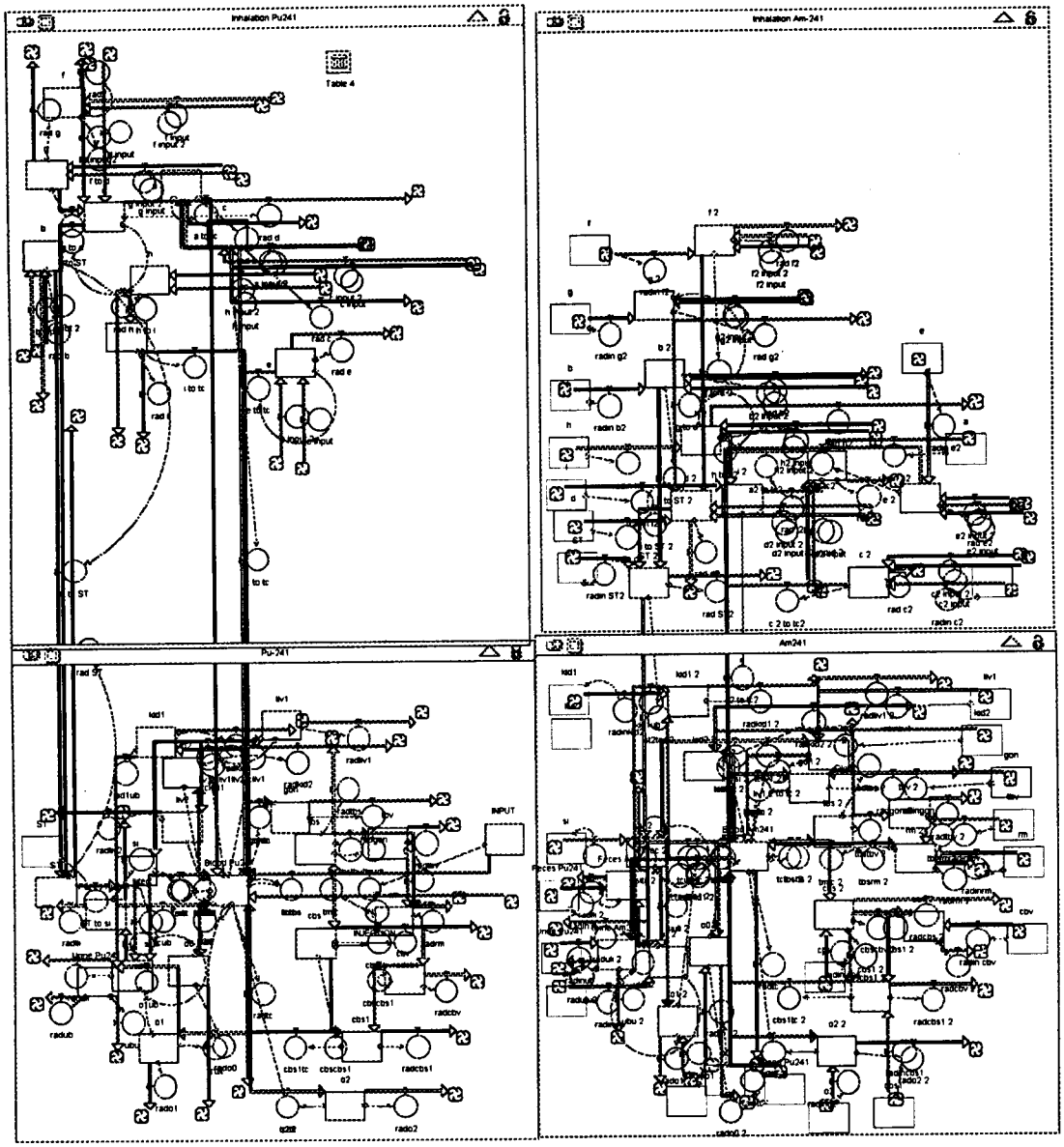


Figure 3-4 Flow diagram of Stella program for Pu-241 and Am-241.

3.7 Model Verification

The implementation of the model was verified by comparing the numerical solution with that obtained by ACTACAL©. Such verification was performed for the same initial conditions, with no other intake occurring.

3.7.1 Verification of Numerical Solver

Any given numerical solver needs to meet certain requirements to be regarded as valid equivalent model. Such requirements include numerical accuracy in comparison to verified models and numerical stability in the selected algorithm when applied to the particular problem types to be encountered[13].

The STELLA data has been verified against the results of the ACTACAL program, but only for the initial conditions of Table 3-11. A comparison was also done for a 90-day period only. The same curve characteristics were obtained and plotted, for both for the ACTACAL and the STELLA program output as well as the percent deviation from the ACTACAL for the corresponding bioassay compartment, as illustrated in Figure 3-5 for Pu-241 in blood, Figure 3-6 for Am-241 in blood, Figure 3-7 for Pu-241 in feces, Figure 3-8 for Am-241 in feces, Figure 3-9 for Pu-241 in urine, Figure 3-10 for Am-241 in urine, Figure 3-11 for Am-241 in the liver, and in Figure 3-12 for Am-241 in the lung.

Table 3-11 Initial conditions for ACTACAL© and Stella® models.

Compartment	Activity[Bq]
a	0.03
b	0.27
c	0.04
d	0.04
e	0.0375
f	0.1
h	0.0125
i	0

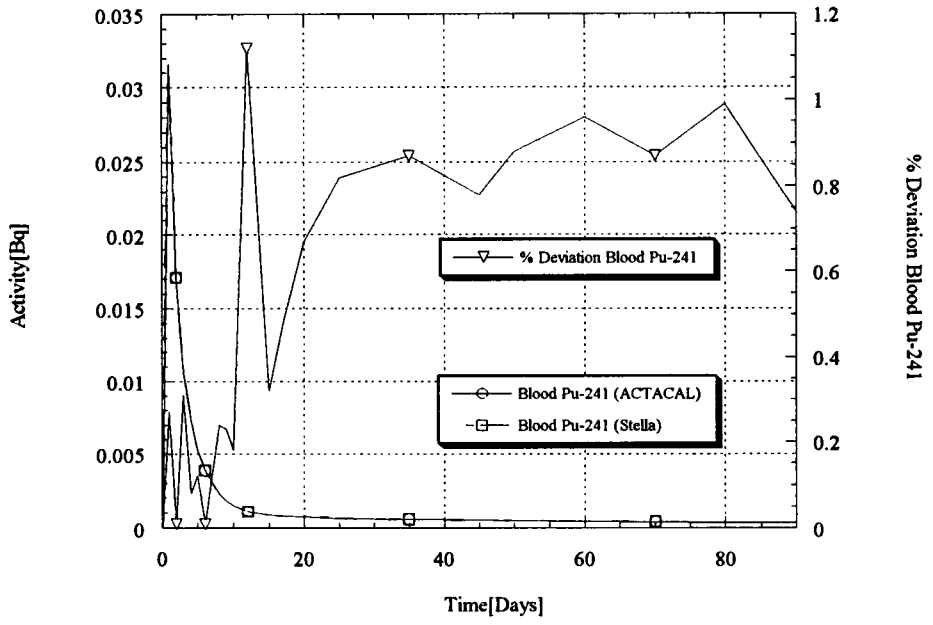


Figure 3-5 Code comparison: Pu-241 in blood.

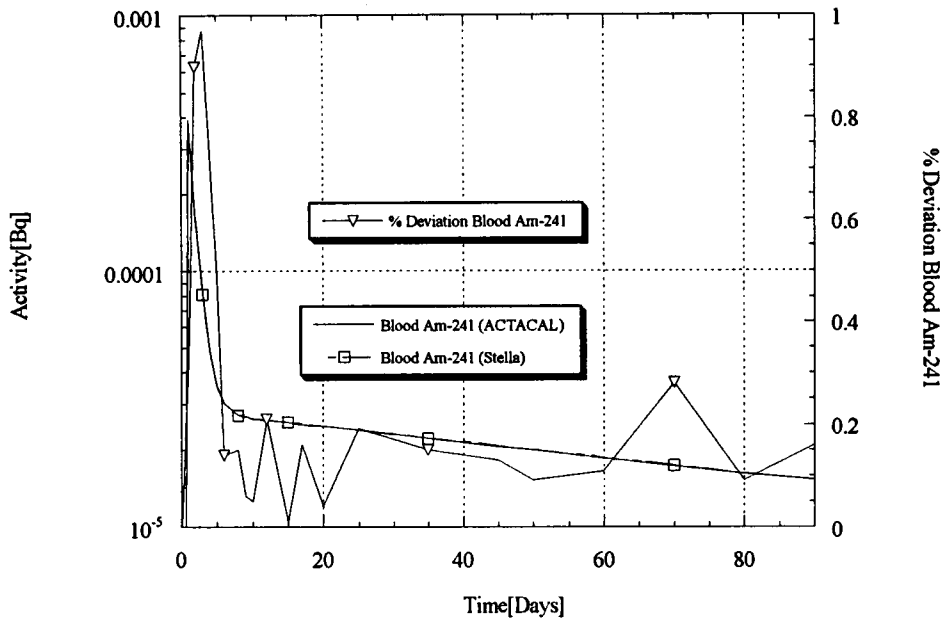


Figure 3-6 Code comparison: Am-241 in blood.

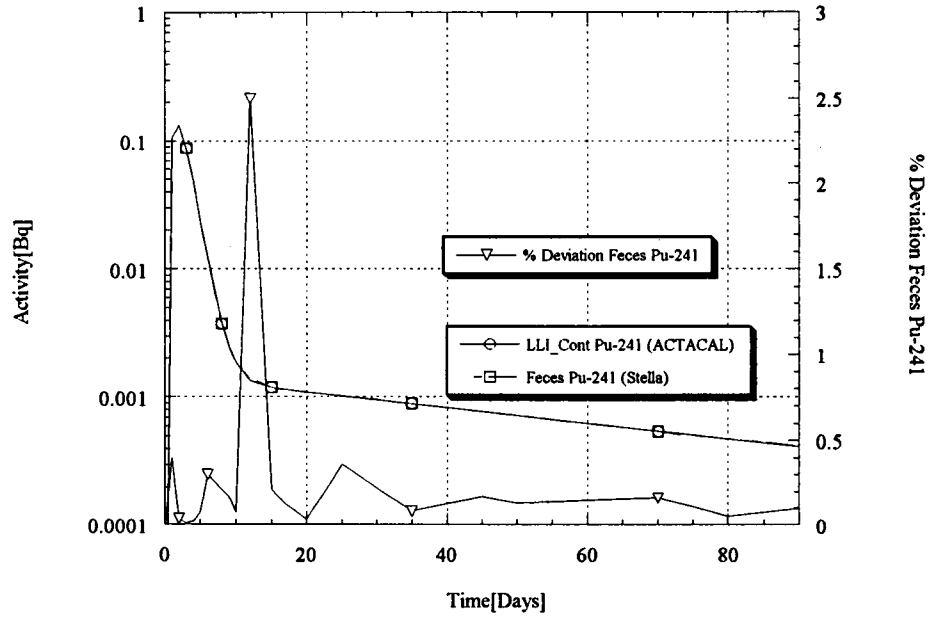


Figure 3-7 Code comparison: Pu-241 in feces.

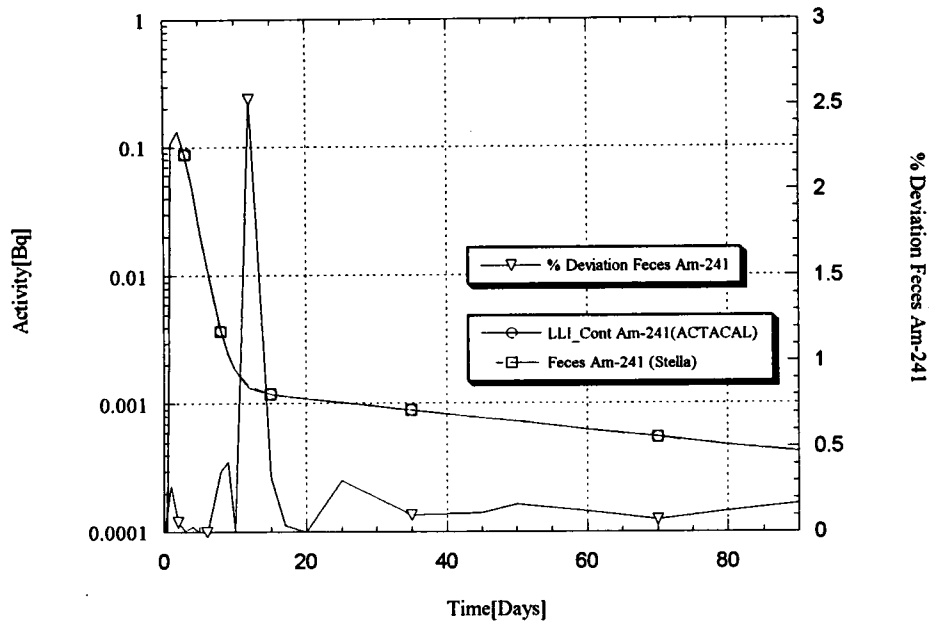


Figure 3-8 Code comparison: Am-241 in feces.

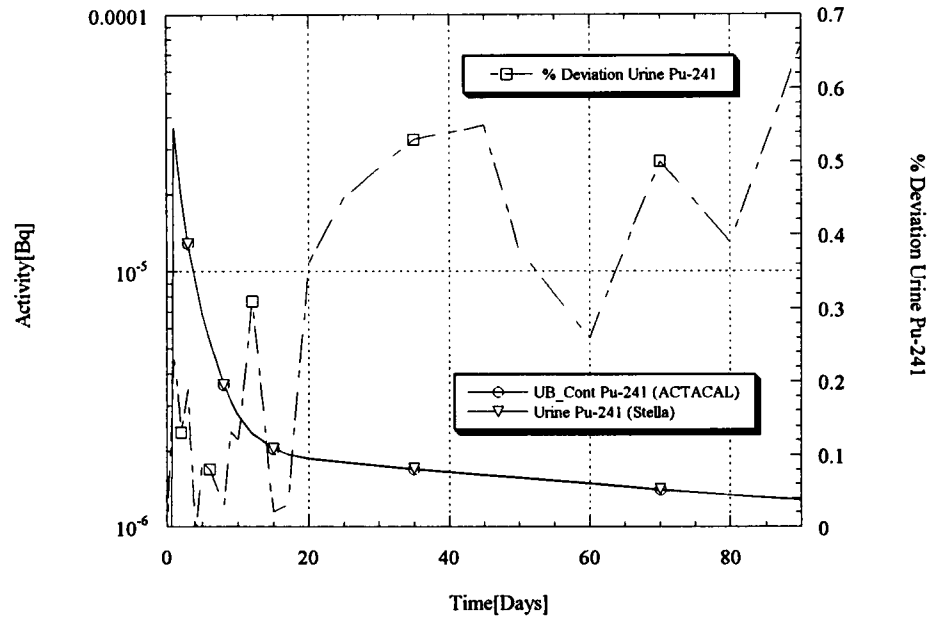


Figure 3-9 Code comparison: Pu-241 in urine.

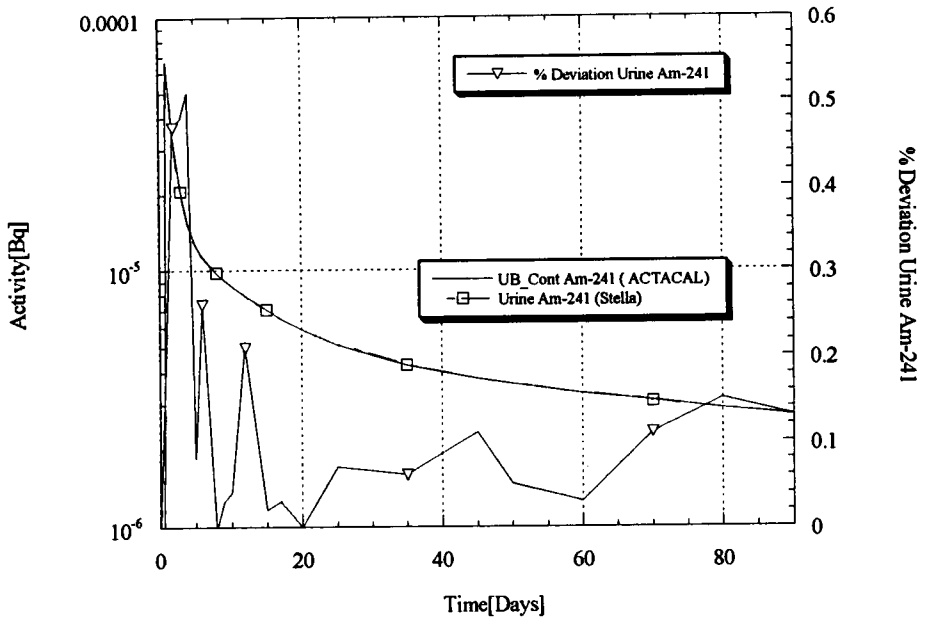


Figure 3-10 Code comparison: Am-241 in urine.

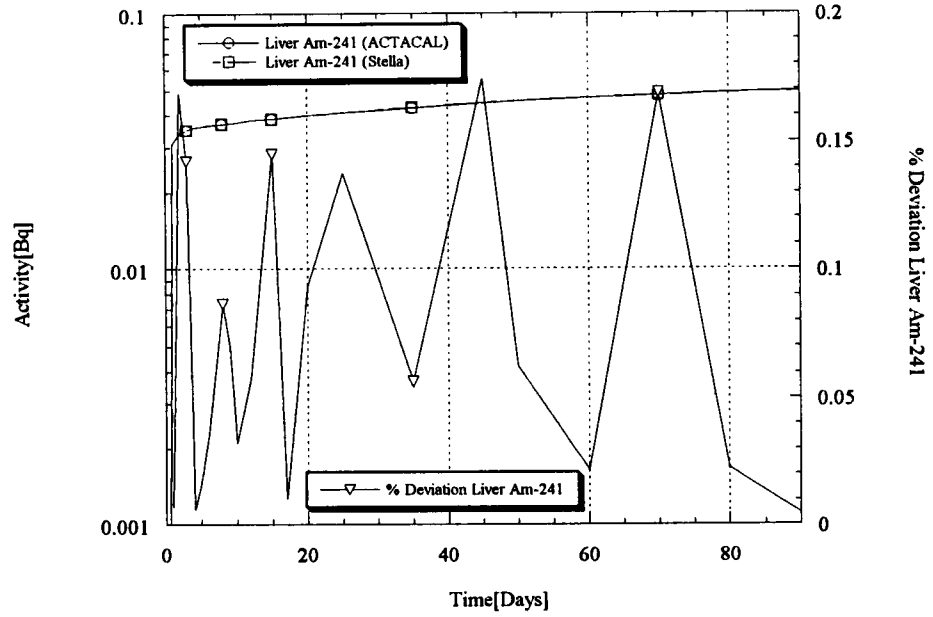


Figure 3-11 Code comparison: Am-241 in liver.

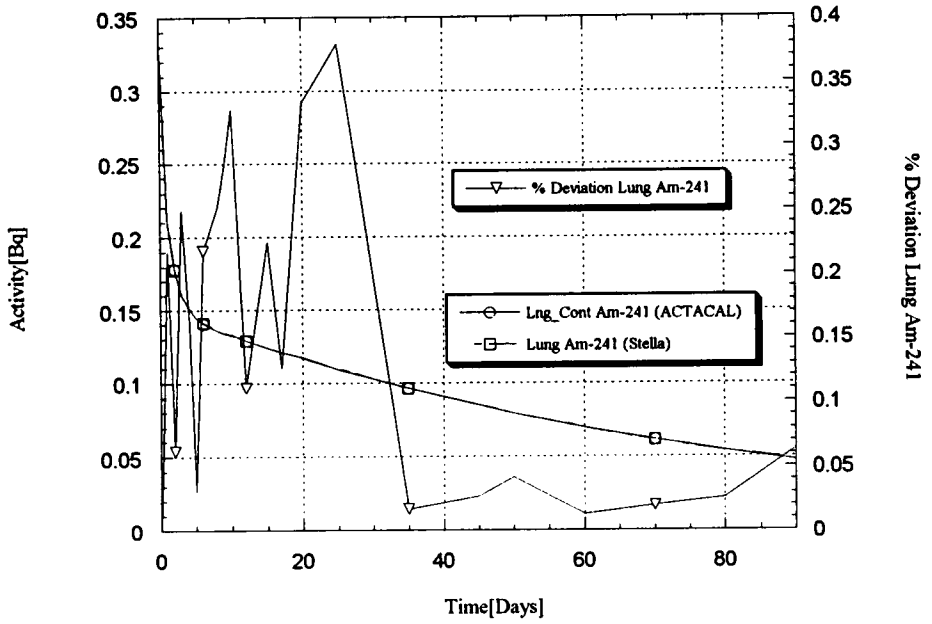


Figure 3-12 Code comparison: Am-241 in lung.

4.0 Analysis of Intake Scenarios

The predictions of the model were investigated by postulating a series of intake scenarios or a variety of intake conditions. To this end, the procedure for collecting bioassay samples, and the limits of detection of the analysis were simulated to provide "realistic" scenarios and results.

4.1 Intake Scenarios

Several scenarios involving single and chronic intakes were investigated. The intakes were assumed to occur by inhalation of a mixture of Pu-241 and Am-241. Both compounds were assumed to be Class W compounds with regard to their clearance rates for the respiratory tract. These scenarios had the same metabolic transfer rates as scenario #1, which was verified against the ACTACAL program.

4.2 Behavior of the biokinetic model

In this section several patterns of intakes were investigated using the insight gained in examining the simplified compartmental model. The biokinetic model indicates that the behavior of Pu-241 and Am-241 follows the general patterns obtained in the analytical treatment of the simple compartmental model, for example Figure 4-1 shows the activity profiles of Pu-241 and Am-241 in feces for two intake scenarios with the strength of the intake being varied, listed in Table 4-1.

Table 4-1 Conditions of doubling the acute intake.

Intake #1	Intake #2
5000 Bq Pu-241 100 Bq Am-241	10000 Bq Pu-241 200 Bq Am-241

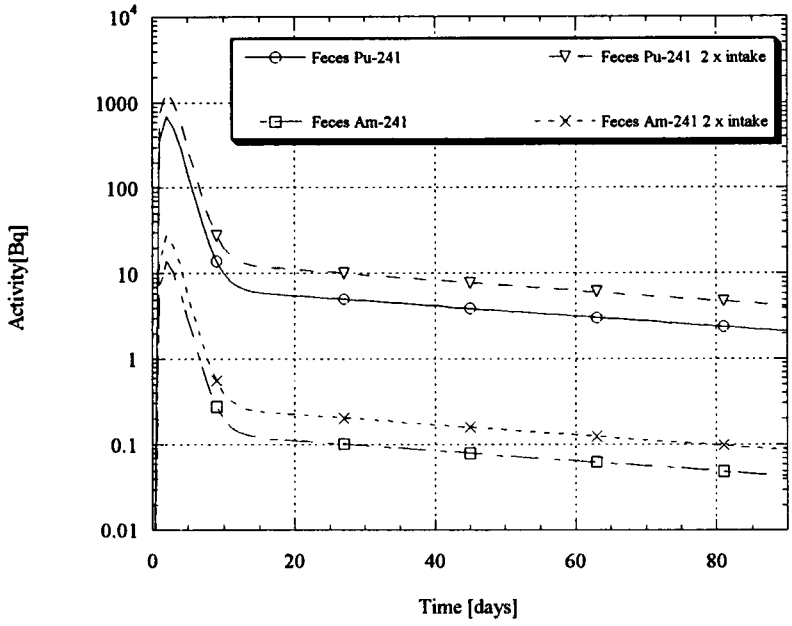


Figure 4-1 Comparing the effect of two different strengths of intake of Pu-241 and Am-241 in feces, subdivided into Am-241 and Pu-241 compartments

Other compartments, not shown illustrated the same agreement in the observed behavior following a change in intake strength. This observation is of course the consequence of a linear system of kinetics, i.e., the solution is directly proportional to the initial conditions.

The second scenario is defined in Table 4-2 and illustrated in Figure 4-2. In this scenario the intake is delayed for 30 days. The characteristics of the solution are the same

Table 4-2 Conditions for the effect of time delayed intake

Intake #1 (day 0)	Delayed Intake (30 day time-delayed }
5000 Bq Pu-241 100 Bq Am-241	5000 Bq Pu-241 100 Bq Am-241

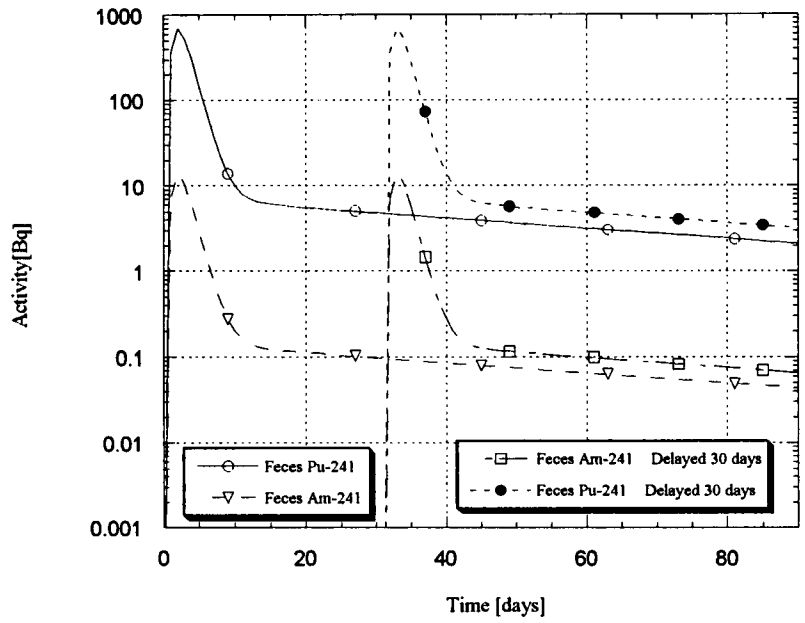


Figure 4-2 Effect of shifting the initial intake 30 days: the delayed curves show the shift of the time-delayed intake by 30 days.

for the intake at t = 0 and the time-delayed intake. This shows the invariance of the behavior of the curve in regard to different strengths of the dose, as well as the behavior when the intake is shifted in time. Such behavior are consistent in the study of the simplified model and the analytical solution discussed in section 2. This observations are important in analyzing the characteristics of the activity profiles of the compartments as well as the ratio of the compartments over a given time frame.

4.3 Analysis of acute intakes

In this section the scenarios analyzed involved acute intakes, e.g. accidental intakes or intakes associated with a scheduled operation, such as maintenance.

Single acute intakes

Since the main focus of this work is the assessment and reconstruction of the intake, in terms of its time of occurrence and strength, several scenarios were analyzed.

4.3.1. Acute Intake Scenario #2

Scenario #2, (the base scenario is scenario #1) is a single intake of a mixture of Pu-241 and Am-241, inhaled over a 12 hour period, shown in Table 4-3. Figure 4-3 shows the profile of the activities in the bioassay compartments as a function of time. We define a bioassay compartment as any compartment of the model for which it might be possible or feasible to make direct measurement by either invivo or invitro means. Figure 4-4 shows the activity profile of Am-241 in the lung and the liver, and also the ratio of the activities. As observed in the analytical treatment of the simplified model, the ratios do not dependent on the strength of the intake and are only functions of time. The curve characteristics of the ratios have unique values, e.g. a ratio of 2 would mean that it the intake was 40 prior to observation. Each value of the curve corresponds to a single specific point in time.

Table 4-3 Intake conditions Scenario #2

Intake (day 0)
5000 Bq Pu-241 100 Bq Am-241

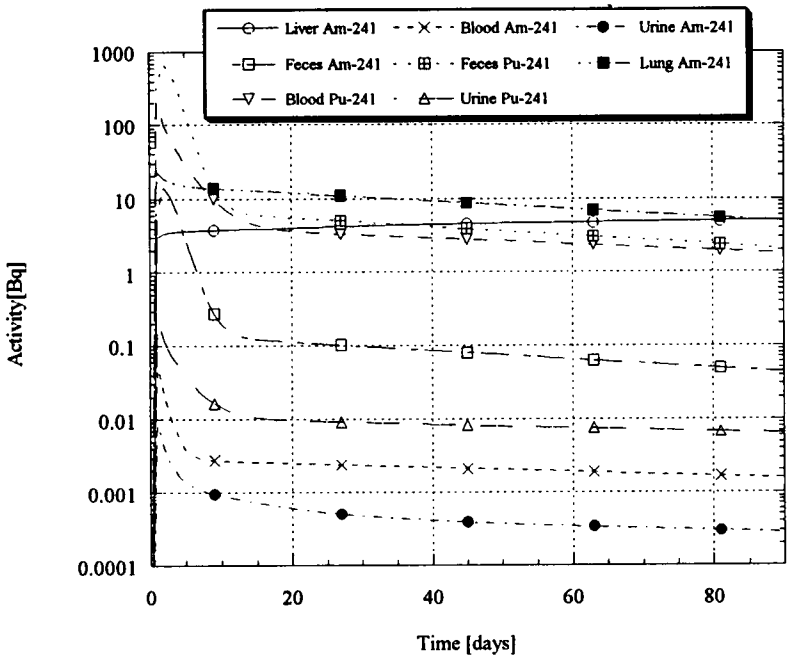


Figure 4-3 Activity profiles of scenario #2: single intake of 5000 Bq Pu-241 and 100 Bq Am-241 within a 12-hour intake period.

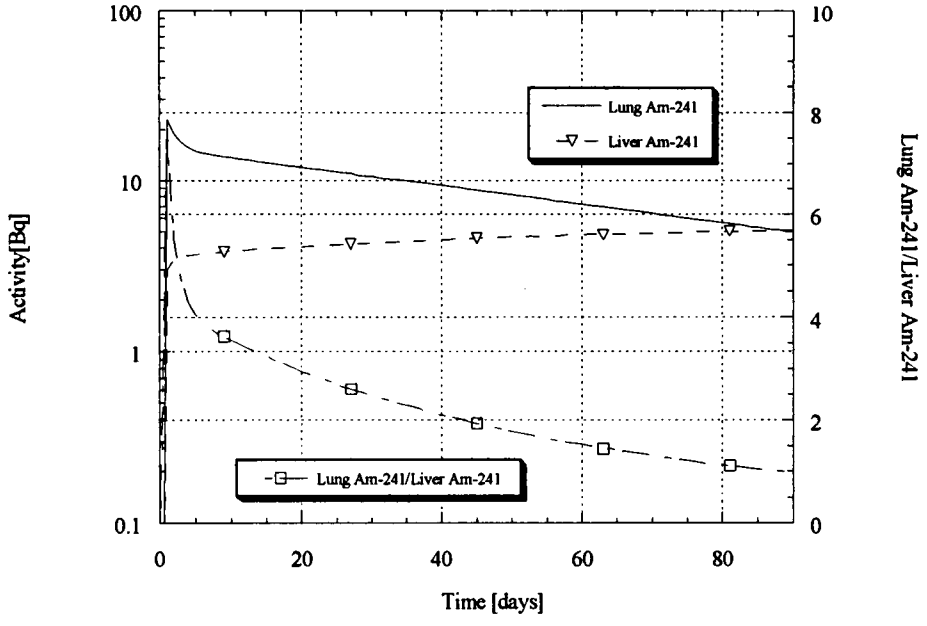


Figure 4-4 Activity profile of Am-241 in lung and liver and the ratio of lung to liver.

Similar behaviors were observed in the ratios of activities of other compartments. Several of the other ratios between compartments/organs are explored on this particular scenario to further the support the estimation of the time of intake and the quantity of such. Not all compartments provide information that can be used to assess the intake. A usable ratio will be defined as a ratio that is unique for most of the time interval of interest. Unique values are values that correspond to a single point of the time interval. The ratio of the activities of Am-241 in lung and feces, shown in Figure 4-5 is a good ratio, and the same applies to the activities of Am-241 in liver and feces and the ratio of liver to feces, as shown in Figure 4-6.

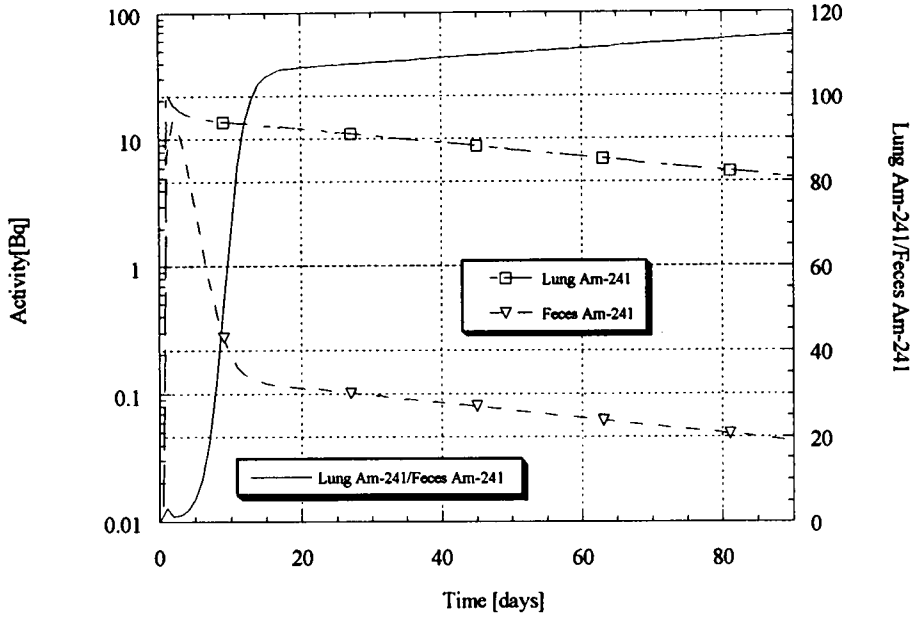


Figure 4-5 Activity profiles of Am-241 in lung and feces and the profile of the ratio of lung to feces.

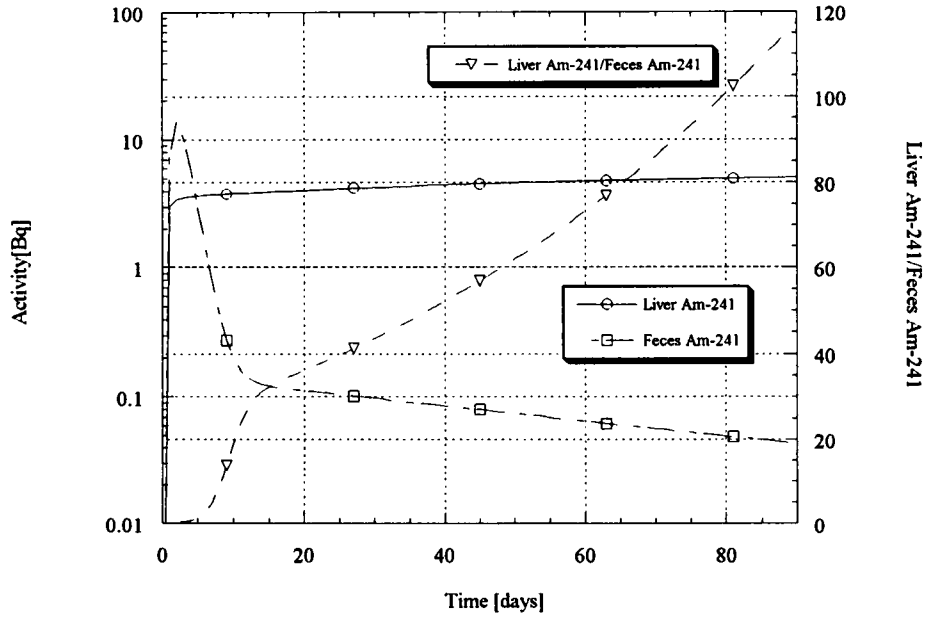


Figure 4-6 Activity profile of Am-241 in liver and feces and the ratio of the activities of liver to feces.

The ratio of liver to blood is analyzed and the profiles of the activities of Am-241 in these compartments and the ratios of the activities of Am-241 of liver to blood is shown in Figure 4-7

The curve characteristics obtained for the ratio in Figure 4-7 are unique. The ratios selected so far in the analysis were good values, i.e., a single value of the ratio at a point in time.. To this point, it was possible to determine how many days elapsed since an intake occurred. This is, however not always the case, as shown in Figure 4-8 where the profile of the ratio of Am-241 of blood to feces does not provide a unique answer during

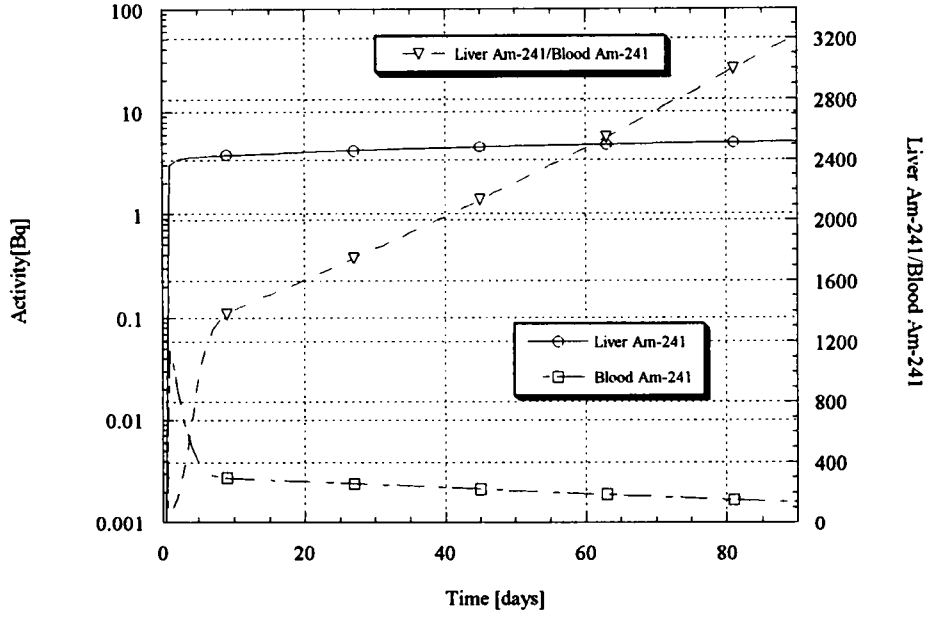


Figure 4-7 Activity profiles of Am-241 in liver and blood and the profile of the ratio of Am-241 of liver to blood.

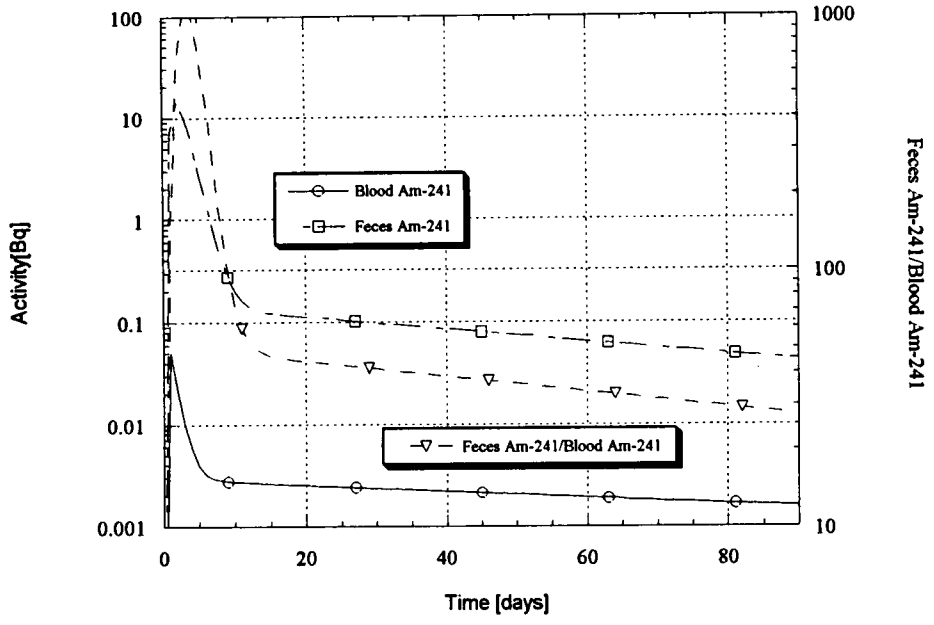


Figure 4-8 Activity profiles of Am-241 in blood and feces and the ratio of the activities of feces to blood.

the first week after the intake. Curve characteristics of the activities of Am-241 in blood and urine and the profile of the ratio are shown in Figure 4-9. The ratio exhibits many non-unique values, and the analyst would be unable to determine on what day the intake occurred, e.g. how many days have elapsed since the intake occurred (2 days or 20 days). However, if several samples were taken during the interval, then an assessment of the time of the intake could be derived.

To this point the study focused on the Am-241 activities. The same approach is used to study the activities of Pu-241. Since Pu-241 does not emit gamma rays, the activities in the lung and liver cannot be measured, i. e, these compartments are not

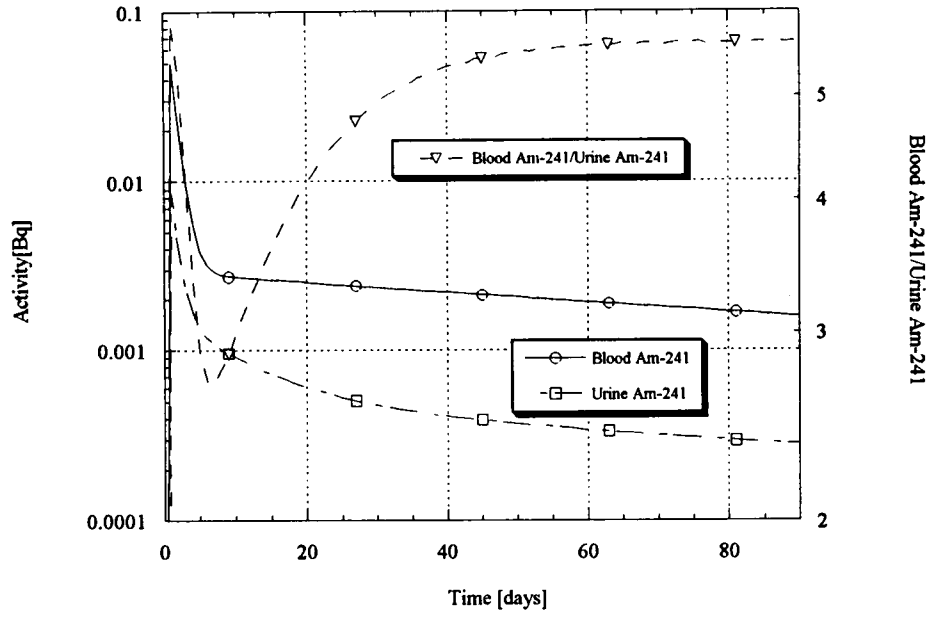


Figure 4-9 Curve characteristics of Am-241 in blood and urine and the ratio of the activities of blood to urine.

bioassay compartments for Pu-241. In Figure 4-10 the profiles of the activities of Pu-241 in blood and feces are shown. When studying the curves one can see that the ratio remains relatively constant over a wide range of time. However for a very short time interval following an intake the ratios are considerably higher than during the later parts of the time frame. It should be also noted that the value of the ratios on day 1 and day 8 following the intake are approximately the same. An estimation of the intake seems to be only possible during the first week following the intake. Another point of reference is the lowest ratio obtained on day 11 past the intake.

The ratios of activities of Pu-241 in blood and urine and the ratio of these activities shown in Fig. 4-11 provide unique answers. Such a uniqueness combined with

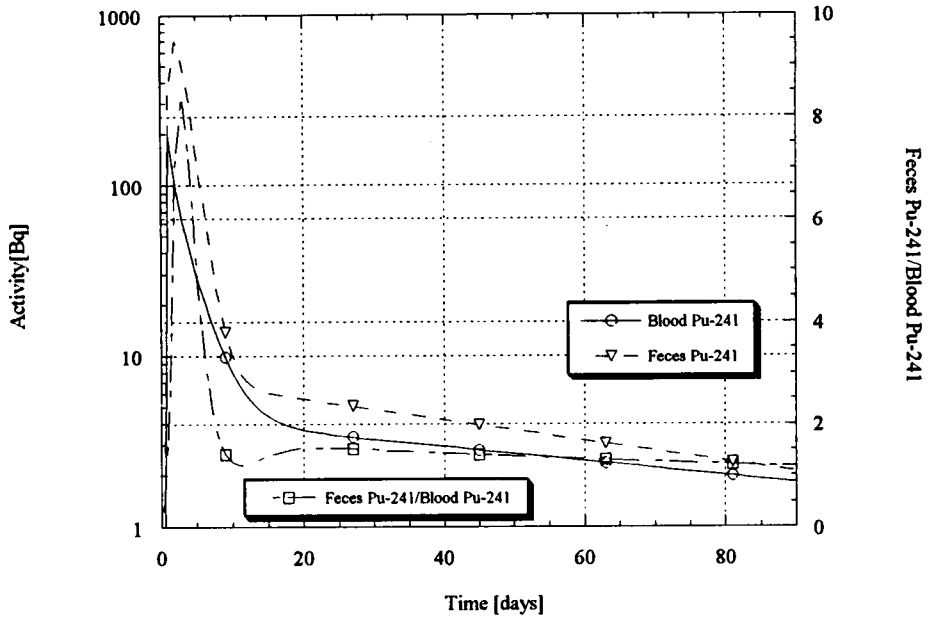


Figure 4-10 Activity profiles of Pu-241 in feces and blood and the profile of the ratio of the Pu-241 activities in blood to feces.

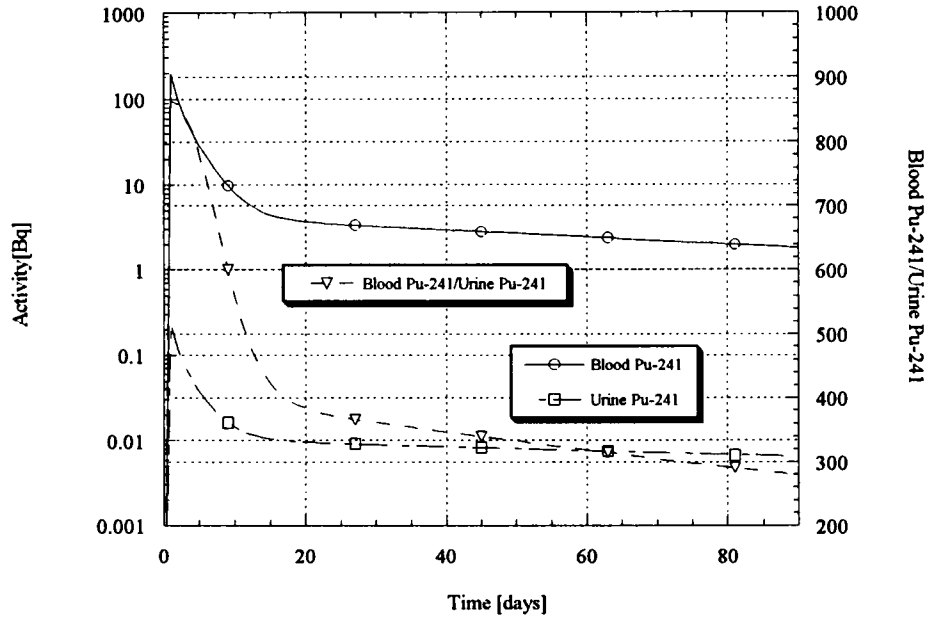


Figure 4-11 Activity profile of Pu-241 in blood and urine and the profile of the ratio of blood to urine.

other findings of the previous curve characteristics, gives the analyst the possibility of accurately determining or at worst, providing a good estimate, of the time that elapsed following the intake.

4.3.2 Example: Acute Intake Scenario #2

This section examines a practical example, scenario #2 for the acute intake of Am-241 and Pu-241 by inhalation.

A worker inhaled a mixture of Pu-241 and Am-241 while performing some maintenance operation. Several weeks following the maintenance operation, the results of two invivo and invitro measurements given to the health physicist. For discussion's purpose we denote the first measurements as time zero and the second measurement occurred 30 days later. The bioassay results are listed in Table 4-4. The calibration curves for the single intake scenario used in this example are shown in Figure 4-3 up to Figure 4-11.

4.3.2.1 Evaluation of acute scenario # 2 data:

The ratios considered for this example are calculated from the measurements obtained in Table 4-3 and are listed in Table 4-5.

Table 4-4 Result of bioassay for scenario #2.

Organ (Compartment)	Nuclide	Activity [Bq] Measurement #1 (t=0)	Activity [Bq] Measurement #2 (t=30)	Ratio Measurement #2 to Measurement #1
Feces	Pu-241	6.27	3.93	0.63
Feces	Am-241	0.125	0.08	0.64
Urine	Pu-241	0.01	0.008	0.8
Urine	Am-24 1	0.0007	0.0004	0.57
Blood	Pu-241	4.74	2.8	0.59
Blood	Am-241	0.00262	0.0021	0.8
Liver	Am-24 1	not detectable	not detectable	N/A
Lung	Am-241	12.8	8.7	0.68

Table 4-5 Values of ratios used from Table 4-4.

Ratio	Ratio between compartment	Value of ratio
Ratio #1	Lung Am-241/Feces Am-241	103
Ratio #2	Feces Am-241/Blood Am-241	48
Ratio #3	Blood Pu-24l/Urine Pu-241	438

On the basis of ratio #1 of Table 4-4 and Figure 4-5, the ratio of activities of Am-241 of lung to feces, it is determined that the intake occurred 14 days ago. The value obtained from ratio #2 of Table 4-5 and Figure 4-8 indicates a time of more than 10 days that passed since the intake occurred. Ratio #3 and Figure 4-11 agree with that conclusion. The determination of the time point of intake allows the analyst to determine the amount of the intake. The magnitude of the intake can be obtained from the strict proportionality between the initial intake and the activity, shown in Figure 4-1 and the knowledge of a calibration curve. Scenario #2 serves as the calibration scenario and example scenario #3 uses the proportionality to determine the amount of the intake.

4.3.3 Example: Acute Intake Scenario # 3

Table 4-6 lists the measurements obtained through bioassay, lung scan, and liver scan:

Table 4-6 Results of measurements for scenario #3.

Organ (Compartment)	Nuclide	Activity [Bq] Measurement #1 (t=0)	Activity [Bq] Measurement #2 (t=32)	Ratio Measurement #1 to Measurement #2
Feces	Pu-241	9.28	5.95	0.64
Feces	Am-241	0.187	0.121	0.65
Urine	Pu-241	0.0175	0.0148	0.85
Urine	Am-24 1	0.0009	0.0007	0.78
Blood	Pu-241	6.28	4.62	0.74
Blood	Am-241	0.0046	0.0037	0.8
Liver	Am-24 1	8.6	9.64	1.12
Lung	Am-241	20.3	13.6	0.67

4.3.3.1 Evaluation of example acute scenario # 3 data:

The ratios of measurement #1 to measurement #2 in Table 4-6 show that the activities in all bioassay compartments other than the liver are declining .Comparing the ratio with that of an epected ratio in the calibration scenario allows the analyst to determine whetehr an chronic or acute intake occurred. The liver retains almost all of the activity, whereas the other organs or compartments listed excrete the activities in their respective compartments. The activity in the liver in this example is detectable, allowing the analyst to calculate the ratios involving the liver and provide additional information that can be used to achieve a better assessment. The values for all the ratios that were detectable are listed in Table 4-7.

Table 4-7 Ratios of compartmental activities.

Ratio	Compartment/Compartment	Value of ratio
Ratio #1	Lung Am-241/Liver Am-241	2.35
Ratio #2	Lung Am-241/Feces Am-241	108
Ratio #3	Feces Am-241/Blood Am-241	41
Ratio #4	Liver Am-241/Feces Am-241	46
Ratio #5	Blood Pu-241/Urine Pu-241	357

Using the value of the ratio #1 and Figure 4-4, the analyst can determine that about 33 days have elapsed since the intake occurred. Since the curve in Figure 4-4 is unique (one single point in time can be associated with a specific value of the ratio), the analyst might stop here and determine the intake. However to ensure that additional analysis concurs with this result, further analysis is required. Using ratio #2, the ratio of Am-241 in lung to feces, for which a value of 108 was calculated and Figure 4-5 , indicate that the intake occurred over 30 days ago. Ratio #3 and the use of Figure 4-5 shows a value about 33 days since the intake occurred. Using ratio #4 and Figure 4-6 , as well as ratio #5 and Figure 4-11 supports the estimate of the intake.. The analyst can conclude that the intake occurred about 33 days ago.

The analytical treatment of the simple two-compartment system as well as the beginning of this section, have shown that the solutions of the biokinetic model are invariant to a change in strength. To determine the intake, the analyst compares the values of activities measured to the established values in the calibration curves.

Table 4-8 lists the data found for scenario #2, also the calibration curve, and scenario #3, the unknown intake. The values at 33 days following the intake need to be

Table 4-8 Activities of scenario #2 and scenario #3 and the respective ratios.

Values for 33 days after intake	Blood Pu-241	Blood Am-241	Feces Pu-241	Feces Am-241	Urine Pu-241	Urine Am-241	Liver Am-241	Lung Am-241
scenario #2	3.14E+00	2.30E-03	4.64E+00	9.36E-02	8.80E-03	4.54E-04	4.31E+00	1.02E+01
scenario #3	6.276586	0.00461	9.276858	0.18716	0.017591	0.000908	8.625042	20.297386
Ratio #3 / #2	2	2	2	2	2	2	2	2

compared for the same nuclide and same compartment. The ratio of measured activity to the calibration activity will be the multiplication factor to calculate the intake.

Since the ratio of the activities of scenario 3 to 2 is the same for all bioassay compartments it can be concluded that the intake in scenario #3 was twice the strength of scenario #2. Scenario #2 intake was 5000 Bq of Pu-241 and 100 Bq of Am-241, and the intake for scenario #3 had to be 10000 Bq of Pu-241 and 200 Bq of Am-241. This assessment concludes the single acute intake study.

4.4 Chronic Intake

Chronic intakes occur where humans are exposed continuously to radioactivity in their work or general environment, usually the consequence of releases into the atmosphere. It is assumed that the intake occurs continuously with a constant intake rate over a certain time period. The resulting activity profiles in the organs for a chronic intake are shown in Figure 4-12.

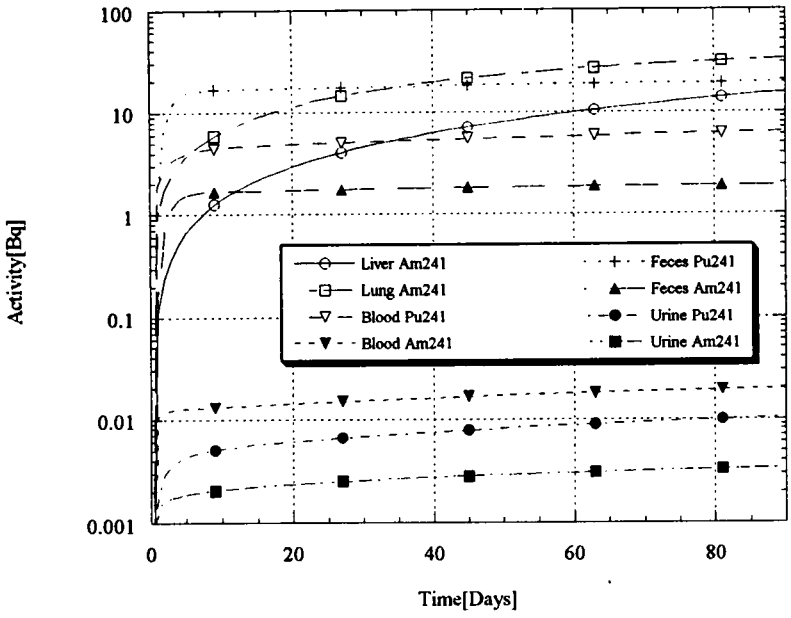


Figure 4-12 Activity profiles of a chronic intake.

All activities in all compartments are increasing, since the biological removal rate is less than the intake rate. The same approach used earlier with respect to acute intakes, is used to investigate the time and strength of the intake on the ratio of the various compartments. The ratio of lung to liver in Figure 4-13 shows the same pattern exists as was observed in the acute case. Although the ratio shown in Figure 4-13 would provide a good estimate of the time that has elapsed since the intake occurred, it is necessary to examine other ratios to provide additional support to the proposed method.

In Figure 4-14 the profiles for Am-241 activities in lung and feces and their corresponding ratio are shown. During the first 20 days, a unique value of time cannot be established, however after 20 days the ratio is monotonically increasing with time.

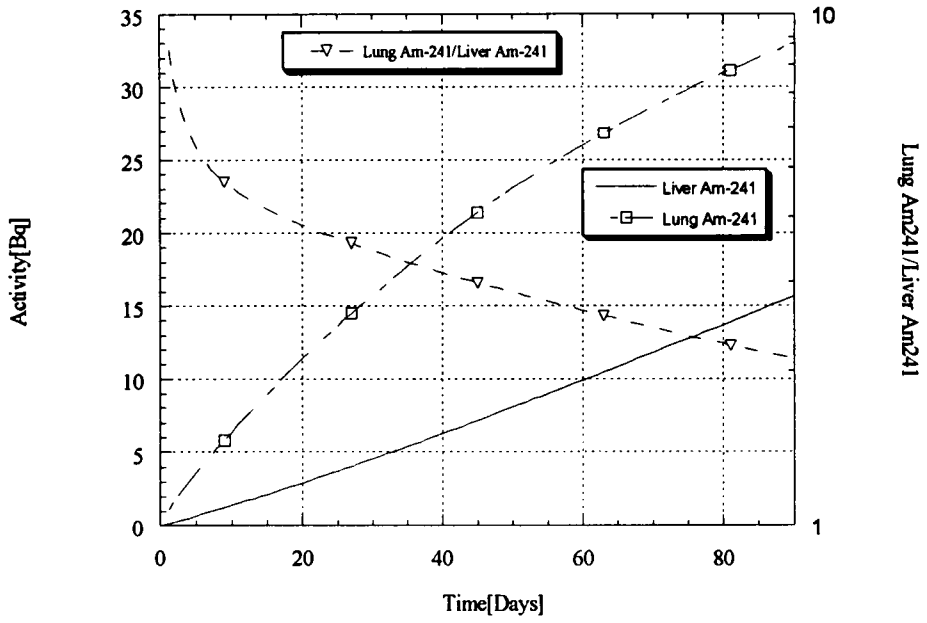


Figure 4-13 Activity profile of Am-241 in lung and liver and the ratio profile of lung to liver.

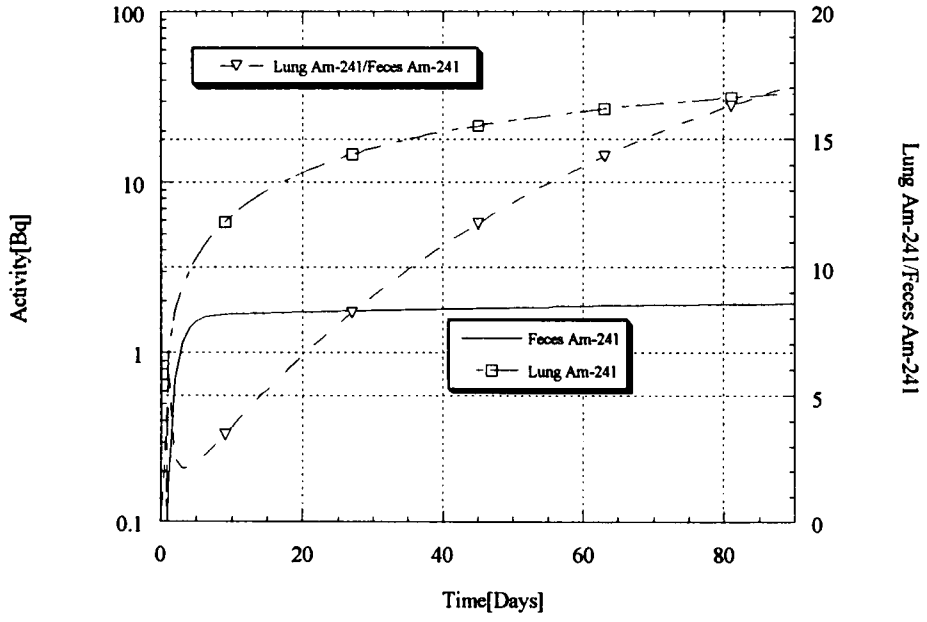


Figure 4-14 Activity profiles of Am-241 in lung and feces and the ratio of Am-241 activities of lung to feces.

This monotonic pattern is also observed in the ratio of the Am-241 activities of the liver to feces, illustrated in Figure 4-15. Both results confirm the hypothesis that this a chronic intake. The curve characteristics for the first 10 days would again provide ambiguous results. The ratio of Pu-241 activities in blood and urine is shown in Figure 4-16. As in the case of the acute intake, the profile of the ratio is unique. Figure 4-17 presents the activity profiles for Pu-241 in feces and in urine and their corresponding ratio. During the first 30 days, the ratio is ambiguous, but uniqueness is found beyond 30 days.

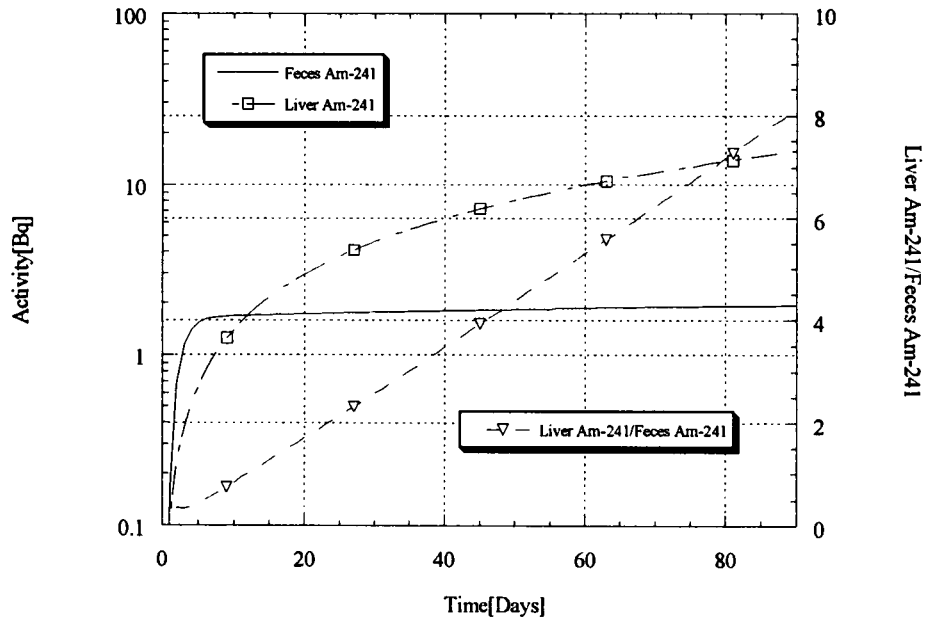
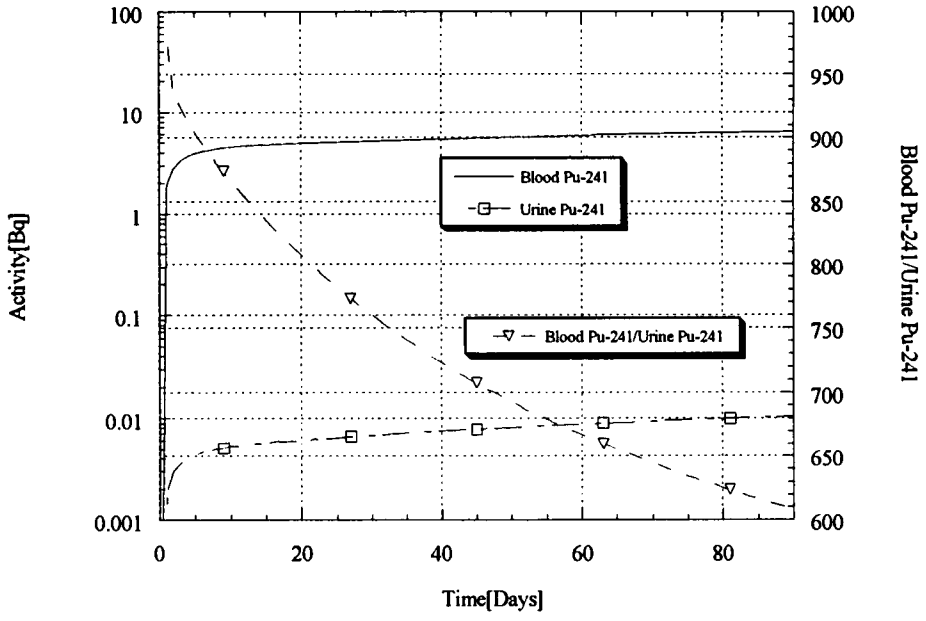


Figure 4-15 Activity profile of Am-241 in liver and feces and the ratio of their respective activities.



+

Figure 4-16 Activity profile of Pu-241 in blood and urine and the ratio of the activities of blood to urine.

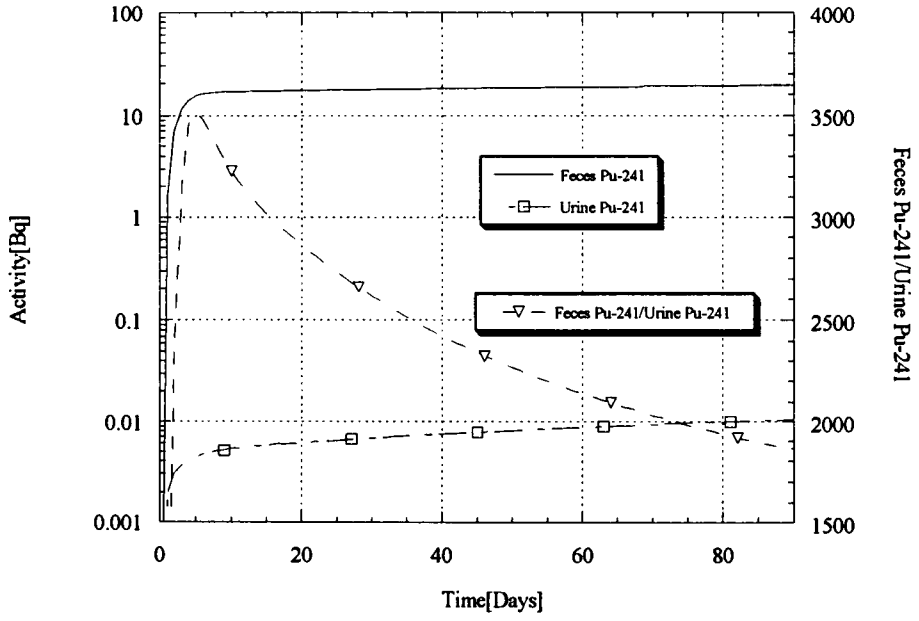


Figure 4-17 Activity profiles of Pu-241 in feces and urine and the profile of the ratio of the activities of feces to urine.

4.4.1 Example: Chronic Intake Scenario #1

This scenario serves as a calibration and is defined in Table 4-9.

Table 4-9 Intake conditions Chronic Scenario #1.

Intake rate [Bq d^{-1}]
Pu-241: 40 Am-241: 4

The results of measurements in the bioassay compartments (blood, feces, urine and lung are given in Table 4-10.

Table 4-10 Bioassay results for chronic scenario #1

Bioassay	Nuclide	Measurement #1 (t=0)	Measurement #2 (t=30)	Ratio Measurement # 2 to Measurement #1
Blood	Pu-241	4.515	5.39	1.2
Blood	Am-241	0.0131	0.016	1.21
Feces	Pu-241	16.82	18.08	1.08
Feces	Am-241	1.682	1.807	1.08
Urine	Pu-241	0.0052	0.0075	1.43
Urine	Am-241	0.0021	0.00275	1.33
Liver	Am-241	N/A	6.28	N/A
Lung	Am-241	6.39	19.6	3.16

The second measurement (measurement #2) is necessary to determine whether the intake was acute or a chronic. Such determination was made on the comparison of this ratio to that that could be expected using the ratio obtained in the calibration scenario (the same criteria was used in the acute case of an intake). The value of the ratio of

measurement #2 to measurement #1 exceeds 1, meaning that the activities in the compartment are increasing over time. A source driving the compartments' activities must be present for this to happen.

4.4.1.1 Evaluation of chronic scenario # 1 bioassay data:

The approach followed here is similar to the one used in the analysis of the acute intake. Also the values obtained in measurement #2 in Table 4-9 should provide an additional certainty that the chronic intake started at the time frame already determined by measurement #1. The ratio of activitiesfor lung to liver, shown in Figure 4-13, of 4.14 (Ratio #1 in Table 4-11 obtained from the results of the bioassay in Table 4-10), the time suggest the time elapsed since the beginning of the intake is about 10 days. This estimate is confirmed when the same point in time is obtained using the ratio of Am-241 in lung to liver, see Figure 4-14. Additional support is provided by the profile of the ratio of Am-241 of liver to feces, shown in Figure 4-15 and the ratio of Pu-241 of blood to urine shown in Figure 4-16 The time elapsed since the onset of the chronic intake is then assessed to be about 40 days. The second measurements listed in Table 4-10 confirm the estimate. This scenario, chronic scenario #1, serves as the calibration scenario and is used in further assessments. The chronic intake rate was 40 Bq/day for Pu-241 and 4 Bq/day for Am-241. The values of the ratios of measurement #2 to measurement #1 show that the intake was a chronic. All ratios are increasing with time, indicating that there is a constant source present.

Table 4-11 Ratios of chronic scenario #1 calculated from Table 4-8.

Ratio	Compartment/Compartment	Ratios Measurement #1 (t=0)	Ratios Measurement #2 (t=30)
Ratio #1	Lung Am-241/Liver Am-241	4.14	2.93
Ratio #2	Lung Am-241/Feces Am-241	3.91	11.4
Ratio #3	Feces Am-241/Blood Am-241	111.9	100.31
Ratio #4	Liver Am-241/Feces Am-241	0.94	0.26
Ratio #5	Blood Pu-241/Urine Am-241	860	720

4.4.2 Example: Chronic Scenario #2

For a further illustration in determining the onset and the intake rate for a chronic intake, the results of the bioassay data, shown in Table 4-12 shall be examined:

Table 4-12 Bioassay results for chronic scenario #2.

Bioassay	Nuclide	Measurement #1 (t=0)	Measurement #2 (t=30)	Ratio of Measurement # 2 to Measurement #1
Blood	Pu-241	9.03	10.8	1.19
Blood	Am-241	0.0263	0.0321	1.22
Feces	Pu-241	33.6	36.2	1.07
Feces	Am-241	3.36	3.6	1.17
Urine	Pu-241	0.0104	0.0149	1.44
Urine	Am-241	0.0042	0.0055	1.31
Liver	Am-241	N/A	12.6	N/A
Lung	Am-241	12.8	39.2	3.06

4.4.2.1 Evaluation of example chronic scenario # 2 data:

The same approach as in the previous scenarios is applied. The ratios of the activities within the compartments are calculated and are shown in Table 4-13.

Table 4-13 Ratios calculated from bioassay results Table 4-12.

Ratio	Compartment/Compartment	Ratios for Measurement #1 (t=0)	Ratios for Measurement #2 (t=30)
Ratio #1	Lung Am-241/Liver Am-241	N/A	3.11
Ratio #2	Lung Am-241/Feces Am-241	N/A	10.8
Ratio #3	Feces Am-241/Blood Am-241	128	112.5
Ratio #4	Liver Am-241/Feces Am-241	N/A	N/A
Ratio #5	Blood Pu-241/Urine Pu-241	870	631

The activities of Am-241 in lung and liver were below the limits of detection for the Invivo measurements. Only two of the ratios in Table 4-13 provide any useful information. The ratio of Pu-241 in blood to that in urine shows that the intake started 10 days ago and measurement #2 taken 30 days later shows that 40 days elapsed since the onset of the chronic intake. The same also applies to the ratio of Am-241 of feces to blood.

The strength of the chronic intake is determined by the ratio of the measured values to the calibration curve of chronic scenario #1. The activities measured 10 days following the intake are compared to the values obtained at 10 days after the intake occurring in scenario #2 and their ratios are listed in Table 4-14.

Table 4-14 Activities of example #1 and example #2 and the respective ratios.

Values for 10 days after intake	Blood Pu-241	Blood Am-241	Feces Pu-241	Feces Am-241	Urine Pu-241	Urine Am-241	Liver Am-241	Lung Am-241
scenario #1	4.52	0.0131	16.82	1.682	0.0052	0.00208	N/A	6.39
scenario #2	9.03	0.0259	33.64	3.362	0.01	0.00417		12.8
Ratio #2 / #1	2	2	2	2	2	2		2

From the constant ratio of the measurements of chronic scenario # 2 to chronic scenario # 1 it is determined that the intake dose rate of chronic scenario #2 was twice the dose rate of the one found in chronic scenario #1. The analyst determined that an intake rate of 80 Bq/day occurred for Pu-241 and 8 Bq/day for the Am-241 nuclide.

5.0 Sensitivity Analysis

The values for the transfer parameters, obtained from the ACTACAL© program have been considered to be exact, and no variability in these parameters have been considered. In this section we investigate the sensitivity of the model to changes in some parameters. In particular, the outflow rate from the liver and the outflow rate from the kidneys are studied, since the liver may be a possible site of the Invivo measurements and the kidneys are associated with urinary excretion, the preferred Invivo bioassay compartment.

5.1 Background and Basics of Sensitivity Analysis

Sensitivity analysis is performed to understand the extent the uncertainties in the parameter values is progated through the analysis and reflected in the results. Uncertainties in the parameter values may reflect these associated with measurement, the definition of the parameters, physiological differences, diets, and other factors.

5.2 Relative Sensitivity Index (RSI) and Sensitivity Index (SI)

In this section the formal definitions of various measures of parameter sensitivity are established.

5.2.1 Relative Sensitivity Index (RSI)

The response of the model is a function of the model parameters and various independent variables. That is the model response M is

$$M = f(a_1, a_2, ..., a_n, x_1, x_2, ..., x_m)$$

where $a_1, a_2, ..., a_n$ are the model parameters and $x_1, x_2, ...x_m$ are the independent variables of the model.

The formal Relative Sensitivity Index (RSI), of the parameter a_i, is defined as the quotient of the relative change in model response M to the relative change of the parameter a_i. That is

$$RSI = \frac{\frac{\Delta M}{M}}{\frac{\Delta a_i}{a_i}} \qquad (5\text{-}1)$$

where ΔM is the change of the model response resulting for a change in parameter Δa_i..

The transfer parameters considered in this analysis were chosen on the basis of their uncertainties as well as on expert elicitation [13]. The study of sensitivity for this work is limited to analyzing the effect that variations in particular transfer coefficients have on the activities in the bioassay compartments. When expressing the RSI, we show in parentheses the multiplication factor by which the transfer rate needs to be multiplied, (e. g. 0.75) would mean that the transfer rate was reduced by 25 % and (1.25) would denote an increase in the transfer rate by 25 %). The numerical value of the RSI reflects

how sensitive the model is to changes of parameters. "A sensitivity index of less than 0.01 indicates numerical insensitivity to changes in the value of a parameter." [15]

Figure 5-1 shows the Relative Sensitivity Indices (RSI) of the model's prediction of the activity in blood to the changes in the removal flow rates from the kidneys are shown as a function of time. All values are below the 0.01, which was the indicator for an insensitivity to changes of the parameter. The values for the indices are nearly the same during the first 14 days and then diverge, although the maximum value is reached at the same point of time.

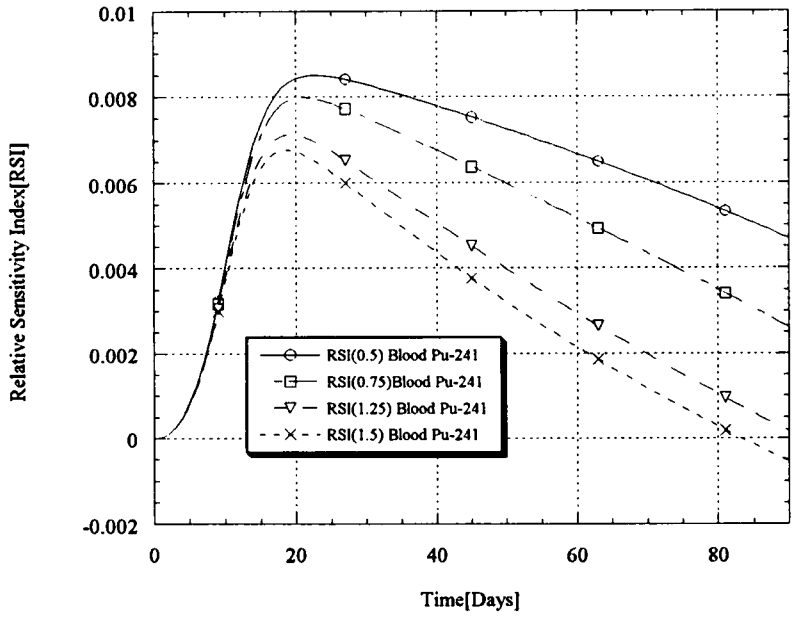


Figure 5-1 Relative Sensitivity Indices curve characteristics varying the outflow rates from the kidneys.

5.2.2 Sensitivy Index [SI]

Hoffman[15] defines the Sensitivity Index (SI) as:

$$SI = 1 - \frac{M_{min}}{M_{max}} \qquad (5\text{-}2)$$

where M_{min} and M_{max} are the minimum and the maximum values of the model response over the range a_i. Hoffman uses the whole range of the parameter to determine the sensitivity index, thus allowing the analyst to have one curve for each parameters of the model. This is illustrated in Figure 5-2 .The shapes of the curves are approximately the same as for the RSI shown in Fig 5-1, and reflects that the response is not sensitive to changes of this particular parameter.

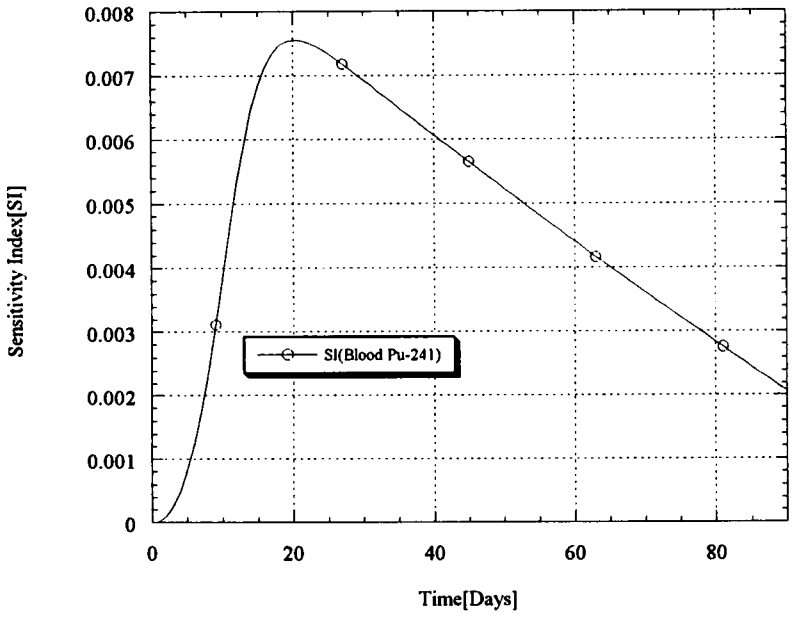


Figure 5-2 Sensitivity index for Pu-241 in blood changing the outflow rates from the kidneys, using Hoffman's Sensitivity Index[SI].

The definition of a sensitivity index allows the graphing of the sensitivity of all changes within the same parameters as a function of time and will be used through the rest of the study.

5.3 Sensitivity Analysis for Intakes of Pu-241 and Am-241

5.3.1 Sensitivity Analysis for an Acute Intake varying the flow from the liver

The transfer coefficient from the liver to other compartments is one of the most varying parameter of the model. The uncertainty in the parameter needs to be analyzed to give the analyst a measure of confidence in the model's predictions. Since this parameter varies over a wide range[16], the analysis will be performed for factors ranging from 0.25 to 4. The sensitivity indices are shown in Figure 5-3, for the Pu-241 nuclide in the bioassay compartments. Even with such wide range for the first 20 days following an intake the sensitivity indices remain below the 0.01 benchmark. The sensitivity to the change in the flow rate from the liver is obvious in Figure 5-4, where the Am-241 in blood, feces, urine and the liver are showing the stronger effect than the Pu-241 nuclide in Figure 5-3.

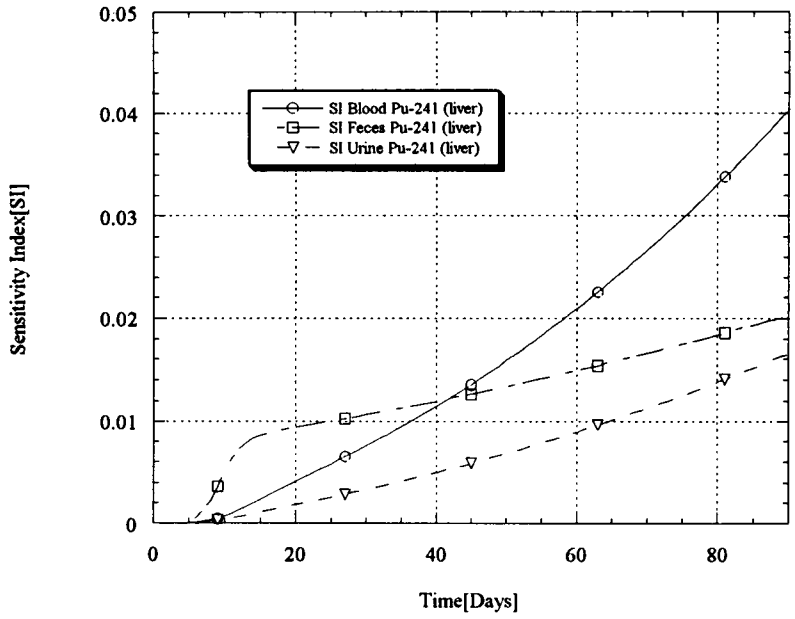


Figure 5-3 Sensitivity indices for Pu-241 in blood, feces and urine.

5.3.2 Sensitivity Analysis for an Acute Intake changing the flow from the kidneys

The parameter values for the senstivity study was deviated by 50 percent of that of Reference Man [16]. The sensitivity indices for the model in all compartments excluding the urine are below the value 0.01, shown in Figure 5-5, reflecting insensitivity in regard to a change in flow rates from the kidneys. This is, however, not the case for the urine, as shown in Figure 5-6. The sensitivity indices are exceeding the set value of 0.01.The urinary excretion rate is obviously very sensitive to a change in parameters. Since the kidneys transport the nuclide to the urinary bladder, this could be expected. However, the other compartments are interconnected and some effect is noticed, it is not of the magnitude observed for the activity in urine.

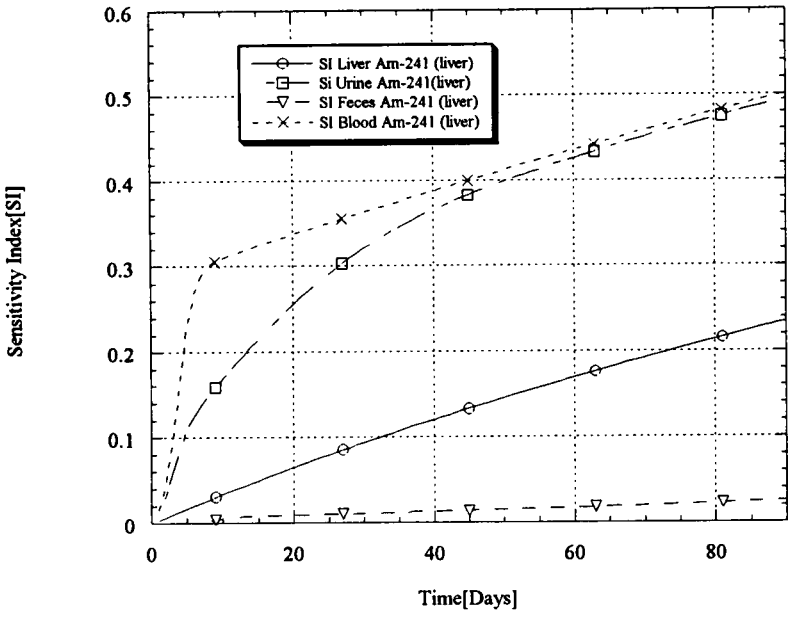


Figure 5-4 Sensitivity indices for Am-241 in blood, feces, urine and liver, showing the effect of a change in the liver outflow rates.

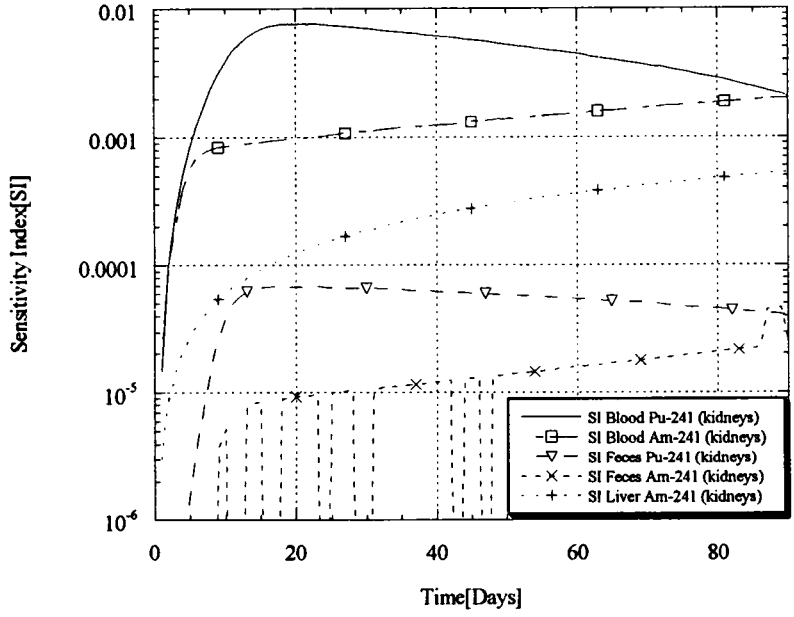


Figure 5-5 Sensitivity indices of measurable compartments excluding urine.

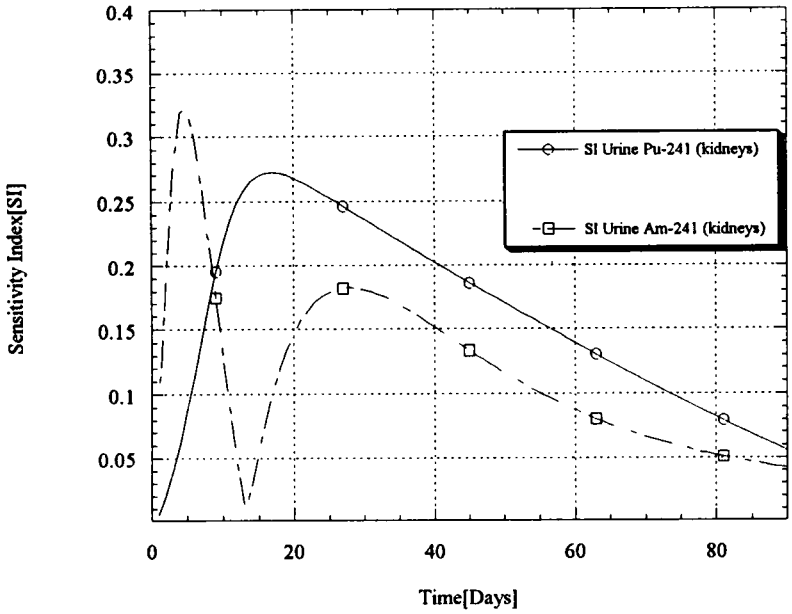


Figure 5-6 Sensitivity Indices for Pu-241 and Am-241 in urine.

6.0 Conclusions

In this section the observations of this work are summarized. Procedures to determining the strength of intakes for both acute chronic developed here are also summarized

A simple two-compartment model was studied analytically to gain insight in the structure and dynamics of the system. The results of this investigation:

i) The time course of the activities in the compartments are independent of intake, however the activities present at any time are proportional to the intake.

ii) The ratios of the activities between the compartments are independent of the intake.

iii) A shift in onset of the intake was simply shifting the activity profiles in time.

In section 3, the two-compartment model was expanded to a more "realistic" model for the Pu-241 and Am-241 nuclides. To gain a better understanding of the model, the metabolism of the human body in regard to the respective nuclides was explained in more detail (transfer rates, flow between compartments) and also further illustrated in the case of the respiratory tract and the gastrointestinal tract. The model was coded in the Stella II program format. Verification of the program was obtained by comparing to the numerical results of the model to the ACTACAL program. The results of two numerical differential solvers were found to be in very close agreement for all compartments.

The investigations reported in section 4 showed that the activities followed a unique pattern as a function of time, and similarity for the ratios of the activities the between the compartments. The activity ratios were found to be independent of the strength of the intake and were only a function of time. Such unique behavior was the basis of the method to estimate the time and the strength of the intake. Several scenarios for both the acute and the chronic case have illustrated such method, described in this work. The present model accounts for the detection limits and shifts in the sampling time by several days

An additional result of this work was the distinction between acute and chronic intakes. This was accomplished by examing the ratio of consecutive measurements arising from the same compartments or organs. With the exception of the liver, which accumulates the nuclides (at least for the times of interest here) all the ratios of the consecutive measurements are declining in case of an acute intake, and increasing (including the liver) in the case of a chronic intake.

An analysis was performed to investigate the sensitivity of the model results as a function of the assigned uncertainties to the model parameters. Both the relative sensitivity index (RSI) and Hoffman's [15] sensitivity index (SI) were used in this analysis. In general very low sensitivities for the Pu-241 were found in this analysis, except for the outflow rates from the kidneys to the urinary tract.

The technique developed in this work allows the analyst to have a better estimate for the time and strength of an intake (acute and chronic).. The study of several scenarios could be of interest for planning and scheduling the radiation monitoring of plant personnel. This technique is applicable for other radionuclides that are of specific interests to the bioassay program in the particular work environment.

Future work should include the study of multiple intakes of varying strength, in repetitive and random patterns.

References

[1] ICRP (International Commission on Radiological Protection). 1975. Report of the Task Group on Reference Man. ICRP Publication N0.23, Permgamon Press, Inc. New York, NY.

[2] ACTACALC©, Keith F. Eckerman

[3] STELLA®, High Performance Systems, 1994

[4] ACSL™ (Advanced Continuous Simulation Language), Mitchell and Gauthier Associates (MGA) Inc.

[5] Scientist™, MicroMath, Inc. 1986-1994

[6] UNESCAR 1993 REPORT, APPENDIX D: OCCUPATIONAL RADIATION EXPOSURE

[7] Lovinger, Robert MIRD (Medical Internal Radiation Dose) primer for absorbed dose calculations, The Society of Nuclear Medicine, Inc. New York, NY.

[8] Berman, M., MIRD (Medical Internal Radiation Dose) Pamphlet No. 12, APPENDIX III, Kinetic Models for Absorbed Dose Calculations, The Society of Nuclear Medicine, Inc. New York, NY.

[9] Table 1 of U. S. Environmental Protection Agency (EPA), EPA-520/1-88-020, "Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion," Federal Guidance Report No. 11 (EPA, 1988).

[10] Thein, Myint, MDA calculations, Oak Ridge National Laboratory, Dosimetry Division, Oak Ridge, Tennessee.

[11] R. B. Falk, W. H. Tyree, C. B. Wood, C. R. Lagerquist, A SYSTEM OF HIGH-PURITY GERMANIUM DETECTORS FOR THE DETECTION AND MEASUREMENT OF INHALED RADIONUCLIDES, Rockwell International Corporation, Rocky Flat Plant, Golden, Colorado, United States of America, IAEA-SM 229/54.

[12] Tyree, W. H., Falk, R. B., Wood, C. B. Liskey, R. W., High Purity Germanium Detection System for the in-vivo Measurement of Americium and Plutonium, Rocky Flats Plant RFP-2525 (1976).

[13] Eckerman, K. F. 1995. Personal and verbal communications. re: Limits of detection of Pu-241 and Am-241,numerical solvers, numerical stability. Oak Ridge National Laboratory, Health and Safety Research Division. Oak Ridge, Tennessee.

[14] Poston, J. W, Reference Man: A system for Internal Dose Calculations, Chapter 6 of Radiological Assessment: A Textbook on Environmental Dose Analysis. Edited by Till, J. E. and Meyer, H. R., NRC Office of Nuclear Reactor Regulation, Washington, D.C..

[15] Hoffman, F.O. and Gardner, R.H. 1983. *Evaluation of Uncertainties in Radiation Assessment Model.* Chapter 11 of Radiological Assessment: A Textbook on Environmental Dose Analysis. Edited by Till, J.E. and Meyer, H.R. NRC Office of Nuclear Reactor Regulation , Washington, DC.

[16] Leggett, R. W., Bioassay Data and A Retention-Excretion Model For Systemic Plutonium, Health and Safety Research Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee. NUREG/CR-3346, ORNL/TM-8795, Dist. Category RH.

Appendix

Appendix A1: ASCII File ACTACALC© program file Pu241W.log

```
This is ACTACAL log file Pu24125W.log

<<  ACTACAL Ver. 2.3 (Feb 13, 1995) --- Run Feb 23, 1995, at 03:16 >>

ACTACAL exe file was:              actacal.exe     419176 02-16-95  11:34a

Activities written to file: Pu24125W.cpt

Title lines (1) follow, if any:
    Pu-241 inhalation

Standard name file was:            StdNames.txt      2444 08-23-94  10:18a

Writing times read from:           writim.dat         652 01-07-94   9:00p

Computational times read from:     timin.dat          336 09-16-92  12:00a

Pu-241 Decay Chain: Half-lives and Branching Fractions

    Nuclide  Halflife    f1       Nuclide   f2       Nuclide   f3       Nuclide
  1 Pu-241      14.4y  1.0+00-> 2 Am-241  2.4-05-> 3 U-237
  2 Am-241     432.2y  1.0+00-> 4 Np-237
  3 U-237       6.75d  1.0+00-> 4 Np-237
  4 Np-237    2.14E6y  1.0+00-> 5 Pa-233
  5 Pa-233      27.0d  1.0+00-> 6 U-233
  6 U-233    1.585E5y  1.0+00-> 7 Th-229
  7 Th-229      7340y  1.0+00-> 8 Ra-225
  8 Ra-225      14.8d  1.0+00-> 9 Ac-225
  9 Ac-225      10.0d  1.0+00->10 Fr-221
 10 Fr-221       4.8m  1.0+00->11 At-217
 11 At-217    0.0323s  1.0+00->12 Bi-213
 12 Bi-213     45.65m  9.8-01->13 Po-213  2.2-02->14 Tl-209
 13 Po-213       4.2us 1.0+00->15 Pb-209
 14 Tl-209      2.20m  1.0+00->15 Pb-209
 15 Pb-209     3.253h

   Pu-241: Activity, Transformations, & Cumulative Energies (MeV) at 100y

    Nuclide     T1/2     A(t)/Ao    intA/Ao(d)   Ealpha    Ebeta    Egamma
  1 Pu-241      14.4y  8.11921D-03 7.52639D+03 7.53E-01 3.91E+01 0.00E+00
  2 Am-241     432.2y  2.90793D-02 9.03713D+02 4.95E+03 8.61E+01 2.94E+01
  3 U-237       6.75d  1.99176D-07 1.84395D-01 4.95E+03 8.62E+01 2.94E+01
  4 Np-237    2.14E6y  8.01557D-07 1.26193D-02 4.95E+03 8.62E+01 2.94E+01
```

```
  5 Pa-233      27.0d  8.00553D-07 1.25881D-02 4.95E+03 8.62E+01 2.94E+01
  6 U-233    1.585E5y  1.50699D-10 1.61012D-06 4.95E+03 8.62E+01 2.94E+01
  7 Th-229      7340y  4.15417D-13 3.38222D-09 4.95E+03 8.62E+01 2.94E+01
  8 Ra-225      14.8d  4.14589D-13 3.37337D-09 4.95E+03 8.62E+01 2.94E+01
  9 Ac-225      10.0d  4.14030D-13 3.36739D-09 4.95E+03 8.62E+01 2.94E+01
 10 Fr-221       4.8m  4.14029D-13 3.36739D-09 4.95E+03 8.62E+01 2.94E+01
 11 At-217    0.0323s  4.14029D-13 3.36739D-09 4.95E+03 8.62E+01 2.94E+01
 12 Bi-213     45.65m  4.14028D-13 3.36737D-09 4.95E+03 8.62E+01 2.94E+01
 13 Po-213       4.2us 4.05085D-13 3.29464D-09 4.95E+03 8.62E+01 2.94E+01
 14 Tl-209      2.20m  8.94300D-15 7.27352D-11 4.95E+03 8.62E+01 2.94E+01
 15 Pb-209     3.253h  4.14020D-13 3.36729D-09 4.95E+03 8.62E+01 2.94E+01

LNG file rd in subr. TIMELNG  was: icrp30W.lng        975 08-21-94   8:00p
GF1 file rd in subr. TIMEF1   was: Pu$W.gf1           218 02-23-95   3:14a
DEF file rd in subr. TIMEBIO  was: Pu.def            3166 01-10-94   9:27p
RNL file rd in subr. TIMEBLD  was: icrp67.bld         331 08-21-94   8:32a
 ------------------------------------------------------------------------

 Source      Biokinetic Compartments
 lng_cont <- lng_cont_c lng_cont_d lng_cont_e lng_cont_f lng_cont_g lng_cont_h lng_cont_i

 st_cont  <- st_cont
 si_cont  <- si_cont
 uli_cont <- uli_cont
 lli_cont <- lli_cont
 blood    <- blood
 liver    <- liver_1    liver_2

 c_bone-s <- c_bone-s   c_bone-s_1

 t_bone-s <- t_bone-s
 ub_cont  <- ub_cont
 kidneys  <- kidneys_1  kidneys_2

 testes   <- testes
 ovaries  <- ovaries
 other    <- other_0    other_1    other_2

 c_bone-v <- c_bone-v
 r_marrow <- r_marrow
 t_bone-v <- t_bone-v
 ------------------------------------------------------------------------

Age 0 mass file rd by READMS  was: RegMass.a00    3013 01-12-95  12:32p
Age 1 mass file rd by READMS  was: RegMass.a01    2689 01-12-95  12:32p
Age 5 mass file rd by READMS  was: RegMass.a05    2689 01-12-95  12:33p
Age 10 mass file rd by READMS was: RegMass.a10    2690 01-12-95  12:33p
Age 15 mass file rd by READMS was: RegMass.a15    2807 01-12-95  12:34p
Adult mass file rd by READMS  was: RegMass.am     2835 01-12-95  12:34p

 Source              Masses (kg) for reference age
```

Region	Newborn	1-y	5-y	10-y	15-y	Adult
Lng_Cont	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
St_Cont	1.06E-02	3.62E-02	7.51E-02	1.33E-01	1.95E-01	2.50E-01
SI_Cont	2.03E-02	5.31E-02	1.06E-01	1.79E-01	3.22E-01	4.00E-01
ULI_Cont	1.12E-02	2.87E-02	5.79E-02	9.75E-02	1.76E-01	2.20E-01
LLI_Cont	6.98E-03	1.83E-02	3.66E-02	6.17E-02	1.09E-01	1.35E-01
Blood	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Liver	1.21E-01	2.92E-01	5.84E-01	8.87E-01	1.40E+00	1.80E+00
C_Bone-S	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
T_Bone-S	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
UB_Cont	1.04E-02	2.60E-02	6.76E-02	7.80E-02	8.84E-02	1.20E-01
Kidneys	2.29E-02	6.29E-02	1.16E-01	1.73E-01	2.48E-01	3.10E-01
Testes	8.43E-04	1.21E-03	1.63E-03	1.89E-03	1.55E-02	3.50E-02
Ovaries	3.28E-04	7.14E-04	1.73E-03	3.13E-03	1.10E-02	1.10E-02
Other	3.17E+00	8.46E+00	1.72E+01	2.87E+01	4.87E+01	5.97E+01
C_Bone-V	0.00E+00	2.99E-01	8.75E-01	1.58E+00	3.22E+00	4.00E+00
R_Marrow	4.70E-02	1.50E-01	3.20E-01	6.10E-01	1.05E+00	1.50E+00
T_Bone-V	1.40E-01	2.00E-01	2.19E-01	3.96E-01	8.06E-01	1.00E+00
Pu-241 : Number of systemic compartments; excluding blood = 14						
Liver	1.21E-01	2.92E-01	5.84E-01	8.87E-01	1.40E+00	1.80E+00
Kidneys	2.29E-02	6.29E-02	1.16E-01	1.73E-01	2.48E-01	3.10E-01
Testes	8.43E-04	1.21E-03	1.63E-03	1.89E-03	1.55E-02	3.50E-02
Ovaries	3.28E-04	7.14E-04	1.73E-03	3.13E-03	1.10E-02	1.10E-02
C_Bone-V	0.00E+00	2.99E-01	8.75E-01	1.58E+00	3.22E+00	4.00E+00
R_Marrow	4.70E-02	1.50E-01	3.20E-01	6.10E-01	1.05E+00	1.50E+00
T_Bone-V	1.40E-01	2.00E-01	2.19E-01	3.96E-01	8.06E-01	1.00E+00
Other	3.17E+00	8.46E+00	1.72E+01	2.87E+01	4.87E+01	5.97E+01

Nuclide: Pu-241 Age(d)--> 9125

lng_cont_a(1)--> blood (14) 6.931E+01

lng_cont_b(2)--> st_cont (10) 1.733E+00

lng_cont_c(3)--> blood (14) 6.931E+01

lng_cont_d(4)--> st_cont (10) 3.466E+00

lng_cont_e(5)--> blood (14) 1.386E-02

lng_cont_f(6)--> lng_cont_d(4) 6.931E-01

lng_cont_g(7)--> lng_cont_d(4) 1.386E-02

lng_cont_h(8)--> lng_cont_i(9) 1.386E-02

lng_cont_i(9)--> blood (14) 1.386E-02

```
st_cont    (10)--> si_cont    (11)  2.400E+01
si_cont    (11)--> uli_cont   (12)  6.000E+00
si_cont    (11)--> blood      (14)  6.006E-03
uli_cont   (12)--> lli_cont   (13)  1.800E+00
lli_cont   (13)--> feces      (31)  1.000E+00
blood      (14)--> uli_cont   (12)  1.290E-02
blood      (14)--> liver_1    (15)  1.941E-01
blood      (14)--> c_bone-s   (16)  1.294E-01
blood      (14)--> t_bone-s   (17)  1.941E-01
blood      (14)--> ub_cont    (18)  1.290E-02
blood      (14)--> kidneys_1  (19)  6.470E-03
blood      (14)--> kidneys_2  (20)  3.230E-03
blood      (14)--> testes     (21)  2.300E-04
blood      (14)--> ovaries    (22)  7.100E-05
blood      (14)--> other_0    (23)  2.773E-01
blood      (14)--> other_1    (24)  8.060E-02
blood      (14)--> other_2    (25)  1.290E-02
liver_1    (15)--> si_cont    (11)  1.330E-04
liver_1    (15)--> liver_2    (26)  1.770E-03
c_bone-s   (16)--> c_bone-s_1(27)  8.210E-05
c_bone-s   (16)--> c_bone-v   (28)  4.110E-05
t_bone-s   (17)--> r_marrow   (29)  4.930E-04
t_bone-s   (17)--> t_bone-v   (30)  2.470E-04
ub_cont    (18)--> urine      (32)  1.200E+01
kidneys_1  (19)--> ub_cont    (18)  1.386E-02
kidneys_2  (20)--> blood      (14)  1.390E-03
testes     (21)--> blood      (14)  1.900E-04
ovaries    (22)--> blood      (14)  1.900E-04
other_0    (23)--> blood      (14)  6.930E-01
other_1    (24)--> blood      (14)  4.750E-04
other_1    (24)--> ub_cont    (18)  4.750E-04
other_2    (25)--> blood      (14)  1.900E-05
liver_2    (26)--> blood      (14)  2.110E-04
c_bone-s_1(27)--> blood       (14)  7.600E-03
c_bone-v   (28)--> c_bone-s_1(27)  8.210E-05
r_marrow   (29)--> blood      (14)  7.600E-03
t_bone-v   (30)--> r_marrow   (29)  4.930E-04
```

```
Nuclide: Am-241  Age(d)-->          9125
lng_cont_a( 1)--> blood     (14)  6.931E+01
lng_cont_b( 2)--> st_cont   (10)  1.733E+00
lng_cont_c( 3)--> blood     (14)  6.931E+01
lng_cont_d( 4)--> st_cont   (10)  3.466E+00
lng_cont_e( 5)--> blood     (14)  1.386E-02
lng_cont_f( 6)--> lng_cont_d( 4)  6.931E-01
lng_cont_g( 7)--> lng_cont_d( 4)  1.386E-02
lng_cont_h( 8)--> lng_cont_i( 9)  1.386E-02
lng_cont_i( 9)--> blood     (14)  1.386E-02
st_cont   (10)--> si_cont   (11)  2.400E+01
si_cont   (11)--> uli_cont  (12)  6.000E+00
si_cont   (11)--> blood     (14)  6.006E-03
uli_cont  (12)--> lli_cont  (13)  1.800E+00
lli_cont  (13)--> feces     (31)  1.000E+00
blood     (14)--> uli_cont  (12)  1.290E-02
blood     (14)--> liver_1   (15)  1.941E-01
blood     (14)--> c_bone-s  (16)  1.294E-01
blood     (14)--> t_bone-s  (17)  1.941E-01
blood     (14)--> ub_cont   (18)  1.290E-02
blood     (14)--> kidneys_1 (19)  6.470E-03
blood     (14)--> kidneys_2 (20)  3.230E-03
blood     (14)--> testes    (21)  2.300E-04
blood     (14)--> ovaries   (22)  7.100E-05
blood     (14)--> other_0   (23)  2.773E-01
blood     (14)--> other_1   (24)  8.060E-02
blood     (14)--> other_2   (25)  1.290E-02
liver_1   (15)--> si_cont   (11)  1.330E-04
liver_1   (15)--> liver_2   (26)  1.770E-03
c_bone-s  (16)--> c_bone-s_1(27)  8.210E-05
c_bone-s  (16)--> c_bone-v  (28)  4.110E-05
t_bone-s  (17)--> r_marrow  (29)  4.930E-04
t_bone-s  (17)--> t_bone-v  (30)  2.470E-04
ub_cont   (18)--> urine     (32)  1.200E+01
kidneys_1 (19)--> ub_cont   (18)  1.386E-02
kidneys_2 (20)--> blood     (14)  1.390E-03
testes    (21)--> blood     (14)  1.900E-04
```

```
ovaries    (22)--> blood      (14)  1.900E-04

other_0    (23)--> blood      (14)  6.930E-01

other_1    (24)--> blood      (14)  4.750E-04

other_1    (24)--> ub_cont    (18)  4.750E-04

other_2    (25)--> blood      (14)  1.900E-05

liver_2    (26)--> blood      (14)  2.110E-04

c_bone-s_1(27)--> blood      (14)  7.600E-03

c_bone-v   (28)--> c_bone-s_1(27)  8.210E-05

r_marrow   (29)--> blood      (14)  7.600E-03

t_bone-v   (30)--> r_marrow   (29)  4.930E-04

 Number of source regions =  17

  Initial Conditions:

 lng_cont_a = 3.000E-02
 lng_cont_b = 2.700E-01
 lng_cont_c = 4.000E-02
 lng_cont_d = 4.000E-02
 lng_cont_e = 3.750E-02
 lng_cont_f = 1.000E-01
 lng_cont_g = 1.000E-01
 lng_cont_h = 1.250E-02
      Total = 6.300E-01
 Other Source Region = 14

 Attained age > 100 y; computations halted.


Calculations completed over 9100 cycles.

Data reported for  98 time steps.

Computational time =     164 s.
Computations ended normally.
ACTACAL exe file was:              actacal.exe     419176 02-16-95  11:34a

SEECAL request file written: Pu24125W.req

END OF ACTACALC LOGFILE (describing the biokinetic model)
```

Appendix A2: ACTACALC© program file Pu241W.cpt

This is ACTACAL cpt file Pu24125W.cpt											$
<< ACTACAL Ver. 2.3 (Feb 13, 1995) — Run Feb 23, 1995, at 03:16 >>											$
ACTACAL exe file was: actacal.exe 419176 02-16-95 11:34a											$
Standard name file was: StdNames.bd 2444 08-23-94 10:18a											$
Writing times read from: writim.dat 652 01-07-94 9:00p											$
Computational times read from: timin.dat 336 09-16-92 12:00a											$
LNG file rd in subr. TIMELNG was: icrp30W.lng 975 08-21-94 8:00p											$
GFI file rd in subr. TIMEFI was: Pu8W.gfi 218 02-23-95 3:14a											$
DEF file rd in subr. TIMEBIO was: Pu.def 3166 01-10-94 9:27p											$
RNL file rd in subr. TIMEBLD was: icrp67.bld 331 08-21-94 8:32a											$
Age 0 mass file rd by READMS was: RegMass.a00 3013 01-12-95 12:32p											$
Age 1 mass file rd by READMS was: RegMass.a01 2689 01-12-95 12:32p											$
Age 5 mass file rd by READMS was: RegMass.a05 2689 01-12-95 12:33p											$
Age 10 mass file rd by READMS was: RegMass.a10 2690 01-12-95 12:33p											$
Age 15 mass file rd by READMS was: RegMass.a15 2807 01-12-95 12:34p											$
Adult mass file rd by READMS was: RegMass.am 2835 01-12-95 12:34p											$
END DIRECTORY INFO ON ACTACAL INPUT FILES											$
1 17 2 98 9125 h											$
1 9125											$
Pu-241 14.4 y 1.0E-03 1.0E+00 W											$
Pu-241 inhalation											$
Nuclide time	Liver	C_Bone-S	T_Bone-S	UB_Cont	Kidneys	Testes	Ovaries	Other	C_Bone-V	R_Marrow	T_Bone-V
Pu-241 0.0E+	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Am-241 0.0E	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pu-241 2.0E-0	1.79E-06	1.19E-06	1.79E-06	1.18E-07	8.94E-08	2.12E-09	6.54E-10	3.42E-06	3.69E-14	6.65E-13	3.33E-13
Am-241 2.0E-	1.75E-14	1.17E-14	1.75E-14	1.15E-15	8.77E-16	2.08E-17	6.42E-18	3.35E-14	0.00E+00	0.00E+00	0.00E+00
Pu-241 1.0E-0	3.77E-05	2.51E-05	3.77E-05	2.40E-06	1.88E-06	4.47E-08	1.38E-08	7.19E-05	3.65E-12	6.57E-11	3.29E-11
Am-241 1.0E-	1.66E-12	1.11E-12	1.66E-12	1.06E-13	8.30E-14	1.97E-15	6.08E-16	3.17E-12	0.00E+00	2.89E-18	1.42E-18
Pu-241 5.0E-0	4.80E-04	3.20E-04	4.80E-04	2.53E-05	2.40E-05	5.69E-07	1.76E-07	9.08E-04	2.68E-10	4.83E-09	2.42E-09
Am-241 5.0E-	1.05E-10	7.03E-11	1.05E-10	5.55E-12	5.27E-12	1.25E-13	3.86E-14	1.99E-10	5.88E-17	1.06E-15	5.31E-16
Pu-241 1.0E-0	1.12E-03	7.45E-04	1.12E-03	4.57E-05	5.58E-05	1.32E-06	4.09E-07	2.09E-03	1.36E-09	2.45E-08	1.23E-08
Am-241 1.0E-	4.91E-10	3.27E-10	4.91E-10	2.01E-11	2.45E-11	5.81E-13	1.79E-13	9.16E-10	5.99E-16	1.08E-14	5.40E-15
Pu-241 2.0E-0	2.32E-03	1.55E-03	2.32E-03	6.00E-05	1.16E-04	2.75E-06	8.49E-07	4.22E-03	6.10E-09	1.10E-07	5.50E-08
Am-241 2.0E-	2.04E-09	1.36E-09	2.04E-09	5.27E-11	1.02E-10	2.41E-12	7.45E-13	3.71E-09	5.36E-15	9.63E-14	4.83E-14
Pu-241 3.0E-0	3.42E-03	2.28E-03	3.42E-03	6.05E-05	1.71E-04	4.06E-06	1.25E-06	6.07E-03	1.40E-08	2.52E-07	1.26E-07
Am-241 3.0E-	4.51E-09	3.01E-09	4.51E-09	7.97E-11	2.25E-10	5.34E-12	1.65E-12	7.99E-09	1.84E-14	3.31E-13	1.66E-13
Pu-241 4.0E-0	4.44E-03	2.96E-03	4.43E-03	5.72E-05	2.21E-04	5.26E-06	1.62E-06	7.65E-03	2.48E-08	4.45E-07	2.23E-07
Am-241 4.0E-	7.79E-09	5.19E-09	7.79E-09	1.01E-10	3.89E-10	9.23E-12	2.85E-12	1.34E-08	4.35E-14	7.82E-13	3.92E-13
Pu-241 6.0E-0	6.23E-03	4.15E-03	6.22E-03	4.92E-05	3.10E-04	7.38E-06	2.28E-06	1.02E-02	5.41E-08	9.72E-07	4.88E-07
Am-241 6.0E-	1.64E-08	1.09E-08	1.64E-08	1.30E-10	8.17E-10	1.94E-11	6.00E-12	2.68E-08	1.43E-13	2.56E-12	1.28E-12
Pu-241 8.0E-0	7.76E-03	5.17E-03	7.75E-03	4.23E-05	3.86E-04	9.19E-06	2.84E-06	1.20E-02	9.25E-08	1.66E-06	8.34E-07
Am-241 8.0E-	2.72E-08	1.82E-08	2.72E-08	1.48E-10	1.36E-09	3.23E-11	9.96E-12	4.23E-08	3.25E-13	5.84E-12	2.93E-12
Pu-241 1.0E+	9.07E-03	6.05E-03	9.07E-03	3.66E-05	4.51E-04	1.08E-05	3.32E-06	1.33E-02	1.39E-07	2.49E-06	1.25E-06
Am-241 1.0E	3.98E-08	2.66E-08	3.98E-08	1.61E-10	1.98E-09	4.72E-11	1.46E-11	5.86E-08	6.09E-13	1.09E-11	5.49E-12
Pu-241 1.5E+	1.17E-02	7.78E-03	1.17E-02	2.63E-05	5.78E-04	1.38E-05	4.27E-06	1.51E-02	2.82E-07	5.05E-06	2.54E-06
Am-241 1.5E	7.68E-08	5.12E-08	7.68E-08	1.73E-10	3.81E-09	9.10E-11	2.81E-11	9.92E-08	1.86E-12	3.32E-11	1.67E-11
Pu-241 2.0E+	1.36E-02	9.05E-03	1.36E-02	2.00E-05	6.71E-04	1.61E-05	4.97E-06	1.55E-02	4.55E-07	8.14E-06	4.10E-06
Am-241 2.0E	1.19E-07	7.95E-08	1.19E-07	1.75E-10	5.89E-09	1.41E-10	4.36E-11	1.36E-07	4.00E-12	7.15E-11	3.60E-11
Pu-241 3.0E+	1.62E-02	1.08E-02	1.62E-02	1.28E-05	7.95E-04	1.92E-05	5.93E-06	1.49E-02	8.66E-07	1.54E-05	7.80E-06
Am-241 3.0E	2.13E-07	1.42E-07	2.13E-07	1.69E-10	1.05E-08	2.53E-10	7.80E-11	1.96E-07	1.14E-11	2.03E-10	1.03E-10
Pu-241 4.0E+	1.79E-02	1.19E-02	1.79E-02	9.08E-06	8.73E-04	2.12E-05	6.55E-06	1.39E-02	1.33E-06	2.37E-05	1.20E-05
Am-241 4.0E	3.15E-07	2.10E-07	3.14E-07	1.59E-10	1.53E-08	3.73E-10	1.15E-10	2.44E-07	2.34E-11	4.17E-10	2.11E-10
Pu-241 5.0E+	1.91E-02	1.28E-02	1.91E-02	6.82E-06	9.24E-04	2.27E-05	6.99E-06	1.31E-02	1.84E-06	3.26E-05	1.66E-05
Am-241 5.0E	4.20E-07	2.80E-07	4.19E-07	1.49E-10	2.03E-08	4.97E-10	1.54E-10	2.87E-07	4.05E-11	7.17E-10	3.64E-10
Pu-241 6.0E+	2.00E-02	1.33E-02	1.99E-02	5.33E-06	9.59E-04	2.37E-05	7.31E-06	1.24E-02	2.38E-06	4.20E-05	2.14E-05
Am-241 6.0E	5.27E-07	3.51E-07	5.25E-07	1.40E-10	2.53E-08	6.24E-10	1.93E-10	3.27E-07	6.27E-11	1.11E-09	5.64E-10
Pu-241 8.0E+	2.11E-02	1.41E-02	2.11E-02	3.60E-06	9.98E-04	2.50E-05	7.73E-06	1.17E-02	3.51E-06	6.15E-05	3.15E-05
Am-241 8.0E	7.43E-07	4.96E-07	7.40E-07	1.26E-10	3.51E-08	8.80E-10	2.72E-10	4.11E-07	1.23E-10	2.16E-09	1.11E-09
Pu-241 9.0E+	2.15E-02	1.44E-02	2.14E-02	3.10E-06	1.01E-03	2.55E-05	7.87E-06	1.15E-02	4.09E-06	7.15E-05	3.67E-05
Am-241 9.0E	8.51E-07	5.68E-07	8.48E-07	1.23E-10	3.99E-08	1.01E-09	3.11E-10	4.55E-07	1.62E-10	2.83E-09	1.45E-09
Pu-241 1.0E+	2.19E-02	1.46E-02	2.17E-02	2.75E-06	1.01E-03	2.59E-05	7.99E-06	1.14E-02	4.69E-06	8.15E-05	4.21E-05
Am-241 1.0E	9.60E-07	6.40E-07	9.55E-07	1.21E-10	4.46E-08	1.14E-09	3.51E-10	5.00E-07	2.06E-10	3.58E-09	1.85E-09
Pu-241 1.2E+	2.23E-02	1.49E-02	2.22E-02	2.32E-06	1.02E-03	2.64E-05	8.16E-06	1.13E-02	5.89E-06	1.02E-04	5.29E-05
Am-241 1.2E	1.18E-06	7.85E-07	1.17E-06	1.21E-10	5.37E-08	1.39E-09	4.30E-10	5.95E-07	3.11E-10	5.37E-09	2.79E-09
Pu-241 1.5E+	2.29E-02	1.53E-02	2.27E-02	2.04E-06	1.02E-03	2.71E-05	8.36E-06	1.13E-02	7.75E-06	1.32E-04	6.94E-05
Am-241 1.5E	1.51E-06	1.01E-06	1.50E-06	1.33E-10	6.71E-08	1.78E-09	5.51E-10	7.46E-07	5.11E-10	8.73E-09	4.57E-09
Pu-241 1.7E+	2.32E-02	1.55E-02	2.30E-02	1.95E-06	1.02E-03	2.74E-05	8.47E-06	1.14E-02	9.01E-06	1.53E-04	8.06E-05
Am-241 1.7E	1.73E-06	1.16E-06	1.72E-06	1.45E-10	7.58E-08	2.05E-09	6.33E-10	8.51E-07	6.73E-10	1.14E-08	6.02E-09
Pu-241 2.0E+	2.36E-02	1.57E-02	2.33E-02	1.87E-06	1.01E-03	2.79E-05	8.62E-06	1.15E-02	1.09E-05	1.83E-04	9.76E-05
Am-241 2.0E	2.07E-06	1.38E-06	2.05E-06	1.64E-10	8.87E-08	2.45E-09	7.58E-10	1.01E-06	9.60E-10	1.61E-08	8.58E-09
Pu-241 2.5E+	2.42E-02	1.62E-02	2.39E-02	1.80E-06	9.96E-04	2.87E-05	8.85E-06	1.18E-02	1.42E-05	2.34E-04	1.26E-04
Am-241 2.5E	2.66E-06	1.78E-06	2.63E-06	1.97E-10	1.09E-07	3.15E-09	9.72E-10	1.29E-06	1.56E-09	2.57E-08	1.39E-08
Pu-241 3.5E+	2.54E-02	1.70E-02	2.49E-02	1.70E-06	9.69E-04	3.00E-05	9.26E-06	1.22E-02	2.09E-05	3.33E-04	1.86E-04

Appendix A3: Stella program for intake scenario #2

```
Blood_Am241(t) = Blood_Am241(t - dt) + (tmtc_2 + gontc_2 + o0tc_2 + kid2tc_2 + sitc_2
+ cbs1tc_2 + o1tc_2 + o2tc_2 + raintc + i2_to_tc2 + a2_to_tc2 + c_2_to_tc2 + e2_to_tc2
+ liv1_2_to_tc_2 - tcliv1_2 - tco2_2 - tco1_2 - tccbs_2 - tckid2_2 - tco0_2 - tcgon_2
- tctbs_2 - tcub_2 - tckid1_2 - tculi_2 - radtc_2) * dt
INIT Blood_Am241 = 0
INFLOWS:
tmtc_2 = 7.6e-3*rm_2
gontc_2 = 1.9e-4*gon_2
o0tc_2 = 1.386*o0_2
kid2tc_2 = 1.39e-3*kid2_2*.5
sitc_2 = 6.006e-3*si_2
cbs1tc_2 = 7.6e-3*cbs1_2
o1tc_2 = 1.39e-2*o1_2
o2tc_2 = 1.9e-5*o2_2
raintc = (LOGN(2)/(432.2*365))*Blood_Pu241
i2_to_tc2 = 1.3863e-2*i_2
a2_to_tc2   (IN SECTOR: Inhalation Am-241)
c_2_to_tc2   (IN SECTOR: Inhalation Am-241)
e2_to_tc2   (IN SECTOR: Inhalation Am-241)
liv1_2_to_tc_2 = 1.85e-3*Liver_Am241
OUTFLOWS:
tcliv1_2 = 11.6*Blood_Am241
tco2_2 = 0.466*Blood_Am241
tco1_2 = 1.67*Blood_Am241
tccbs_2 = 3.49*Blood_Am241
tckid2_2 = 1.16e-1*Blood_Am241*.5
tco0_2 = 10*Blood_Am241
tcgon_2 = 8.2e-3*Blood_Am241
tctbs_2 = 3.49*Blood_Am241
tcub_2 = 1.63*Blood_Am241
tckid1_2 = 0.466*Blood_Am241
tculi_2 = 3.03e-1*Blood_Am241
radtc_2 = (LOGN(2)/(432.2*365))*Blood_Am241

cbs1_2(t) = cbs1_2(t - dt) + (cbscbs1_2 + cbvcbs1_2 + radincbs1 - cbs1tc_2 - radcbs1_2) * dt
INIT cbs1_2 = 0
INFLOWS:
cbscbs1_2 = 8.21e-5*cbs_2
cbvcbs1_2 = 8.21e-5*cbv_2
radincbs1 = (LOGN(2)/(432.2*365))*cbs1
OUTFLOWS:
cbs1tc_2 = 7.6e-3*cbs1_2
radcbs1_2 = (LOGN(2)/(432.2*365))*cbs1_2

cbs_2(t) = cbs_2(t - dt) + (tccbs_2 + radin_cbs - cbscbs1_2 - cbscbv_2 - radcbs_2) * dt
INIT cbs_2 = 0
INFLOWS:
tccbs_2 = 3.49*Blood_Am241
radin_cbs = (LOGN(2)/(432.2*365))*cbs
OUTFLOWS:
cbscbs1_2 = 8.21e-5*cbs_2
cbscbv_2 = 4.11e-5*cbs_2
radcbs_2 = (LOGN(2)/(432.2*365))*cbs_2
```

```
cbv_2(t) = cbv_2(t - dt) + (cbscbv_2 + radin_cbv - cbvcbs1_2 - radcbv_2) * dt
INIT cbv_2 = 0
INFLOWS:
cbscbv_2 = 4.11e-5*cbs_2
radin_cbv = (LOGN(2)/(432.2*365))*cbv
OUTFLOWS:
cbvcbs1_2 = 8.21e-5*cbv_2
radcbv_2 = (LOGN(2)/(432.2*365))*cbv_2

Feces_Am241(t) = Feces_Am241(t - dt) + (ulilli_2 + radin_lli - llifec_2 - radlli_2) * dt
INIT Feces_Am241 = 0
INFLOWS:
ulilli_2 = 1.8*uli_2
radin_lli = (LOGN(2)/(432.2*365))*Feces_Pu241
OUTFLOWS:
llifec_2 = 1*Feces_Am241
radlli_2 = (LOGN(2)/(432.2*365))*Feces_Am241

gon_2(t) = gon_2(t - dt) + (tcgon_2 + radingon - gontc_2 - radgon_2) * dt
INIT gon_2 = 0
INFLOWS:
tcgon_2 = 8.2e-3*Blood_Am241
radingon = (LOGN(2)/(432.2*365))*gon
OUTFLOWS:
gontc_2 = 1.9e-4*gon_2
radgon_2 = (LOGN(2)/(432.2*365))*gon_2

kid1_2(t) = kid1_2(t - dt) + (tckid1_2 + radinkid2 - kid1ub_2 - radkid1_2) * dt
INIT kid1_2 = 0
INFLOWS:
tckid1_2 = 0.466*Blood_Am241
radinkid2 = (LOGN(2)/(432.2*365))*kid1
OUTFLOWS:
kid1ub_2 = 9.9e-2*kid1_2*.5
radkid1_2 = (LOGN(2)/(432.2*365))*kid1_2

kid2_2(t) = kid2_2(t - dt) + (tckid2_2 + Dkid2 - kid2tc_2 - radkid2_2) * dt
INIT kid2_2 = 0
INFLOWS:
tckid2_2 = 1.16e-1*Blood_Am241*.5
Dkid2 = (LOGN(2)/(432.2*365))*kid2
OUTFLOWS:
kid2tc_2 = 1.39e-3*kid2_2*.5
radkid2_2 = (LOGN(2)/(432.2*365))*kid2_2

Liver_Am241(t) = Liver_Am241(t - dt)
+ (tcliv1_2 + rainliv1 - liv1si_2 - radliv1_2 - liv1_2_to_tc_2) * dt
INIT Liver_Am241 = 0
INFLOWS:
tcliv1_2 = 11.6*Blood_Am241
rainliv1 = (LOGN(2)/(432.2*365))*liv1
OUTFLOWS:
liv1si_2 = 4.9e-5*Liver_Am241
radliv1_2 = (LOGN(2)/(432.2*365))*Liver_Am241

liv1_2_to_tc_2 = 1.85e-3*Liver_Am241
oO_2(t) = oO_2(t - dt) + (tcoO_2 + radin_o2 - oOtc_2 - radoO_2) * dt
INIT oO_2 = 0
INFLOWS:
tcoO_2 = 10*Blood_Am241
radin_o2 = (LOGN(2)/(432.2*365))*oO
OUTFLOWS:
oOtc_2 = 1.386*oO_2
radoO_2 = (LOGN(2)/(432.2*365))*oO_2
```

```
o1_2(t) = o1_2(t - dt) + (tco1_2 + radino1 - o1tc_2 - rado1_2) * dt
INIT o1_2 = 0
INFLOWS:
tco1_2 = 1.67*Blood_Am241
radino1 = (LOGN(2)/(432.2*365))*o1
OUTFLOWS:
o1tc_2 = 1.39e-2*o1_2
rado1_2 = (LOGN(2)/(432.2*365))*o1_2

o2_2(t) = o2_2(t - dt) + (tco2_2 + radino2 - o2tc_2 - rado2_2) * dt
INIT o2_2 = 0
INFLOWS:
tco2_2 = 0.466*Blood_Am241
radino2 = (LOGN(2)/(432.2*365))*o2
OUTFLOWS:
o2tc_2 = 1.9e-5*o2_2
rado2_2 = (LOGN(2)/(432.2*365))*o2_2

rm_2(t) = rm_2(t - dt) + (tbsrm_2 + tbvrm_2 + radinrm - tmtc_2 - radrm_2) * dt
INIT rm_2 = 0
INFLOWS:
tbsrm_2 = 4.93e-4*tbs_2
tbvrm_2 = 4.93e-4*tbv_2
radinrm = (LOGN(2)/(432.2*365))*rm
OUTFLOWS:
tmtc_2 = 7.6e-3*rm_2
radrm_2 = (LOGN(2)/(432.2*365))*rm_2

si_2(t) = si_2(t - dt) + (liv1si_2 + radinsi + st2tosi2 - sitc_2 - siuli_2) * dt
INIT si_2 = 0
INFLOWS:
liv1si_2 = 4.9e-5*Liver_Am241
radinsi = (LOGN(2)/(432.2*365))*si
st2tosi2 = 24*ST_2
OUTFLOWS:
sitc_2 = 6.006e-3*si_2
siuli_2 = 6*si_2

tbs_2(t) = tbs_2(t - dt) + (tctbs_2 - tbsrm_2 - tbstbv_2 - radtbs_2) * dt
INIT tbs_2 = 0
INFLOWS:
tctbs_2 = 3.49*Blood_Am241
OUTFLOWS:
tbsrm_2 = 4.93e-4*tbs_2
tbstbv_2 = 2.47e-4*tbs_2
radtbs_2 = (LOGN(2)/(432.2*365))*tbs_2

tbv_2(t) = tbv_2(t - dt) + (tbstbv_2 + radintbv - tbvrm_2 - radtbv_2) * dt
INIT tbv_2 = 0
INFLOWS:
tbstbv_2 = 2.47e-4*tbs_2
radintbv = (LOGN(2)/(432.2*365))*tbv
OUTFLOWS:
tbvrm_2 = 4.93e-4*tbv_2
radtbv_2 = (LOGN(2)/(432.2*365))*tbv_2

uli_2(t) = uli_2(t - dt) + (tculi_2 + radinuli + siuli_2 - ulilli_2 - raduli_2) * dt
INIT uli_2 = 0
INFLOWS:
tculi_2 = 3.03e-1*Blood_Am241
radinuli = (LOGN(2)/(432.2*365))*uli
siuli_2 = 6*si_2
OUTFLOWS:
ulilli_2 = 1.8*uli_2
raduli_2 = (LOGN(2)/(432.2*365))*uli_2
```

```
Urine_Am241(t) = Urine_Am241(t - dt)
+ (tcub_2 + kid1ub_2 + radinub - ubu_2 - radub_2) * dt
INIT Urine_Am241 = 0
INFLOWS:
tcub_2 = 1.63*Blood_Am241
kid1ub_2 = 9.9e-2*kid1_2*.5
radinub = (LOGN(2)/(432.2*365))*Urine_Pu241
OUTFLOWS:
ubu_2 = 12*Urine_Am241
radub_2 = (LOGN(2)/(432.2*365))*Urine_Am241

a_2(t) = a_2(t - dt) + (a2_input + radin_a2 + a2_input_2 + rad_i2 - a2_to_tc2 - rad_a2) * dt
INIT a_2 = 0
INFLOWS:
a2_input = IF TIME<0.5 THEN 0.3*0.1*PULSE(100*2*DT,0,DT)
ELSE PULSE(0,0,0)
radin_a2 = (LOGN(2)/(432.2*365))*a
a2_input_2 = IF TIME<40.5 THEN 0.3*0.1*PULSE(100*2*DT,100,DT)
ELSE PULSE(0,0,0)
rad_i2 = (LOGN(2)/(432.2*365))*i_2
OUTFLOWS:
a2_to_tc2 = 69.31472*a_2
rad_a2 = (LOGN(2)/(432.2*365))*a_2

b_2(t) = b_2(t - dt) + (b2_input + radin_b2 + b2_input_2 - b_to_ST_2 - rad_b2) * dt
INIT b_2 = 0
INFLOWS:
b2_input = IF TIME <0.5 THEN 0.3*0.9*PULSE(100*2*DT,0,DT)
ELSE PULSE(0,0,0)
radin_b2 = (LOGN(2)/(432.2*365))*b
b2_input_2 = IF TIME <40.5 THEN 0.3*0.9*PULSE(100*2*DT,100,DT)
ELSE PULSE(0,0,0)
OUTFLOWS:
b_to_ST_2 = 1.73287*b_2
rad_b2 = (LOGN(2)/(432.2*365))*b_2

c_2(t) = c_2(t - dt) + (c2_input + radin_c2 + c2_input_2 - c_2_to_tc2 - rad_c2) * dt
INIT c_2 = 0
INFLOWS:
c2_input = IF TIME<0.5 THEN 0.08*0.5*PULSE(100*2*DT,0,DT)
ELSE PULSE(0,0,0)
radin_c2 = (LOGN(2)/(432.2*365))*c
c2_input_2 = IF TIME<40.5 THEN 0.08*0.5*PULSE(100*2*DT,100,DT)
ELSE PULSE(0,0,0)
OUTFLOWS:
c_2_to_tc2 = 69.31472*c_2
rad_c2 = (LOGN(2)/(432.2*365))*c_2

d_2(t) = d_2(t - dt)
 + (d2_input + f_to_d_2 + g_to_d_2 + radin_d2 + d2_input_2 - d_to_ST_2 - rad_d2) * dt
INIT d_2 = 0
INFLOWS:
d2_input = IF TIME<0.5 THEN 0.08*0.5*PULSE(100*2*DT,0,DT)
ELSE PULSE(0,0,0)
f_to_d_2 = (LOGN(2)*f_2)
g_to_d_2 = 1.3863e-2*g_2
radin_d2 = (LOGN(2)/(432.2*365))*d
d2_input_2 = IF TIME<40.5 THEN 0.08*0.5*PULSE(100*2*DT,100,DT)
ELSE PULSE(0,0,0)
OUTFLOWS:
d_to_ST_2 = 3.46574*d_2
rad_d2 = (LOGN(2)/(432.2*365))*d_2
```

```
e_2(t) = e_2(t - dt) + (e2_input + radin_e2 + e2_input_2 - e2_to_tc2 - rad_e2) * dt
INIT e_2 = 0
INFLOWS:
e2_input = IF TIME <0.5 THEN 0.25*0.15*PULSE(100*2*DT,0,DT)
ELSE PULSE(0,0,0)
radin_e2 = (LOGN(2)/(432.2*365))*e
e2_input_2 = IF TIME <40.5 THEN 0.25*0.15*PULSE(100*2*DT,100,DT)
ELSE PULSE(0,0,0)
OUTFLOWS:
e2_to_tc2 = 1.3863e-2*e_2
rad_e2 = (LOGN(2)/(432.2*365))*e_2

f_2(t) = f_2(t - dt) + (f2_input + radin_f2 + f2_input_2 - f_to_d_2 - rad_f2) * dt
INIT f_2 = 0
INFLOWS:
f2_input = IF TIME<0.5 THEN 0.25*0.4*PULSE(100*2*DT,0,DT)
ELSE PULSE(0,0,0)
radin_f2 = (LOGN(2)/(432.2*365))*f
f2_input_2 = IF TIME<40.5 THEN 0.25*0.4*PULSE(100*2*DT,100,DT)
ELSE PULSE(0,0,0)
OUTFLOWS:
f_to_d_2 = (LOGN(2)*f_2)
rad_f2 = (LOGN(2)/(432.2*365))*f_2

g_2(t) = g_2(t - dt) + (g2_input + radin_g2 + g2_input_2 - g_to_d_2 - rad_g2) * dt
INIT g_2 = 0
INFLOWS:
g2_input = IF TIME <0.5 THEN 0.25*0.4*PULSE(100*2*DT,0,DT)
ELSE PULSE(0,0,0)
radin_g2 = (LOGN(2)/(432.2*365))*g
g2_input_2 = IF TIME <40.5 THEN 0.25*0.4*PULSE(100*2*DT,100,DT)
ELSE PULSE(0,0,0)
OUTFLOWS:
g_to_d_2 = 1.3863e-2*g_2
rad_g2 = (LOGN(2)/(432.2*365))*g_2

h_2(t) = h_2(t - dt) + (radin_h2 + h2_input_2 + h2_input - h_to_i_2 - rad_h2) * dt
INIT h_2 = 0
INFLOWS:
radin_h2 = (LOGN(2)/(432.2*365))*h
h2_input_2 = IF TIME<0.5 THEN 0.25*0.05*PULSE(100*2*DT,0,DT)
ELSE PULSE(0,0,0)
h2_input = IF TIME<40.5 THEN 0.25*0.05*PULSE(100*2*DT,100,DT)
ELSE PULSE(0,0,0)
OUTFLOWS:
h_to_i_2 = 1.3863e-2*h_2
rad_h2 = (LOGN(2)/(432.2*365))*h_2

i_2(t) = i_2(t - dt) + (h_to_i_2 + radin_i2 - i2_to_tc2 - rad_i2) * dt
INIT i_2 = 0
INFLOWS:
h_to_i_2 = 1.3863e-2*h_2
radin_i2 = (LOGN(2)/(432.2*365))*i
OUTFLOWS:
i2_to_tc2   (IN SECTOR: Am241)
rad_i2 = (LOGN(2)/(432.2*365))*i_2

ST_2(t) = ST_2(t - dt) + (b_to_ST_2 + d_to_ST_2 + radin_ST2 - st2tosi2 - rad_ST2) * dt
INIT ST_2 = 0
INFLOWS:
b_to_ST_2 = 1.73287*b_2
d_to_ST_2 = 3.46574*d_2
radin_ST2 = (LOGN(2)/(432.2*365))*ST
OUTFLOWS:
st2tosi2   (IN SECTOR: Am241)
rad_ST2 = (LOGN(2)/(432.2*365))*ST_2
```

```
a(t) = a(t - dt) + (a_input + a_input_2 - a_to_tc - rad_a) * dt
INIT a = 0
INFLOWS:
a_input = IF TIME<0.5 THEN 0.3*0.1*PULSE(5000*2*DT,0,DT)
ELSE PULSE(0,0,0)
a_input_2 = IF TIME<40.5 THEN 0.3*0.1*PULSE(5000*2*DT,100,DT)
ELSE PULSE(0,0,0)
OUTFLOWS:
a_to_tc = 69.31472*a
rad_a = (LOGN(2)/(14.4*365))*a

b(t) = b(t - dt) + (b_input + b_input_2 - b_to_ST - rad_b) * dt
INIT b = 0
INFLOWS:
b_input = IF TIME<0.5 THEN 0.3*0.9*PULSE(5000*2*DT,0,DT)
ELSE PULSE(0,0,0)
b_input_2 = IF TIME<40.5 THEN 0.3*0.9*PULSE(5000*2*DT,100,DT)
ELSE PULSE(0,0,0)
OUTFLOWS:
b_to_ST = 1.73287*b
rad_b = (LOGN(2)/(14.4*365))*b

c(t) = c(t - dt) + (c_input + c_input_2 - c_to_tc - rad_c) * dt
INIT c = 0
INFLOWS:
c_input = IF TIME <0.5 THEN 0.08*0.5*PULSE(5000*2*DT,0,DT)
ELSE PULSE(0,0,0)
c_input_2 = IF TIME <40.5 THEN 0.08*0.5*PULSE(5000*2*DT,100,DT)
ELSE PULSE(0,0,0)
OUTFLOWS:
c_to_tc = 69.31472*c
rad_c = (LOGN(2)/(14.4*365))*c

d(t) = d(t - dt) + (d_input + f_to_d + g_to_d + d_input_2 - d_to_ST - rad_d) * dt
INIT d = 0
INFLOWS:
d_input = IF TIME <0.5 THEN 0.08*0.5*PULSE(5000*2*DT,0,DT)
ELSE PULSE(0,0,0)
f_to_d = (LOGN(2)*f)
g_to_d = 1.3863e-2*g
d_input_2 = IF TIME <40.5 THEN 0.08*0.5*PULSE(5000*2*DT,100,DT)
ELSE PULSE(0,0,0)
OUTFLOWS:
d_to_ST = 3.46574*d
rad_d = (LOGN(2)/(14.4*365))*d

e(t) = e(t - dt) + (e_input + e_input_2 - e_to_tc - rad_e) * dt
INIT e = 0
INFLOWS:
e_input = IF TIME<0.5 THEN 0.25*0.15*PULSE(5000*2*DT,0,DT)
ELSE PULSE(0,0,0)
e_input_2 = IF TIME<40.5 THEN 0.25*0.15*PULSE(5000*2*DT,100,DT)
ELSE PULSE(0,0,0)
OUTFLOWS:
e_to_tc = 1.3863e-2*e
rad_e = (LOGN(2)/(14.4*365))*e
```

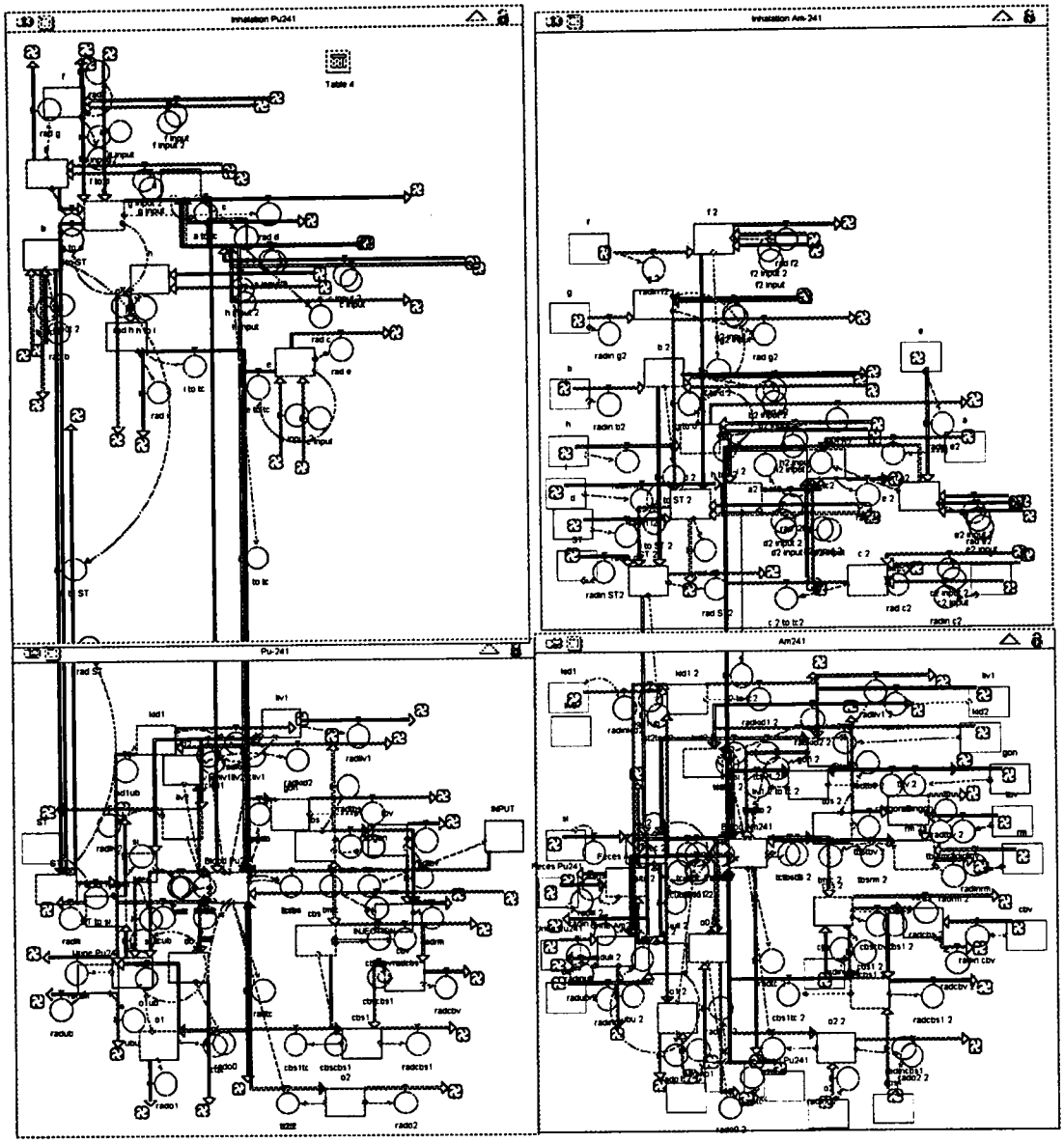
```
f(t) = f(t - dt) + (f_input + f_input_2 - f_to_d - rad_f) * dt
INIT f = 0
INFLOWS:
f_input = IF TIME <0.5 THEN 0.25*0.4*PULSE(5000*2*DT,0,DT)
ELSE PULSE(0,0,0)
f_input_2 = IF TIME <40.5 THEN 0.25*0.4*PULSE(5000*2*DT,100,DT)
ELSE PULSE(0,0,0)
OUTFLOWS:
f_to_d = (LOGN(2)*f)
rad_f = (LOGN(2)/(14.4*365))*f

g(t) = g(t - dt) + (g_input + g_input_2 - g_to_d - rad_g) * dt
INIT g = 0
INFLOWS:
g_input = IF TIME <0.5 THEN 0.25*0.4*PULSE(5000*2*DT,0,DT)
ELSE PULSE(0,0,0)
g_input_2 = IF TIME <40.5 THEN 0.25*0.4*PULSE(5000*2*DT,100,DT)
ELSE PULSE(0,0,0)
OUTFLOWS:
g_to_d = 1.3863e-2*g
rad_g = (LOGN(2)/(14.4*365))*g

h(t) = h(t - dt) + (h_input + h_input_2 - h_to_i - rad_h) * dt
INIT h = 0
INFLOWS:
h_input = IF TIME<0.5 THEN 0.25*0.05*PULSE(5000*2*DT,0,DT)
ELSE PULSE(0,0,0)
h_input_2 = IF TIME<40.5 THEN 0.25*0.05*PULSE(5000*2*DT,100,DT)
ELSE PULSE(0,0,0)
OUTFLOWS:
h_to_i = 1.3863e-2*h
rad_h = (LOGN(2)/(14.4*365))*h

i(t) = i(t - dt) + (h_to_i - i_to_tc - rad_i) * dt
INIT i = 0
INFLOWS:
h_to_i = 1.3863e-2*h
OUTFLOWS:
i_to_tc = 1.3863e-2*i
rad_i = (LOGN(2)/(14.4*365))*i
Pu-241

Blood_Pu241(t) = Blood_Pu241(t - dt)
+ (tmtc + gontc + o0tc + kid2tc + liv2tc + sitc + cbs1tc + o1tc + o2tc + IN + INJECTION
+ e_to_tc + c_to_tc + a_to_tc + i_to_tc - tcliv1 - tco2 - tco1 - tccbs - tckid2 - tco0 - tcgon
- tctbs - tcub - tckid1 - tculi - radtc) * dt
INIT Blood_Pu241 = 0
INFLOWS:
tmtc = 7.6e-3*rm
gontc = 1.9e-4*gon
o0tc = 6.93e-1*o0
kid2tc = 1.39e-2*kid2*.5
liv2tc = 2.11e-4*liv2
sitc = 6.006e-3*si
cbs1tc = 7.6e-3*cbs1
o1tc = 4.75e-4*o1
o2tc = 1.9e-5*o2
IN = INPUT
INJECTION = PULSE(0,0,DT)
e_to_tc   (IN SECTOR:  Inhalation Pu241)
c_to_tc   (IN SECTOR:  Inhalation Pu241)
a_to_tc   (IN SECTOR:  Inhalation Pu241)
i_to_tc   (IN SECTOR:  Inhalation Pu241)
```

```
OUTFLOWS:
tcliv1 = 1.941e-1*Blood_Pu241
tco2 = 1.29e-2*Blood_Pu241
tco1 = 8.06e-2*Blood_Pu241
tccbs = 1.294e-1*Blood_Pu241
tckid2 = 3.23e-3*Blood_Pu241
tco0 = 2.773e-1*Blood_Pu241
tcgon = 2.3e-4*Blood_Pu241
tctbs = 1.941e-1*Blood_Pu241
tcub = 1.29e-2*Blood_Pu241
tckid1 = 6.47e-3*Blood_Pu241
tculi = 1.294e-2*Blood_Pu241
radtc = (LOGN(2)/(14.4*365))*Blood_Pu241

cbs(t) = cbs(t - dt) + (tccbs - cbscbs1 - cbscbv - radcbs) * dt
INIT cbs = 0
INFLOWS:
tccbs = 1.294e-1*Blood_Pu241
OUTFLOWS:
cbscbs1 = 8.21e-5*cbs
cbscbv = 4.11e-5*cbs
radcbs = (LOGN(2)/(14.4*365))*cbs

cbs1(t) = cbs1(t - dt) + (cbscbs1 + cbvcbs1 - cbs1tc - radcbs1) * dt
INIT cbs1 = 0
INFLOWS:
cbscbs1 = 8.21e-5*cbs
cbvcbs1 = 8.21e-5*cbv
OUTFLOWS:
cbs1tc = 7.6e-3*cbs1
radcbs1 = (LOGN(2)/(14.4*365))*cbs1

cbv(t) = cbv(t - dt) + (cbscbv - cbvcbs1 - radcbv) * dt
INIT cbv = 0
INFLOWS:
cbscbv = 4.11e-5*cbs
OUTFLOWS:
cbvcbs1 = 8.21e-5*cbv
radcbv = (LOGN(2)/(14.4*365))*cbv

Feces_Pu241(t) = Feces_Pu241(t - dt) + (ulilli - llifec - radlli) * dt
INIT Feces_Pu241 = 0
INFLOWS:
ulilli = 1.8*uli
OUTFLOWS:
llifec = 1*Feces_Pu241
radlli = (LOGN(2)/(14.4*365))*Feces_Pu241

gon(t) = gon(t - dt) + (tcgon - gontc - radgon) * dt
INIT gon = 0
INFLOWS:
tcgon = 2.3e-4*Blood_Pu241
OUTFLOWS:
gontc = 1.9e-4*gon
radgon = (LOGN(2)/(14.4*365))*gon

INPUT(t) = INPUT(t - dt) + (- IN) * dt
INIT INPUT = 0
OUTFLOWS:
IN = INPUT
```

```
kid1(t) = kid1(t - dt) + (tckid1 - kid1ub - radkid1) * dt
INIT kid1 = 0
INFLOWS:
tckid1 = 6.47e-3*Blood_Pu241
OUTFLOWS:
kid1ub = 1.386e-2*kid1*.5
radkid1 = (LOGN(2)/(14.4*365))*kid1

kid2(t) = kid2(t - dt) + (tckid2 - kid2tc - radkid2) * dt
INIT kid2 = 0
INFLOWS:
tckid2 = 3.23e-3*Blood_Pu241
OUTFLOWS:
kid2tc = 1.39e-2*kid2*.5
radkid2 = (LOGN(2)/(14.4*365))*kid2

liv1(t) = liv1(t - dt) + (tcliv1 - liv1liv2 - liv1si - radliv1) * dt
INIT liv1 = 0
INFLOWS:
tcliv1 = 1.941e-1*Blood_Pu241
OUTFLOWS:
liv1liv2 = 1.77e-3*liv1
liv1si = 1.33e-4*liv1
radliv1 = (LOGN(2)/(14.4*365))*liv1

liv2(t) = liv2(t - dt) + (liv1liv2 - liv2tc - radliv2) * dt
INIT liv2 = 0
INFLOWS:
liv1liv2 = 1.77e-3*liv1
OUTFLOWS:
liv2tc = 2.11e-4*liv2
radliv2 = (LOGN(2)/(14.4*365))*liv2
o0(t) = o0(t - dt) + (tco0 - o0tc - rado0) * dt
INIT o0 = 0
INFLOWS:
tco0 = 2.773e-1*Blood_Pu241
OUTFLOWS:
o0tc = 6.93e-1*o0
rado0 = (LOGN(2)/(14.4*365))*o0

o1(t) = o1(t - dt) + (tco1 - o1tc - o1ub - rado1) * dt
INIT o1 = 0
INFLOWS:
tco1 = 8.06e-2*Blood_Pu241
OUTFLOWS:
o1tc = 4.75e-4*o1
o1ub = 4.75e-4*o1
rado1 = (LOGN(2)/(14.4*365))*o1

o2(t) = o2(t - dt) + (tco2 - o2tc - rado2) * dt
INIT o2 = 0
INFLOWS:
tco2 = 1.29e-2*Blood_Pu241
OUTFLOWS:
o2tc = 1.9e-5*o2
rado2 = (LOGN(2)/(14.4*365))*o2

rm(t) = rm(t - dt) + (tbsrm + tbvrm - tmtc - radrm) * dt
INIT rm = 0
INFLOWS:
tbsrm = 4.93e-4*tbs
tbvrm = 4.93e-4*tbv
OUTFLOWS:
tmtc = 7.6e-3*rm
radrm = (LOGN(2)/(14.4*365))*rm
```

```
si(t) = si(t - dt) + (liv1si + ST_to_si - sitc - siuli) * dt
INIT si = 0
INFLOWS:
liv1si = 1.33e-4*liv1
ST_to_si = 24*ST
OUTFLOWS:
sitc = 6.006e-3*si
siuli = 6*si

ST(t) = ST(t - dt) + (b_to_ST + d_to_ST - rad_ST - ST_to_si) * dt
INIT ST = 0
INFLOWS:
b_to_ST    (IN SECTOR:  Inhalation Pu241)
d_to_ST    (IN SECTOR:  Inhalation Pu241)
OUTFLOWS:
rad_ST = (LOGN(2)/(14.4*365))*ST
ST_to_si = 24*ST

tbs(t) = tbs(t - dt) + (tctbs - tbsrm - tbstbv - radtbs) * dt
INIT tbs = 0
INFLOWS:
tctbs = 1.941e-1*Blood_Pu241
OUTFLOWS:
tbsrm = 4.93e-4*tbs
tbstbv = 2.47e-4*tbs
radtbs = (LOGN(2)/(14.4*365))*tbs

tbv(t) = tbv(t - dt) + (tbstbv - tbvrm - radtbv) * dt
INIT tbv = 0
INFLOWS:
tbstbv = 2.47e-4*tbs
OUTFLOWS:
tbvrm = 4.93e-4*tbv
radtbv = (LOGN(2)/(14.4*365))*tbv

uli(t) = uli(t - dt) + (tculi + siuli - ulilli - raduli) * dt
INIT uli = 0
INFLOWS:
tculi = 1.294e-2*Blood_Pu241
siuli = 6*si
OUTFLOWS:
ulilli = 1.8*uli
raduli = (LOGN(2)/(14.4*365))*uli

Urine_Pu241(t) = Urine_Pu241(t - dt) + (tcub + kid1ub + o1ub - ubu - radub) * dt
INIT Urine_Pu241 = 0
INFLOWS:
tcub = 1.29e-2*Blood_Pu241
kid1ub = 1.386e-2*kid1*.5
o1ub = 4.75e-4*o1
OUTFLOWS:
ubu = 12*Urine_Pu241
radub = (LOGN(2)/(14.4*365))*Urine_Pu241
```

Appendix A4: Stella Flow Diagram for Biokinetic Model of Pu-241 and Am-241 by Inhalation



Appendix A5: Stella II generated output file acute scenario #2 (Excel format)

Days	Blood Pu241	Blood Am241	Feces Pu241	Feces Am241	Urine Pu241	Urine Am241	Liver Am241	c2	d2	e2	f2	g2	h2	i2
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	194.850307	0.050206	357.37984	7.166633	0.225638	8.58E-03	3.005965	0	1.691446	3.773904	6.095679	10.063745	1.257968	0.012999
2	100.542058	0.021046	701.317401	14.03094	0.117025	4.04E-03	3.386785	0	0.805965	3.722749	3.048495	9.92733	1.240916	0.030026
3	61.044891	9.84E-03	510.977749	10.216457	0.07241	2.35E-03	3.549448	0	0.420596	3.672286	1.524576	9.792763	1.224095	0.046588
4	40.959681	5.52E-03	284.227643	5.678969	0.050183	1.66E-03	3.628191	0	0.229412	3.622508	0.762452	9.66002	1.207503	0.062697
5	29.038687	3.84E-03	144.80453	2.890268	0.037171	1.34E-03	3.674464	0	0.133596	3.573403	0.381308	9.529075	1.191134	0.078359
6	21.288605	3.18E-03	73.039571	1.455658	0.028768	1.18E-03	3.708045	0	0.085424	3.524964	0.190695	9.399905	1.174988	0.093586
7	16.020828	2.92E-03	38.292714	0.761702	0.023071	1.09E-03	3.736552	0	0.061081	3.477182	0.095368	9.272485	1.159061	0.108386
8	12.367708	2.80E-03	21.737794	0.431575	0.019121	1.01E-03	3.76293	0	0.048658	3.430047	0.047694	9.146792	1.143349	0.122767
9	9.810821	2.74E-03	13.819381	0.274047	0.016353	9.57E-04	3.788318	0	0.042199	3.38355	0.023852	9.022801	1.12785	0.136738
10	8.012262	2.71E-03	9.978128	0.197901	0.014402	9.07E-04	3.81316	0	0.038727	3.337684	0.011929	8.900491	1.112561	0.150308
11	6.742414	2.68E-03	8.073376	0.160334	0.01302	8.63E-04	3.837629	0	0.036752	3.292439	5.97E-03	8.779838	1.09748	0.163484
12	5.842391	2.66E-03	7.097808	0.141226	0.012086	8.23E-04	3.861796	0	0.035528	3.247808	2.98E-03	8.66082	1.082603	0.176276
13	5.201413	2.64E-03	6.573082	0.131036	0.011331	7.87E-04	3.885689	0	0.034684	3.203781	1.49E-03	8.543415	1.067927	0.188691
14	4.742005	2.62E-03	6.269574	0.125196	0.010821	7.54E-04	3.909322	0	0.034032	3.16035	7.46E-04	8.4276	1.05345	0.200738
15	4.409912	2.61E-03	6.075895	0.121498	0.010448	7.23E-04	3.932699	0	0.03348	3.117508	3.73E-04	8.313355	1.039169	0.212422
16	4.167123	2.59E-03	5.937497	0.118863	0.010171	6.96E-04	3.955825	0	0.032981	3.075247	1.87E-04	8.200658	1.025082	0.223753
17	3.987001	2.57E-03	5.827437	0.116767	9.96E-03	6.71E-04	3.978703	0	0.032511	3.033558	9.33E-05	8.089488	1.011186	0.234738
18	3.850878	2.55E-03	5.732296	0.114947	9.80E-03	6.47E-04	4.001335	0	0.032059	2.992434	4.67E-05	7.979825	0.997478	0.245384
19	3.74567	2.54E-03	5.645338	0.113275	9.67E-03	6.26E-04	4.023723	0	0.031619	2.951868	2.33E-05	7.871648	0.983956	0.255698
20	3.662207	2.52E-03	5.563148	0.111687	9.56E-03	6.07E-04	4.045868	0	0.031187	2.911851	1.17E-05	7.764936	0.970617	0.265687
21	3.594063	2.50E-03	5.483975	0.110151	9.48E-03	5.89E-04	4.067773	0	0.030763	2.872377	5.84E-06	7.659671	0.957459	0.275359
22	3.536733	2.48E-03	5.406908	0.108652	9.40E-03	5.72E-04	4.08944	0	0.030346	2.833437	2.92E-06	7.555832	0.944479	0.284719
23	3.487059	2.47E-03	5.331463	0.10718	9.33E-03	5.57E-04	4.11087	0	0.029934	2.795025	1.46E-06	7.4534	0.931675	0.293775
24	3.442828	2.45E-03	5.257376	0.105732	9.27E-03	5.43E-04	4.132065	0	0.029528	2.757134	7.30E-07	7.352356	0.919045	0.302533
25	3.402489	2.43E-03	5.184496	0.104306	9.21E-03	5.30E-04	4.153026	0	0.029127	2.719756	3.65E-07	7.252682	0.906585	0.311
26	3.364954	2.42E-03	5.112734	0.102899	9.15E-03	5.18E-04	4.173757	0	0.028732	2.682884	1.83E-07	7.154358	0.894295	0.319181
27	3.32946	2.40E-03	5.042033	0.101513	9.10E-03	5.07E-04	4.194257	0	0.028343	2.646513	9.13E-08	7.057367	0.882171	0.327084
28	3.295474	2.38E-03	4.972353	0.100145	9.04E-03	4.96E-04	4.21453	0	0.027959	2.610634	4.57E-08	6.96169	0.870211	0.334713
29	3.262619	2.37E-03	4.903665	0.098796	8.99E-03	4.87E-04	4.234577	0	0.02758	2.575241	2.28E-08	6.86731	0.858414	0.342076
30	3.230632	2.35E-03	4.835947	0.097465	8.94E-03	4.78E-04	4.254399	0	0.027206	2.540328	1.14E-08	6.774208	0.846776	0.349177
31	3.199329	2.34E-03	4.76918	0.096152	8.89E-03	4.69E-04	4.273998	0	0.026837	2.505888	5.71E-09	6.682369	0.835296	0.356023
32	3.16858	2.32E-03	4.703345	0.094857	8.84E-03	4.61E-04	4.293377	0	0.026473	2.471915	2.86E-09	6.591774	0.823972	0.362619
33	3.138293	2.30E-03	4.638429	0.09358	8.80E-03	4.54E-04	4.312536	0	0.026114	2.438402	1.43E-09	6.502406	0.812801	0.368971
34	3.108404	2.29E-03	4.574416	0.09232	8.75E-03	4.47E-04	4.331478	0	0.02576	2.405344	7.15E-10	6.41425	0.801781	0.375083
35	3.078868	2.27E-03	4.511293	0.091077	8.70E-03	4.41E-04	4.350204	0	0.025411	2.372733	3.57E-10	6.327289	0.790911	0.380962
36	3.049652	2.26E-03	4.449047	0.08985	8.65E-03	4.34E-04	4.368716	0	0.025066	2.340565	1.79E-10	6.241506	0.780188	0.386613
37	3.020733	2.24E-03	4.387665	0.088641	8.61E-03	4.29E-04	4.387016	0	0.024727	2.308832	8.94E-11	6.156885	0.769611	0.392041
38	2.992095	2.23E-03	4.327134	0.087447	8.56E-03	4.23E-04	4.405104	0	0.024391	2.277529	4.47E-11	6.073412	0.759176	0.39725
39	2.963726	2.21E-03	4.267443	0.08627	8.51E-03	4.18E-04	4.422984	0	0.024061	2.246651	2.24E-11	5.991069	0.748884	0.402246
40	2.935618	2.20E-03	4.20858	0.085109	8.47E-03	4.13E-04	4.440656	0	0.023734	2.216191	1.12E-11	5.909843	0.73873	0.407033
41	2.907763	2.18E-03	4.150533	0.083963	8.42E-03	4.08E-04	4.458123	0	0.023413	2.186144	5.59E-12	5.829717	0.728715	0.411617
42	2.880157	2.17E-03	4.093291	0.082833	8.38E-03	4.04E-04	4.475386	0	0.023095	2.156504	2.80E-12	5.750678	0.718835	0.416002
43	2.852796	2.15E-03	4.036842	0.081718	8.33E-03	4.00E-04	4.492446	0	0.022782	2.127266	1.40E-12	5.672709	0.709089	0.420191
44	2.825677	2.14E-03	3.981176	0.080619	8.29E-03	3.95E-04	4.509305	0	0.022473	2.098424	6.99E-13	5.595798	0.699475	0.424191
45	2.798798	2.12E-03	3.926281	0.079534	8.24E-03	3.91E-04	4.525965	0	0.022168	2.069973	3.50E-13	5.519928	0.689991	0.428005
46	2.772155	2.11E-03	3.872147	0.078464	8.20E-03	3.88E-04	4.542428	0	0.021868	2.041908	1.75E-13	5.445087	0.680636	0.431638
47	2.745748	2.09E-03	3.818764	0.077408	8.15E-03	3.84E-04	4.558695	0	0.021571	2.014223	8.75E-14	5.37126	0.671408	0.435093
48	2.719575	2.08E-03	3.76612	0.076367	8.11E-03	3.80E-04	4.574767	0	0.021279	1.986913	4.37E-14	5.298434	0.662304	0.438376
49	2.693633	2.07E-03	3.714207	0.075339	8.07E-03	3.77E-04	4.590647	0	0.02099	1.959973	2.19E-14	5.226595	0.653324	0.441489
50	2.667922	2.05E-03	3.663012	0.074326	8.02E-03	3.74E-04	4.606336	0	0.020706	1.933398	1.09E-14	5.155729	0.644466	0.444437
51	2.64244	2.04E-03	3.612527	0.073326	7.98E-03	3.70E-04	4.621835	0	0.020425	1.907184	5.47E-15	5.085824	0.635728	0.447224
52	2.617185	2.02E-03	3.562742	0.07234	7.94E-03	3.67E-04	4.637146	0	0.020148	1.881325	2.74E-15	5.016856	0.627108	0.449854
53	2.592157	2.01E-03	3.513647	0.071367	7.89E-03	3.64E-04	4.652271	0	0.019875	1.855816	1.37E-15	4.948843	0.618605	0.45233
54	2.567353	2.00E-03	3.465232	0.070408	7.85E-03	3.61E-04	4.667211	0	0.019605	1.830653	6.84E-16	4.881742	0.610218	0.454657
55	2.542772	1.98E-03	3.417489	0.069461	7.81E-03	3.58E-04	4.681968	0	0.01934	1.805832	3.42E-16	4.815551	0.601944	0.456837
56	2.518413	1.97E-03	3.370406	0.068527	7.77E-03	3.55E-04	4.696543	0	0.019077	1.781346	1.71E-16	4.750256	0.593782	0.458874
57	2.494274	1.96E-03	3.323977	0.067606	7.73E-03	3.53E-04	4.710938	0	0.018819	1.757193	8.56E-17	4.685847	0.585731	0.460772
58	2.470355	1.94E-03	3.278191	0.066697	7.69E-03	3.50E-04	4.725155	0	0.018564	1.733366	4.28E-17	4.62231	0.577789	0.462534
59	2.446653	1.93E-03	3.233039	0.065801	7.64E-03	3.47E-04	4.739194	0	0.018312	1.709863	2.14E-17	4.559635	0.569954	0.464164
60	2.423168	1.92E-03	3.188513	0.064917	7.60E-03	3.45E-04	4.753058	0	0.018064	1.686678	1.07E-17	4.497809	0.562226	0.465664
61	2.399897	1.91E-03	3.144604	0.064044	7.56E-03	3.42E-04	4.766748	0	0.017819	1.663808	5.36E-18	4.436821	0.554603	0.467038
62	2.37684	1.89E-03	3.101304	0.063184	7.52E-03	3.40E-04	4.780265	0	0.017577	1.641248	2.68E-18	4.37666	0.547083	0.468292
63	2.353995	1.88E-03	3.058604	0.062335	7.48E-03	3.37E-04	4.793611	0	0.017339	1.618993	1.34E-18	4.317315	0.539664	0.469421
64	2.33136	1.87E-03	3.016495	0.061497	7.44E-03	3.35E-04	4.806787	0	0.017104	1.59704	6.70E-19	4.258773	0.532347	0.470436
65	2.308935	1.86E-03	2.97497	0.060671	7.41E-03	3.32E-04	4.819795	0	0.016872	1.575384	3.35E-19	4.201025	0.525128	0.471337
66	2.286718	1.84E-03	2.934021	0.059856	7.37E-03	3.30E-04	4.832637	0	0.016643	1.554023	1.68E-19	4.14405	0.518008	0.472127
67	2.264708	1.83E-03	2.893639	0.059052	7.33E-03	3.28E-04	4.845313	0	0.016417	1.53295	8.38E-20	4.087867	0.510983	0.472809
68	2.242902	1.82E-03	2.853816	0.058259	7.29E-03	3.25E-04	4.857825	0	0.016195	1.512163	4.19E-20	4.032436	0.504054	0.473385
69	2.2213	1.81E-03	2.814543	0.057477	7.25E-03	3.23E-04	4.870175	0	0.015975	1.491658	2.10E-20	3.977756	0.497219	0.473859
70	2.1999	1.80E-03	2.775819	0.056705	7.21E-03	3.21E-04	4.882364	0	0.015758	1.471431	1.05E-20	3.923817	0.490477	0.474233
71	2.178701	1.78E-03	2.737629	0.055944	7.18E-03	3.19E-04	4.894394	0	0.015545	1.451479	5.24E-21	3.87061	0.483826	0.474509

Appendix A6: Stella II generated output file acute scenario #3 (Excel format)

Days	Blood Pu241	Blood Am241	Feces Pu241	Feces Am241	Urine Pu241	Urine Am241	Liver Am241	c 2	d 2	e 2	f 2	g 2	h 2	i 2
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	389.700613	0.100411	714.75968	14.333265	0.451277	0.017158	6.01193	0	3.382893	7.547809	12.191357	20.12749	2.515936	0.025998
2	201.084117	0.042092	1,402.63	28.061879	0.234051	8.08E-03	6.77357	0	1.611929	7.445497	6.096991	19.85466	2.481832	0.060052
3	122.089782	0.019686	1,021.96	20.432915	0.144819	4.71E-03	7.098896	0	0.841192	7.344572	3.049151	19.585527	2.448191	0.093177
4	81.919361	0.011044	568.455286	11.357937	0.100367	3.31E-03	7.256382	0	0.458824	7.245015	1.524903	19.32004	2.415005	0.125393
5	58.077373	7.69E-03	289.60906	5.780536	0.074342	2.69E-03	7.348929	0	0.267193	7.146807	0.762616	19.058151	2.382269	0.156719
6	42.57721	6.37E-03	146.079142	2.911316	0.057536	2.37E-03	7.41609	0	0.170849	7.049929	0.38139	18.79981	2.349976	0.187172
7	32.041657	5.83E-03	76.585427	1.523405	0.046142	2.17E-03	7.473105	0	0.122162	6.954364	0.190736	18.54497	2.318121	0.216771
8	24.735415	5.60E-03	43.475587	0.86315	0.038242	2.03E-03	7.525861	0	0.097315	6.860094	0.095388	18.293583	2.286698	0.245533
9	19.621641	5.48E-03	27.638761	0.548093	0.032706	1.91E-03	7.576636	0	0.084399	6.767101	0.047704	18.045603	2.2557	0.273475
10	16.024523	5.42E-03	19.956255	0.395801	0.028804	1.81E-03	7.626319	0	0.077454	6.675368	0.023857	17.800982	2.225123	0.300615
11	13.484828	5.37E-03	16.146751	0.320668	0.02604	1.73E-03	7.675258	0	0.073504	6.584879	0.011931	17.559676	2.19496	0.326969
12	11.684781	5.33E-03	14.195616	0.282452	0.024072	1.65E-03	7.723592	0	0.071057	6.495615	5.97E-03	17.32164	2.165205	0.352553
13	10.402827	5.29E-03	13.146163	0.262073	0.022662	1.57E-03	7.771379	0	0.069368	6.407561	2.98E-03	17.086829	2.135854	0.377383
14	9.48401	5.25E-03	12.539147	0.250393	0.021642	1.51E-03	7.818643	0	0.068065	6.3207	1.49E-03	16.855201	2.1069	0.401475
15	8.819825	5.21E-03	12.15179	0.242995	0.020896	1.45E-03	7.865398	0	0.066961	6.235016	7.46E-04	16.626711	2.078339	0.424845
16	8.334247	5.18E-03	11.874995	0.237727	0.020342	1.39E-03	7.91165	0	0.065962	6.150494	3.73E-04	16.401317	2.050165	0.447507
17	7.974002	5.14E-03	11.654873	0.233533	0.019923	1.34E-03	7.957406	0	0.065023	6.067116	1.87E-04	16.178977	2.022372	0.469477
18	7.701755	5.11E-03	11.464592	0.229893	0.019598	1.29E-03	8.00267	0	0.064119	5.984869	9.34E-05	15.95965	1.994956	0.490768
19	7.491339	5.07E-03	11.290676	0.22655	0.01934	1.25E-03	8.047445	0	0.063238	5.903736	4.67E-05	15.743295	1.967912	0.511396
20	7.324414	5.04E-03	11.126296	0.223374	0.019129	1.21E-03	8.091736	0	0.062375	5.823702	2.33E-05	15.529872	1.941234	0.531375
21	7.188126	5.00E-03	10.96795	0.220303	0.018951	1.18E-03	8.135547	0	0.061527	5.744753	1.17E-05	15.319342	1.914918	0.550718
22	7.073465	4.97E-03	10.813817	0.217303	0.018796	1.14E-03	8.17888	0	0.060691	5.666874	5.84E-06	15.111664	1.888958	0.569439
23	6.974117	4.93E-03	10.662927	0.21436	0.018658	1.11E-03	8.221739	0	0.059868	5.59005	2.92E-06	14.9068	1.86335	0.587551
24	6.885656	4.90E-03	10.514752	0.211464	0.018531	1.09E-03	8.264129	0	0.059056	5.514267	1.46E-06	14.704713	1.838089	0.605067
25	6.804977	4.87E-03	10.368993	0.208611	0.018412	1.06E-03	8.306052	0	0.058255	5.439511	7.30E-07	14.505364	1.81317	0.622
26	6.729908	4.83E-03	10.225468	0.205799	0.0183	1.04E-03	8.347513	0	0.057465	5.365769	3.65E-07	14.308716	1.78859	0.638363
27	6.658921	4.80E-03	10.084065	0.203025	0.018192	1.01E-03	8.388514	0	0.056686	5.293025	1.83E-07	14.114734	1.764342	0.654168
28	6.590948	4.77E-03	9.944705	0.20029	0.018087	9.92E-04	8.42906	0	0.055917	5.221267	9.14E-08	13.92338	1.740422	0.669427
29	6.525238	4.74E-03	9.80733	0.197592	0.017985	9.73E-04	8.469153	0	0.055159	5.150482	4.57E-08	13.734619	1.716827	0.684151
30	6.461265	4.70E-03	9.671894	0.19493	0.017884	9.55E-04	8.508798	0	0.054411	5.080656	2.28E-08	13.548417	1.693552	0.698354
31	6.398659	4.67E-03	9.538359	0.192304	0.017785	9.38E-04	8.547997	0	0.053674	5.011777	1.14E-08	13.364737	1.670592	0.712046
32	6.33716	4.64E-03	9.406691	0.189715	0.017687	9.23E-04	8.586754	0	0.052946	4.94383	5.71E-09	13.183547	1.647943	0.725238
33	6.276586	4.61E-03	9.276858	0.18716	0.017591	9.08E-04	8.625073	0	0.052228	4.876805	2.86E-09	13.004813	1.625602	0.737941
34	6.216809	4.58E-03	9.148833	0.184639	0.017495	8.94E-04	8.662956	0	0.05152	4.810688	1.43E-09	12.8285	1.603563	0.750167
35	6.157736	4.54E-03	9.022587	0.182153	0.017399	8.81E-04	8.700408	0	0.050822	4.745467	7.15E-10	12.654577	1.581822	0.761925
36	6.099304	4.51E-03	8.898094	0.1797	0.017305	8.69E-04	8.737432	0	0.050133	4.681129	3.57E-10	12.483011	1.560376	0.773227
37	6.041466	4.48E-03	8.77353	0.177281	0.017211	8.57E-04	8.774031	0	0.049453	4.617664	1.79E-10	12.313771	1.539221	0.784082
38	5.984191	4.45E-03	8.654269	0.174894	0.017118	8.46E-04	8.810209	0	0.048783	4.555059	8.94E-11	12.146823	1.518353	0.7945
39	5.927453	4.42E-03	8.534887	0.17254	0.017025	8.36E-04	8.845968	0	0.048121	4.493302	4.47E-11	11.982139	1.497767	0.804492
40	5.871236	4.39E-03	8.41716	0.170217	0.016933	8.26E-04	8.881313	0	0.047469	4.432382	2.24E-11	11.819686	1.477461	0.814067
41	5.815526	4.36E-03	8.301066	0.167926	0.016842	8.17E-04	8.916246	0	0.046825	4.372288	1.12E-11	11.659435	1.457429	0.823234
42	5.760314	4.33E-03	8.186582	0.165666	0.016751	8.08E-04	8.950771	0	0.04619	4.313008	5.59E-12	11.501356	1.437669	0.832003
43	5.705592	4.30E-03	8.073684	0.163437	0.016661	7.99E-04	8.984891	0	0.045564	4.254532	2.80E-12	11.345419	1.418177	0.840383
44	5.651354	4.27E-03	7.962352	0.161237	0.016571	7.91E-04	9.01861	0	0.044946	4.196848	1.40E-12	11.191595	1.398949	0.848382
45	5.597595	4.25E-03	7.852562	0.159068	0.016482	7.83E-04	9.05193	0	0.044337	4.139946	7.00E-13	11.039856	1.379982	0.85601
46	5.544311	4.22E-03	7.744295	0.156927	0.016393	7.75E-04	9.084856	0	0.043736	4.083815	3.50E-13	10.890174	1.361272	0.863276
47	5.491497	4.19E-03	7.637528	0.154816	0.016305	7.68E-04	9.117389	0	0.043143	4.028445	1.75E-13	10.74252	1.342815	0.870186
48	5.43915	4.16E-03	7.532241	0.152733	0.016217	7.61E-04	9.149534	0	0.042558	3.973825	8.75E-14	10.596868	1.324608	0.876751
49	5.387267	4.13E-03	7.428413	0.150679	0.01613	7.54E-04	9.181294	0	0.041981	3.919946	4.38E-14	10.45319	1.306649	0.882978
50	5.335844	4.10E-03	7.326024	0.148652	0.016044	7.47E-04	9.212671	0	0.041412	3.866797	2.19E-14	10.311458	1.288932	0.888874
51	5.28488	4.08E-03	7.225055	0.146653	0.015958	7.41E-04	9.24367	0	0.04085	3.814368	1.09E-14	10.171648	1.271456	0.894448
52	5.234371	4.05E-03	7.125484	0.14468	0.015873	7.35E-04	9.274292	0	0.040296	3.76265	5.47E-15	10.033733	1.254217	0.899708
53	5.184313	4.02E-03	7.027294	0.142735	0.015788	7.28E-04	9.304542	0	0.03975	3.711633	2.74E-15	9.897687	1.237211	0.90466
54	5.134705	3.99E-03	6.930465	0.140816	0.015703	7.22E-04	9.334422	0	0.039211	3.661307	1.37E-15	9.763485	1.220436	0.909313
55	5.085543	3.97E-03	6.834977	0.138922	0.01562	7.17E-04	9.363936	0	0.038679	3.611663	6.85E-16	9.631102	1.203888	0.913673
56	5.036826	3.94E-03	6.740813	0.137055	0.015536	7.11E-04	9.393087	0	0.038155	3.562692	3.42E-16	9.500513	1.187564	0.917748
57	4.988549	3.92E-03	6.647954	0.135212	0.015454	7.05E-04	9.421877	0	0.037637	3.514385	1.71E-16	9.371694	1.171462	0.921544
58	4.94071	3.89E-03	6.556381	0.133395	0.015371	7.00E-04	9.45031	0	0.037127	3.466733	8.56E-17	9.244621	1.155578	0.925068
59	4.893306	3.86E-03	6.466078	0.131602	0.01529	6.95E-04	9.478388	0	0.036624	3.419726	4.28E-17	9.11927	1.139909	0.928327
60	4.846335	3.84E-03	6.377026	0.129833	0.015209	6.89E-04	9.506116	0	0.036127	3.373357	2.14E-17	8.995619	1.124452	0.931328
61	4.799794	3.81E-03	6.289209	0.128088	0.015128	6.84E-04	9.533495	0	0.035637	3.327616	1.07E-17	8.873643	1.109205	0.934077
62	4.75368	3.79E-03	6.202608	0.126367	0.015048	6.79E-04	9.560529	0	0.035154	3.282495	5.36E-18	8.753321	1.094165	0.93658
63	4.70799	3.76E-03	6.117208	0.124669	0.014969	6.74E-04	9.587221	0	0.034677	3.237986	2.68E-18	8.634629	1.079329	0.938843
64	4.662721	3.74E-03	6.03299	0.122995	0.01489	6.69E-04	9.613574	0	0.034207	3.19408	1.34E-18	8.517546	1.064693	0.940872
65	4.617871	3.71E-03	5.94994	0.121342	0.014811	6.65E-04	9.63959	0	0.033743	3.150769	6.70E-19	8.402051	1.050256	0.942674
66	4.573437	3.69E-03	5.868041	0.119713	0.014733	6.60E-04	9.665273	0	0.033286	3.108045	3.35E-19	8.28812	1.036015	0.944254
67	4.529415	3.66E-03	5.787277	0.118105	0.014656	6.55E-04	9.690626	0	0.032834	3.0659	1.68E-19	8.175734	1.021967	0.945617
68	4.485804	3.64E-03	5.707632	0.116519	0.014579	6.51E-04	9.71565	0	0.032389	3.024327	8.38E-20	8.064872	1.008109	0.94677
69	4.4426	3.61E-03	5.629091	0.114954	0.014502	6.46E-04	9.740351	0	0.03195	2.983317	4.19E-20	7.955512	0.994439	0.947718
70	4.3998	3.59E-03	5.551638	0.113411	0.014426	6.42E-04	9.764729	0	0.031517	2.942863	2.10E-20	7.847634	0.980954	0.948466
71	4.357402	3.57E-03	5.475258	0.111888	0.014351	6.37E-04	9.788788	0	0.031089	2.902957	1.05E-20	7.741219	0.967652	0.949019
72	4.315403	3.54E-03	5.399936	0.110386	0.014276	6.33E-04	9.812531	0	0.030668	2.863592	5.24E-21	7.636246	0.954531	0.949383

Vita

Alfred Rybka was born in Nidiza Poland (formerly Eastern Prussia, Germany) on August 3, 1995. He attended elementary middle and main school until 1970, then entered a 3.5-year coop-vocational program-between Veba Chemie AG, Herne, Germany and Technical Professional School Bochum, Germany for the training of chemical laboratory technician. After completion of vocational training and board certification, he continued being employed by Veba Chemie AG in a pilot miniature chemical plant for photo chemicals. He returned to Technical Highschool in Bochum, Germany, to complete the requirements for entrance of university studies. After graduation in 1976, he entered The University of Essen, Germany, majoring in physics, and in 1979 The University of Stockholm, Sweden, where after language studies he studied chemistry. In 1980, he came to the United States of America and enrolled in course work at Roane State Community College, Harriman, Tennessee. In 1982, he entered the University of Tennessee, where in December 1989 he received the Bachelor of Science in Mathematics with a concentration in Applied Mathematics/Numerical Mathematics. Since 1984 he has been employed at EG&G ORTEC as a Germanium Detector Engineer (solid state radiation detection). In 1991, he entered the Master's program in Nuclear Engineering. Although initially concentrating in the area of Radiation Protection the course work was expanded to include traditional nuclear engineering courses as well as nuclear criticality safety. The Master of Science degree was received in August 1997.