

APPENDIX A

EXAMPLE OF USE AND VERIFICATION BASED ON ACTUAL EXPERIENCES

1. INTRODUCTION

Bioassay models may be tested by comparing calculated estimates of excreted radionuclides with bioassay measurement results obtained from actual workers who have been accidentally contaminated.

Because the excretion of radionuclides may be influenced by diet, the health condition of the worker, age and level of physical and metabolic activity, and voiding frequency, variation from predicted results and individual variability should be expected.

There are other possible reasons for actual bioassay data to vary from expected results. Several simplifying assumptions are used in bioassay models, e.g. the lung clearance classifications (D, W, and Y) are known, and particle size distributions have a characteristic 1.0 micrometer activity median aerodynamic diameter. The solubility of the inhaled radionuclide and the actual particle size distribution are often not known. The time at which a urine or fecal sample was obtained may not have been well-documented. Additionally, it may not be known whether the sample represents a complete or partial sample. In the general evaluation of bioassay results, assumptions regarding volume of urine excreted per day or total mass of feces excreted per day may be necessary due to the lack of specific detail. Using Reference Man (ICRP74) one assumes a daily urinary excretion of 1.4 L/day and a mass of fecal excretion of 135 g/day.

Some of the examples in the following sections have been modified so that specific persons cannot be identified with specific times or places. On the other hand, the measurements are real and reflect the uncertainty associated with the interpretation of bioassay measurements.

2. INHALATION OF CLASS D URANIUM

An accident happened and some UF_6 was accidentally released from Sequoyah Fuels Corporation's Facility at Gore, Oklahoma. In order to assess the public health impact associated with it, urine samples were collected and analyzed for uranium. The results showed the maximum uranium intake among on-site workers was approximately 28 mg (AHIPHATF86). The estimated effective dose equivalent for this worker was approximately 0.46 mSv (46 mrem). The dose to the maximally exposed off-site individual, based on uranium bioassay measurements, was calculated to be 0.014 mSv (1.4 mrem). The potential dose to a maximally exposed off-site resident based on source term and plume modeling calculations was 0.022 mSv (2.2 mrem). These radiological doses are insignificant compared with the background radiation of 1.06 mSv/yr (106 mrem/yr) in the area.

The following is an example showing how to use tables presented here to assess the intake for three people, whose urine samples were collected and measured.

From the tabulation for Class D inhalation of uranium, obtain the fractional values of intake in accumulated urine. Decay correction is not necessary because of the very long halflives of U-234, U-235 and U-238. Calculate the accumulated U in urine excreta as follows:

$$\Delta t_i = t_i - t_{i-1} \quad (A.2.1)$$

$$\Delta A_i = C_i \times 1.4 \text{ L/day} \times \Delta t_i \quad (A.2.2)$$

$$A_i = \Delta A_1 + \Delta A_2 + \dots + \Delta A_i \quad (A.2.3)$$

where:

- i = sequence number of sample,
- t_i = time post intake for i th sampling (days),
- C_i = concentration of uranium in urine from i^{th} sampling (μg uranium per liter),
- ΔA_i = uranium in i^{th} urine sample (μg uranium),
- A_i = uranium in accumulated urine up to time = t_i (μg uranium),
- and 1.4 L/day is the daily urine volume for Reference Man.

The best estimate of the intake is:

$$I = \frac{\sum_i r_i A_i}{\sum_i r_i} \quad (A.2.4)$$

where:

- I = best estimate of intake in μg (or Bq for radioactivity),
- A_i = sample measurement, μg (or Bq for radioactivity),
- r_i = fraction of intake in accumulated urine at time of i^{th} sampling.

Values of r_i , for sampling times shown in Table A.2, were obtained from the Table on page B-163. The results can be seen in Table A.2. Some sampling times are not listed on page B-163 and values for r_i were determined from equation 2.5.1 for these times.

Table A.2 Example of Intake Estimates Based on Measurements of Uranium in Urine

Individual Number	Time of Sample Post Intake, t_i (days)	Conc. Of Uranium in Urine, C_i ($\mu\text{g/l}$)	Calculated Frac. of Intake in Accum. Urine, r_i	Estimated Value of Uranium in Accum. Urine, A_i (μg)	Best Estimate of Intake, I (μg)
1	0.20	6,100	0.0500	1,700	
1	0.60	990	0.132	2,300	
1	2.0	90	0.259	2,500	
1	3.0	210	0.291	2,700	1.1E04
2	0.20	9,600	0.0500	2,700	
2	0.40	2,600	0.0950	3,400	
2	0.80	1,300	0.162	4,100	
2	2.8	220	0.287	4,700	2.1E04
3	0.36	540	0.0867	270	
3	0.50	310	0.114	330	
3	0.65	110	0.140	350	
3	2.0	8	0.259	370	
3	2.8	12	0.287	380	1.7E03

Values for the best estimate of intake were based on the minimum value of the chi-squared statistic, X^2 , which is defined as the ratio of the sum of the squares of the differences between measured values, A_i , and expectation values, $\langle r_i I \rangle$, and the variance, δ_i^2 . Thus,

$$X^2 = \sum (A_i - \langle r_i I \rangle)^2 / \delta_i^2, \text{ and}$$

$$\frac{dX^2}{dI} = 0,$$

and for constant variance, equation A.2.4 is the result. Values measured for individual number 2 have been plotted versus calculated values in Figure A.2.1. The calculated mass of natural uranium in urinary excreta was determined by multiplying the best estimate of intake by the fraction of intake in accumulated urine.

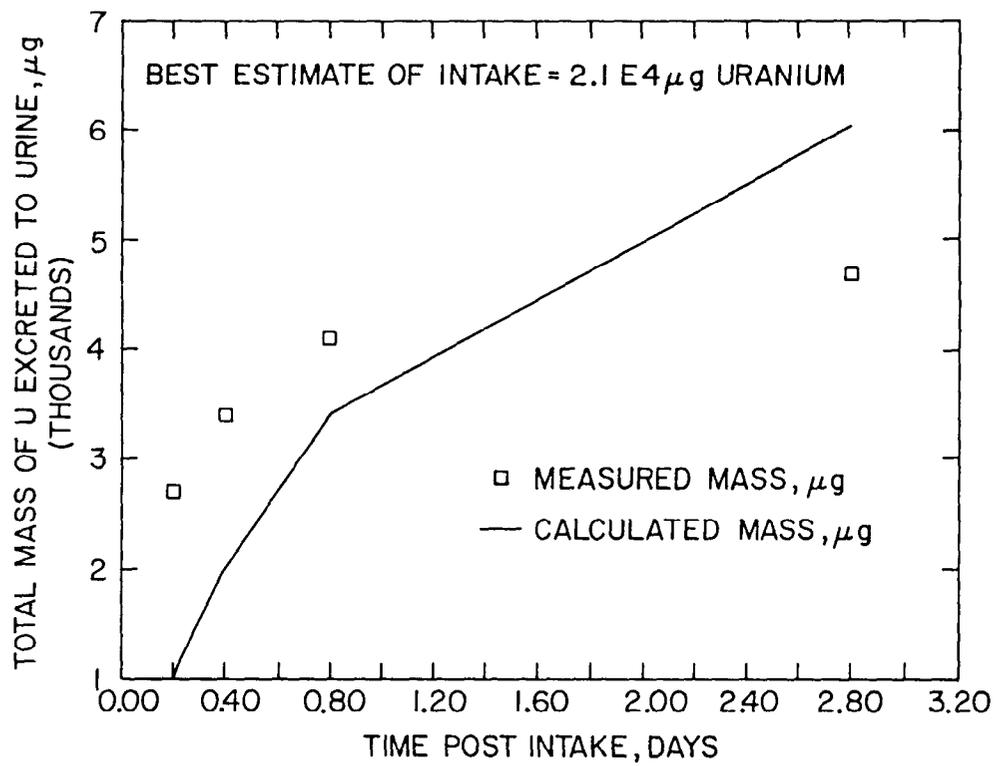


FIGURE A.2.1 Calculated and Measured Values for Uranium Excreted to Urine from Individual Number 2 Following Inhalation of Uranium Hexafluoride.

3. INHALATION OF CLASS D Cs-137 and CLASS W Co-60

Through routine whole-body counting of personnel at a national laboratory, workers were found with detectable body burdens of both Cs-137 and Co-60. Monitoring was at one year intervals; thus, we assumed the intake occurred just after the last monitoring, or one year previous to sampling.

The whole-body monitoring results were as follows:

<u>Case</u>	<u>Incorporated Nuclide (Amount)</u>
1	Cs-137 (52 Bq) ; Co-60 (192 Bq)
2	Cs-137 (133 Bq) ; Co-60 (48 Bq)

From the Class D and Class W tables (pages B-111 and B-212), the total body retention fractions for Cs-137 and Co-60, respectively are 5.93×10^{-2} and 1.30×10^{-2} . Class W was assumed for Co-60 because the associated committed effective dose equivalent was greater than that computed by assuming Class Y. The retention fraction at 365 days post intake was obtained from interpolation between the values tabulated for 300 and 400 days.

The estimated intakes are as follows:

<u>Case</u>	<u>Estimated Intake</u>
1	$192 / (1.30 \times 10^{-2}) = 14,800 \text{ Bq for Co-60}$ $52 / (5.93 \times 10^{-2}) = 878 \text{ Bq for Cs-137}$
2	$48 / (1.30 \times 10^{-2}) = 3,700 \text{ Bq for Co-60}$ $133 / (5.93 \times 10^{-2}) = 2,240 \text{ Bq for Cs-137}$

The stochastic ALI values for the inhalation of Class W Co-60 and Class D Cs-137 are both $6 \times 10^6 \text{ Bq}$. Thus, estimates of the committed effective dose equivalent are:

<u>Case</u>	<u>Estimated Committed Effective Dose Equivalent</u>
1	$\left(\frac{878}{6.0\text{E}+06} + \frac{14,800}{6.0\text{E}+06} \right) \times 0.05 \text{ Sv} = 1.3\text{E}-04\text{Sv} (0.013 \text{ rem})$
2	$\left(\frac{2,240}{6.0\text{E}+06} + \frac{3,700}{6.0\text{E}+06} \right) \times 0.05 \text{ Sv} = 4.95\text{E}-05\text{Sv} (0.0050 \text{ rem})$

Because of the conservative assumptions about the time of intake, doses are probably less than the estimates above.

4. RADIOIODINE INGESTION AND INHALATION

Case I: Ingestion of I-131

A known amount of I-131 was given to a patient for diagnostic purposes (Li86). The patient was found to have normal thyroid function. On the 7th day after iodine administration, bioassay was started and included in vivo measurements and analysis of the nuclide concentration in urine samples. Experimental data from the patient are shown in Table A.4.1, together with the Appendix B intake retention fractions.

Based on comparison of experimental and Appendix B IRFs, we conclude that the iodine models for ingestion and for systemic iodine incorporation are representative of the patient's metabolism of iodine. When monitoring is done through urine analysis, samples have to be repeated to reduce the uncertainty associated with normal fluctuations, which are expected due to daily differences in diet. Urine data were also influenced by the assumption of a 24-hour urinary volume of 1.4 liters. However, in vitro bioassay through urine analysis is a good method of detection of abnormal situations.

Table A.4.1 Comparison of Patient's Results with IRFs in Appendix B (p. B-587) for Iodine-131

Time After Intake days	Measured Fraction of Ingested Activity In:		Appendix B IRFs for I-131:	
	Total Body	24-Hour Urine	Total Body	24-Hour Urine
7	1.8E-01	-	1.63E-01	-
8	1.5E-01	3.9E-04	1.49E-01	2.93E-04
9	-	3.6E-04	-	2.99E-04
10	-	3.5E-04	-	2.99E-04
20	4.7E-02	1.3E-04	5.10E-02	2.00E-04
40	-	3.4E-05	-	4.32E-05

Case II: Accidental Overexposure by Inhalation

A worker involved in I-131 labeling of radiopharmaceutical substances was accidentally overexposed (Li85). This was detected by abnormally high concentrations of I-131 in urine samples which were collected on a bi-weekly basis. Due to a holiday, there was no work in the week when the sample was taken, thus exposure was assumed to have occurred ten days before. The accident was due to a problem in the exhaust of the evaporation box, and this was reported by the worker. Thereafter, the worker was restricted from working in the area where I-131 labeling was performed. Daily urinary samples were taken from day 16 to day 26 after the probable exposure. In vivo counting of the thyroid was performed on days 18 and 20. A summary of the results for the bioassay measurements is given in the Table A.4.2 together with the IRFs expected in urine and in the thyroid.

Table A.4.2 Bioassay Results and IRFs for Accidental Iodine-131 Inhalation

Time After Accident, Days	24-Hour Urine Bioassay Result, Bq	24-Hour Urine IRF, Appendix B	Thyroid Results, Bq	Thyroid IRF, Appendix B
10	1440	1.88 E-04		7.51 E-02
16	987	1.57 E-04*		
17	970	1.50 E-04*		
18	419	1.42 E-04*	4.81 E+05	3.55 E-02*
19	318	1.34 E-04*		
20	378	1.27 E-04	3.90 E+05	2.95 E-02
21	557	1.19 E-04*		
22	543	1.11 E-04*		
23	574	1.04 E-04*		
24	318	9.72 E-05*		
25	305	9.06 E-05*		
26	311	8.43 E-05*		
30		6.25 E-05		1.16 E-02

*Values obtained by interpolation of Appendix B (p. B-103) values

A best estimate of intake based on the urine bioassay results, which is given by equation A.2.4, yields an intake of $4.99 \text{ E}+06 \text{ Bq}$. A best estimate of intake based on thyroid measurements yields $1.34 \text{ E}+07 \text{ Bq}$. Intake based on urinary results is a factor of 2.7 lower than intake based on thyroid measurements. Calculated and measured values for I-131 in daily excreta are plotted in Figure A.4.1. Calculated values were obtained by multiplying $4.99 \text{ E}+06 \text{ Bq}$ by the IRF for 24-hour urinary excretion of I-131.

The early excreta measurement on day 10 tends to agree with intake based on thyroid counting. Variation may be due to dietary factors, radiation damage to the thyroid or biological variation of the individual; for example, the person may be iodine deficient. In this situation, intake should be based on thyroid measurements since radioactivity in the thyroid represents a large fraction of the intake and since thyroid dose equivalent dominates the effective dose equivalent. Thus, the best estimate of intake is $1.34 \text{ E}+07 \text{ Bq}$. The committed effective dose equivalent per unit of intake, from ICRP Publication 30, is $1.4\text{E}-08 \text{ Sv per Bq}$. Thus, the committed effective dose equivalent is $1.8\text{E}-01 \text{ Sv}$ ($1.8\text{E}+01 \text{ rem}$). However, in the case of I-131, the committed dose to the thyroid per unit of intake is given as $4.8\text{E}-07 \text{ Sv per Bq}$. Thus, the committed thyroid dose equivalent is 6.2 Sv (620 rem). Because the level of thyroid dose is high, medical follow-up is recommended since late effects such as hypothyroidism, thyroid adenoma, and thyroid cancer are possible but not highly probable 10 to 30 years after the exposure (Ad86, NCRP85).

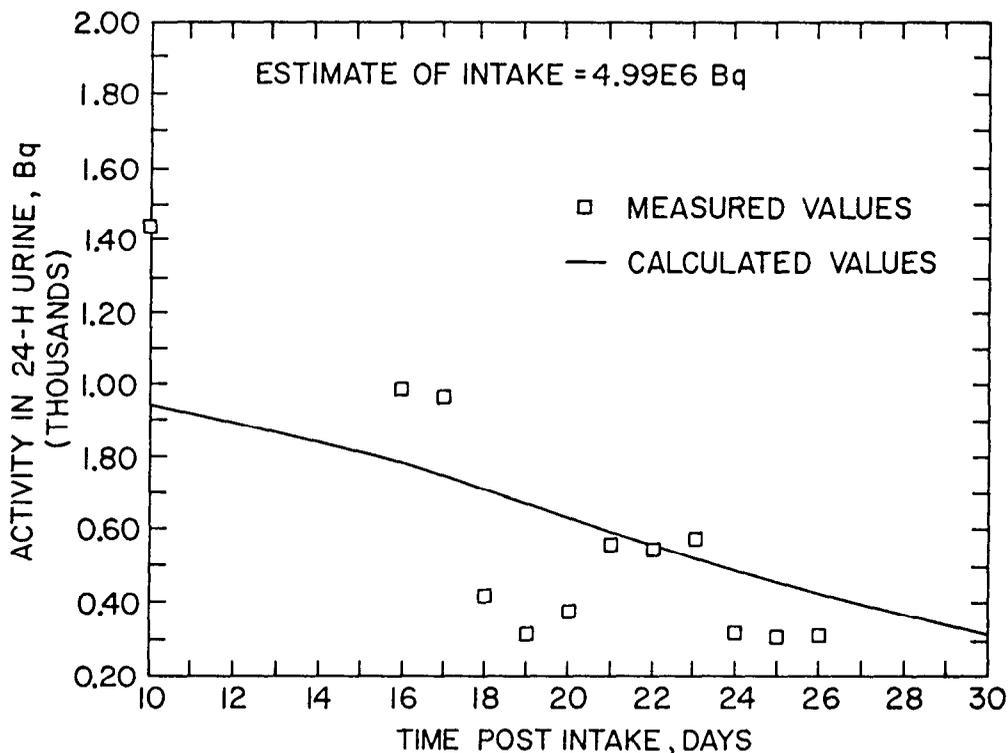


FIGURE A.4.1 Calculated and Measured Values for I-131 Activity in One Day Urine Samples for Worker in Case II. The Estimate of Intake is Based on Urinary Measurements Only.

Case III Unknown Day of Inhalation of I-131

In the same installation as in Case II, but two years later, routine bioassay monitoring showed the following on two workers:

Table A.4.3 I-131 Measurements on Two Workers

Date of Monitoring May	Activity in 24-Hour Urine, Bq Bq	Activity in Whole Body,
<u>Worker A</u>		
18		Background
22	3500	4,070
27	2.0	1,110
<u>Worker B</u>		
15	63	
22	4700	8,140
27	62	2,960
28	17	

We conclude, by comparing these results with IRFs from Appendix B (p. B-101, 103), that the probable time of the exposure of the two workers was between 1 and 2 days prior to the May 22 whole-body count. This conclusion came from analyses of the rate of disappearance of iodine. Results of the analyses are shown in Table A.4.4.

Table A.4.4 Determination of Unknown Time Post Intake of Iodine 131

Assumed Day Post Intake days	Date of Measurement	Worker A Ratio*	Worker B Ratio*	Appendix B IRF Ratio**
1	May 22	8.6 E-01	5.8 E-01	1.1 E+00
2	May 22	8.6 E-01	5.9 E-01	3.3 E-01
5	May 27	1.8 E-03	2.1 E-02	1.1 E-02
6	May 27	1.8 E-03	2.1 E-02	4.1 E-03

* $\frac{\text{24-hour urine activity}}{\text{whole-body activity}}$

** $\frac{\text{24-hour urine IRF}}{\text{whole-body IRF}}$

The counting error relative to the net count associated with the May 27 urine activity is greater than that associated with the May 22 measurements, thus the May 22 ratios may be more reliable indicators of time post intake. However, day to day variation in individual diet and urinary excretion will generally have greater impact on the result than does counting error.

These examples illustrate how well the IRFs from Appendix B represent iodine incorporation and excretion; although, there are some differences according to individual metabolism. Comparing the tables in Appendix B and the data from the workers, we conclude that for a single intake:

- (1) bioassay through urinalysis is a method that is truly capable of detecting abnormal exposures to I-131 if it is performed promptly after exposure since typical minimum detectable urine activity is on the order of 2 Bq (50 pCi) per liter for I-131,
- (2) in vivo monitoring is useful in order to detect exposures after a longer period of time since typical minimum detectable thyroid activity is on the order of 750 Bq (20 nCi) for I-131, and
- (3) in cases where exposure is detected by chance, from routine bioassay monitoring, it is useful to have both in vitro and in vivo results in order to determine when exposure took place.

5. INHALATION OF THORIUM AND URANIUM

Case I: Thorium

For thorium, the amount which is inhaled and subsequently excreted through the gastrointestinal tract is much greater than the amount excreted through the urine pathway. Additionally, the portion of intake that is cleared to the gastrointestinal tract is one that results from the non-systemic deposit. The annual limits on intake for Class W and Class Y 1 micrometer AMAD aerosols of thorium 232 are 40 Bq and 100 Bq, respectively. Examination of the IRFs in Appendix B provides the following insight into routine bioassay monitoring for inhalation of 1 ALI of thorium 232:

Table A.5.1 IRFs and Urine Activity Corresponding to 1 ALI of Thorium-232

Time After Intake days	Class W IRF 24-Hour Urine	Activity in 24-Hour Urine, Bq	Class Y IRF 24-Hour Urine	Activity in 24-Hour Urine, Bq
1	5.33E-03	2.13E-01	2.85E-04	2.85E-02
2	1.42E-03	5.68E-02	7.81E-05	7.81E-03
3	4.09E-04	1.64E-02	2.23E-05	2.23E-03
4	1.54E-04	6.16E-03	7.88E-06	7.88E-04
5	9.04E-05	3.62E-03	4.13E-06	4.13E-04

For single intake of 1 ALI of thorium 232, we conclude that bioassay through urine analyses is not suitable unless one collects the urine sample immediately following the accidental exposure. We also conclude that routine monitoring of occupationally exposed persons is not practical if one monitors urinary excretion of thorium since recording and investigation levels would be difficult to detect since the typical minimum detection limits for alpha counting is 4E-03 Bq (0.1 pCi) per liter of urine.

One approach to monitoring workers on a routine basis is to examine the feces for thorium 232. The minimum detection limit is on the order of 4E-03 Bq (0.1 pCi) per feces sample. An excretion corresponding to the ALI would be as follows:

Table A.5.2 IRFs and Feces Activity Corresponding to 1 ALI of Thorium-232

Time After Intake days	Class W IRF 24-Hour Feces	Activity in 24-Hour Feces, Bq	Class Y IRF 24-Hour Feces	Activity in 24-Hour Feces, Bq
1	4.22E-02	1.69E+00	5.10E-02	5.10E+00
2	1.35E-01	5.40E+00	1.57E-01	1.57E+01
3	1.14E-01	4.56E+00	1.28E-01	1.28E+00
4	6.65E-02	2.66E+00	7.23E-02	7.23E+00
5	3.42E-02	1.37E+00	3.59E-02	3.59E+00

As an example of occupational exposure, routine monitoring of exposed persons in a monazite plant produced the bioassay results which are in Table A.5.3.

Table A.5.3 Thorium Levels in Workers and the General Public

Exposed Group	Activity in 24-Hour Feces, Bq	Activity in 24-Hour Urine, Bq
Class W Exposure		
Worker #1	1.9E+00	7.0E-02
Worker #2	9.0E-01	1.3E-02
Class Y Exposure		
Worker #3	3.0E-01	7.0E-03
Worker #4	4.0E-02	below detection limit
Non-Exposed People, Sao Paulo, Brazil Mean	5.0E-03	3.0E-03

A problem with fecal monitoring is that in order to assess exposure to thorium 232, which has an ALI based on the 0.50 sv (50 rem) committed dose equivalent limit to bone surface, one must rely on measurements which reflect the non-systemic burden of thorium in the lungs. Urine sample results, which are given in the above example, are based on samples collected on the last day of the work week. If the radiation protection program is successful, urine bioassay should not show thorium 232 concentrations in urine significantly higher than detection limits and different from comparison samples from non-exposed persons.

Based on the 24-hour fecal measurement, an estimate of intake and committed effective dose equivalent can be assigned to the workers in Table A.5.3. Based on Table A.5.2, one would expect between 1.37 and 5.40 Bq in feces if a 40 Bq intake of thorium-232 occurred between 1 and 5 days prior to sampling, for Class W materials. Thus, worker #1 inhaled as little as 14 or as much as 55 Bq. His committed effective dose equivalent is bracketed between 0.02 Sv and 0.07 Sv. For worker #3, his intake ranged between 1.9 and 8 Bq and his committed effective dose equivalent ranged between 9.5E-04 Sv and 4.0E-03 Sv. Urinary measurements yield wider ranges of estimated intake and dose equivalent by an order of magnitude or better.

In vivo monitoring relies on measurements of nuclides at the end of the thorium series, mainly thalium 208, thus requiring an estimate of intake of all daughters including radon 220. Therefore, the algorithm used to interpret results of in vivo measurements is complex, and variation in particle size and the behavior of daughter nuclides would compound the uncertainties which are associated with intake and dose equivalent estimates for thorium. Thus, while fecal monitoring is not an appropriate way to estimate the thorium accumulated in systemic organs, fecal monitoring is the acceptable option for routine monitoring.

The gathering of data for occupationally exposed Th workers and for normal excretion was done by J. Lipsztein, C.A. Nogueira, L. Berteli, A. Fonseca, and J. Gaburo from Comissao Nacional de Energia Nuclear, S. Paulo and rio de Janeiro.

Case II: Uranium

The following discussions regarding uranium are based on the tabulated values in Appendix B, and these data are summarized here for uranium 238:

Table A.5.4 IRFs For Uranium 238

Time After Intake, days	Class D IRF		Class W IRF		Class Y IRF	
	Systemic Region	24-Hour Urine	Lungs	24-Hour Urine	Lungs	24-Hour Urine
1	2.22E-01	1.87E-01	2.11E-01	4.13E-02	2.14E-01	2.28E-03
5	1.65E-01	1.31E-02	1.45E-01	2.69E-03	1.53E-01	1.28E-04
10	1.21E-01	7.26E-03	1.32E-01	1.75E-03	1.49E-01	8.26E-05
20	7.36E-02	3.26E-03	1.16E-01	1.03E-03	1.47E-01	4.62E-05
100	1.47E-02	1.11E-04	4.18E-02	2.43E-04	1.35E-01	1.87E-05

Additionally, the ALI's for uranium 238 are $5E+04$ Bq for Class D, $3E+04$ for Class W and $2E+03$ for Class Y aerosols having an AMAD of 1 micrometer. The minimum detection limit for daily urine sampling is typically 7 ug ($1.7E-02$ Bq), and for in vivo lung monitoring 100 Bq.

For uranium, an appropriate bioassay technique is in vivo lung monitoring for class W and Class Y compounds, and urinary measurement, or in vivo bone measurement, for Class D compounds. For Class W and Class Y compounds, the IRF for the 24-hour urine compartment decreases rapidly, and low levels of natural uranium in urine make it difficult to assess an accidental exposure. Thus, if it is possible to perform in vivo lung monitoring, it should be chosen for Class W and Class Y compounds.

For Class D compounds of uranium, an appropriate monitoring method is to analyze urine samples in the first few days after an accidental intake. After a few days, urinary excretion decreases to the extent that in vivo phoswich detectors positioned near bone, for example the head, are practical.

In summary and in addition, when dealing with uranium it is important to know that: 1) generally exposures are to a mixture of uranium isotopes; 2) when dealing with class D compounds of uranium, chemical toxicity of the kidneys is more important than radiotoxicity; 3) many bioassay methods are useful if the accidental intake is on the order of 1 ALI and measurement occurs during the first few days following the accident; 4) routine monitoring of urinary samples is appropriate for Class D compounds and marginal for Class W compounds of uranium; and 5) in vivo counting of the lungs is the best choice for routine monitoring of Class Y compounds of uranium; 6) actual exposures to uranium have often been found to be comprised of mixture of compound classes including a large fraction of Class D compounds. When a significant fraction of the intake is from Class D compounds, then this component can be used as a

tracer for the estimation of the intake from all compounds. Thus, it may be possible to use urine analysis for the estimation of intake of all compound classes of uranium provided some Class D is present and provided the distribution of compound classes has been determined from simulated lung solubility tests.

6. TRITIUM EXPOSURE INCIDENT

A reactor at a national laboratory is moderated, cooled and reflected by heavy water. Neutrons interact with the heavy water to produce tritium, thus the coolant becomes contaminated with radioactivity. On one occasion, the coolant purification system was being used by new employees who had limited experience. The purification system procedures, which were unwritten at that time, called for a hose to be attached from a light water line to the outlet side of a resin bed and a second hose to be connected to the inlet side of the bed and allowed to drain into a 5-gallon pail. When questioned, the operators who were filling the resin bed remembered that they had the light water supply connected to the bed inlet and the discharge hose leading to the pail connected to the bed outlet, which was the reverse of the procedure. In addition, the technician performing the throttling operation inadvertently caused a rapid increase in pressure, which resulted in immediate ejection of about 3 gallons of tritiated heavy water from the bed into the pail.

The person closest to the pail received the highest exposure to tritium and the following bioassay measurements were recorded.

Time Post Incident, days	Urine Activity Concentration, $\mu\text{Ci/l}$	IRF, from Appendix B, Section 6	Estimated Intake, mCi
1	5.80	0.0392	0.15
3	5.53	0.0340	0.16
9	3.73	0.0224	0.17
10	4.24	0.0209	0.20
30	1.21	0.0051	0.24

The best estimate of intake in this case is obtained from all of the data collectively by using equation A.2.4, which gives an intake of 8.4 MBq (0.23 mCi). This corresponds to a committed effective dose equivalent of (1.0E-04 Sv) 14 mrem based on the intake to dose conversion factor in ICRP Publication 30. Our estimate of intake is based on the assumption of a single exposure to tritium. However, persons working at the HFBR received additional chronic exposures to low levels of tritium in the course of routine operations, and the measurements at 10 and 30 days post the incident are less than ideal because they could be affected by this chronic exposure. The only way to avoid interference would be to remove exposed persons from the working environment until their exposures have been fully evaluated. An ideal case history would be a single exposure starting at a known point in time. Unfortunately, case histories with ideal characteristics do not usually occur in practice.

7. VERIFICATION OF INHALATION AND INGESTION MODELS FOR Mn-54, Co-60, Sr-90, Nb-95, Cs-137, Ce-141, Ce-144, U-233 and Am-241

Actual case studies were used to verify the tabulated results from the bioassay model. Four accidental exposure cases were obtained from the personnel dosimetry files of a large government nuclear site. The four cases represented major internal contamination incidents in which no chelating agents were administered in order to accelerate the excretion of internally deposited radionuclides.

Most of the measurements in this section are associated with early excretion rates and they do not necessarily verify that the committed dose estimates, obtained using the models, are correct. This is because the longer term components of retention often dominate the committed dose calculation, and these components are not evaluated in all cases. However, Mn-54 and Co-60 body-burden measurements are evaluated over the long-term, and in the case of Pu-239 excretion, Jones has evaluated the longer term components (Jo85).

It is noted that the total fecal excretion over the first few days is a measure of the fraction of the inhaled activity that is deposited on the ciliated region of the bronchial tree for "non-soluble" materials, and is essentially independent of whether the material is Class W or Y. This integrated early excretion is very useful for the early evaluation of the seriousness of an inhalation exposure. The ICRP task group that is revising the lung model is considering having early excretion as an explicit feature of the new model.

Case I: Inhalation of Mn-54, Co-60, Sr-90, Ce-141 and Ce-144

A 33-year old, male boilermaker with inadequate protective clothing was performing maintenance work on a steam generator when a contamination incident occurred involving inhalation of mixed fission and activation products. Follow-up dosimetry evaluation included whole-body counting, urine sampling, and fecal sampling; however, useful data were not obtained from urine measurements. Initial intakes of radionuclides were estimated from whole-body counting. Data were subsequently available on the amount of Co-60, Mn-54, Sr-90, Ce-141, and Ce-144 in feces. The inhaled radionuclides were assumed to be Class W for Co-60, Ce-141, and Ce-144 and Class D for the Mn-54 and Sr-90. This exposure incident was evaluated over a period of about two weeks.

Case II: Ingestion of Co-60, Sr-90, Nb-95, Cs-137, Ce-141 and Ce-144

A 35-year old, male maintenance worker, was contaminated with mixed fission and activation products during a leak of primary coolant. Internal contamination occurred when the worker accidentally ingested an unknown quantity of contaminated primary coolant. Dosimetry evaluation included whole-body counting, urine sampling and fecal sampling. Initial intakes of radionuclides were estimated from whole-body counting. Data were subsequently obtained on the amounts of Co-60, Nb-95, Cs-137, Ce-141, Ce-144 and Sr-90 in feces, and on Sr-90 in urine. Bioassay results were evaluated over a period of 4-6 days.

Case III: Inhalation of Highly Soluble, Class D U-233

A 43-year old, female laboratory-chemistry technician was accidentally contaminated when a liquid solution of U-233 standard exploded and sprayed the

victim with a highly soluble, Class D nitrate solution. The intake of U-233 occurred primarily by inhalation. Follow-up dosimetry evaluation involved whole-body counting and urine bioassay. Initial intakes of U-233 were estimated from urine excretion results, and urine samples were collected over a period of more than two months.

Case IV: Inhalation of Class W Am-241

A 46-year old, male chemistry-process technician was accidentally contaminated with soluble Am-241 nitrate during a chemical explosion involving a resin ion-exchange column. We assumed that the Am-241 solution behaved like a Class W compound. This worker received a measurable intake of Am-241 by inhalation. Follow-up internal dosimetry evaluation was based on whole-body counting, urine sampling and fecal sampling. Initial intakes of Am-241 were estimated from whole-body counting, and bioassay results were collected over a period of about two weeks following the accident.

For Case Studies I through IV for Sr-90, Ce-141, Ce-144 and U-233, the initial intakes were calculated using excretion measurements and methods described in this report. For Mn-54, Cs-137, Co-60, N6-95 and Am-241, whole-body counting measurements and methods described in this report were used to estimate initial intakes. All aerosols were assumed to have a 1 micrometer AMAD. Results of the bioassay measurements for Cases I through IV are plotted in Figures A.7.1 through A.7.15. Amounts of radionuclide in urine or feces are plotted as the fraction of the estimated initial intake for various times post intake and are represented by dots. Expected values from the bioassay model are plotted using a continuous line on the same figure for comparison with the observed values. Fractions of initial intake in excreta are given in Table A.7.1 along with associated IRFs.

Table A.7.1 Verification of Measurements in Terms of Fraction of Intake and Time Post Intake for Cases I through IV

Case, Nuclide (Bioassay Compartment)	Time Post Intake, days	Measured Fraction of Intake	IRF*
I, Co-60 (feces)	0.5	6.73E-2	1.10E-2
	1.5	4.00E-1	1.04E-1
	4.5	3.18E-3	4.61E-2
	20.5	1.38E-4	1.10E-3
I, Mn-54 (feces)	0.5	2.45E-2	9.94E-3
	1.5	1.14E-1	6.21E-2
	4.5	1.08E-3	6.78E-3
	20.5	7.24E-5	6.06E-4
I, Sr-90 (feces)	0.5	2.49E-2	1.89E-2
	1.5	1.11E-1	5.83E-2
	4.5	2.68E-3	1.01E-2
	15.5	8.66E-3	7.68E-4

Table A.7.1 Continued

Case, Nuclide (Bioassay Compartment)	Time Post Intake, days	Measured Fraction of Intake	IRF*
I, Ce-141 (feces)	0.5	2.47E-2	5.22E-3
	1.5	1.74E-1	9.78E-2
	4.5	6.17E-4	4.36E-2
I, Ce-144 (feces)	0.5	3.82E-2	4.10E-3
	1.5	2.72E-1	1.01E-1
	4.5	2.93E-3	4.70E-2
II, Co-60 (feces)	0.5	1.30E-1	7.26E-2
	1.5	3.35E-1	4.18E-1
	2.5	1.51E+0	2.73E-1
II, Nb-95 (feces)	0.5	8.95E-2	7.07E-2
	1.5	1.64E-1	4.16E-1
	2.5	1.10E-1	2.62E-1
II, Cs-137 (feces)	0.5	2.42E-3	3.46E-3
	1.5	7.55E-3	6.13E-3
	2.5	4.26E-3	4.61E-3
II, Ce-141 (feces)	0.5	1.83E-1	7.17E-2
	1.5	3.14E-1	4.21E-1
	2.5	2.13E-1	2.73E-1
II, Sr-90 (feces)	0.5	1.06E-1	6.60E-2
	1.5	3.62E-1	3.16E-1
	2.5	1.60E-1	1.98E-1
	3.5	2.88E-3	8.70E-2
	4.5	1.13E-3	3.50E-2
II Sr-90 (urine)	0.5	5.23E-2	4.30E-2
	1.5	2.16E-2	2.83E-2
	2.5	1.39E-2	2.16E-2
II Ce-144 (urine)	0.5	1.84E-1	7.17E-2
	1.5	3.45E-1	4.32E-1
	2.5	2.09E-1	2.85E-2
III U-233 (urine)	0.5	3.78E-1	1.14E-1
	1.5	3.94E-2	1.17E-1
	15.5	1.22E-3	4.58E-3
	29.5	4.72E-4	1.76E-3
	63.5	1.40E-4	3.99E-4
IV Am-241 (urine)	0.5	4.07E-3	5.25E-3
	1.5	1.15E-3	1.79E-3
	2.5	1.22E-3	1.66E-4

Table A.7.1 Continued

Case, Nuclide (Bioassay Compartment)	Time Post Intake, days	Measured Fraction of Intake	IRF*
	3.5	6.84E-4	6.08E-5
	4.5	3.53E-4	5.31E-5
	9.5	1.03E-4	5.00E-5
	10.5	3.93E-4	4.95E-5
	11.5	1.75E-4	4.91E-5
	12.5	1.09E-4	4.87E-5
	13.5	2.63E-5	4.82E-5
IV Am-241 (feces)	0.5	3.09E-1	5.28E-3
	1.5	6.55E-2	1.01E-1
	2.5	9.27E-3	1.35E-1
	3.5	2.48E-3	8.93E-2
	4.5	8.52E-4	4.80E-2
	9.5	3.23E-4	2.43E-3
	10.5	5.56E-4	1.81E-3
	11.5	2.88E-4	1.50E-3
	12.5	1.56E-4	1.34E-3
	13.5	6.78E-5	1.25E-3

*Values of IRF were obtained from equation 2.5.1, Section 2.5.1.

In general, there was agreement between predicted and actual results. The values measured for Cs-137, Ce-141, Ce-144 and Sr-90 were closest to those predicted. Actual measurements made at early times post-exposure typically exceeded the values predicted by the model, which could have resulted from an error in the estimate of initial intake. The model did not fit particularly well for Co-60 in feces, nor for inhalation of the cerium isotopes. The model predicts 2.5 times more than the amount of Nb-95 excreted in feces.

A weighted estimate of intake can be derived from the definition of the chi-squared statistic given in section A.2 and by assuming the variance is that associated with counting errors. Since the weight is the inverse of the variance, and since the variance is the number of counts for radioactivity measurements, the largest values measured will have their impact on best estimate of intake reduced the most. Equation A.7.1 is the result of propagating the counting error into the best estimate of intake.

$$I = \frac{\sum_i r_i}{\sum_i r_i^2 / A_i} \quad \text{A.7.1}$$

where:

I = best estimate of intake,

A_i = the value of the i th measurement, and

r_i = the IRF associated with the i th measurement.

If one uses all the data to obtain the best estimate of intake by using equation A.7.1 or equation A.2.4, the value of intake should approach 1.0 since measured values in Table A.7.1 are given in terms of the fraction of intake. That is, we can compare intake based on whole-body counting to intake based on excretion measurements for the same person. For example, in Case IV for Am-241 in urine, the value of intake equaled 0.77; that is, the unweighted estimate of intake based on ten urinary activity measurements was 77% of the value of intake which was estimated based on whole-body counting measurements. A number of samples may be useful in order to reduce the variation associated with estimating intake from excretion measurements, which is largely due to daily variations in diet and health, and sometimes due to counting errors. Also, a single measurement on an aliquot of a ten sample composit would be cost effective.

The impact of counting error on the best estimate of intake can be inferred by comparing all the unweighted and weighted values given in Table A.7.2. The mean and standard deviation of the unweighted values are 1.5 +/- 1.1 and for the weighted values are 0.73 +/- 0.52. Thus, for these cases it appears that weighted values of intake based on excreta measurements tend to underestimate the intake. This may be due to the fact that early excretion results are given more weight because they have more radioactivity and because IRFs underpredict the amount of intake present in early fecal samples (see Table A.7.1).

The large variations introduced by differences in uptake following inhalation of radioactive materials which result from changes in chemical form and particle size which may occur after deposition, may be reduced by collecting urinary samples several weeks after the intake incident. Thus, in addition to collecting early samples, one should follow-up after an appropriate interval of time for uptake to occur, which could be several months post intake for Class Y material. Thus, collecting and analyzing a number of urinary or fecal samples over a period of time will help to reduce the uncertainty associated with the estimate of intake from excreta measurements.

Table A.7.2 Unweighted Intake Based on Excreta Measurements Divided by Unweighted Intake Based on Whole-Body Counting (U) and Weighted Intake Based on Excreta Measurements Divided by Unweighted Intake Based on Whole-Body Counting (W)

Case	Nuclide	Number of Samples	Type of Sample	U	W
I	Co-60	4	feces	3.2	0.23
I	Mn-54	4	feces	1.8	0.93
II	Co-60	3	feces	2.2	1.3
II	Nb-95	3	feces	0.42	0.43
II	Cs-137	3	feces	2.1	1.4
IV	Am-241	10	urine	0.77	0.78
IV	Am-241	10	feces	0.25	0.048

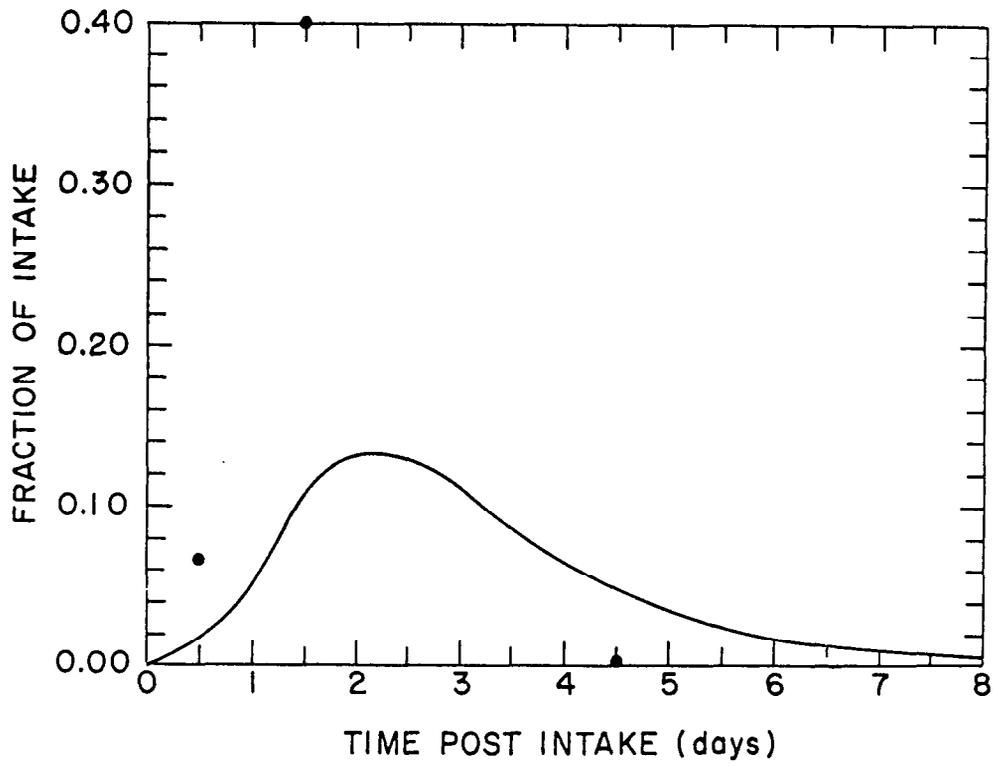


FIGURE A.7.1 Co-60 Inhalation; Feces; Class W

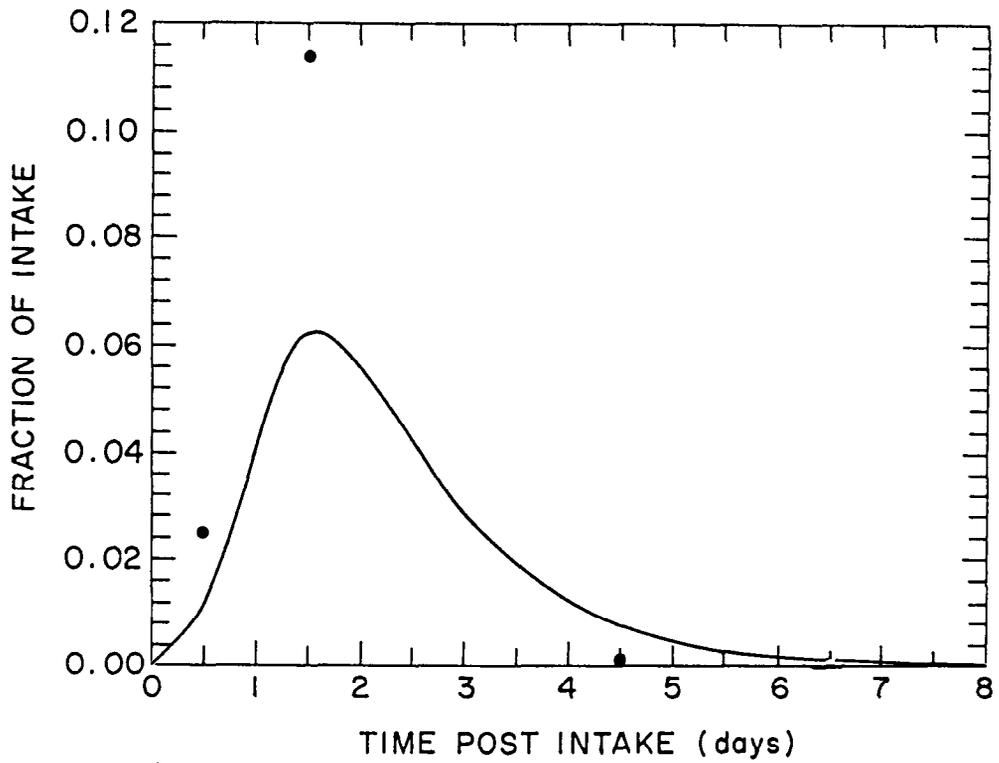


FIGURE A.7.2 Mn-54 Inhalation; Feces; Class D

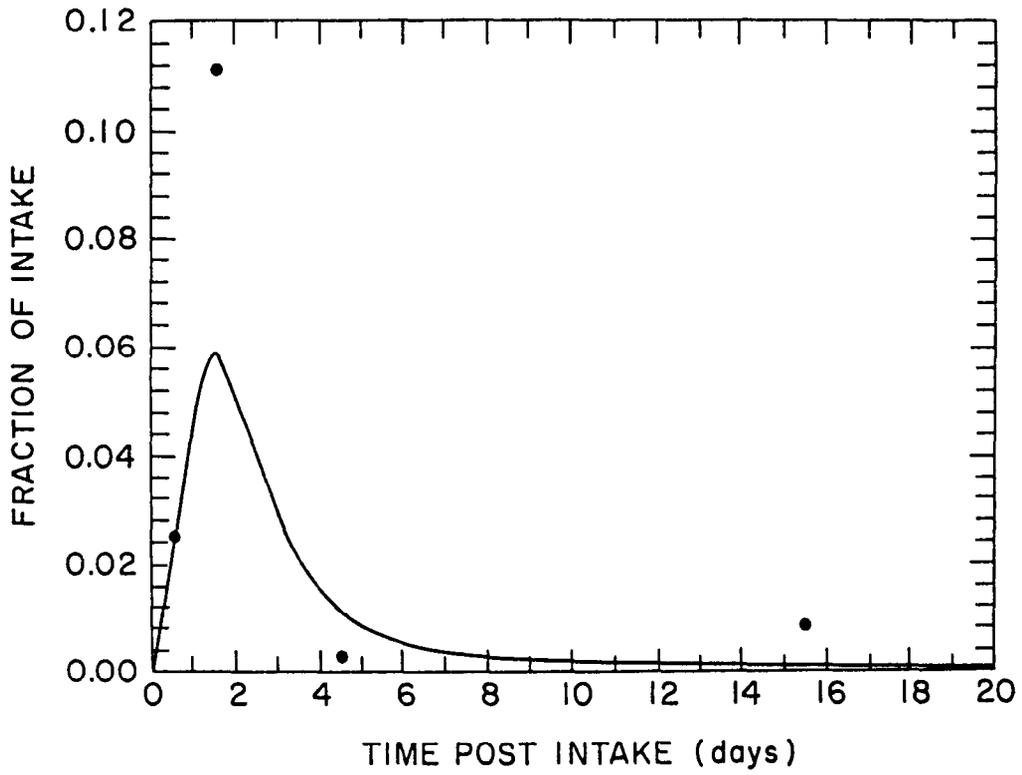


FIGURE A.7.3 Sr-90 Inhalation; Feces; Class D

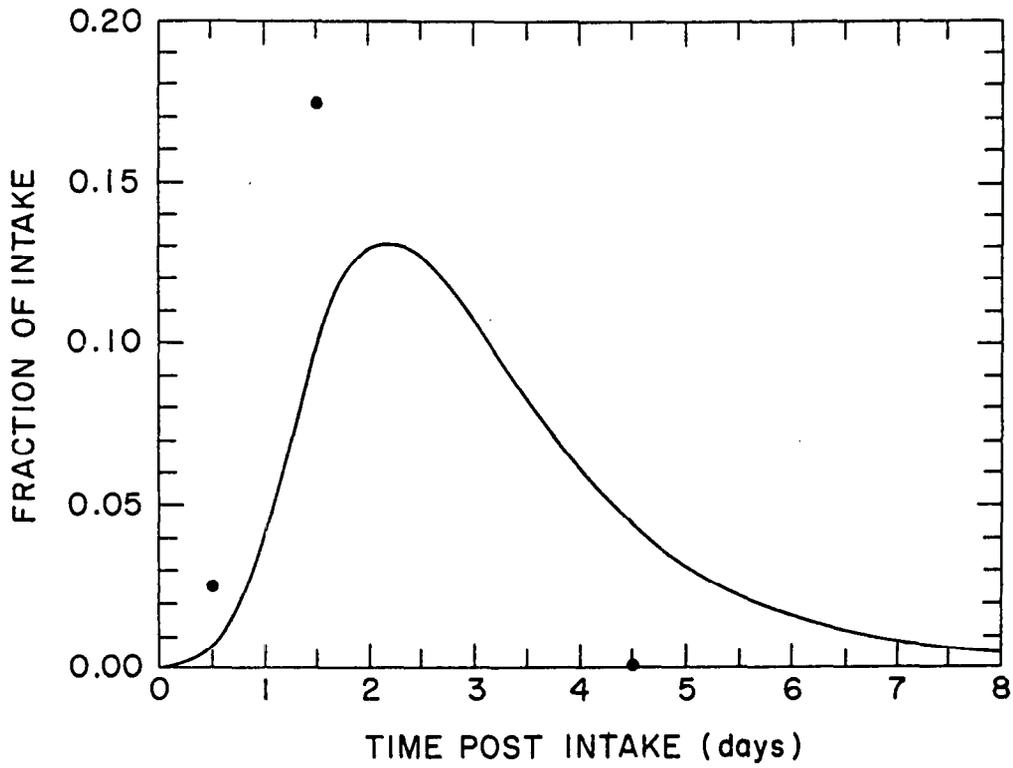


FIGURE A.7.4 Ce-141 Inhalation; Feces; Class W

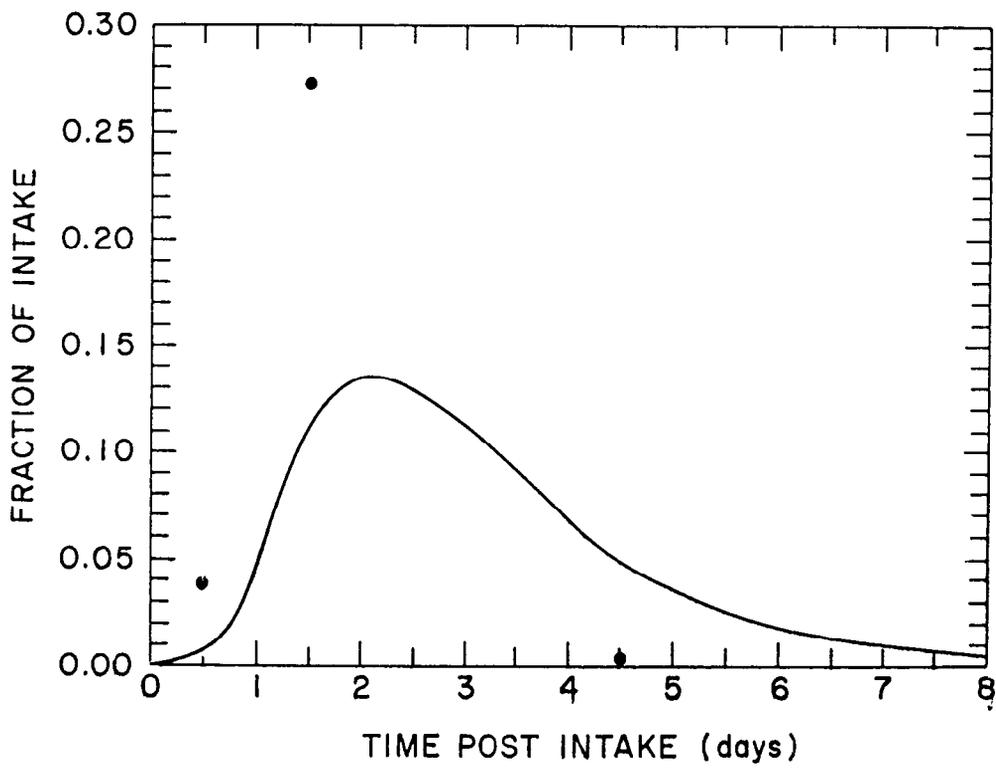


FIGURE A.7.5 Ce-141 Inhalation; Feces; Class W

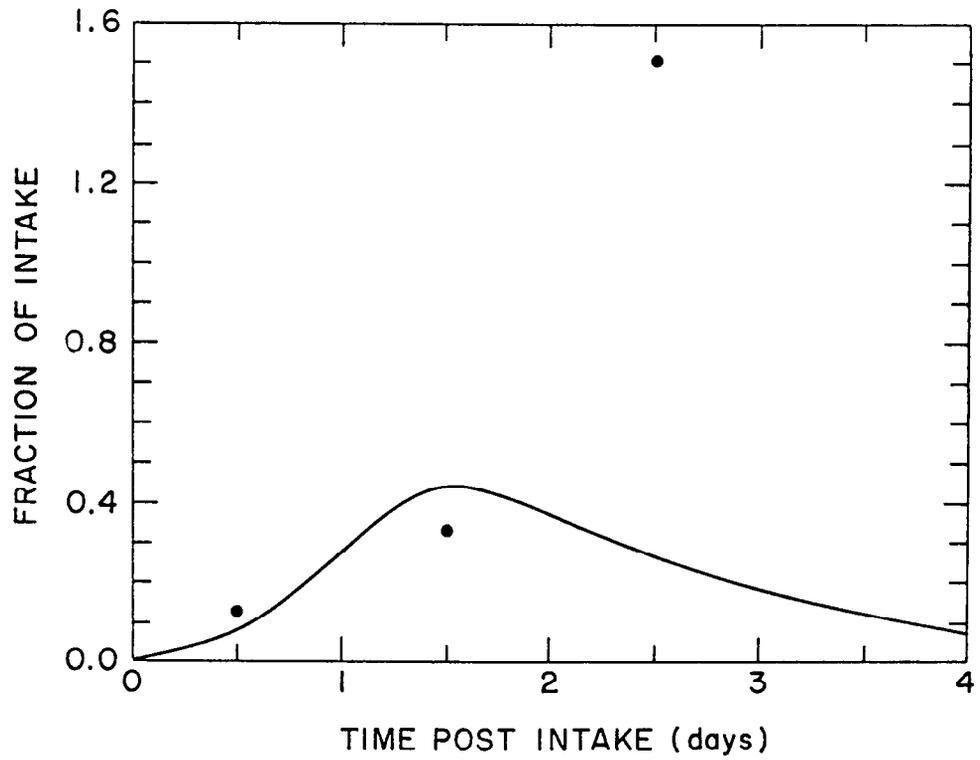


FIGURE A.7.6 Co-60 Ingestion; Feces

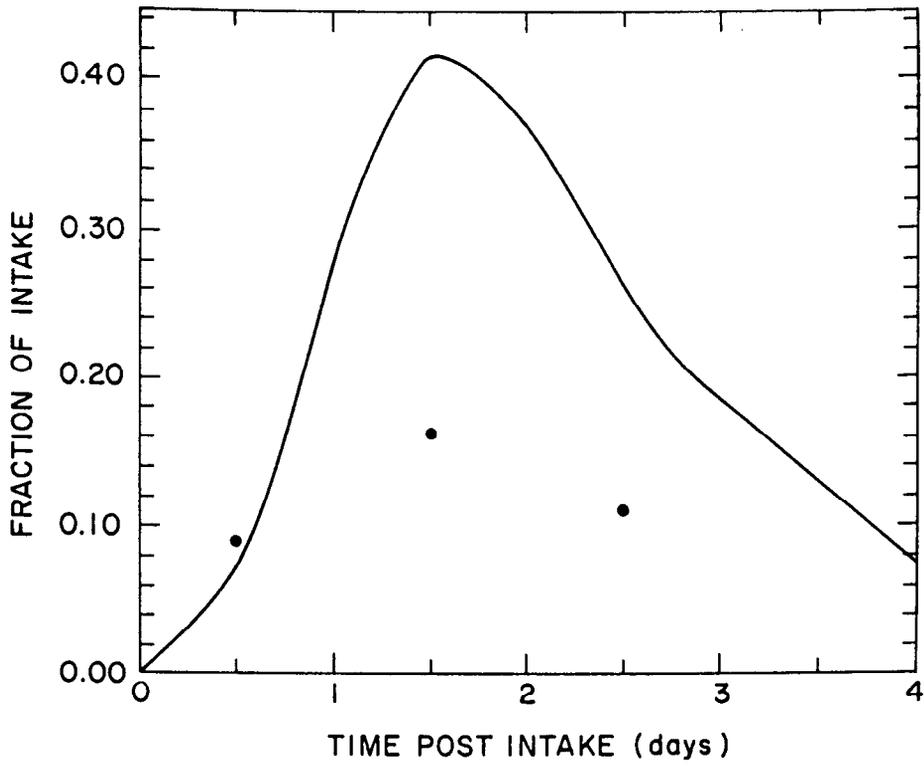


FIGURE A.7.7 Nb-95 Ingestion; Feces

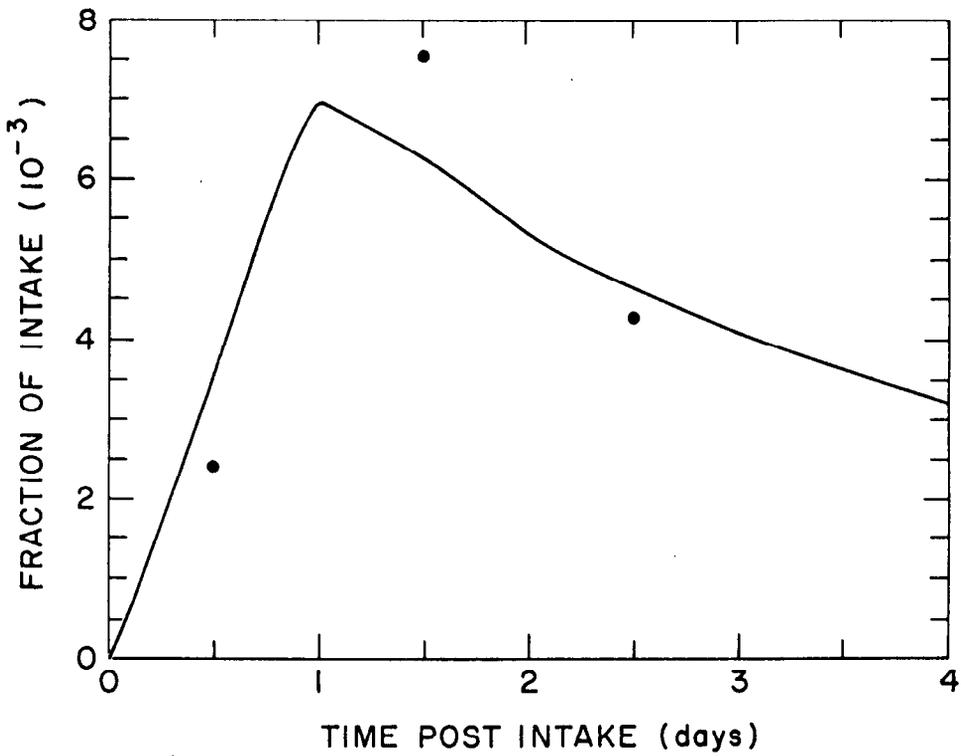


FIGURE A.7.8 Cs-137 Ingestion; Feces

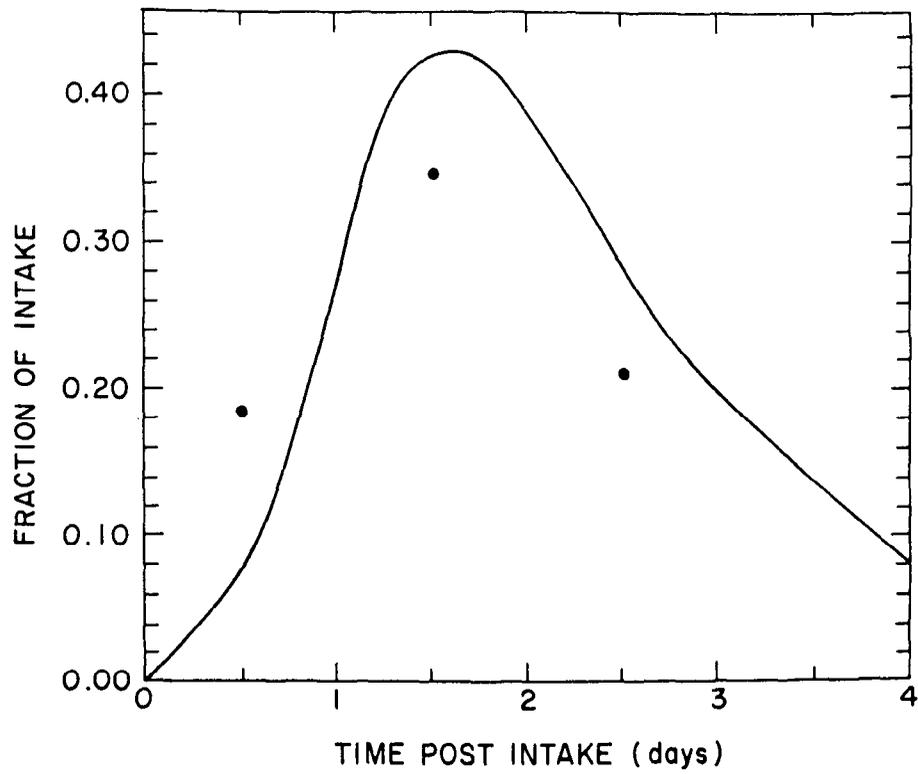


FIGURE A.7.10 Sr-90 Ingestion; Feces

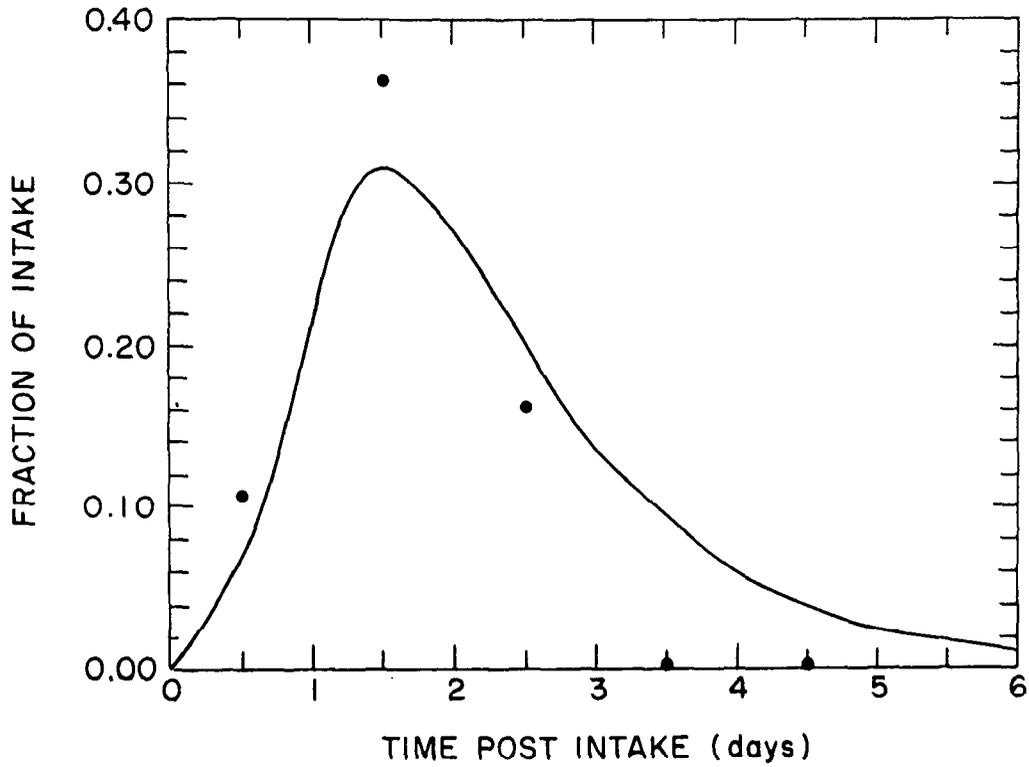


FIGURE A.7.9 Ce-141 Ingestion; Feces

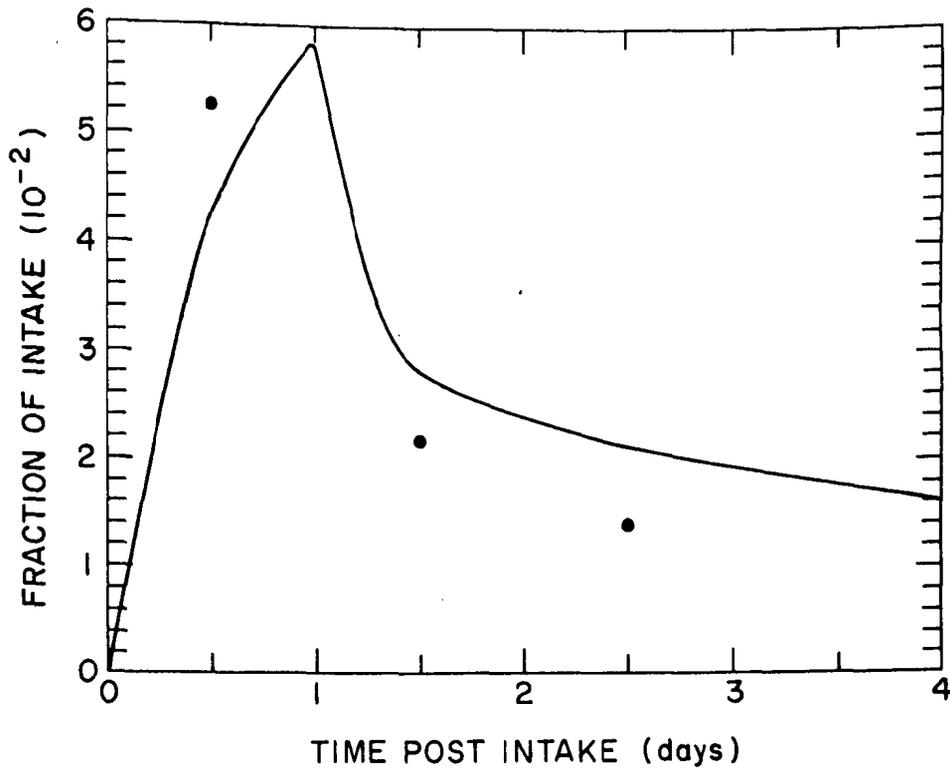


FIGURE A.7.11 Sr-90 Ingestion, Urine

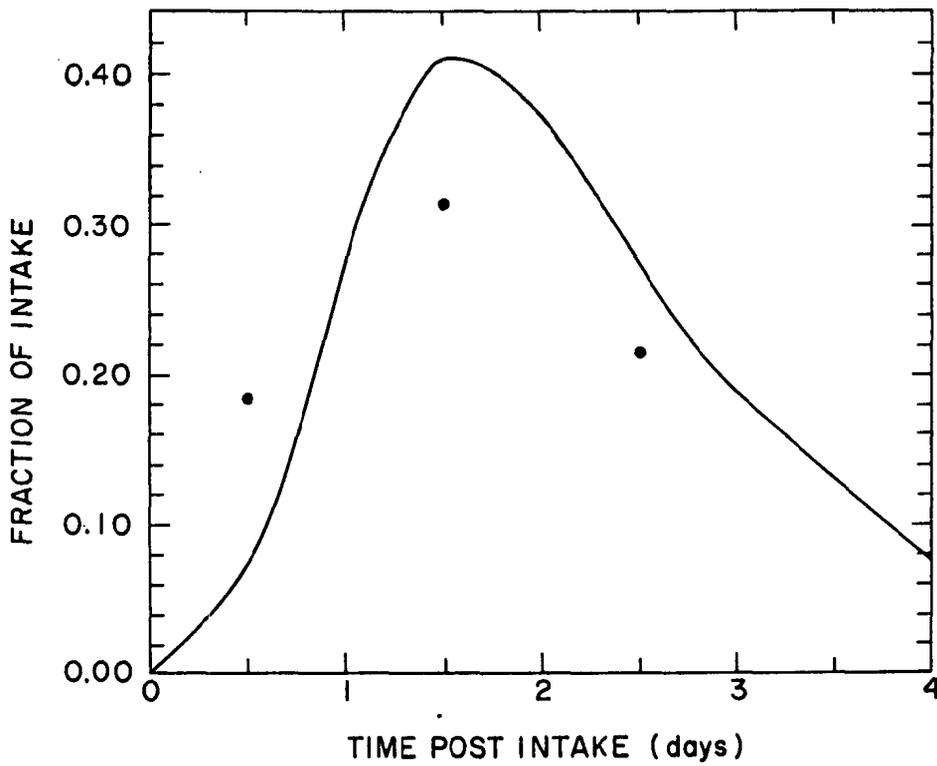


FIGURE A.7.12 Ce-144 Ingestion; Feces

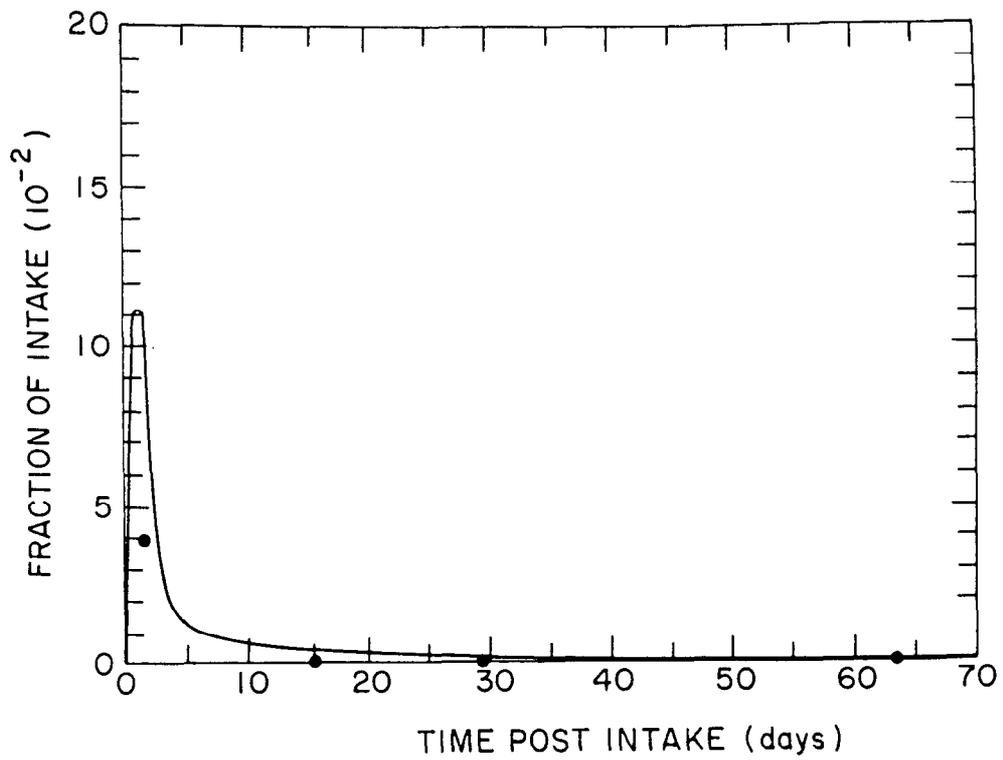


FIGURE A.7.13 U-233 Inhalation; Urine; Class D

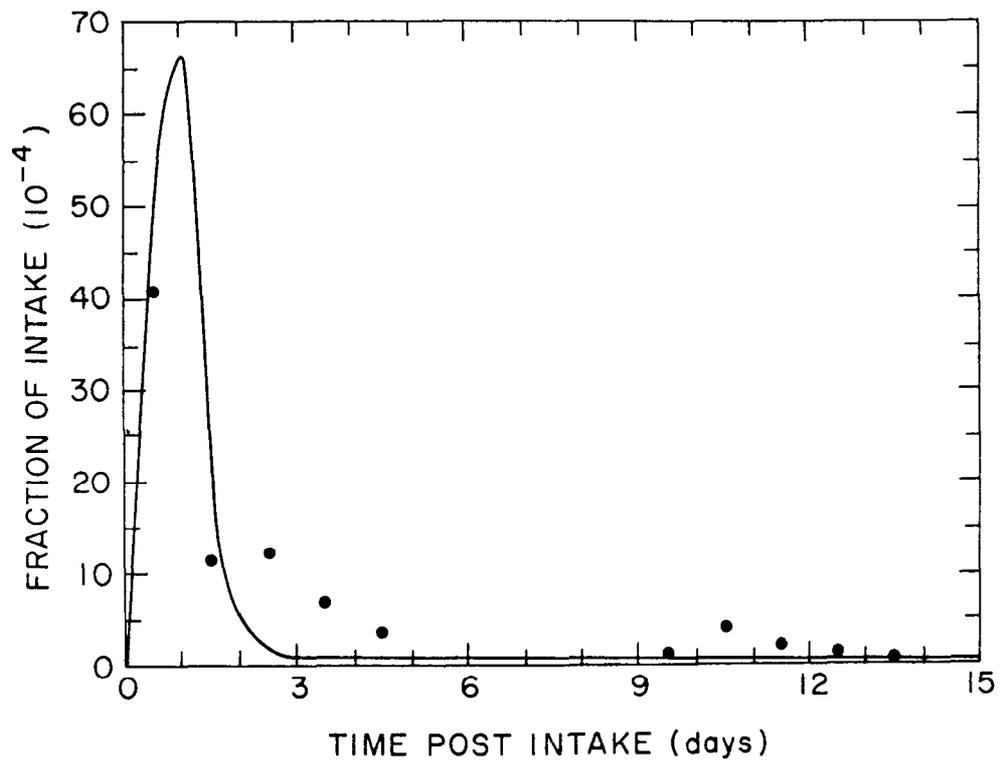


FIGURE A.7.14 Am-241 Inhalation; Urine; Class W

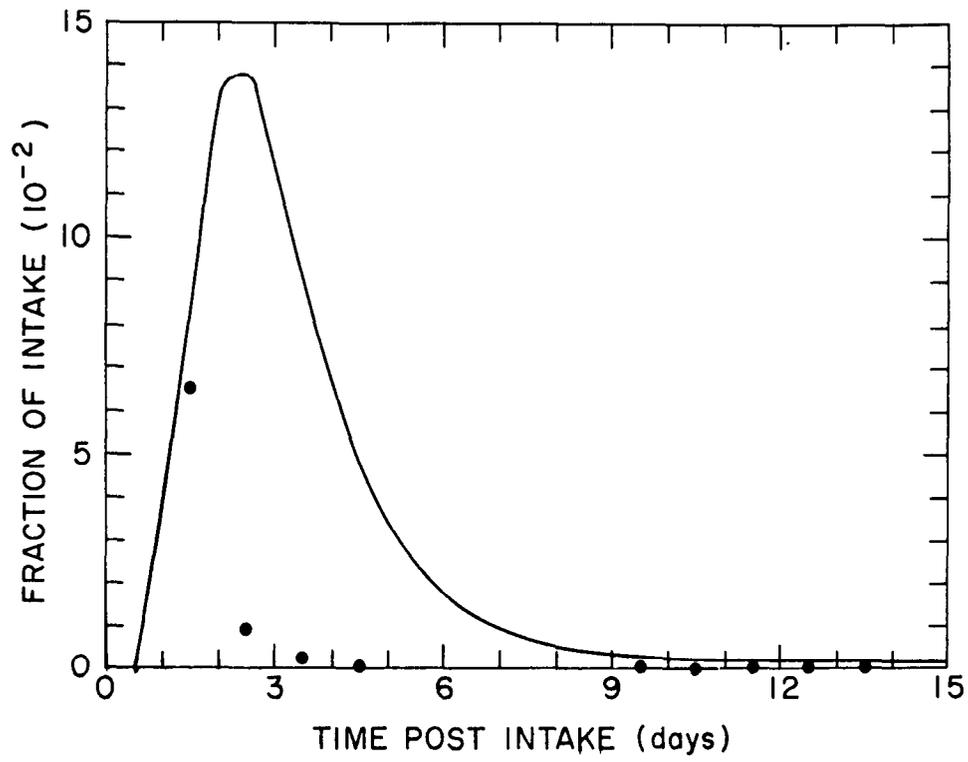


FIGURE A.7.15 Am-241 Inhalation; Feces; Class W

Direct comparison of whole body counting measurements to expectation values of intake in the whole body are presented in Table A.7.3. The expected value of body burden is the product of the IRF and the best estimate of intake. The IRFs were obtained by using equation 2.5.1. The unweighted value of intake was based on equation A.2.4 and the weighted value of intake was based on equation A.7.1.

Table A.7.3 Verification of IRFs Using Whole-Body Counting Measurements

Case	Nuclide	Day Post Intake, days	Measured Body Burden, Bq	Total Body IRF	Unweighted Expectation Value of Body Burden, Bq	Weighted Expectation Value of Body Burden, Bq
I	Co-60	1	3.4E04	5.66E-01	3.7E04	2.1E04
		2	3.7E04	4.23E-01	2.7E04	1.6E04
		8	2.2E03	1.71E-01	1.1E04	6.5E03
		41	1.9E03	1.08E-01	6.7E03	4.1E03
		80	2.0E03	7.08E-02	5.1E03	2.9E03
		148	1.6E03	3.68E-02	2.4E03	1.4E03
		202	1.3E03	2.40E-02	1.6E03	9.1E02
		325	1.0E03	1.28E-02	8.3E02	4.8E02
		667	5.6E02	6.71E-03	4.3E02	2.5E02
		1025	1.5E02	4.30E-03	2.8E02	1.6E02
		1370	1.6E02	2.82E-03	1.8E02	1.1E02
		1751	8.9E01	1.77E-03	1.2E02	6.7E01
		I	Mn-54	1	1.0E04	5.77E-01
2	1.2E04			4.96E-01	8.4E03	7.8E02
8	2.2E02			3.39E-01	5.7E03	5.3E02
41	5.6E01			1.57E-01	2.7E03	2.5E02
148	2.7E02			1.94E-02	3.3E02	3.0E01
325	2.1E02			6.10E-04	1.0E01	9.6-01

A plot of the relative residuals, which is the squared difference between measured value and expectation value divided by expectation value, versus expectation value, reveals no discernable pattern for unweighted or weighted data. However, the residuals are smaller for the unweighted data which indicates to us that the unweighted estimate of intake, equation A.2.4, is best suited for estimating intakes from several measurements. A plot of total body activity predicted by using both the weighted and unweighted estimates of intake is given by Figure A.7.16. It should be noted that on the average, measured values are closer to the unweighted expectation values.

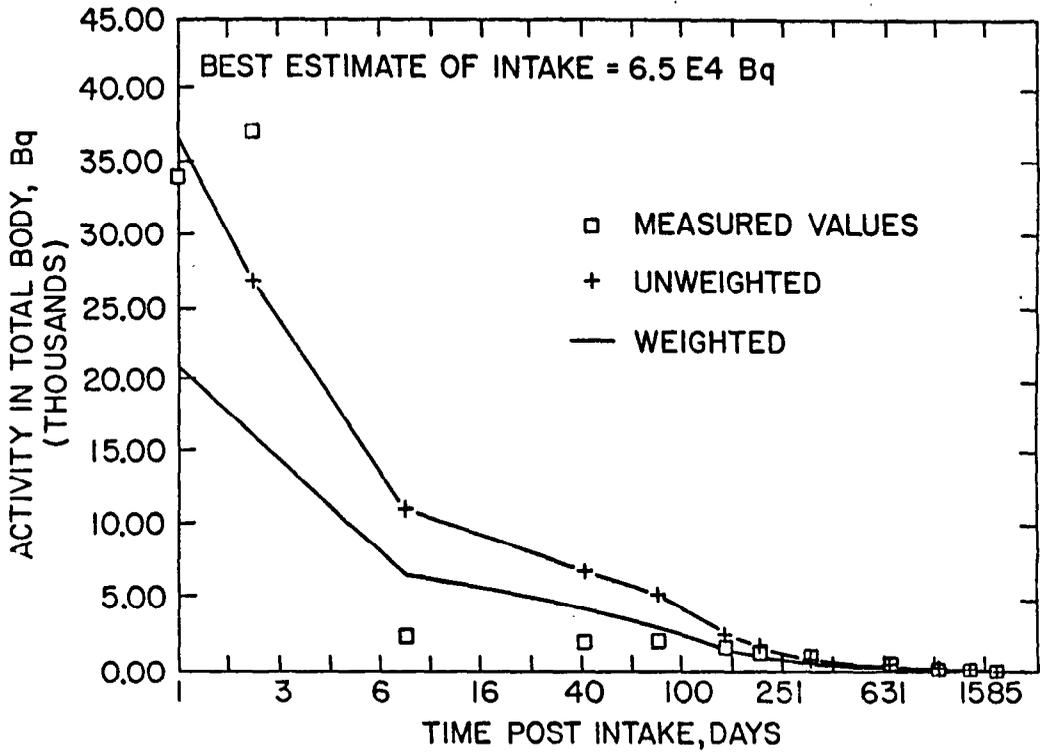


FIGURE A.7.16 Calculated and Measured Values of Total Body Activity Following Inhalation of Class W Co-60.

8. BIBLIOGRAPHY

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- Li85 A paper on this accident was published in Anais do Primeiro Congresso Brasileiro de Energia Nuclear, Rio de Janeiro, 1986 and in summary in the Brazilian journal Ciencia e Cultura, Vol. 37, No. 7, 1985. Measurements were performed by Joyce L. Lipsztein, Janete C. Gaburo, and Carlos H. Mesquita from Comissao Nacional de Energia Nuclear Brazil.
- Li86 Patient results for this example were obtained by Joyce L. Lipsztein, Janete C. Gaburo, C. H. Mesquita and M. O. Enocles from Comissao Nacional de Energia Nuclear Brasil. They were presented in the First Meeting of the Brazilian Atomic Energy Association in Rio de Janeiro, 1986, and were accepted for publication in summary form at the journal Ciencia e Cultura.