

6. GENERAL EVALUATION

6.1 Validation of Tabulated Results

This section describes the methods used in the validation of tabular values, and presents results of selected validation tests.

Validation was a process aimed at confirming that tabular data were correctly presented in Appendix B. However, the validation procedure does not verify or substantiate the correctness of model assumptions. Evidence which serves to verify the exactness of our methods is presented in Appendix A, Example of Use and Verification Based on Experiences. The validation study was performed by R. Belanger of Science Applications International Corporation, San Diego, California.

Validation was performed by comparison of selected tabular results with those generated by other computer models using the same set of assumptions. The programs used in the validation processes were REMedy and DOSEDAY/DOSEYR, both of which are proprietary programs. REMedy invokes an analytic solution algorithm to solve the ICRP Publication 30 retention functions in a manner similar to that used by the model which generated the tabular results in Appendix B. The DOSEDAY/DOSEYR program uses a Runge-Kutta integration routine to numerically solve the rate equations presented in ICRP Publication 30.

A third computer program was used to evaluate the tables in Appendix B and the output was similar to REMedy. However, this third validation study was performed by J. R. Johnson of the Dosimetric Research Branch, Chalk River Nuclear Laboratory, Canada, and Dr. Johnson validated the tables corresponding to the stable elements. Since tables for radioisotopes differ from the table for the stable elements by the decay factor, it was felt that this third study was comprehensive. The errors discovered by this study were corrected. Since output of Dr. Johnson's study was similar (within a few %) to REMedy output, we felt specific details need not be reproduced here.

6.1.1 General Description of the REMedy Model

REMedy is a Pascal-language program which uses an analytic solution algorithm to predict the fraction of an intake present in a bioassay compartment at some time post-intake. The program is capable of calculating fraction of intake in the whole body, lung, 24-Hr urine, cumulative urine, 24-Hr feces, cumulative feces, and thyroid (for radioiodine) bioassay compartments as a result of ingestion or inhalation. Both acute and chronic intake modes are evaluated and corrections can be made for deposition as a function of particle size.

The general form equation used in REMedy to solve retention function problems is identical to that presented as equation (1) in Section 2.5 of this report. One notable change in the REMedy metabolic model from the BNL model, however, is that REMedy assumes the existence of a transfer compartment as discussed in ICRP Publication 30. For purposes of validation, the clearance halftime for the transfer compartment was set equal to the halftime of the first exponential term of the BNL model for the respective radionuclides. As is discussed below, this fact may account for minor differences in calculations of retention for a few to several days post-intake.

The radionuclide library contents of REMedy was edited for this task to set all assumed values equal to those contained in the Element Data Sheets of Appendix B. For those cases in which the fractions of systemic excretion leaving the body via urine and feces are not defined (e.g., iron), the fraction assigned to urine excretion was unity. In this case, the urine retention values calculated by REMedy can be compared to the systemic excretion values in the tables.

6.1.2 General Description of DOSEDAY and DOSEYR

DOSEDAY and DOSEYR are programs which numerically integrate the rate equations presented in ICRP Publication 30. The numerical integration routine used is a simple Runge-Kutta method. Since the rate equations form a system of very stiff differential equations, special attention must be paid to step size. Step sizes are chosen on the basis of the fastest compartment clearance rate. Compartments which contain retention fractions of less than $1.0E-6$ are assumed to equal zero, except in the cases of closely coupled flow, for example from lung compartments f to d to the GI tract, or the case of a positive derivative. A material balance is maintained for activity present in all compartments, activity lost by radiodecay, and all losses assumed equal to zero.

DOSEDAY integrates on a time scale of days. Once all lung and GI compartment retention values reach zero, the integration is passed to the DOSEYR routine, which integrates on a time scale of years. Results may be printed from either routine for fractions or multiples of days or years.

Deposition fractions, removal rate constants and compartmental fractions assumed for the inhalation model may be changed from those specified by Figure 5.2 of ICRP Publication 30 as keyboard input. While not clearly specified by ICRP Publication 30, for cases where f_1 is equal to unity, all contents of the stomach are assumed to be absorbed at a rate equal to the translocation rate of stomach contents, which is 24 day^{-1} .

6.1.3 Input Values for Validation Tests

The DOSEDAY/DOSEYR routines use the compartment transfer rate constants for each radioelement given in ICRP Publication 30, as opposed to retention functions. Where differences in rate constants for males and females are specified, for example, for Pu and Am, the values for Reference Male were used. The lung deposition fractions and excretion pathway fractions used were the same as those specified in the Element Data Sheets of Appendix B. Where systemic excretion pathway fractions were listed as not defined, it was assumed that the fraction of systemic excretion going to urine was unity.

The physical halflives used for the radionuclides were obtained from the Radiological Health Handbook (USDHEW70), and are as follows:

<u>Nuclide</u>	<u>Halflife(Year)</u>	<u>Halflife(Day)</u>
Co-60	5.26 E+00	1.92 E+03
I-131	2.21 E-02	8.05 E+00
U-235	7.10 E+08	2.59 E+11
Pu-239	2.40 E+04	8.78 E+06
Am-241	4.58 E+02	1.67 E+05

Excretion compartment values are cumulative from the time of intake, so hand calculations were necessary to estimate 24-hour incremental urine and fecal values. The excretion compartment retention was obtained using the following formula:

$$24\text{-Hr Total} = (B - A) \times \text{EXP} (-\lambda \times T)$$

where: B is the stable element cumulative fraction at time T days post intake,

A is the stable element cumulative fraction at time T - 1 days post intake, and

λ is the radiodecay constant, day^{-1} .

This equation corrects the value calculated at 24 hours for any activity present at the start of the 24-hour period.

6.1.4 Validation Results

The results of the validation tests are presented in Tables 6.1.1 through 6.1.4. All results generated by REMedy or DOSEDAY/DOSEYR have been rounded to two decimal places. Wherever dashes appear in the tables, no results are available. Values presented as 0.00E+00 represented values less than 1.0E-6 for DOSEDAY/DOSEYR results, and values less than approximately 1.0E-10 for REMedy results.

Table 6.1.1 presents the results of validation runs for excreta retention following inhalation of particles of 1 micrometer AMAD. For these cases, the deposition values in REMedy and DOSEDAY/DOSEYR have been set to 0.31 for nasal passages, 0.08 for the trachea and bronchial tree, and 0.249 for the pulmonary region. The results of this test can be summarized as follows:

1. For Class D compounds, there is good agreement for Sr-90, I-131, and U-235. There are relatively minor (<11%) urine and fecal retention discrepancies for Fe-59 and Cs-137 up to 10 days post-intake, and for Fe-59 cumulative feces at 500 days.
2. For Class W compounds, there is very good agreement for Co-60, Th-232, and U-235. There are discrepancies (<11%) in the case of Fe-59, Ce-144, and Pu-239 for urine retention at 1 day. There are also minor discrepancies (<3%) for fecal retention for Fe-59 beyond 100 days and Co-60 at 5 days.
3. For Class Y compounds, there is very good agreement for all four nuclides tested. There are minor discrepancies (<10%) in each case, but these differences may be explained by the difference in use of the transfer compartment.

Validation results of whole body and lung retention following inhalation are presented in Table 6.1.2. There is very close agreement between BNL and REMedy results for all cases of Class D, Class W and Class Y nuclides except for minor discrepancies (<5%) between the I-131 results of BNL and REMedy compared to those predicted by DOSEDAY.

Table 6.1.3 presents validation test results for ingestion. Except for

isolated cases, there is very close agreement between the BNL and REMedy results. The DOSEDAY/DOSEYR routines were not used in the ingestion tests. Whole body retention results agreed very closely in all cases. Incremental urine retention of Am-241 (by 6%) varies between the models for times after 5 days, and excreta retention for Cs-137 varies somewhat (<11%) for the first few days post-intake, after which time close agreement is reached.

Table 6.1.4 presents predicted thyroid retention following inhalation of Class D I-131. There is a minor (<6%) discrepancy between the BNL and REMedy results for day 1, although the BNL and DOSEDAY results for this time agree closely. There is very good agreement between results at day 5, and there are relatively minor (<6%) variations thereafter.

6.1.5 Conclusions Drawn from Validation Studies

Several meaningful conclusions can be drawn from the results of the validation tests. It can be concluded that for almost all cases of in vivo retention, the tabular results appear to accurately represent a retention value expected on the basis of ICRP Publication 30 metabolic models. It is difficult to explain the apparent discrepancies in some cases of expected excreta retention. These discrepancies are attributed to slightly different interpretations of the metabolic models presented in ICRP Publication 30. In particular, two distinct variations of ICRP models are employed in the algorithms contained in the programs used in the validation tests. The algorithms used in the REMedy and DOSEDAY/DOSEYR codes include a single catenary transfer compartment as a component of the metabolic model. An example of a lung-to-excretion pathway for such a model would be: Lung Compartment "a" -> Transfer Compartment -> Systemic Compartment -> Excretion. An alternative approach is employed in the model described in Section 2 of this report. This approach neglects the existence of the Transfer Compartment, so the corresponding pathway would be described by: Lung Compartment "a" -> Systemic Compartment -> Excretion.

Since the Transfer Compartment is assumed to have a relatively short clearance half-time, 0.25 to 0.5 days, systemic retention and excretion results calculated using these alternative approaches can differ significantly for times up to several days post-intake. Little difference would usually be exhibited beyond this time. The use of alternative models is believed to account for many of the discrepancies mentioned above.

Table 6.1.1 Validation of Inhalation Results for Excreta Measurements

		CLASS D					
		24-HOUR URINE			ACCUMULATED URINE		
NUCLIDE (CLASS)	DAY	BNL	REMedy	DOSEDAY	BNL	REMedy	DOSEDAY
Fe-59(D) fu=1	1	1.16E-04	7.25E-05	---	1.16E-04	7.25E-05	---
	5	1.58E-04	1.58E-04	---	7.23E-04	6.67E-04	---
	10	1.47E-04	1.47E-04	---	1.40E-03	1.35E-03	---
	50	7.76E-05	7.90E-05	---	3.88E-03	3.92E-03	---
	100	3.50E-05	3.63E-05	---	3.55E-03	3.66E-03	---
	500	6.03E-08	7.23E-08	---	3.29E-05	3.94E-05	---
Sr-90(D) fu=0.85	1	8.57E-02	8.04E-02	---	8.57E-02	8.04E-02	---
	5	2.45E-02	2.60E-02	---	2.23E-01	2.19E-01	---
	10	1.04E-02	1.11E-02	---	2.97E-01	2.98E-01	---
	50	1.94E-04	1.89E-04	---	3.63E-01	3.63E-01	---
	100	1.26E-04	1.26E-04	---	3.83E-01	3.83E-01	---
	500	2.86E-05	2.93E-05	---	3.83E-01	3.83E-01	---
I-131(D) fu=1	1	3.13E-01	3.13E-01	---	3.13E-01	3.13E-01	3.08E-01
	5	1.35E-03	1.34E-03	---	2.91E-01	2.91E-01	2.87E-01
	10	1.93E-04	1.88E-04	---	1.90E-01	1.91E-01	1.87E-01
	50	1.20E-05	1.21E-05	---	6.47E-03	6.50E-03	6.87E-03
	100	1.27E-07	1.29E-07	---	9.41E-05	9.50E-05	---
	500	---	---	---	---	---	---
Cs-137(D) fu=0.8	1	1.35E-02	8.74E-03	---	1.35E-02	8.74E-03	---
	5	7.16E-03	7.75E-03	---	5.38E-02	5.13E-02	---
	10	3.51E-03	3.63E-03	---	7.63E-02	7.51E-02	---
	50	2.12E-03	2.13E-03	---	1.74E-01	1.73E-01	---
	100	1.54E-03	1.55E-03	---	2.64E-01	2.63E-01	---
	500	1.21E-04	1.21E-04	---	4.76E-01	4.76E-01	---
U-235(D) fu=1	1	1.87E-01	1.93E-01	1.93E-01	1.87E-01	1.93E-01	1.93E-01
	5	1.31E-02	1.32E-02	1.32E-02	3.23E-01	3.19E-01	3.19E-01
	10	7.26E-03	7.49E-03	7.50E-03	3.67E-01	3.65E-01	3.65E-01
	50	6.67E-04	6.77E-04	---	4.59E-01	4.60E-01	---
	100	1.11E-04	1.13E-04	---	4.73E-01	4.74E-01	---
	500	1.64E-06	1.63E-06	---	4.77E-01	4.78E-01	---

Table 6.1.1 (continued)

		CLASS D					
NUCLIDE (CLASS)	DAY	24-HOUR FECES			ACCUMULATED FECES		
		BNL	REMedy	DOSEDAY	BNL	REMedy	DOSEDAY
Fe-59(D) fu=1	1	4.01E-02	3.95E-02	---	4.01E-02	3.95E-02	---
	5	4.08E-03	4.18E-03	---	1.30E-01	1.30E-01	---
	10	2.62E-05	2.71E-05	---	1.22E-01	1.23E-01	---
	50	0.00E+00	0.00E+00	---	6.57E-02	6.69E-02	---
	100	0.00E+00	0.00E+00	---	3.02E-02	3.13E-02	---
	500	0.00E+00	0.00E+00	---	5.96E-05	7.16E-05	---
Sr-90(D) fu=0.85	1	4.85E-02	4.71E-02	---	4.85E-02	4.71E-02	---
	5	7.62E-03	7.97E-03	---	1.49E-01	1.48E-01	---
	10	1.85E-03	1.97E-03	---	1.64E-01	1.64E-01	---
	50	3.42E-05	3.33E-05	---	1.75E-01	1.75E-01	---
	100	2.22E-05	2.23E-05	---	1.76E-01	1.76E-01	---
	500	5.04E-06	5.17E-06	---	1.75E-01	1.75E-01	---
I-131(D) fu=1	1	5.18E-08	---	---	5.18E-08	---	---
	5	4.86E-08	---	---	1.02E-07	---	---
	10	0.00E+00	---	---	6.17E-08	---	---
	50	0.00E+00	---	---	2.13E-09	---	---
	100	---	---	---	0.00E+00	---	---
	500	---	---	---	---	---	---
Cs-137(D) fu=0.8	1	3.37E-03	2.18E-03	---	3.37E-03	2.20E-03	---
	5	1.79E-03	1.94E-03	---	1.35E-02	1.28E-02	---
	10	8.77E-04	9.07E-04	---	1.91E-02	1.88E-02	---
	50	5.30E-04	5.31E-04	---	4.35E-02	4.33E-02	---
	100	3.86E-04	3.86E-04	---	6.60E-02	6.59E-02	---
	500	3.03E-05	3.03E-05	---	1.19E-01	1.19E-01	---
U-235(D) fu=1	1	4.24E-02	4.18E-02	4.18E-02	4.24E-02	4.18E-02	4.18E-02
	5	4.70E-03	4.81E-03	4.80E-03	1.48E-01	1.48E-01	1.48E-01
	10	3.26E-05	3.37E-05	4.00E-04	1.51E-01	1.51E-01	1.51E-01
	50	0.00E+00	0.00E+00	---	1.51E-01	1.51E-01	1.51E-01
	100	0.00E+00	0.00E+00	---	1.51E-01	1.51E-01	1.51E-01
	500	0.00E+00	0.00E+00	---	1.51E-01	1.51E-01	1.51E-01

Table 6.1.1 (continued)

		CLASS W					
		24-HOUR URINE			ACCUMULATED URINE		
NUCLIDE (CLASS)	DAY	BNL	REMedy	DOSEDAY	BNL	REMedy	DOSEDAY
Fe-59(W) fu=1	1	2.87E-05	1.82E-05	---	2.87E-05	1.82E-05	---
	5	3.68E-05	3.67E-05	---	1.69E-04	1.57E-04	---
	10	3.51E-05	3.52E-05	---	3.30E-04	3.19E-04	---
	50	2.17E-05	2.20E-05	---	9.93E-04	1.00E-03	---
	100	1.09E-05	1.13E-05	---	9.79E-04	1.01E-03	---
	500	2.12E-08	2.54E-08	---	1.08E-05	1.29E-05	---
Co-60(W) fu=0.7	1	2.27E-02	2.17E-02	2.16E-02	2.27E-02	2.17E-02	2.16E-02
	5	1.98E-03	2.08E-03	2.06E-03	4.14E-02	4.03E-02	4.03E-02
	10	1.11E-03	1.18E-03	---	4.81E-02	4.74E-02	4.74E-02
	50	2.72E-04	2.73E-04	---	6.59E-02	6.58E-02	6.57E-02
	100	1.62E-04	1.63E-04	---	7.51E-02	7.50E-02	7.50E-02
	500	6.69E-06	6.70E-06	---	7.99E-02	7.99E-02	7.98E-02
Ce-144(W) fu=1	1	1.39E-05	9.12E-06	---	1.39E-05	9.12E-06	---
	5	1.43E-05	1.43E-05	---	7.05E-05	6.54E-05	---
	10	1.46E-05	1.46E-06	---	1.42E-04	1.37E-04	---
	50	1.59E-05	1.59E-05	---	7.17E-04	7.12E-04	---
	100	1.59E-05	1.59E-05	---	1.39E-03	1.38E-03	---
	500	---	---	---	3.13E-03	3.12E-03	---
Th-232(W) fu=1	1	5.33E-03	5.32E-03	---	5.33E-03	5.32E-03	---
	5	9.04E-05	9.02E-05	---	7.41E-03	7.40E-03	---
	10	6.72E-05	6.71E-05	---	7.76E-03	7.74E-03	---
	50	5.52E-05	5.51E-05	---	1.02E-02	1.02E-02	---
	100	4.44E-05	4.43E-05	---	1.27E-02	1.26E-02	---
	500	2.24E-05	2.24E-05	---	2.43E-02	2.42E-02	---
U-235(W) fu=1	1	4.13E-02	4.24E-02	4.24E-02	4.13E-02	4.24E-02	4.24E-02
	5	2.69E-03	2.73E-03	2.73E-03	6.28E-02	6.20E-02	6.20E-02
	10	1.75E-03	1.79E-03	1.78E-03	7.30E-02	7.25E-02	7.25E-02
	50	4.80E-04	4.82E-04	---	1.06E-01	1.06E-01	1.06E-01
	100	2.43E-04	2.43E-04	---	1.23E-01	1.23E-01	1.23E-01
	500	2.46E-06	2.46E-06	---	1.43E-01	1.43E-01	1.43E-01
Pu-239(W) fu=0.54	1	2.83E-04	1.97E-04	---	2.83E-04	1.97E-04	---
	5	5.39E-05	6.14E-05	---	7.01E-04	6.86E-04	---
	10	2.54E-05	2.60E-05	---	8.59E-04	8.54E-04	---
	50	1.45E-05	1.46E-05	---	1.58E-03	1.58E-03	---
	100	1.12E-05	1.12E-05	---	2.21E-03	2.21E-03	---
	500	3.59E-06	3.60E-06	---	4.73E-03	4.71E-03	---

Table 6.1.1 (continued)

		CLASS W					
		24-HOUR FECES			ACCUMULATED FECES		
NUCLIDE (CLASS)	DAY	BNL	REMedy	DOSEDAY	BNL	REMedy	DOSEDAY
Fe-59(W) fu=1	1	3.87E-02	---	---	3.87E-02	3.80E-02	---
	5	2.81E-02	---	---	3.27E-01	3.27E-01	---
	10	1.58E-03	---	---	3.30E-01	3.13E-01	---
	50	2.96E-04	---	---	1.93E-01	1.97E-01	---
	100	6.79E-05	---	---	9.35E-02	9.70E-02	---
	500	0.00E+00	---	---	1.94E-04	2.33E-04	---
Co-60(W) fu=0.7	1	5.04E-02	4.93E-02	4.94E-02	5.04E-02	4.93E-02	4.94E-02
	5	3.03E-03	3.35E-02	3.33E-02	3.90E-01	3.89E-01	3.89E-01
	10	2.43E-03	2.47E-03	---	4.26E-01	4.26E-01	4.26E-01
	50	7.84E-04	7.85E-04	---	4.64E-01	4.64E-01	4.64E-01
	100	3.97E-04	3.98E-04	---	4.84E-01	4.83E-01	4.84E-01
	500	3.98E-06	3.98E-06	---	4.45E-01	4.45E-01	4.45E-01
Ce-144(W) fu=1	1	4.20E-02	4.14E-02	---	4.20E-02	4.14E-02	---
	5	3.37E-02	3.42E-02	---	3.88E-01	3.87E-01	---
	10	2.02E-03	2.03E-03	---	4.18E-01	4.18E-01	---
	50	6.33E-04	6.33E-04	---	4.13E-01	4.13E-01	---
	100	2.80E-04	2.80E-04	---	3.86E-01	3.86E-01	---
	500	4.13E-07	4.12E-07	---	1.53E-01	1.53E-01	---
Th-232(W) fu=1	1	4.22E-02	4.15E-02	---	4.22E-02	4.15E-02	---
	5	3.42E-02	3.46E-02	---	3.93E-01	3.92E-01	---
	10	2.07E-03	2.08E-03	---	4.28E-01	4.28E-01	---
	50	7.16E-04	7.15E-04	---	4.67E-01	4.67E-01	---
	100	3.58E-04	3.58E-04	---	4.93E-01	4.92E-01	---
	500	1.62E-06	1.40E-06	---	5.18E-01	5.18E-01	---
U-235(W) fu=1	1	4.07E-02	4.01E-02	4.01E-02	4.07E-02	4.01E-02	4.01E-02
	5	3.23E-02	3.27E-02	3.27E-03	3.73E-01	3.73E-01	3.73E-01
	10	1.97E-03	1.97E-03	2.00E-03	4.07E-01	4.07E-01	4.07E-01
	50	6.80E-04	6.80E-04	---	4.44E-01	4.44E-01	4.44E-01
	100	3.40E-04	3.40E-04	---	4.68E-01	4.68E-01	4.69E-01
	500	1.33E-06	1.33E-06	---	4.92E-01	4.92E-01	4.93E-01
Pu-239(W) fu=0.54	1	4.24E-02	4.16E-02	---	4.24E-02	4.16E-02	---
	5	3.42E-02	3.46E-02	---	3.93E-01	3.93E-01	---
	10	2.09E-03	2.10E-02	---	4.29E-01	4.29E-01	---
	50	7.28E-04	7.28E-04	---	4.68E-01	4.68E-01	---
	100	3.67E-04	3.67E-04	---	4.94E-01	4.94E-01	---
	500	4.46E-06	4.47E-06	---	5.22E-01	5.22E-01	---

Table 6.1.1 (continued)

		CLASS Y					
		24-HOUR URINE			ACCUMULATED URINE		
NUCLIDE (CLASS)	DAY	BNL	REMedy	DOSEDAY	BNL	REMedy	DOSEDAY
Co-60(Y) fu=0.7	1	4.64E-03	3.87E-03	---	4.63E-03	3.90E-03	---
	5	8.17E-04	7.41E-04	---	1.38E-02	1.17E-02	---
	10	3.33E-04	3.14E-04	---	1.60E-02	1.38E-02	---
	50	3.52E-05	3.19E-05	---	1.95E-02	1.70E-02	---
	100	2.60E-05	2.43E-05	---	2.06E-02	1.81E-02	---
	500	1.48E-05	1.64E-05	---	2.45E-02	2.26E-02	---
Th-232(Y) fu=1	1	2.95E-04	2.95E-04	---	2.95E-04	2.95E-04	---
	5	4.22E-06	4.22E-06	---	4.12E-04	4.11E-04	---
	10	2.81E-06	2.84E-06	---	4.26E-04	4.26E-04	---
	50	2.98E-06	3.13E-06	---	5.42E-04	5.45E-04	---
	100	3.19E-06	3.49E-06	---	6.97E-04	7.11E-04	---
	500	4.51E-06	5.67E-06	---	2.26E-03	2.59E-03	---
U-235(Y) fu=1	1	2.23E-03	2.29E-03	---	2.23E-03	2.29E-03	---
	5	1.31E-04	1.34E-04	---	3.30E-03	3.26E-03	---
	10	8.42E-05	8.66E-05	---	3.79E-03	3.77E-03	---
	50	2.34E-05	2.47E-05	---	5.32E-03	5.34E-03	---
	100	1.87E-05	2.11E-05	---	6.33E-03	6.45E-03	---
	500	1.81E-05	2.44E-05	---	1.36E-02	1.58E-02	---
Pu-239(Y) fu=0.54	1	1.55E-05	1.08E-05	---	1.55E-05	1.08E-05	---
	5	2.87E-06	3.28E-06	---	3.82E-05	3.74E-05	---
	10	1.29E-06	1.33E-06	---	4.63E-05	4.61E-05	---
	50	7.57E-07	7.79E-07	---	8.27E-05	8.32E-05	---
	100	6.99E-07	7.47E-07	---	1.18E-04	1.21E-04	---
	500	8.45E-07	1.07E-06	---	4.29E-04	4.94E-04	---

Table 6.1.1 (continued)

CLASS Y

NUCLIDE (CLASS)	DAY	24-HOUR FECES			ACCUMULATED FECES		
		BNL	REMedy	DOSEDAY	BNL	REMedy	DOSEDAY
Co-60(Y) fu=0.7	1	5.15E-02	5.11E-02	---	5.15E-02	5.11E-02	---
	5	3.45E-02	3.51E-02	---	4.34E-01	4.35E-01	---
	10	1.01E-03	1.08E-03	---	4.64E-01	4.66E-01	---
	50	1.29E-04	1.34E-04	---	4.64E-01	4.66E-01	---
	100	1.17E-04	1.21E-04	---	4.62E-01	4.64E-01	---
	500	5.87E-05	6.20E-05	---	4.31E-01	4.34E-01	---
Th-232(Y) fu=1	1	5.21E-02	5.12E-02	---	5.21E-02	5.12E-02	---
	5	3.64E-02	3.69E-02	---	4.51E-01	4.53E-01	---
	10	9.85E-04	1.00E-03	---	4.86E-01	4.86E-01	---
	50	1.29E-04	1.29E-04	---	4.92E-01	4.92E-01	---
	100	1.21E-04	1.21E-04	---	4.98E-01	4.98E-01	---
	500	6.94E-05	6.93E-05	---	5.35E-01	5.35E-01	---
U-235(Y) fu=1	1	5.20E-02	5.12E-02	---	5.20E-02	5.12E-02	---
	5	3.63E-02	3.68E-02	---	4.53E-01	4.52E-01	---
	10	9.83E-04	9.98E-04	---	4.85E-01	4.85E-01	---
	50	1.29E-04	1.29E-04	---	4.91E-01	4.91E-01	---
	100	1.20E-04	1.20E-04	---	4.97E-01	4.97E-01	---
	500	6.92E-05	6.91E-05	---	5.34E-01	5.34E-01	---
Pu-239(Y) fu=0.54	1	5.21E-02	5.12E-02	---	5.21E-02	5.12E-02	---
	5	3.64E-02	3.69E-02	---	4.54E-01	4.53E-01	---
	10	9.87E-04	1.00E-03	---	4.86E-01	4.86E-01	---
	50	1.30E-04	1.30E-04	---	4.92E-01	4.92E-01	---
	100	1.21E-04	1.21E-04	---	4.98E-01	4.98E-01	---
	500	7.00E-05	7.02E-05	---	5.36E-01	5.36E-01	---

Table 6.1.2 Validation of Inhalation Results for In Vivo Measurements

CLASS D

NUCLIDE (CLASS)	DAY	WHOLE BODY			LUNGS		
		BNL	REMedy	DOSEDAY	BNL	REMedy	DOSEDAY
Fe-59(D)	1	5.89E-01	5.90E-01	---	7.85E-02	7.84E-02	---
	5	4.61E-01	4.61E-01	---	5.37E-04	5.37E-04	---
	10	4.23E-01	4.25E-01	---	7.67E-07	7.68E-07	---
	50	2.24E-01	2.28E-01	---	0.00E+00	0.00E+00	---
	100	1.01E-01	1.05E-01	---	0.00E+00	0.00E+00	---
	500	1.74E-04	2.09E-04	---	0.00E+00	0.00E+00	---
Sr-90(D)	1	5.05E-01	5.11E-01	---	7.97E-02	7.96E-02	---
	5	2.67E-01	2.72E-01	---	5.80E-04	6.00E-04	---
	10	1.78E-01	1.76E-01	---	8.96E-07	8.57E-07	---
	50	9.91E-02	9.90E-02	---	0.00E+00	0.00E+00	---
	100	8.99E-02	8.98E-02	---	0.00E+00	0.00E+00	---
	500	6.07E-02	6.03E-02	---	0.00E+00	0.00E+00	---
I-131(D)	1	2.74E-01	2.74E-01	2.70E-01	7.31E-02	7.31E-02	7.34E-02
	5	1.25E-01	1.25E-01	1.23E-01	3.77E-04	3.77E-04	3.73E-04
	10	8.00E-02	8.02E-02	7.94E-02	3.79E-07	3.78E-07	0.00E+00
	50	2.11E-03	2.10E-03	2.49E-03	0.00E+00	0.00E+00	0.00E+00
	100	---	---	---	0.00E+00	---	---
	500	---	---	---	---	---	---
Cs-137(D)	1	6.22E-01	6.28E-01	---	7.97E-02	7.96E-02	---
	5	5.72E-01	5.75E-01	---	5.80E-04	5.80E-04	---
	10	5.43E-01	5.45E-01	---	8.96E-07	8.95E-07	---
	50	4.19E-01	4.20E-01	---	0.00E+00	0.00E+00	---
	100	3.05E-01	3.06E-01	---	0.00E+00	0.00E+00	---
	500	2.39E-02	2.40E-02	---	0.00E+00	0.00E+00	---
U-235(D)	1	4.10E-01	4.04E-01	4.05E-01	7.97E-02	7.96E-02	7.99E-02
	5	1.69E-01	1.72E-01	1.72E-01	5.81E-04	5.80E-04	5.83E-04
	10	1.21E-01	1.23E-01	1.24E-01	8.96E-07	8.95E-07	0.00E+00
	50	2.96E-01	2.98E-02	2.93E-02	0.00E+00	0.00E+00	---
	100	1.47E-02	1.47E-02	1.45E-02	0.00E+00	0.00E+00	---
	500	1.09E-02	1.09E-02	1.09E-02	0.00E+00	0.00E+00	---

Table 6.1.2 (continued)

NUCLIDE (CLASS)	DAY	CLASS W			LUNGS		
		WHOLE BODY		DOSEDAY	BNL	REMedy	DOSEDAY
Fe-59(W)	1	5.91E-01	5.91E-01				
	5	2.64E-01	2.65E-01	---	1.34E-01	1.34E-01	---
	10	2.17E-01	2.18E-01	---	1.13E-01	1.13E-01	---
	50	9.95E-02	1.01E-01	---	3.64E-02	3.70E-02	---
	100	4.03E-02	4.18E-02	---	8.81E-03	9.13E-03	---
	500	6.12E-05	7.35E-05	---	9.62E-08	1.15E-07	---
Co-60(W)	1	5.66E-01	5.68E-01	5.68E-01	2.11E-01	2.10E-01	2.11E-01
	5	2.06E-01	2.08E-01	2.08E-01	1.44E-01	1.44E-01	1.44E-01
	10	1.63E-01	1.64E-01	1.64E-01	1.32E-01	1.32E-01	1.32E-01
	50	9.78E-02	9.79E-02	9.79E-02	7.78E-02	7.78E-02	7.78E-02
	100	5.77E-02	5.78E-02	5.78E-02	4.03E-02	4.03E-02	4.03E-02
	500	8.49E-03	8.44E-03	8.49E-03	1.93E-04	1.93E-04	1.93E-04
Ce-144(W)	1	5.96E-01	5.96E-01	---	2.10E-01	2.10E-01	---
	5	2.44E-01	2.44E-01	---	1.43E-01	1.43E-01	---
	10	2.06E-01	2.06E-01	---	1.29E-01	1.29E-01	---
	50	1.52E-01	1.52E-01	---	7.02E-02	7.01E-02	---
	100	1.13E-01	1.13E-01	---	3.27E-02	3.27E-02	---
	500	3.27E-02	3.26E-02	---	6.82E-05	6.80E-05	---
Th-232(W)	1	5.92E-01	5.92E-01	---	2.11E-01	2.11E-01	---
	5	2.39E-01	2.40E-01	---	1.45E-01	1.44E-01	---
	10	2.03E-01	2.03E-01	---	1.32E-01	1.32E-01	---
	50	1.62E-01	1.62E-01	---	7.93E-02	7.92E-02	---
	100	1.34E-01	1.34E-01	---	4.18E-02	4.18E-02	---
	500	9.68E-02	9.68E-02	---	2.31E-04	2.31E-04	---
U-235(W)	1	5.57E-01	5.57E-01	5.57E-01	2.11E-01	2.11E-01	2.11E-01
	5	2.03E-01	2.04E-01	2.05E-01	1.45E-01	1.44E-01	1.45E-01
	10	1.59E-01	1.60E-01	1.60E-01	1.32E-01	1.32E-01	1.33E-01
	50	8.95E-02	8.95E-02	8.98E-02	7.93E-02	7.92E-02	7.95E-02
	100	4.81E-02	4.81E-02	4.83E-02	4.18E-02	4.18E-02	4.19E-02
	500	3.54E-03	3.53E-03	3.54E-03	2.31E-04	2.31E-04	2.31E-04
Pu-239(W)	1	5.96E-01	5.97E-01	---	2.11E-01	2.11E-01	---
	5	2.45E-01	2.46E-01	---	1.45E-01	1.44E-01	---
	10	2.09E-01	2.09E-01	---	1.32E-01	1.32E-01	---
	50	1.69E-01	1.69E-01	---	7.93E-02	7.92E-02	---
	100	1.42E-01	1.42E-01	---	4.18E-02	4.18E-02	---
	500	1.12E-01	1.12E-01	---	2.31E-04	2.31E-04	---

Table 6.1.2 (continued)

		CLASS Y					
		WHOLE BODY			LUNGS		
NUCLIDE (CLASS)	DAY	BNL	REMedy	DOSEDAY	BNL	REMedy	DOSEDAY
Am-241(W)	1	---	5.91E-01	5.92E-01	---	2.11E-01	2.11E-01
	5	---	2.40E-01	2.40E-01	---	1.44E-01	1.45E-01
	10	---	2.03E-01	2.04E-01	---	1.32E-01	1.33E-01
	50	---	1.63E-01	1.63E-01	---	7.92E-02	7.95E-02
	100	---	1.36E-01	1.36E-01	---	4.17E-02	4.19E-02
	500	---	1.08E-01	---	---	2.30E-04	---
Co-60(Y)	1	5.83E-01	5.84E-01	---	2.13E-01	2.13E-01	---
	5	1.90E-01	1.91E-01	---	1.52E-01	1.52E-01	---
	10	1.57E-01	1.57E-01	---	1.48E-01	1.47E-01	---
	50	1.44E-01	1.44E-01	---	1.39E-01	1.39E-01	---
	100	1.34E-01	1.34E-01	---	1.30E-01	1.30E-01	---
	500	7.82E-02	7.65E-02	---	7.56E-02	7.37E-02	---
Th-232(Y)	1	5.87E-01	5.87E-01	---	2.13E-01	2.13E-01	---
	5	1.85E-01	1.85E-01	---	1.53E-01	1.53E-01	---
	10	1.53E-01	1.53E-01	---	1.48E-01	1.48E-01	---
	50	1.47E-01	1.46E-01	---	1.42E-01	1.42E-01	---
	100	1.40E-01	1.40E-01	---	1.35E-01	1.35E-01	---
	500	1.02E-01	1.01E-01	---	9.06E-02	8.82E-02	---
U-235(Y)	1	5.85E-01	5.86E-01	---	2.13E-01	2.13E-01	---
	5	1.83E-01	1.83E-01	---	1.53E-01	1.53E-01	---
	10	1.50E-01	1.50E-01	---	1.48E-01	1.48E-01	---
	50	1.43E-01	1.43E-01	---	1.42E-01	1.42E-01	---
	100	1.35E-01	1.35E-01	---	1.35E-01	1.35E-01	---
	500	9.12E-02	8.89E-02	---	9.06E-02	8.82E-02	---
Pu-239(Y)	1	5.87E-01	5.88E-01	5.88E-01	2.13E-01	2.13E-01	2.14E-01
	5	1.85E-01	1.86E-01	1.86E-01	1.53E-01	1.53E-01	1.53E-01
	10	1.53E-01	1.53E-01	1.53E-01	1.48E-01	1.48E-01	1.49E-01
	50	1.47E-01	1.47E-01	1.47E-01	1.42E-01	1.42E-01	1.42E-01
	100	1.41E-01	1.40E-01	1.41E-01	1.35E-01	1.35E-01	1.35E-01
	500	1.03E-01	1.03E-01	1.03E-01	9.06E-02	8.82E-02	9.09E-02

Table 6.1.3 Validation of Ingestion Results

NUCLIDE (CLASS)	DAY	24-HOUR URINE		WHOLE-BODY		24-HOUR FECES	
		BNL	REMedy	BNL	REMedy	BNL	REMedy
Co-60 $f_1=0.05$	1	1.25E-02	1.20E-02	7.10E-01	7.11E-01	2.77E-01	2.77E-01
	5	8.50E-04	9.12E-04	3.59E-02	3.68E-02	2.99E-02	2.99E-02
	10	4.54E-04	4.90E-04	1.43E-02	1.48E-02	4.01E-04	4.16E-04
	50	2.99E-05	2.99E-05	7.51E-03	7.43E-03	0.00E+00	1.28E-05
	100	1.56E-05	1.52E-05	5.95E-03	5.96E-03	---	6.51E-06
	500	2.09E-06	1.75E-06	2.72E-03	2.72E-03	---	7.50E-07
Sr-90 $f_1=0.3$	1	5.48E-02	5.48E-02	7.18E-01	7.22E-01	2.27E-01	2.23E-01
	5	1.30E-02	1.40E-02	1.58E-01	1.61E-01	2.26E-02	2.33E-02
	10	5.60E-03	5.95E-03	9.90E-02	9.81E-02	1.13E-03	1.20E-03
	50	1.10E-04	1.07E-04	5.63E-02	5.62E-02	1.93E-05	1.88E-05
	100	7.15E-05	7.18E-05	5.11E-02	5.10E-02	1.26E-05	1.27E-05
	500	1.62E-05	1.67E-05	3.45E-02	3.43E-02	2.86E-06	2.94E-06
I-131 $f_1=1.0$	1	6.02E-01	5.97E-01	3.16E-01	3.21E-01	0.00E+00	0.00E+00
	5	2.52E-04	2.31E-04	1.94E-01	1.95E-01	0.00E+00	0.00E+00
	10	3.09E-04	3.00E-04	1.25E-01	1.25E-01	0.00E+00	0.00E+00
	50	1.87E-05	1.89E-05	3.30E-03	3.33E-03	0.00E+00	0.00E+00
	100	1.99E-07	2.02E-07	3.29E-05	3.34E-05	0.00E+00	0.00E+00
Cs-137 $f_1=1.0$	1	2.80E-02	1.80E-02	9.65E-01	9.77E-01	6.99E-03	4.51E-03
	5	1.03E-02	1.12E-02	8.89E-01	8.95E-01	2.57E-03	2.80E-03
	10	5.20E-03	5.48E-03	8.48E-01	8.50E-01	1.33E-03	1.37E-03
	50	3.31E-03	3.32E-03	6.55E-01	6.56E-01	8.28E-04	8.30E-04
	100	2.41E-03	2.41E-03	4.76E-01	4.77E-01	6.02E-04	6.04E-04
	500	1.89E-04	1.89E-04	3.74E-02	3.74E-02	4.72E-05	4.73E-05
U-235 $f_1=0.05$	1	2.34E-02	2.43E-02	7.05E-01	7.04E-01	2.72E-01	2.72E-01
	5	1.15E-03	1.18E-03	3.42E-02	3.46E-02	2.96E-02	2.96E-02
	10	7.25E-04	7.49E-04	1.23E-02	1.26E-02	2.07E-04	2.07E-04
	50	6.76E-05	6.86E-05	3.01E-03	3.03E-03	0.00E+00	0.00E+00
	100	1.13E-05	1.14E-05	1.50E-03	1.50E-03	0.00E+00	---
	500	1.68E-07	1.67E-07	1.11E-03	1.11E-03	---	---
Pu-239 $f_1=1E-4$	1	3.31E-07	2.13E-07	7.18E-01	7.18E-01	2.82E-01	2.82E-01
	5	7.42E-08	8.61E-08	1.88E-02	1.88E-02	3.14E-02	3.14E-02
	10	2.84E-08	2.94E-08	2.26E-04	2.26E-04	2.20E-04	2.20E-04
	50	1.13E-08	1.14E-08	9.67E-05	9.67E-05	0.00E+00	9.67E-09
	100	---	7.64E-09	9.58E-05	9.58E-05	---	6.51E-09
	500	---	2.70E-09	9.25E-05	9.25E-05	---	2.30E-09
Am-241 $f_1=5E4$	1	4.34E-05	4.34E-05	7.18E-01	7.18E-01	2.82E-01	2.82E-01
	5	1.65E-08	1.26E-08	1.92E-02	1.92E-02	3.14E-02	3.14E-02
	10	1.49E-08	1.11E-08	5.78E-04	5.78E-04	2.19E-04	2.19E-04
	50	1.49E-08	1.11E-08	4.49E-04	4.54E-04	0.00E+00	0.00E+00
	100	1.49E-08	1.11E-08	4.48E-04	4.49E-04	0.00E+00	0.00E+00
	500	1.46E-08	1.08E-08	4.42E-04	4.44E-04	0.00E+00	0.00E+00

Table 6.1.4 Validation of Thyroid Retention Results

NUCLIDE (CLASS)	DAYS	BNL	REMedy	DOSEDAY
I-131(D)	1	1.33E-01	1.68E-01	1.32E-01
	5	1.20E-01	1.22E-01	1.23E-01
	10	7.51E-02	7.72E-02	9.77E-02
	50	1.82E-03	2.06E-03	2.50E-03
	100	1.80E-05	2.26E-05	---
	500	---	---	---

6.2 Applications and Limitations of IRF Values

This manual is a compilation of an evaluated approach for interpreting measurements of radioactivity in body organs, in the whole body or in excreta in terms of the quantity of radioactive material taken into the body. Calculations based on information in this manual provide a mechanism to determine compliance with regulations on the intake of radioactivity and dose equivalent. Estimates of intake are needed not only to assess dose but to determine the need for medical follow-up on significantly exposed workers.

Section 2 describes a method to obtain intake retention functions. These functions give the fraction of intake expected to be present in a bioassay compartment at any time after an acute exposure. Because these functions are a relationship between bioassay measurement and intake, and because intake and effective dose equivalent are directly related in ICRP Publication 30, this manual provides a way to combine external and internal doses, a proposed requirement of the NRC and a recommendation of the ICRP.

Tables of intake retention fractions (IRFs) are provided for estimating inhalation or ingestion intakes for about 100 different nuclides. These tables give the fraction of intake retained in the lungs, systemic region of the body, gastrointestinal tract, nasal passages, thyroid (for iodine), the whole body, accumulated excreta, and 24-hour collections of excreta as a function of time post intake. Intakes are easily determined by dividing the value of the bioassay measurement by the appropriate fraction given in the tables.

This manual provides guidance for the design and conduct a bioassay program. Examples are given for the determination of derived investigation levels above which further measurement to estimate committed effective dose equivalent and other appropriate investigations and actions should be made. Derived investigation levels are listed for several commonly used radionuclides for various monitoring frequencies based on recommendations of ICRP. However, other factors may effect one's choice for derived investigation levels and monitoring frequencies. These factors may be related to plant operating history, equipment availability or specific NRC recommendations. Methods to determine the minimum monitoring frequency are provided along with sensitivity requirements.

6.2.1 Pitfalls Associated with Interpreting Bioassay Measurements

On the basis of independent validation studies, it is concluded that the tabular results accurately represent retention fractions and excretion fractions that are based on the models and calculational methods outlined in the manual. Thus, computational errors encountered when one calculates an IRF are avoided by use of tabulated values. Further, it is concluded that the methods of ICRP are accurately represented by the mathematical models used here. Some care must be exercised when excretion fractions expected at one day or less post intake are used in order to estimate intake from alternative models that use or don't use the ICRP transfer compartment. However, in most cases this difference is minor and in all cases this difference does not impact the tabulations beyond several days post intake. Because the retention of any transfer compartment is, in fact, included in the empirical uptake retention functions for the systemic whole body and because ICRP only included its transfer compartment for mathematical convenience, the authors of this report agreed to exclude it from the bioassay models presented here.

It is unrealistic to assume that individual results will fit model results in most exposure cases. Verification studies indicate that a reasonably accurate estimate of intake is derived from 3 to 10 measurements on excreta. On-the-other-hand, an accurate estimate of intake is derived from fewer in vivo measurements. Obtaining several measurements in sequence may identify the need for (1) correcting intake estimates for particle size differences; (2) adjusting intake estimates for single versus multiple or continuous intakes; and (3) adjusting intake estimates for an accurate time post intake. These adjustments are made by using methods given in Appendix A and Appendix B of this manual and use of these adjustments may in some cases provide a better fit of the bioassay measurements when compared to expectation values. However, many assumptions are required to translate bioassay measurements into estimates of intake and internal radiation doses. In most cases, it is practical to assume 1 micrometer particle size and use Reference Man models unless specific information is obtained for the exposed individual or for the physical and biochemical characteristics of the inhaled or ingested radio-nuclide. It is our experience that the variance associated with the stochastic nature of radioactive decay is overshadowed by the variance associated with the behavior of radioactive materials within the body. Thus, propagating only the counting error into the estimate of intake is not recommended. It is our recommendation that the best estimate of intake be made from an unweighted and minimized value of the chi-squared statistic. Thus, equation 3.1 in section 3.1, or equation A.2.4 in Appendix A, should be used with a series of measurements associated with exposure of an individual.

It is our experience that following an accident, a large portion of the intake will be in the fecal and urinary excreta eliminated during the first 5 days after an accident. The best estimate of intake may be determined by obtaining measurements on the first 5 days of excreta, particularly fecal excreta. Fecal sample results will help one to focus on the appropriate inhalation class. If one misses the first 5 days of excreta, large error in estimating the intake from excreta measurements could be encountered because one is forced to examine only a tiny fraction of the intake which may then be eliminated each day. Because of this the following bioassay strategy is noted.

After the first few days post intake, the behavior of radioactive materials in the body is described by parameters which apply over an extended period of time. These long-term parameters dominate model results for time post intake greater than a few days so that models are applicable over the time period from intake to excretion. Users of ICRP models should be aware that short-term-observations of small fractions of the intake, which may be excreted from the body each day after the intake, may not be the optimum way to obtain bioassay measurements. That is, after the first week passes, if radioactive material is measured 5 times in urinary samples which are collected 5 days in a row, and if the majority of the fraction of intake which remains in the body is to be excreted from the body over a much longer period of time, such as months to years, the estimate of intake may be better determined by obtaining the 5 measurements spaced evenly over a longer duration of time. In this way, errors due to short-term changes in metabolism are avoided, and the parameters which are associated with the long-term portions of the metabolic model are appropriate for the bioassay collection strategy.

6.3 Recommendations for Further Study

Good case studies for verification of bioassay excretion models are difficult to obtain. When accidents do occur, it is important that the maximum possible information be obtained from bioassay measurements to verify and improve bioassay models.

There appears to be a paucity of evaluated bioassay data applicable to a verification of the computational models and biokinetic parameters presented in this report. Further study should be devoted to refinement of models and parameters using actual bioassay results from studies involving exposure of humans. When significant accidental intakes occur, one should immediately collect nasal smears and urine and fecal samples, document the times of collection post-intake, and perform measurements on the collected samples and the body. Such measurements should be made even when it may be known that the exposure may be insignificant with respect to regulatory limits. To avoid undue concern among exposed workers, it should be explained that such measurements are voluntary and are being taken to improve the models.

Accidental intakes of transuranic radionuclides are usually followed by administration of the chelating agent diethylenetriaminepentaacetic acid (DPTA) in order to accelerate the excretion of bone-seeking radionuclides and to prevent their deposition on bone surfaces, and the soft tissues. Models should be developed for chelated radionuclides in order to estimate the urinary excretion of transuranic materials following an intake. Because of the enhanced excretion following chelation, research might be considered on workers known to have large exposures in the past. It may be possible to establish a relationship between chelated urinary excretion and the worker's current burden and perhaps his original intake.

Within the radiation worker community there is an expanding group of people who produce or administer radiopharmaceutical substances and there is a need to develop models for the retention and excretion of these substances.

In many instances, ICRP Publication 30 provides several values for f_1 , the fraction in the gastrointestinal tract which is absorbed into the blood. We have chosen the values which we feel are most common for worker exposures. Additional tabulations for different values for f_1 should be made.

Our tabulations apply to Reference Man and in most cases this is the appropriate model to use following accidental exposure. However, it is known that retention of certain nuclides varies with organ size and body weight, most notably iodine, cesium and strontium. Additionally, f_1 may vary with age of the person and this has been observed for plutonium. Other factors such as bone turnover rate, differences in organ uptake as a function of age, and remaining lifespan influence either the retention or the dose assessment and these influences may be considerable for infants and children. Methods to interpret bioassay measurements for these circumstances should be developed.