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Dose Estimation from Intakes of Exotic Radionuclides at the Los Alamos Neutron Science Center, 1996 to 2005	ORAUT-RPRT-0107	Rev. 00
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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
09/15/2023	00	New report to address concerns about the ability to reconstruct Los Alamos Neutron Science Center worker doses from “exotic” radionuclides. Incorporates formal internal and NIOSH review comments. Training is not required. Initiated by Pat McCloskey and authored by Thomas R. LaBone.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

CED	committed effective dose
d	day
DCF	dose conversion factor
DOE	U.S. Department of Energy
F	fast (absorption type)
ICRP	International Commission on Radiological Protection
LANL	Los Alamos National Laboratory
LANSCE	Los Alamos Neutron Science Center
M	moderate (absorption type)
MDA	minimum detectable amount
mrem	millirem
nCi	nanocurie
NCRP	National Council on Radiological Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
OBT	organically bound tritium
ORAU	Oak Ridge Associated Universities
ORAUT	ORAU Team
ppm	parts per million
S	slow (absorption type)
SRDB Ref ID	Site Research Database Reference Identification (number)
V	vapor

1.0 INTRODUCTION

In Los Alamos National Laboratory (LANL) work group discussions, concerns have been raised about the group's ability to assess doses to Los Alamos Neutron Science Center (LANSCE) workers delivered by intakes of "exotic" radionuclides.[1] In this document, exotic radionuclides are defined as activation and spallation products generated directly or indirectly by the accelerator proton beam for which bioassay results are not available for dose reconstruction.[2] The question addressed here is how to bound the potential dose to workers at LANSCE from intakes of radionuclides that were not adequately measured by whole body counting (i.e., exotic radionuclides).

The strategy used to answer this question is similar to that in ORAUT-OTIB-0054, *Fission and Activation Product Assignment for Internal Dose-Related Gross Beta and Gross Gamma Analyses* [Oak Ridge Associated Universities (ORAU) Team (ORAUT) 2015]. The proof-of-principle calculations presented here (1) identify a reference radionuclide mixture that contains exotics and (2) identify an appropriate indicator in the mixture (i.e., a radionuclide that was monitored in routine bioassay of LANSCE workers). The radionuclide mixtures in seven different accelerator components are calculated in Section 2.1. Subsequently, the indicator radionuclide and the reference radionuclide mixture are selected. The number of radionuclides in the reference mixture can be quite large, making dose calculations unwieldy. Thus, in Section 2.2, the mixture is simplified by removing dosimetrically insignificant radionuclides using committed effective dose (CED) dose conversion factors (DCFs) for three versions of the reference mixture that have different solubilities in the respiratory tract. The final products of the source term analysis are lists of radionuclides and the relative quantities of activity (Table 2-2 in Section 2.2). Intakes of the indicator radionuclide are calculated using standard dose reconstruction methods, from which the intakes of the exotics in the mixture are calculated by looking at the relative abundance of the indicator to each exotic. Example missed committed organ doses are calculated in Section 3.0 to illustrate how to apply this method. All calculations [ORAUT 2023a] were performed with the statistical computing software R.

2.0 REFERENCE RADIONUCLIDE MIXTURE AND INDICATOR

In CN-LANSCE-LFO-07-002 [Kelsey 2007a, p. 16–81], LANL calculated the composition of various components of the accelerator under typical operational parameters (e.g., beam current and length of exposure). The goal of the analysis was to identify a bounding radionuclide mixture to calculate dose to the maximally exposed offsite individual resulting from the maximum credible incident. In that report, the mixture of radionuclides at the end of bombardment for nine different components of the accelerator were reported:

1. Concrete,
2. Uranium shielding,
3. Two beam inserts,
4. Two shields,

[1] For example: concern about spallation products from accelerator [National Institute for Occupational Safety and Health (NIOSH) 2017, p. 80]; how to monitor for exotics [NIOSH 2017 p. 57]; and issues in monitoring for short-lived radionuclides [NIOSH 2018, p. 68].

[2] In a LANL Work Group discussion [NIOSH 2018, p. 6] it was suggested that "exotics" are radionuclides for which "NIOSH lacked the sufficient information necessary to complete individual dose reconstructions with sufficient accuracy." Here that definition is defined so that it focuses on the lack of bioassay results for a radionuclide being the perceived cause of the inability to reconstruct dose.

5. A beam window,

6. A beam stop, and

7. A tungsten spallation target.

The beam stop and tungsten target were expected to be the primary components of interest because there are no significant activation and spallation products produced in the depleted uranium shielding [ORAUT 2022a]. In the analysis, a loss of coolant accident involving an irradiated Mark-I1L tungsten target was selected as the design basis accident for the LANSCE facility. An updated Mark-I1L radionuclide inventory presented in CN-LANSCE-LFO-07-014 subsequently provided by LANL [Kelsey 2007b; ORAUT 2022b] was considered by the LANL scientists as more representative of actual accelerator operating conditions during the period of interest. The inventory presented for the tungsten target in Appendix 3 of CN-LANSCE-LFO-07-014 is used here as the reference mixture. LANL scientists confirmed that this radionuclide mixture for the Mark-I1L target would be bounding for all of LANSCE including areas where isotope production took place (A Area) and the Weapons Neutron Research Facility [ORAUT 2023b]. In Section 2.1, summaries for the radionuclide mixtures in accelerator components are given to show that, of all the mixtures considered, the tungsten target would deliver the largest internal dose. Radionuclides produced by neutron activation of elements present in ambient air and coolant water, like ^{7}Be, ^{11}C, ^{13}N, and ^{41}Ar [National Council on Radiological Protection and Measurements (NCRP) 2003, Table 6.5], are frequently detected by stack and workplace air monitoring. These radionuclides are not considered here because they are dosimetrically insignificant in comparison with the inventory of the tungsten target.

Ideally, the indicator radionuclide should be a component of the mixture that is readily detected and quantified by standard bioassay methods while having a high activity fraction in the mixture. Using these criteria, ^{60}Co was chosen as the indicator radionuclide. Using standard dose reconstruction methods, the intake of the ^{60}Co is calculated from the in vivo bioassay and the intakes of the other radionuclides in the mixture are calculated from the activity ratio of the components to the ^{60}Co.

2.1 RADIONUCLIDE MIXTURES IN ACCELERATOR COMPONENTS

The radionuclide mixtures in LANSCE components were extracted from Appendix 3 of CN-LANSCE-LFO-07-014 [Kelsey 2007b]. The number of radionuclides in each component considered for dose assessments were reduced by applying the following successive criteria to radionuclides reported for the mixture:

1. Target must have ^{60}Co listed as a significant component by activity since it is the indicator radionuclide.[3] Thus, all targets other than depleted uranium (which has no ^{60}Co) and concrete (which has ~2 ppm ^{60}Co by activity) are considered. Both depleted uranium and concrete are structural/shielding materials, and there is no plausible mechanism for releasing contamination from these materials into the workplace [ORAUT 2022a, p. 8].

2. All radionuclides in the target that do not have an International Commission on Radiological Protection (ICRP) Publication 68 [ICRP 1995] DCF are removed. The original number of radionuclides in each target and the number that have ICRP Publication 68 DCF[4] are given in Table 2-1.

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[3] The next best choice for an indicator radionuclide is ^{22}Na, but it is less desirable as an indicator because, as will be seen, the ^{148}Gd/^{22}Na activity ratio is much higher than the ^{148}Gd/^{60}Co activity ratio.

[4] ICRP Publication 68 does not provide DCFs for noble gases and radionuclides with a half-life of less than 10 minutes. The tungsten target had eight additional radionuclides that were not in ICRP Publication 68, reportedly because of large uncertainty associated with their decay schemes.

Table 2-1. Number of nuclides in targets.[a]

Target	N0	N
Mark-I1L	156	136
Beam stop	27	24
Beam window	27	24
Insert 1	22	19
Insert 2	23	20
Shielding 1	26	23
Shielding 2	21	18

a. N0 = number from ICRP [1995]; N = number from ICRP [1995] having DCF.

The number of radionuclides in each component and the proportion of dose delivered by the radionuclides are shown in the bar plots in Figures 2-1 to 2-7 (the Attachment B tables contain the data for those figures). Radionuclides in the component that deliver more than 1% of the total dose are given their own bar in the bar plots while the rest are combined under "Other." Note that this is to facilitate construction of the bar plot and that all the radionuclides are retained for dose calculations. The DCF given in each plot is the CED delivered by the radionuclide mixture in the component for each nCi of ^{60}Co inhaled. Note that the DCF for the mixture was calculated using the largest DCF for each radionuclide. For example, if the DCF for Type S of a given radionuclide was higher than the DCF for Type M of the radionuclide, then the DCF for Type S was used. The factor X, which is used to select the target that gives the highest dose, is how much the dose increases over that expected from an intake of 1 nCi of pure Type S ^{60}Co. The number over "Other" is the proportion of the total dose delivered by all the radionuclides not specifically named.

Cobalt-60 is the primary dose contributor for all components except the Mark-I1L tungsten target (Figure 2-1). This target is of particular interest because the major contributor to the CED is the alpha emitter ^{148}Gd, which is a spallation product of tungsten. Gadolinium-148 is known as the radionuclide of primary internal dosimetry concern for the tungsten targets because of its 75-year half-life [Kelley 2004]. A complete listing of the 136 nuclides for the tungsten target is given in Table A-1 (Attachment A). Based on the plots in Figures 2-1 to 2-7 and the likelihood of individuals being exposed to material from each target, the Mark-I1L tungsten target is the most appropriate for bounding doses to workers from intakes of exotic radionuclides at LANSCE. Note that for the plots in Figures 2-1 to 2-7, N is the number of radionuclides in the target, DCF is the CED in millirem from the mixture for every nanocurie of inhaled ^{60}Co, and X is the factor by which the dose increases in the mixture in comparison with pure ^{60}Co.

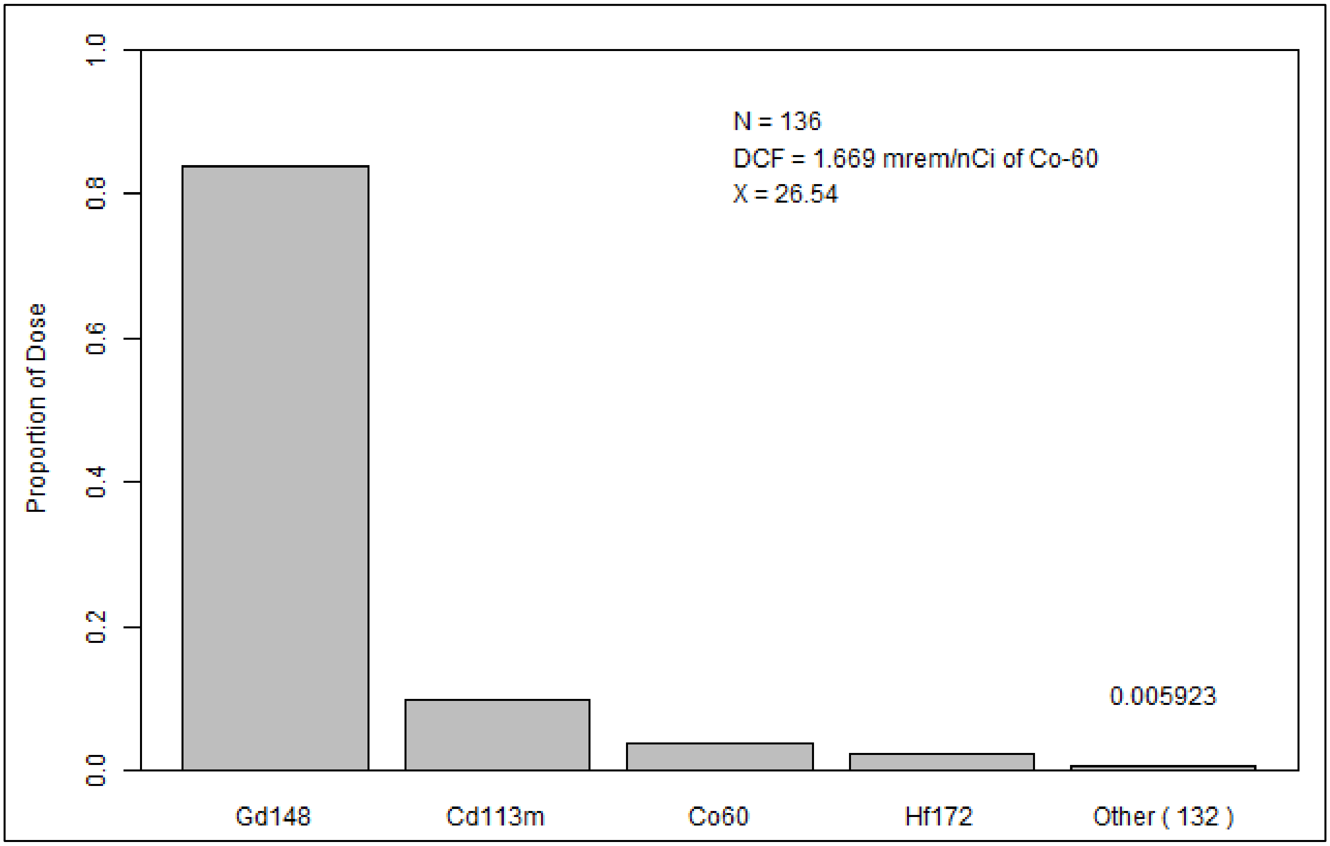

Figure 2-1. Mark-I1L tungsten target (data in Table B-1).

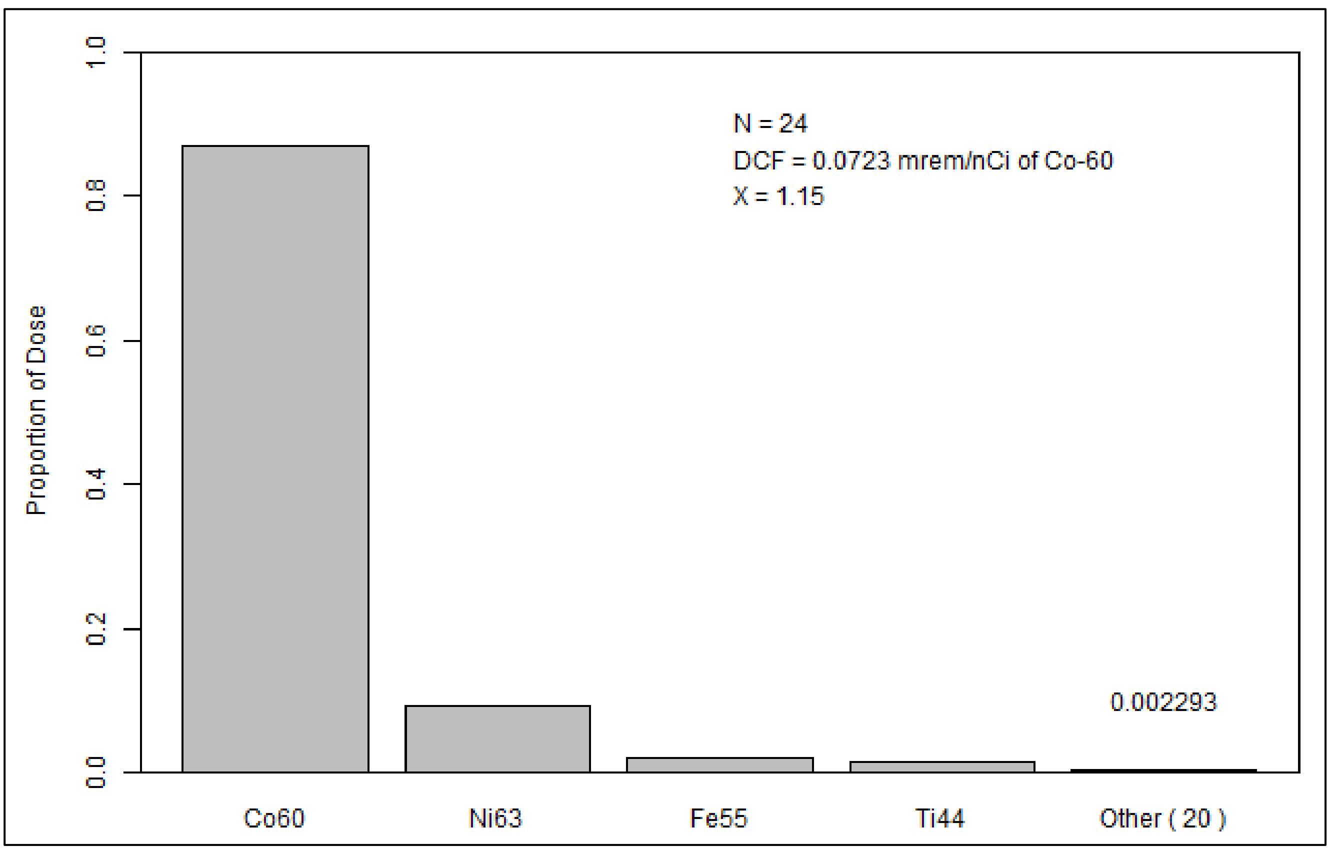

Figure 2-2. Beam stop (data in Table B-2).

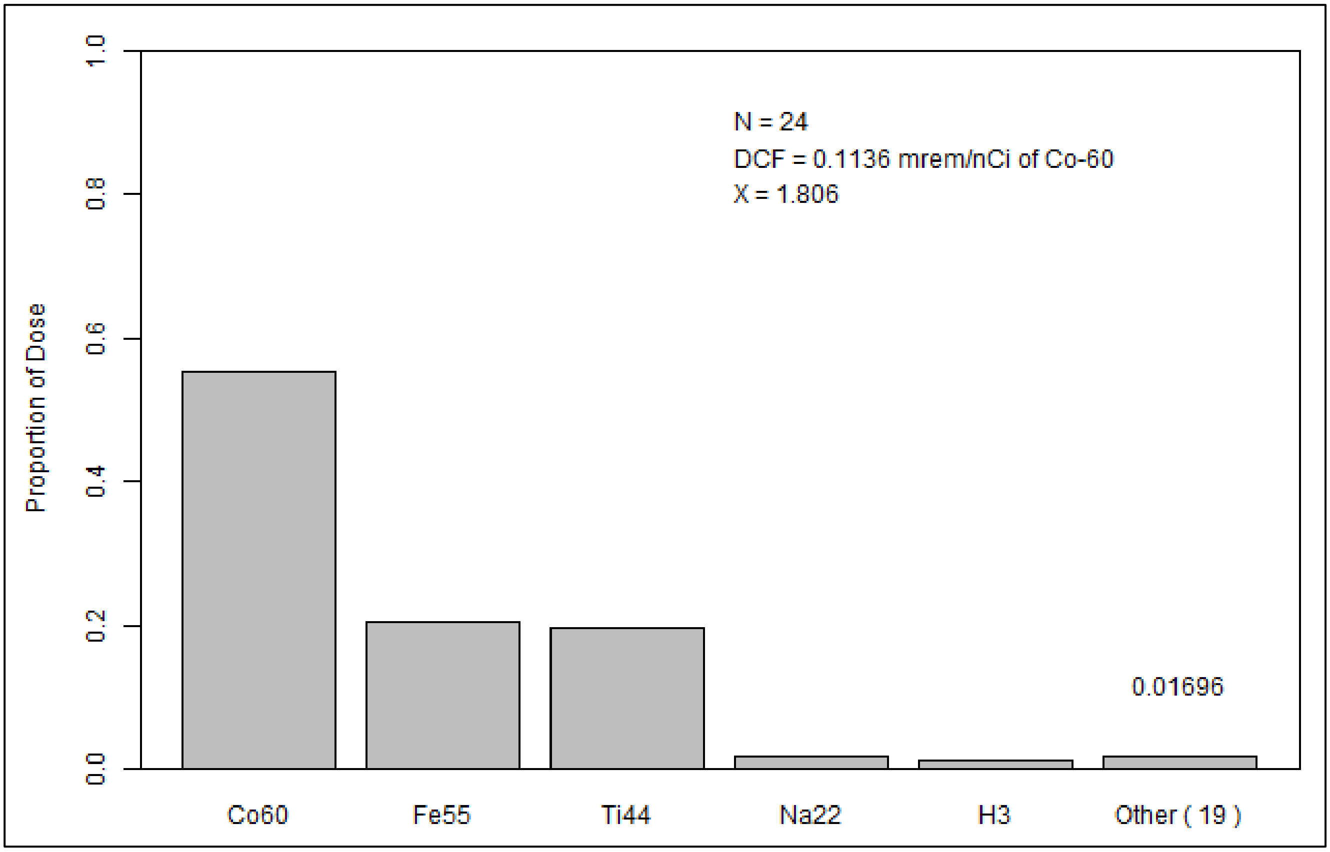

Figure 2-3. Beam window (data in Table B-3).

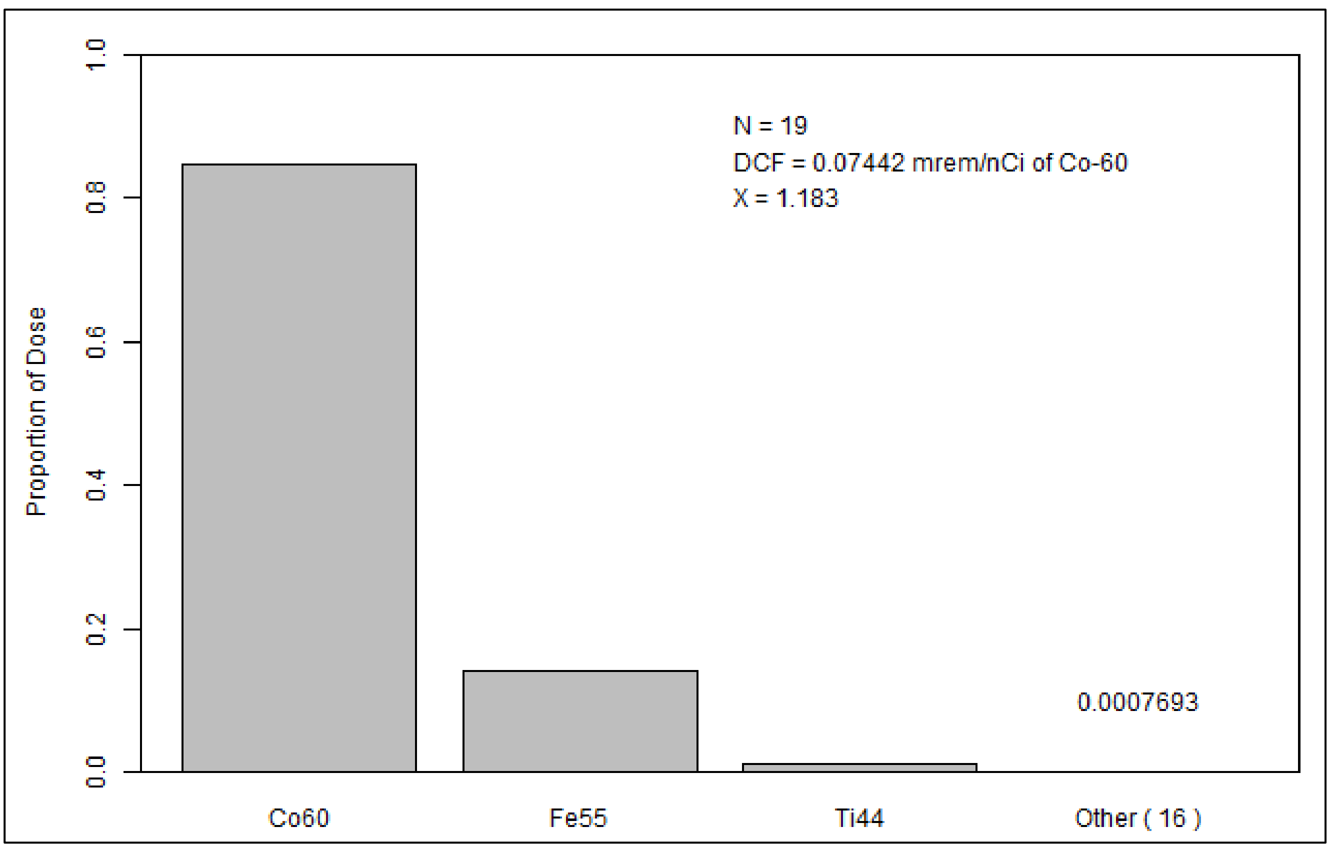

Figure 2-4. Insert 1 (data in Table B-4).

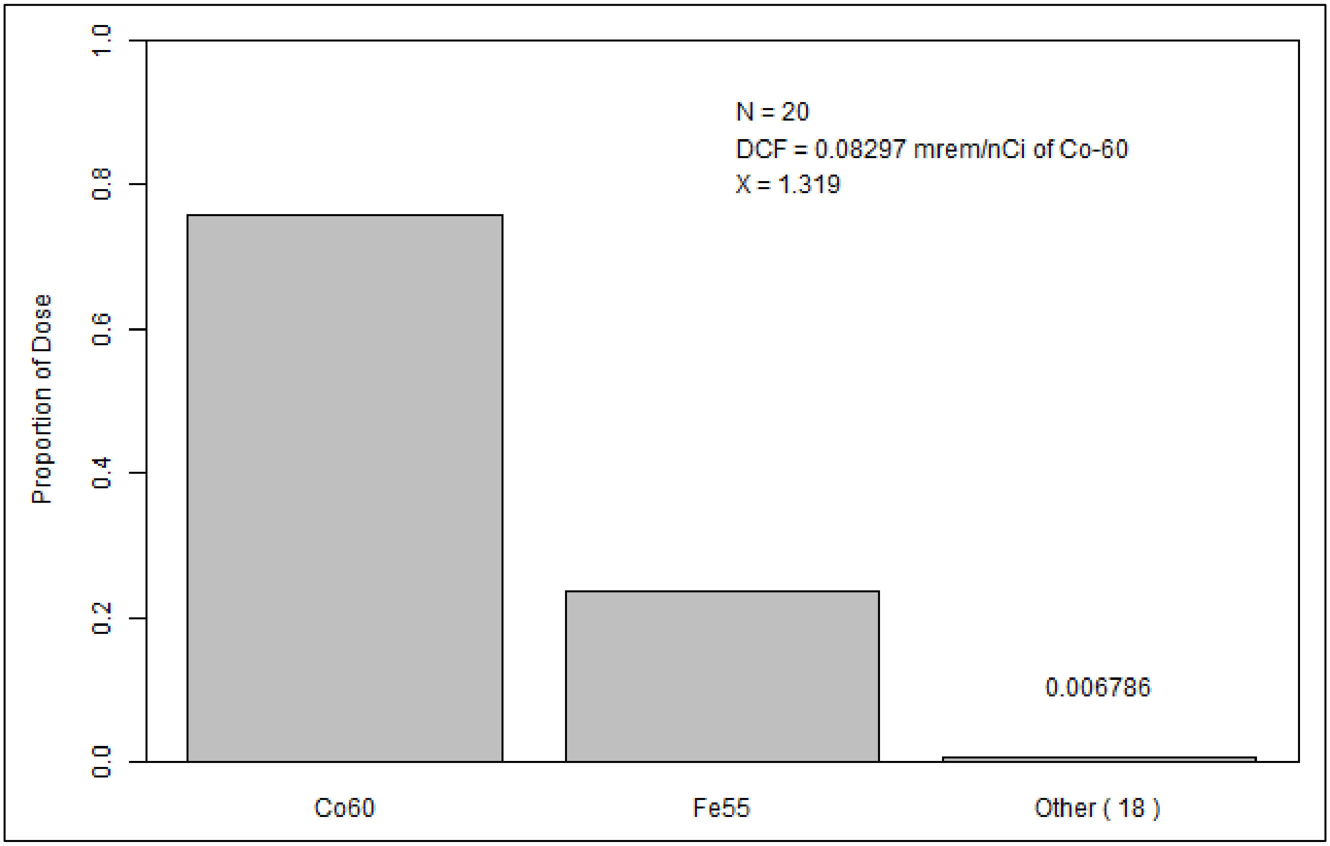

Figure 2-5. Insert 2 (data in Table B-5).

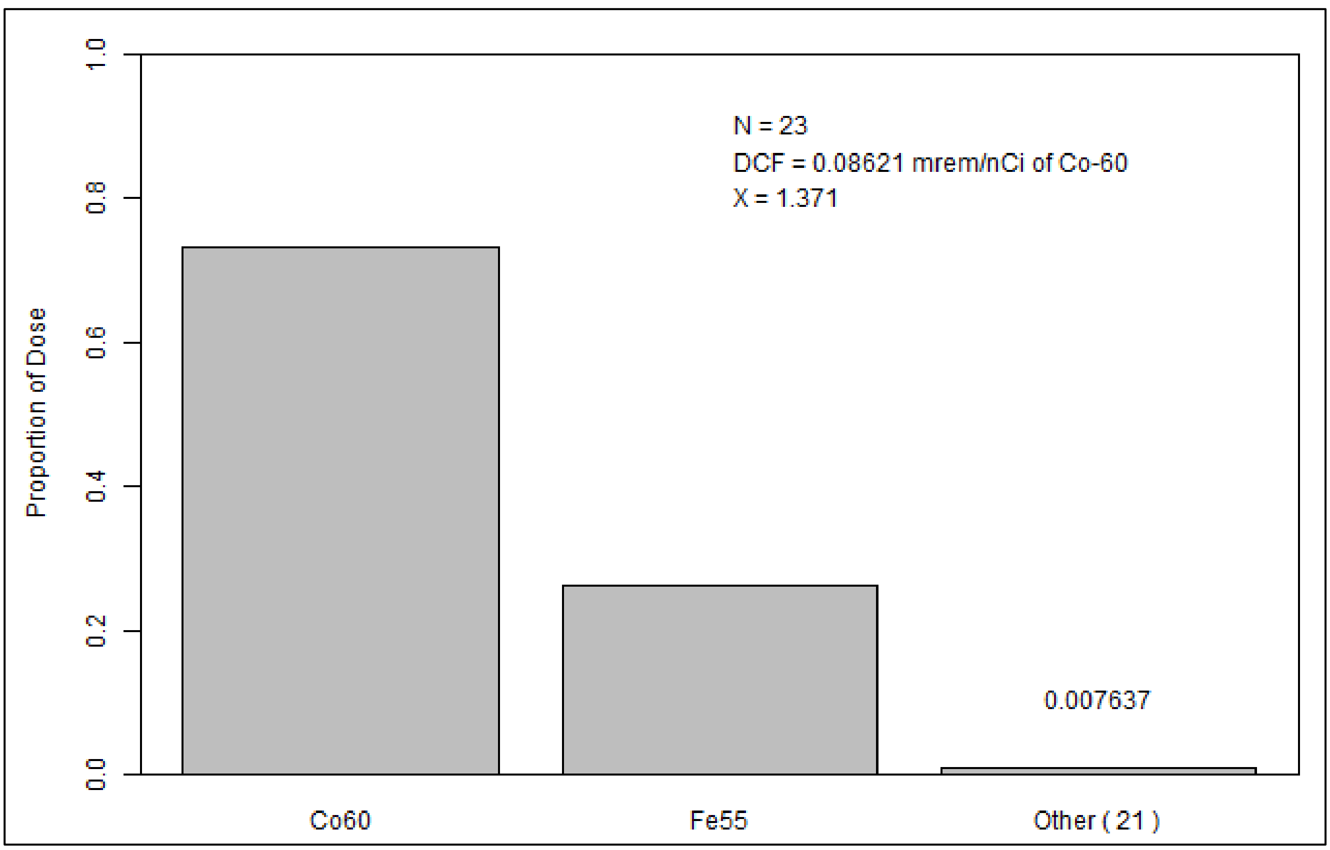

Figure 2-6. Shielding 1 (data in Table B-6).

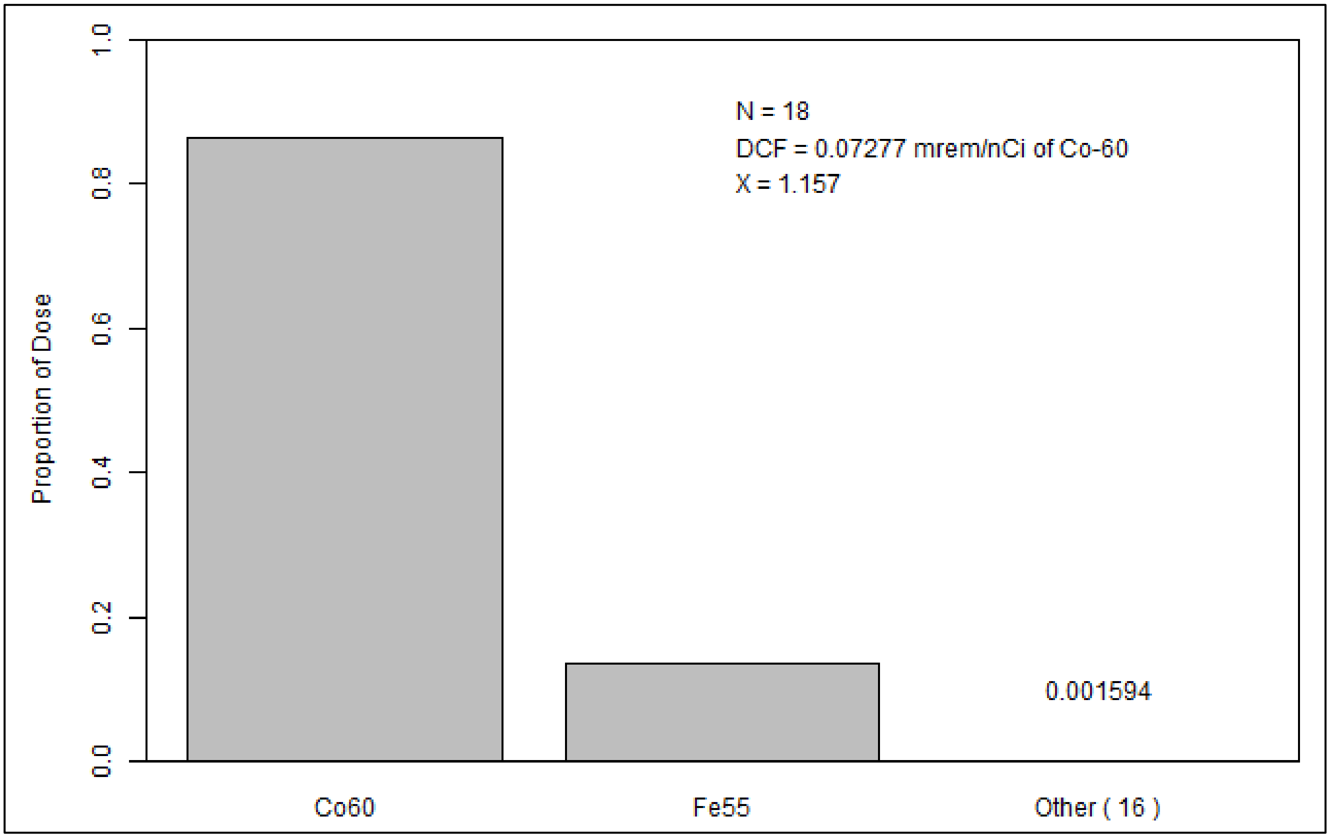

Figure 2-7. Shielding 2 (data in Table B-7).

2.2 DOSIMETRICALLY SIGNIFICANT RADIONUCLIDES IN MARK-I1L TUNGSTEN TARGET

To remove radionuclides in the tungsten target that do not have significant dosimetric impact, three solubility groups are created: soluble, moderate, and insoluble. For each of the 136 radionuclides in the Mark-I1L tungsten target, the ICRP Publication 68 absorption type (F, M, or S) that best agrees with the solubility group is assigned. This is essentially the same procedure used in ORAUT-OTIB-0054 [ORAUT 2015], with the possible exception of how vapors (V) are handled.[5] The complete list of 136 radionuclides is given in Table A-1 (Attachment A). Next, select significant radionuclides for the Mark-I1L target in each of the three solubility categories based on committed organ dose:

1. For each of the 26 organs, calculate the relative dose from all 136 radionuclides.
2. Retain radionuclides that contribute at least 1% of the dose to any of the 26 organs.

Finally, take the union of the radionuclides in the three lists, which gives the 13 dosimetrically significant radionuclides shown in Table 2-2. These are the same criteria used in ORAUT-OTIB-0054 to select dosimetrically significant radionuclides. Maximum committed organ DCF for adrenals, bone surface, and lung are provided in Table 2-2 for use in the next section.

5 For radionuclides with multiple types of vapors, use the one with the highest DCF. In particular, use the organically bound tritium (OBT) DCF for tritium.

Table 2-2. Dosimetrically significant Mark-I1L nuclides with ICRP Publication 68 organ DCFs (mrem/nCi of nuclide).[a]

i[b]	Nuclide	Activity[c]	DCF adrenal	DCF bone surface	DCF lung
1	Cd-113m	0.0581	0.07400	0.07400	0.34410
2	Co-60	0.1713	0.04070	0.01813	0.35520
3	Fe-55	0.1127	0.00096	0.00666	0.00096
4	Gd-148	0.0022	0.00481	3,700.0000	21.83000
5	H-3	0.3278	0.00015	0.00015	0.00015
6	Hf-172	0.0456	0.10730	3.29300	0.15170
7	Hg-194	0.0003	0.17760	0.14430	0.18130
8	Lu-172	0.0461	0.00081	0.00278	0.02664
9	Lu-173	0.0319	0.00185	0.09250	0.03515
10	Na-22	0.0039	0.00629	0.01147	0.00481
11	Ni-63	0.0121	0.00629	0.00629	0.01036
12	Ta-179	0.1516	0.00044	0.00063	0.00666
13	Tl-204	0.0363	0.00118	0.00118	0.00130

a. Source: ICRP [1995].
b. See the equations below for the use of i.
c. Note that the activity sums to 1.

3.0 EXAMPLE COMMITTED ORGAN DOSE CALCULATION

In in vivo counts performed in 1996 to 2005 at LANL, ^{60}Co was specifically reported only if it was identified by a peak search. Out of 330 whole body counts performed in 1996 to 2005, ^{60}Co was identified in only one instance [ORAUT 2023a]. Counts on the LANL whole body counter where no ^{60}Co is reported are interpreted as being less than the minimum detectable amount (MDA) of 0.83 nCi for ^{60}Co [Archuleta 2022]. In this example, the MDA for ^{60}Co will be used to calculate the missed dose from a <MDA result.

Assuming a constant chronic intake of Type S ^{60}Co for 1 year, a ^{60}Co body burden of MDA/2 at the end of the chronic intake implies a total intake I_S of 10.7 nCi (intake rate of 0.0293 nCi/d). Using the relative activities A_i of the radionuclides in the target and the committed organ DCF in Table 2-2, the 50-year committed organ doses from the intake of the mixture are:

$$H_{\text{lung}} = \sum_{i=1}^{13} I_S \left(\frac{A_i}{A_2} \right) DCF_{\text{lung},i} = 8.66 \text{ mrem} \tag{3-1}$$

$$H_{\text{bs}} = \sum_{i=1}^{13} I_S \left(\frac{A_i}{A_2} \right) DCF_{\text{bs},i} = 508 \text{ mrem} \tag{3-2}$$

$$H_{\text{adrenals}} = \sum_{i=1}^{13} I_S \left(\frac{A_i}{A_2} \right) DCF_{\text{adrenals},i} = 1.04 \text{ mrem} \tag{3-3}$$

where

A_2 = activity of ^{60}Co in the mixture.

Next, assuming a constant chronic intake of Type M ^{60}Co for 1 year, a ^{60}Co body burden of MDA/2 at the end of the chronic intake implies a total intake I_M of 14.3 nCi (intake rate of 0.0392 nCi/d). Using the relative activities A_i of the radionuclides in the target and the committed organ DCF in Table 2-2, the 50-year committed organ doses from the intake of the moderately soluble mixture are:

$$H_{\text{lung}} = \sum_{i=1}^{13} I_{\text{M}} \left(\frac{A_i}{A_2} \right) DCF_{\text{lung},i} = 11.6 \text{ mrem} \tag{3-4}$$

$$H_{\text{bs}} = \sum_{i=1}^{13} I_{\text{M}} \left(\frac{A_i}{A_2} \right) DCF_{\text{bs},i} = 679 \text{ mrem} \tag{3-5}$$

$$H_{\text{adrenals}} = \sum_{i=1}^{13} I_{\text{M}} \left(\frac{A_i}{A_2} \right) DCF_{\text{adrenals},i} = 1.39 \text{ mrem} \tag{3-6}$$

Note that different absorption types of ^{60}Co were used to evaluate the bioassay data but the same maximum DCFs were used in both cases. In practice, the annual doses would be required for each organ, but this example shows how the calculations can be performed.

4.0 SUMMARY

The question addressed here is how to bound the potential dose to workers at LANSCE from intakes of radionuclides not adequately measured by whole body counting. This proof-of-principle calculation:

1. Specifies a reference source that defines the relative amounts of all dosimetrically significant radionuclides in the Mark-I1L tungsten target, which is bounding for exposures of workers;

2. Specifies ^{60}Co as the indicator radionuclide in the source for whole body counting;

3. Uses standard dose reconstruction procedures to estimate the intake of ^{60}Co from whole body count results reported by LANL;

4. Uses the estimated ^{60}Co intake and the reference source to estimate the intakes of all radionuclides in the reference source; and

5. Assigns committed organ doses from the intake of the radionuclide mixture.

This approach accounts for the dose from all radionuclides with a half-life of greater than 10 minutes, a restriction imposed by the availability of DCFs in ICRP Publication 68 [ICRP 1995]. In general, the missed 50-year committed organ doses associated with a <MDA result for ^{60}Co on an annual in vivo count are less than approximately 10 mrem except for bone surfaces doses, which are about 50 times higher. The implementation of the method for an actual dose reconstruction requires annual organ doses, which is a more complex calculation that might require the use of a software tool.

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ATTACHMENT A
ALL NUCLIDES IN MARK-I1L TARGET ASSIGNED TO THREE SOLUBILITY CATEGORIES

Table A-1. All nuclides in Mark-I1L target assigned to three solubility categories with absorption types V (vapor), F, M, or S. In the case where a radionuclide has multiple types (e.g., multiple vapors), the most restrictive one is used.

Nuclide	Half-life (d)	Soluble	Moderate	Insoluble
H-3	4.510837E+03	V (OBT)	V (OBT)	V (OBT)
Be-7	5.330000E+01	M	M	S
Be-10	5.844000E+08	M	M	S
C-11	1.415280E−02	V	V	V
C-14	2.092883E+06	V	V	V
F-18	7.622920E−02	F	M	S
Na-22	9.503805E+02	F	F	F
Na-24	6.250000E−01	F	F	F
Mg-28	8.712500E−01	F	M	M
Al-26	2.615190E+08	F	M	M
Si-31	1.092361E−01	F	M	S
Si-32	1.643625E+05	F	M	S
P-32	1.429000E+01	F	M	M
P-33	2.540000E+01	F	M	M
S-35	8.744000E+01	V	F	M
Cl-36	1.099403E+08	F	M	M
Cl-38	2.584030E−02	F	M	M
Cl-39	3.861110E−02	F	M	M
K-40	4.675200E+11	F	F	F
K-42	5.150000E−01	F	F	F
K-43	9.416667E−01	F	F	F
K-44	1.536810E−02	F	F	F
K-45	1.388890E−02	F	F	F
Ca-41	5.113500E+07	M	M	M
Ca-45	1.630000E+02	M	M	M
Ca-47	4.530000E+00	M	M	M
Sc-43	1.621250E−01	S	S	S
Sc-44	1.636250E−01	S	S	S
Sc-44m	2.441667E+00	S	S	S
Sc-46	8.383000E+01	S	S	S
Sc-47	3.351000E+00	S	S	S
Sc-48	1.820833E+00	S	S	S
Sc-49	3.986110E−02	S	S	S
Ti-44	1.727633E+04	F	M	S
Ti-45	1.283333E−01	F	M	S
V-47	2.263890E−02	F	M	M
V-48	1.623800E+01	F	M	M
V-49	3.300000E+02	F	M	M
Cr-48	9.566667E−01	F	M	S
Cr-49	2.922920E−02	F	M	S
Cr-51	2.770400E+01	F	M	S
Mn-51	3.208330E−02	F	M	M
Mn-52	5.591000E+00	F	M	M
Mn-52m	1.465280E−02	F	M	M
Mn-53	1.351425E+09	F	M	M
Mn-54	3.125000E+02	F	M	M
Mn-56	1.074375E−01	F	M	M
Fe-52	3.447917E−01	F	M	M

ATTACHMENT A
ALL NUCLIDES IN MARK-I1L TARGET ASSIGNED TO THREE SOLUBILITY CATEGORIES
(continued)

Nuclide	Half-life (d)	Soluble	Moderate	Insoluble
Fe-55	9.861750E+02	F	M	M
Fe-59	4.452900E+01	F	M	M
Fe-60	3.652500E+07	F	M	M
Co-55	7.308333E−01	M	M	S
Co-56	7.876000E+01	M	M	S
Co-57	2.709000E+02	M	M	S
Co-58	7.080000E+01	M	M	S
Co-58m	3.812500E−01	M	M	S
Co-60	1.925233E+03	M	M	S
Co-60m	7.270800E−03	M	M	S
Co-61	6.875000E−02	M	M	S
Co-62m	9.659700E−03	M	M	S
Ni-56	6.100000E+00	V	F	M
Ni-57	1.503333E+00	V	F	M
Ni-59	2.739375E+07	V	F	M
Ni-63	3.506400E+04	V	F	M
Ni-65	1.050000E−01	V	F	M
Ni-66	2.275000E+00	V	F	M
Cu-60	1.611110E−02	F	M	S
Cu-61	1.420000E−01	F	M	S
Cu-64	5.292083E−01	F	M	S
Cu-67	2.577500E+00	F	M	S
Zn-62	3.858333E−01	S	S	S
Zn-63	2.645830E−02	S	S	S
Zn-65	2.439000E+02	S	S	S
Zn-69	3.958330E−02	S	S	S
Zn-69m	5.733333E−01	S	S	S
Zn-71m	1.633333E−01	S	S	S
Zn-72	1.937500E+00	S	S	S
Ga-65	1.055560E−02	F	M	M
Ga-66	3.916667E−01	F	M	M
Ga-67	3.260833E+00	F	M	M
Ga-68	4.722220E−02	F	M	M
Ga-70	1.468750E−02	F	M	M
Ga-72	5.875000E−01	F	M	M
Ga-73	2.045833E−01	F	M	M
Ge-66	9.458330E−02	F	M	M
Ge-67	1.298610E−02	F	M	M
Ge-68	2.880000E+02	F	M	M
Ge-69	1.627083E+00	F	M	M
Ge-71	1.180000E+01	F	M	M
Ge-75	5.748610E−02	F	M	M
Ge-77	4.708333E−01	F	M	M
Ge-78	6.041670E−02	F	M	M
As-69	1.055560E−02	M	M	M
As-70	3.652780E−02	M	M	M
As-71	2.700000E+00	M	M	M
As-72	1.083333E+00	M	M	M
As-73	8.030000E+01	M	M	M
As-74	1.776000E+01	M	M	M

ATTACHMENT A
ALL NUCLIDES IN MARK-I1L TARGET ASSIGNED TO THREE SOLUBILITY CATEGORIES (continued)

Nuclide	Half-life (d)	Soluble	Moderate	Insoluble
As-76	1.096667E+00	M	M	M
As-77	1.616667E+00	M	M	M
As-78	6.298610E−02	M	M	M
Se-70	2.847220E−02	F	M	M
Se-73	2.979167E−01	F	M	M
Se-73m	2.708330E−02	F	M	M
Se-75	1.198000E+02	F	M	M
Se-79	2.374125E+07	F	M	M
Se-81	1.284720E−02	F	M	M
Se-81m	3.975690E−02	F	M	M
Se-83	1.562500E−02	F	M	M
Br-74	1.756940E−02	F	M	M
Br-74m	2.881940E−02	F	M	M
Br-75	6.805560E−02	F	M	M
Br-76	6.750000E−01	F	M	M
Br-77	2.333333E+00	F	M	M
Br-80	1.208330E−02	F	M	M
Br-80m	1.841667E−01	F	M	M
Br-82	1.470833E+00	F	M	M
Br-83	9.958330E−02	F	M	M
Br-84	2.208330E−02	F	M	M
Rb-79	1.590280E−02	F	F	F
Rb-81	1.908333E−01	F	F	F
Rb-81m	2.222220E−02	F	F	F
Rb-82m	2.583333E−01	F	F	F
Rb-83	8.620000E+01	F	F	F
Rb-84	3.277000E+01	F	F	F
Rb-86	1.866000E+01	F	F	F
Rb-87	1.716675E+13	F	F	F
Rb-88	1.236110E−02	F	F	F
Rb-89	1.055560E−02	F	F	F
Sr-80	6.944440E−02	F	F	S
Sr-81	1.770830E−02	F	F	S
Sr-82	2.500000E+01	F	F	S
Sr-83	1.350000E+00	F	F	S
Sr-85	6.484000E+01	F	F	S
Sr-85m	4.826390E−02	F	F	S
Sr-87m	1.168750E−01	F	F	S
Sr-89	5.050000E+01	F	F	S
Sr-90	1.063608E+04	F	F	S
Sr-91	3.958333E−01	F	F	S
Sr-92	1.129167E−01	F	F	S
Y-86	6.141667E−01	M	M	S
Y-86m	3.333330E−02	M	M	S
Y-87	3.345833E+00	M	M	S
Y-88	1.066400E+02	M	M	S
Y-90	2.666667E+00	M	M	S
Y-90m	1.329167E−01	M	M	S
Y-91	5.851000E+01	M	M	S
Y-91m	3.452080E−02	M	M	S

ATTACHMENT A
ALL NUCLIDES IN MARK-I1L TARGET ASSIGNED TO THREE SOLUBILITY CATEGORIES
(continued)

Nuclide	Half-life (d)	Soluble	Moderate	Insoluble
Y-92	1.475000E−01	M	M	S
Y-93	4.208333E−01	M	M	S
Y-94	1.326390E−02	M	M	S
Y-95	7.430600E−03	M	M	S
Zr-86	6.875000E−01	F	M	S
Zr-88	8.340000E+01	F	M	S
Zr-89	3.267917E+00	F	M	S
Zr-93	5.588325E+08	F	M	S
Zr-95	6.398000E+01	F	M	S
Zr-97	7.041667E−01	F	M	S
Nb-88	9.930600E−03	M	M	S
Nb-89	8.472220E−02	M	M	S
Nb-89m	4.583330E−02	M	M	S
Nb-90	6.083333E−01	M	M	S
Nb-93m	4.967400E+03	M	M	S
Nb-94	7.414575E+06	M	M	S
Nb-95	3.515000E+01	M	M	S
Nb-95m	3.608333E+00	M	M	S
Nb-96	9.729167E−01	M	M	S
Nb-97	5.006940E−02	M	M	S
Nb-98	3.576390E−02	M	M	S
Mo-90	2.362500E−01	F	F	S
Mo-93	1.278375E+06	F	F	S
Mo-93m	2.854167E−01	F	F	S
Mo-99	2.750000E+00	F	F	S
Mo-101	1.015280E−02	F	F	S
Tc-93	1.145833E−01	F	M	M
Tc-93m	3.020830E−02	F	M	M
Tc-94	2.034722E−01	F	M	M
Tc-94m	3.611110E−02	F	M	M
Tc-95	8.333333E−01	F	M	M
Tc-95m	6.100000E+01	F	M	M
Tc-96	4.280000E+00	F	M	M
Tc-96m	3.576390E−02	F	M	M
Tc-97	9.496500E+08	F	M	M
Tc-97m	8.700000E+01	F	M	M
Tc-98	1.534050E+09	F	M	M
Tc-99	7.779825E+07	F	M	M
Tc-99m	2.508333E−01	F	M	M
Tc-101	9.861100E−03	F	M	M
Tc-104	1.263890E−02	F	M	M
Ru-94	3.597220E−02	V	F	M
Ru-97	2.900000E+00	V	F	M
Ru-103	3.928000E+01	V	F	M
Ru-105	1.850000E−01	V	F	M
Ru-106	3.682000E+02	V	F	M
Rh-99	1.600000E+01	F	M	S
Rh-99m	1.958333E−01	F	M	S
Rh-100	8.666667E−01	F	M	S
Rh-101	1.168800E+03	F	M	S

ATTACHMENT A
ALL NUCLIDES IN MARK-I1L TARGET ASSIGNED TO THREE SOLUBILITY CATEGORIES
(continued)

Nuclide	Half-life (d)	Soluble	Moderate	Insoluble
Rh-101m	4.340000E+00	F	M	S
Rh-102m	1.059225E+03	F	M	S
Rh-102	2.070000E+02	F	M	S
Rh-103m	3.897220E−02	F	M	S
Rh-105	1.473333E+00	F	M	S
Rh-106m	9.166670E−02	F	M	S
Rh-107	1.506940E−02	F	M	S
Pd-100	3.630000E+00	F	M	S
Pd-101	3.445833E−01	F	M	S
Pd-103	1.696000E+01	F	M	S
Pd-107	2.374125E+09	F	M	S
Pd-109	5.594583E−01	F	M	S
Ag-102	8.958300E−03	F	M	S
Ag-103	4.562500E−02	F	M	S
Ag-104	4.805560E−02	F	M	S
Ag-104m	2.326390E−02	F	M	S
Ag-105	4.100000E+01	F	M	S
Ag-106	1.663890E−02	F	M	S
Ag-106m	8.410000E+00	F	M	S
Ag-108m	4.638675E+04	F	M	S
Ag-110m	2.499000E+02	F	M	S
Ag-111	7.450000E+00	F	M	S
Ag-112	1.300000E−01	F	M	S
Ag-115	1.388890E−02	F	M	S
Cd-104	4.006940E−02	F	M	S
Cd-107	2.704167E−01	F	M	S
Cd-109	4.640000E+02	F	M	S
Cd-113	3.396825E+18	F	M	S
Cd-113m	4.967400E+03	F	M	S
Cd-115	2.227500E+00	F	M	S
Cd-115m	4.460000E+01	F	M	S
Cd-117	1.037500E−01	F	M	S
Cd-117m	1.400000E−01	F	M	S
In-109	1.750000E−01	F	M	M
In-110	2.041667E−01	F	M	M
In-110m	4.798610E−02	F	M	M
In-111	2.830000E+00	F	M	M
In-112	1.000000E−02	F	M	M
In-113m	6.908330E−02	F	M	M
In-114m	4.951000E+01	F	M	M
In-115	1.862775E+18	F	M	M
In-115m	1.869167E−01	F	M	M
In-116m	3.760420E−02	F	M	M
In-117	3.041670E−02	F	M	M
In-117m	8.090280E−02	F	M	M
In-119m	1.250000E−02	F	M	M
Sn-110	1.666667E−01	F	M	M
Sn-111	2.451390E−02	F	M	M
Sn-113	1.151000E+02	F	M	M
Sn-117m	1.361000E+01	F	M	M

ATTACHMENT A
ALL NUCLIDES IN MARK-I1L TARGET ASSIGNED TO THREE SOLUBILITY CATEGORIES
(continued)

Nuclide	Half-life (d)	Soluble	Moderate	Insoluble
Sn-119m	2.930000E+02	F	M	M
Sn-121	1.127500E+00	F	M	M
Sn-121m	2.008875E+04	F	M	M
Sn-123	1.292000E+02	F	M	M
Sn-123m	2.783330E−02	F	M	M
Sn-125	9.640000E+00	F	M	M
Sn-126	3.652500E+07	F	M	M
Sn-127	8.750000E−02	F	M	M
Sn-128	4.104170E−02	F	M	M
Sb-115	2.208330E−02	F	M	M
Sb-116	1.097220E−02	F	M	M
Sb-116m	4.187500E−02	F	M	M
Sb-117	1.166667E−01	F	M	M
Sb-118m	2.083333E−01	F	M	M
Sb-119	1.587500E+00	F	M	M
Sb-120m	5.760000E+00	F	M	M
Sb-120	1.103470E−02	F	M	M
Sb-122	2.700000E+00	F	M	M
Sb-124	6.020000E+01	F	M	M
Sb-124n	1.402780E−02	F	M	M
Sb-125	1.011742E+03	F	M	M
Sb-126	1.240000E+01	F	M	M
Sb-126m	1.319440E−02	F	M	M
Sb-127	3.850000E+00	F	M	M
Sb-128	3.754167E−01	F	M	M
Sb-128m	7.222200E−03	F	M	M
Sb-129	1.800000E−01	F	M	M
Sb-130	2.777780E−02	F	M	M
Sb-131	1.597220E−02	F	M	M
Te-116	1.037500E−01	V	F	M
Te-121	1.700000E+01	V	F	M
Te-121m	1.540000E+02	V	F	M
Te-123	3.652500E+15	V	F	M
Te-123m	1.197000E+02	V	F	M
Te-125m	5.800000E+01	V	F	M
Te-127	3.895833E−01	V	F	M
Te-127m	1.090000E+02	V	F	M
Te-129	4.833330E−02	V	F	M
Te-129m	3.360000E+01	V	F	M
Te-131	1.736110E−02	V	F	M
Te-131m	1.250000E+00	V	F	M
Te-132	3.258333E+00	V	F	M
Te-133	8.645800E−03	V	F	M
Te-133m	3.847220E−02	V	F	M
Te-134	2.902780E−02	V	F	M
I-120	5.625000E−02	V	F	F
I-120m	3.680560E−02	V	F	F
I-121	8.833330E−02	V	F	F
I-123	5.500000E−01	V	F	F
I-124	4.180000E+00	V	F	F

ATTACHMENT A
ALL NUCLIDES IN MARK-I1L TARGET ASSIGNED TO THREE SOLUBILITY CATEGORIES
(continued)

Nuclide	Half-life (d)	Soluble	Moderate	Insoluble
I-125	6.014000E+01	V	F	F
I-126	1.302000E+01	V	F	F
I-128	1.735420E−02	V	F	F
I-129	5.734425E+09	V	F	F
I-130	5.150000E−01	V	F	F
I-131	8.040000E+00	V	F	F
I-132	9.583330E−02	V	F	F
I-132m	5.805560E−02	V	F	F
I-133	8.666667E−01	V	F	F
I-134	3.652780E−02	V	F	F
I-135	2.754167E−01	V	F	F
Cs-125	3.125000E−02	F	F	F
Cs-127	2.604167E−01	F	F	F
Cs-129	1.335833E+00	F	F	F
Cs-130	2.076390E−02	F	F	F
Cs-131	9.690000E+00	F	F	F
Cs-132	6.475000E+00	F	F	F
Cs-134	7.531455E+02	F	F	F
Cs-134m	1.208333E−01	F	F	F
Cs-135	8.400750E+08	F	F	F
Cs-135m	3.680560E−02	F	F	F
Cs-136	1.310000E+01	F	F	F
Cs-137	1.095750E+04	F	F	F
Cs-138	2.236110E−02	F	F	F
Ba-126	6.701390E−02	F	F	F
Ba-128	2.430000E+00	F	F	F
Ba-131	1.180000E+01	F	F	F
Ba-131m	1.013890E−02	F	F	F
Ba-133	3.922785E+03	F	F	F
Ba-133m	1.620833E+00	F	F	F
Ba-135m	1.195833E+00	F	F	F
Ba-139	5.743060E−02	F	F	F
Ba-140	1.274000E+01	F	F	F
Ba-141	1.268750E−02	F	F	F
Ba-142	7.361100E−03	F	F	F
La-131	4.097220E−02	F	M	M
La-132	2.000000E−01	F	M	M
La-135	8.125000E−01	F	M	M
La-137	2.191500E+07	F	M	M
La-138	4.930875E+13	F	M	M
La-140	1.678000E+00	F	M	M
La-141	1.637500E−01	F	M	M
La-142	6.423610E−02	F	M	M
La-143	9.881900E−03	F	M	M
Ce-134	3.000000E+00	M	M	S
Ce-135	7.333333E−01	M	M	S
Ce-137	3.750000E−01	M	M	S
Ce-137m	1.433333E+00	M	M	S
Ce-139	1.376600E+02	M	M	S
Ce-141	3.250100E+01	M	M	S

ATTACHMENT A
ALL NUCLIDES IN MARK-I1L TARGET ASSIGNED TO THREE SOLUBILITY CATEGORIES
(continued)

Nuclide	Half-life (d)	Soluble	Moderate	Insoluble
Ce-143	1.375000E+00	M	M	S
Ce-144	2.843000E+02	M	M	S
Pr-136	9.097200E−03	M	M	S
Pr-137	5.319440E−02	M	M	S
Pr-138m	8.750000E−02	M	M	S
Pr-139	1.879167E−01	M	M	S
Pr-142	7.970833E−01	M	M	S
Pr-142m	1.013890E−02	M	M	S
Pr-143	1.356000E+01	M	M	S
Pr-144	1.200000E−02	M	M	S
Pr-145	2.491667E−01	M	M	S
Pr-147	9.444400E−03	M	M	S
Nd-136	3.517360E−02	M	M	S
Nd-138	2.100000E−01	M	M	S
Nd-139	2.062500E−02	M	M	S
Nd-139m	2.291667E−01	M	M	S
Nd-141	1.037500E−01	M	M	S
Nd-147	1.098000E+01	M	M	S
Nd-149	7.208330E−02	M	M	S
Nd-151	8.638900E−03	M	M	S
Pm-141	1.451390E−02	M	M	S
Pm-143	2.650000E+02	M	M	S
Pm-144	3.630000E+02	M	M	S
Pm-145	6.464925E+03	M	M	S
Pm-146	2.020000E+03	M	M	S
Pm-147	9.581969E+02	M	M	S
Pm-148	5.370000E+00	M	M	S
Pm-148m	4.130000E+01	M	M	S
Pm-149	2.211667E+00	M	M	S
Pm-150	1.116667E−01	M	M	S
Pm-151	1.183333E+00	M	M	S
Sm-141	7.083300E−03	M	M	M
Sm-141m	1.569440E−02	M	M	M
Sm-142	5.034030E−02	M	M	M
Sm-145	3.400000E+02	M	M	M
Sm-146	3.762075E+10	M	M	M
Sm-147	3.871650E+13	M	M	M
Sm-151	3.287250E+04	M	M	M
Sm-153	1.945833E+00	M	M	M
Sm-155	1.534720E−02	M	M	M
Sm-156	3.916667E−01	M	M	M
Eu-145	5.940000E+00	M	M	M
Eu-146	4.610000E+00	M	M	M
Eu-147	2.400000E+01	M	M	M
Eu-148	5.450000E+01	M	M	M
Eu-149	9.310000E+01	M	M	M
Eu-150	1.249155E+04	M	M	M
Eu-150m	5.258333E−01	M	M	M
Eu-152	4.868783E+03	M	M	M
Eu-152m	3.883333E−01	M	M	M

ATTACHMENT A
ALL NUCLIDES IN MARK-I1L TARGET ASSIGNED TO THREE SOLUBILITY CATEGORIES (continued)

Nuclide	Half-life (d)	Soluble	Moderate	Insoluble
Eu-154	3.214200E+03	M	M	M
Eu-155	1.811640E+03	M	M	M
Eu-156	1.519000E+01	M	M	M
Eu-157	6.312500E−01	M	M	M
Eu-158	3.187500E−02	M	M	M
Gd-145	1.590280E−02	F	M	M
Gd-146	4.830000E+01	F	M	M
Gd-147	1.587500E+00	F	M	M
Gd-148	3.396825E+04	F	M	M
Gd-149	9.400000E+00	F	M	M
Gd-151	1.200000E+02	F	M	M
Gd-152	3.944700E+16	F	M	M
Gd-153	2.420000E+02	F	M	M
Gd-159	7.733333E−01	F	M	M
Tb-147	6.875000E−02	M	M	M
Tb-149	1.729167E−01	M	M	M
Tb-150	1.362500E−01	M	M	M
Tb-151	7.333333E−01	M	M	M
Tb-153	2.340000E+00	M	M	M
Tb-154	8.916667E−01	M	M	M
Tb-155	5.320000E+00	M	M	M
Tb-156	5.340000E+00	M	M	M
Tb-156n	2.083333E−01	M	M	M
Tb-156m	1.016667E+00	M	M	M
Tb-157	5.478750E+04	M	M	M
Tb-158	5.478750E+04	M	M	M
Tb-160	7.230000E+01	M	M	M
Tb-161	6.910000E+00	M	M	M
Dy-155	4.166667E−01	M	M	M
Dy-157	3.375000E−01	M	M	M
Dy-159	1.444000E+02	M	M	M
Dy-165	9.725000E−02	M	M	M
Dy-166	3.400000E+00	M	M	M
Ho-155	3.333330E−02	M	M	M
Ho-157	8.750000E−03	M	M	M
Ho-159	2.291670E−02	M	M	M
Ho-161	1.041667E−01	M	M	M
Ho-162	1.041670E−02	M	M	M
Ho-162m	4.722220E−02	M	M	M
Ho-164	2.013890E−02	M	M	M
Ho-164m	2.604170E−02	M	M	M
Ho-166	1.116667E+00	M	M	M
Ho-166m	4.383000E+05	M	M	M
Ho-167	1.291667E−01	M	M	M
Er-161	1.350000E−01	M	M	M
Er-165	4.316667E−01	M	M	M
Er-169	9.300000E+00	M	M	M
Er-171	3.133333E−01	M	M	M
Er-172	2.054167E+00	M	M	M
Tm-162	1.506940E−02	M	M	M

ATTACHMENT A
ALL NUCLIDES IN MARK-I1L TARGET ASSIGNED TO THREE SOLUBILITY CATEGORIES (continued)

Nuclide	Half-life (d)	Soluble	Moderate	Insoluble
Tm-166	3.208333E−01	M	M	M
Tm-167	9.240000E+00	M	M	M
Tm-170	1.286000E+02	M	M	M
Tm-171	7.012800E+02	M	M	M
Tm-172	2.650000E+00	M	M	M
Tm-173	3.433333E−01	M	M	M
Tm-175	1.055560E−02	M	M	M
Yb-162	1.312500E−02	M	M	S
Yb-166	2.362500E+00	M	M	S
Yb-167	1.215280E−02	M	M	S
Yb-169	3.201000E+01	M	M	S
Yb-175	4.190000E+00	M	M	S
Yb-177	7.916670E−02	M	M	S
Yb-178	5.138890E−02	M	M	S
Lu-169	1.419167E+00	M	M	S
Lu-170	2.000000E+00	M	M	S
Lu-171	8.220000E+00	M	M	S
Lu-172	6.700000E+00	M	M	S
Lu-173	5.003925E+02	M	M	S
Lu-174	1.208977E+03	M	M	S
Lu-174m	1.420000E+02	M	M	S
Lu-176	1.314900E+13	M	M	S
Lu-176m	1.533333E−01	M	M	S
Lu-177	6.710000E+00	M	M	S
Lu-177m	1.609000E+02	M	M	S
Lu-178	1.972220E−02	M	M	S
Lu-178m	1.576390E−02	M	M	S
Lu-179	1.912500E−01	M	M	S
Hf-170	6.670833E−01	F	M	M
Hf-172	6.830175E+02	F	M	M
Hf-173	1.000000E+00	F	M	M
Hf-175	7.000000E+01	F	M	M
Hf-177m	3.569440E−02	F	M	M
Hf-178m	1.132275E+04	F	M	M
Hf-179m	2.510000E+01	F	M	M
Hf-180m	2.291667E−01	F	M	M
Hf-181	4.240000E+01	F	M	M
Hf-182	3.287250E+09	F	M	M
Hf-182m	4.270830E−02	F	M	M
Hf-183	4.444440E−02	F	M	M
Hf-184	1.716667E−01	F	M	M
Ta-172	2.555560E−02	M	M	S
Ta-173	1.520833E−01	M	M	S
Ta-174	5.000000E−02	M	M	S
Ta-175	4.375000E−01	M	M	S
Ta-176	3.366667E−01	M	M	S
Ta-177	2.358333E+00	M	M	S
Ta-178m	9.166670E−02	M	M	S
Ta-179	6.649000E+02	M	M	S
Ta-180m	3.652500E+15	M	M	S

ATTACHMENT A
ALL NUCLIDES IN MARK-I1L TARGET ASSIGNED TO THREE SOLUBILITY CATEGORIES
(continued)

Nuclide	Half-life (d)	Soluble	Moderate	Insoluble
Ta-180	3.375000E−01	M	M	S
Ta-182	1.150000E+02	M	M	S
Ta-182m	1.100000E−02	M	M	S
Ta-183	5.100000E+00	M	M	S
Ta-184	3.625000E−01	M	M	S
Ta-185	3.402780E−02	M	M	S
Ta-186	7.291700E−03	M	M	S
W-176	9.583330E−02	F	F	F
W-177	9.375000E−02	F	F	F
W-178	2.170000E+01	F	F	F
W-179	2.604170E−02	F	F	F
W-181	1.212000E+02	F	F	F
W-185	7.510000E+01	F	F	F
W-187	9.958333E−01	F	F	F
W-188	6.940000E+01	F	F	F
Re-177	9.722200E−03	F	M	M
Re-178	9.166700E−03	F	M	M
Re-181	8.333333E−01	F	M	M
Re-182	2.666667E+00	F	M	M
Re-182m	5.291667E−01	F	M	M
Re-184	3.800000E+01	F	M	M
Re-184m	1.650000E+02	F	M	M
Re-186	3.776667E+00	F	M	M
Re-186m	7.305000E+07	F	M	M
Re-187	1.826250E+13	F	M	M
Re-188	7.075000E−01	F	M	M
Re-188m	1.291670E−02	F	M	M
Re-189	1.012500E+00	F	M	M
Os-180	1.527780E−02	F	M	S
Os-181	7.291670E−02	F	M	S
Os-182	9.166667E−01	F	M	S
Os-185	9.400000E+01	F	M	S
Os-189m	2.500000E−01	F	M	S
Os-191	1.540000E+01	F	M	S
Os-191m	5.429167E−01	F	M	S
Os-193	1.250000E+00	F	M	S
Os-194	2.191500E+03	F	M	S
Ir-182	1.041670E−02	F	M	S
Ir-184	1.258333E−01	F	M	S
Ir-185	5.833333E−01	F	M	S
Ir-186	6.583333E−01	F	M	S
Ir-186m	7.291670E−02	F	M	S
Ir-187	4.375000E−01	F	M	S
Ir-188	1.729167E+00	F	M	S
Ir-189	1.330000E+01	F	M	S
Ir-190	1.210000E+01	F	M	S
Ir-190n	1.291667E−01	F	M	S
Ir-190m	5.000000E−02	F	M	S
Ir-192	7.402000E+01	F	M	S
Ir-192n	8.802525E+04	F	M	S

ATTACHMENT A
ALL NUCLIDES IN MARK-I1L TARGET ASSIGNED TO THREE SOLUBILITY CATEGORIES
(continued)

Nuclide	Half-life (d)	Soluble	Moderate	Insoluble
Ir-193m	1.190000E+01	F	M	S
Ir-194	7.979167E−01	F	M	S
Ir-194m	1.710000E+02	F	M	S
Ir-195	1.041667E−01	F	M	S
Ir-195m	1.583333E−01	F	M	S
Pt-186	8.333330E−02	F	F	F
Pt-188	1.020000E+01	F	F	F
Pt-189	4.529167E−01	F	F	F
Pt-191	2.800000E+00	F	F	F
Pt-193	1.826250E+04	F	F	F
Pt-193m	4.330000E+00	F	F	F
Pt-195m	4.020000E+00	F	F	F
Pt-197	7.625000E−01	F	F	F
Pt-197m	6.555560E−02	F	F	F
Pt-199	2.138890E−02	F	F	F
Pt-200	5.208333E−01	F	F	F
Au-193	7.354167E−01	F	M	S
Au-194	1.645833E+00	F	M	S
Au-195	1.830000E+02	F	M	S
Au-198	2.696000E+00	F	M	S
Au-198m	2.300000E+00	F	M	S
Au-199	3.139000E+00	F	M	S
Au-200	3.361110E−02	F	M	S
Au-200m	7.791667E−01	F	M	S
Au-201	1.833330E−02	F	M	S
Hg-193	1.458333E−01	V	F	M
Hg-193m	4.625000E−01	V	F	M
Hg-194	9.496500E+04	V	F	M
Hg-195	4.125000E−01	V	F	M
Hg-195m	1.733333E+00	V	F	M
Hg-197	2.670833E+00	V	F	M
Hg-197m	9.916667E−01	V	F	M
Hg-199m	2.958330E−02	V	F	M
Hg-203	4.660000E+01	V	F	M
Tl-194	2.291670E−02	F	F	F
Tl-194m	2.277780E−02	F	F	F
Tl-195	4.833330E−02	F	F	F
Tl-197	1.183333E−01	F	F	F
Tl-198	2.208333E−01	F	F	F
Tl-198m	7.791670E−02	F	F	F
Tl-199	3.091667E−01	F	F	F
Tl-200	1.087500E+00	F	F	F
Tl-201	3.044000E+00	F	F	F
Tl-202	1.223000E+01	F	F	F
Tl-204	1.380280E+03	F	F	F
Pb-195m	1.097220E−02	F	F	F
Pb-198	1.000000E−01	F	F	F
Pb-199	6.250000E−02	F	F	F
Pb-200	8.958333E−01	F	F	F
Pb-201	3.916667E−01	F	F	F

ATTACHMENT A
ALL NUCLIDES IN MARK-I1L TARGET ASSIGNED TO THREE SOLUBILITY CATEGORIES
(continued)

Nuclide	Half-life (d)	Soluble	Moderate	Insoluble
Pb-202	1.095750E+08	F	F	F
Pb-202m	1.508333E−01	F	F	F
Pb-203	2.168750E+00	F	F	F
Pb-205	5.223075E+09	F	F	F
Pb-209	1.355417E−01	F	F	F
Pb-210	8.145075E+03	F	F	F
Pb-211	2.506940E−02	F	F	F
Pb-212	4.433333E−01	F	F	F
Pb-214	1.861110E−02	F	F	F
Bi-200	2.527780E−02	F	M	M
Bi-201	7.500000E−02	F	M	M
Bi-202	6.958330E−02	F	M	M
Bi-203	4.900000E−01	F	M	M
Bi-205	1.531000E+01	F	M	M
Bi-206	6.243000E+00	F	M	M
Bi-207	1.387950E+04	F	M	M
Bi-210	5.012000E+00	F	M	M
Bi-210m	1.095750E+09	F	M	M
Bi-212	4.204860E−02	F	M	M
Bi-213	3.170140E−02	F	M	M
Bi-214	1.381940E−02	F	M	M
Po-203	2.548610E−02	F	M	M
Po-205	7.500000E−02	F	M	M
Po-207	2.430556E−01	F	M	M
Po-210	1.383800E+02	F	M	M
At-207	7.500000E−02	F	M	M
At-211	3.005833E−01	F	M	M
Fr-222	1.000000E−02	F	F	F
Fr-223	1.513890E−02	F	F	F
Ra-223	1.143400E+01	M	M	M
Ra-224	3.660000E+00	M	M	M
Ra-225	1.480000E+01	M	M	M
Ra-226	5.844000E+05	M	M	M
Ra-227	2.930560E−02	M	M	M
Ra-228	2.100188E+03	M	M	M
Ac-224	1.208333E−01	F	M	S
Ac-225	1.000000E+01	F	M	S
Ac-226	1.208333E+00	F	M	S
Ac-227	7.952588E+03	F	M	S
Ac-228	2.554167E−01	F	M	S
Th-226	2.145830E−02	M	M	S
Th-227	1.871800E+01	M	M	S
Th-228	6.987598E+02	M	M	S
Th-229	2.680935E+06	M	M	S
Th-230	2.812425E+07	M	M	S
Th-231	1.063333E+00	M	M	S
Th-232	5.131763E+12	M	M	S
Th-234	2.410000E+01	M	M	S
Pa-227	2.659720E−02	M	M	S
Pa-228	9.166667E−01	M	M	S

ATTACHMENT A
ALL NUCLIDES IN MARK-I1L TARGET ASSIGNED TO THREE SOLUBILITY CATEGORIES
(continued)

Nuclide	Half-life (d)	Soluble	Moderate	Insoluble
Pa-230	1.740000E+01	M	M	S
Pa-231	1.196559E+07	M	M	S
Pa-232	1.310000E+00	M	M	S
Pa-233	2.700000E+01	M	M	S
Pa-234	2.791667E−01	M	M	S
U-230	2.080000E+01	F	M	S
U-231	4.200000E+00	F	M	S
U-232	2.629800E+04	F	M	S
U-233	5.789213E+07	F	M	S
U-234	8.930363E+07	F	M	S
U-235	2.570630E+11	F	M	S
U-236	8.552329E+09	F	M	S
U-237	6.750000E+00	F	M	S
U-238	1.631937E+12	F	M	S
U-239	1.634720E−02	F	M	S
U-240	5.875000E−01	F	M	S
Np-232	1.020830E−02	M	M	M
Np-233	2.513890E−02	M	M	M
Np-234	4.400000E+00	M	M	M
Np-235	3.961000E+02	M	M	M
Np-236	4.200375E+07	M	M	M
Np-236m	9.375000E−01	M	M	M
Np-237	7.816350E+08	M	M	M
Np-238	2.117000E+00	M	M	M
Np-239	2.355000E+00	M	M	M
Np-240	4.513890E−02	M	M	M
Pu-234	3.666667E−01	M	M	S
Pu-235	1.756940E−02	M	M	S
Pu-236	1.041328E+03	M	M	S
Pu-237	4.530000E+01	M	M	S
Pu-238	3.204703E+04	M	M	S
Pu-239	8.789741E+06	M	M	S
Pu-240	2.387639E+06	M	M	S
Pu-241	5.259600E+03	M	M	S
Pu-242	1.374436E+08	M	M	S
Pu-243	2.065000E−01	M	M	S
Pu-244	3.016965E+10	M	M	S
Pu-245	4.375000E−01	M	M	S
Pu-246	1.085000E+01	M	M	S
Am-237	5.069440E−02	M	M	M
Am-238	6.805560E−02	M	M	M
Am-239	4.958333E−01	M	M	M
Am-240	2.116667E+00	M	M	M
Am-241	1.578610E+05	M	M	M
Am-242	6.675000E−01	M	M	M
Am-242m	5.551800E+04	M	M	M
Am-243	2.695545E+06	M	M	M
Am-244	4.208333E−01	M	M	M
Am-244m	1.805560E−02	M	M	M
Am-245	8.541670E−02	M	M	M

ATTACHMENT A
ALL NUCLIDES IN MARK-I1L TARGET ASSIGNED TO THREE SOLUBILITY CATEGORIES (continued)

Nuclide	Half-life (d)	Soluble	Moderate	Insoluble
Am-246	2.708330E−02	M	M	M
Am-246m	1.736110E−02	M	M	M
Cm-238	1.000000E−01	M	M	M
Cm-240	2.700000E+01	M	M	M
Cm-241	3.280000E+01	M	M	M
Cm-242	1.628000E+02	M	M	M
Cm-243	1.040963E+04	M	M	M
Cm-244	6.614677E+03	M	M	M
Cm-245	3.104625E+06	M	M	M
Cm-246	1.727633E+06	M	M	M
Cm-247	5.697900E+09	M	M	M
Cm-248	1.238198E+08	M	M	M
Cm-249	4.454860E−02	M	M	M
Cm-250	2.520225E+06	M	M	M
Bk-245	4.940000E+00	M	M	M
Bk-246	1.830000E+00	M	M	M
Bk-247	5.040450E+05	M	M	M
Bk-249	3.200000E+02	M	M	M
Bk-250	1.342500E−01	M	M	M
Cf-244	1.347220E−02	M	M	M
Cf-246	1.487500E+00	M	M	M
Cf-248	3.335000E+02	M	M	M
Cf-249	1.280566E+05	M	M	M
Cf-250	4.777470E+03	M	M	M
Cf-251	3.279945E+05	M	M	M
Cf-252	9.635295E+02	M	M	M
Cf-253	1.781000E+01	M	M	M
Cf-254	6.050000E+01	M	M	M
Es-250m	8.750000E−02	M	M	M
Es-251	1.375000E+00	M	M	M
Es-253	2.047000E+01	M	M	M
Es-254	2.757000E+02	M	M	M
Es-254m	1.637500E+00	M	M	M
Fm-252	9.458333E−01	M	M	M
Fm-253	3.000000E+00	M	M	M
Fm-254	1.350000E−01	M	M	M
Fm-255	8.362500E−01	M	M	M
Fm-257	1.005000E+02	M	M	M
Md-257	2.166667E−01	M	M	M
Md-258	5.500000E+01	M	M	M

ATTACHMENT B
TABLES FROM WHICH THE BAR PLOTS IN FIGURES 2-1 THROUGH 2-7 WERE CONSTRUCTED

LIST OF TABLES

ATTACHMENT B
TABLES FROM WHICH THE BAR PLOTS IN FIGURES 2-1 THROUGH 2-7 WERE CONSTRUCTED (continued)

Table B-1. Dosimetrically significant nuclides in Mark-I1L.

Nuclide	Proportion of dose[a]
Gd-148	0.8367640
Cd-113m	0.0977961
Co-60	0.0376775
Hf-172	0.0218392
Other (132)	0.0059230

a. The proportion of the total DCF attributable to each radionuclide.

Table B-2. Dosimetrically significant nuclides in beam stop.

Nuclide	Proportion of dose[a]
Co-60	0.8699270
Ni-63	0.0929931
Fe-55	0.0193571
Ti-44	0.0154296
Other (20)	0.0022930

a. The proportion of the total DCF attributable to each radionuclide.

Table B-3. Dosimetrically significant nuclides in beam window.

Nuclide	Proportion of dose[a]
Co-60	0.5537620
Fe-55	0.2043030
Ti-44	0.1970990
Na-22	0.0165377
H-3	0.0113393
Other (19)	0.0169600

a. The proportion of the total DCF attributable to each radionuclide.

Table B-4. Dosimetrically significant nuclides in Insert 1.

Nuclide	Proportion of dose[a]
Co-60	0.8451750
Fe-55	0.1418230
Ti-44	0.0122323
Other (16)	0.0007693

a. The proportion of the total DCF attributable to each radionuclide.

Table B-5. Dosimetrically significant nuclides in Insert 2.

Nuclide	Proportion of dose[a]
Co-60	0.758114
Fe-55	0.235100
Other (18)	0.006786

a. The proportion of the total DCF attributable to each radionuclide.

Table B-6. Dosimetrically significant nuclides in Shielding 1.

Nuclide	Proportion of dose[a]
Co-60	0.729635
Fe-55	0.262729
Other (21)	0.007637

a. The proportion of the total DCF attributable to each radionuclide.

ATTACHMENT B
TABLES FROM WHICH THE BAR PLOTS IN FIGURES 2-1 THROUGH 2-7 WERE CONSTRUCTED (continued)

Table B-7. Dosimetrically significant nuclides in Shielding 2.

Nuclide	Proportion of dose[a]
Co-60	0.864343
Fe-55	0.134063
Other (16)	0.001594

a. The proportion of the total DCF attributable to each radionuclide.