Method to Assess Internal Dose Using Gross Alpha, Beta, and Gamma Bioassay and Air Sampling at the Lawrence Berkeley National Laboratory

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EXECUTIVE SUMMARY

This white paper provides methods for assessing internal dose using gross alpha, gross beta, and gross gamma bioassay results and air sampling data at Lawrence Berkeley National Laboratory (LBNL). Methods are provided for assessing gross alpha, gross beta, and gross gamma results bioassay results that are below and above the minimum detectable activity. Air sampling data is used to assign internal dose from shorter-lived radionuclides that may not be detected by bioassay. In addition, a method is provided for assigning internal dose to an unmonitored worker using air sampling data. Example calculations are provided validating the proof of concept. This method would apply for 1962 and later. The methods described in this white paper will need to be implemented in an internal dose tool.

INTRODUCTION

The Lawrence Berkeley National Laboratory monitored workers using gross alpha, beta, and gamma bioassay analyses from the start of its bioassay program in 1962 at least into the mid-1990s. The gross alpha and beta analyses were used primarily for screening purposes. The gross beta procedure was done after gamma-counting the gamma emitters. This would not have identified the specific radionuclides, so positive gross alpha and beta results typically were followed by specific procedures to identify the particular radionuclides. Gamma emitters were analyzed via gamma spectroscopy (Low-Beer 1964; Buckley 1969; LBNL 1985a, 1985b; LBL 1989). LBNL did not typically identify the radionuclides for results that were less than the minimum detection limit for these bioassay methods.

Bioassay requests were generally made either once or twice per year for each employee in the bioassay program. Workers who worked with or in areas that contained unsealed radioactive materials typically received bioassays (Soule 1962; Schmidt et al. 1973). Therefore, based on the typical LBNL bioassay monitoring frequencies, a single bioassay result indicates that the worker had, at most, one year of internal exposure potential before the date of the bioassay. For example, a single bioassay on December 31, 1967, implies, at most, an intake potential from January 1, 1967, through December 31, 1967. Non-routine bioassays were made in cases where other evidence (survey results, air samples, wound from contaminated object) indicated a potential significant exposure (Howe 1961). All other employment periods with no bioassay indicate a potential exposure to environmental levels only.

When non-detectable gross alpha, beta, and gamma bioassay results are indicated in a worker's records, there typically is no information as to the specific radionuclides to which they might have been exposed. Bioassay lists might provide this information (LBL 1979, 1981a; LBNL 1985a). In cases where no specific radionuclide information is available, a method for assessing missed dose from gross alpha, beta, and gamma bioassay results is necessary. A list of potential alpha, beta, and gamma emitters was compiled based on Table 2-1 of the *Site Profile for the Lawrence Berkeley National Laboratory* (ORAUT 2010), bioassay lists (LBL 1979, 1981a; LBNL 1985a), and the Pit Room inventory list from 1952 to 1981 (LBNL 1952). In compiling these lists, there were radionuclides with half-lives less than 100 days, which this document refers to as "short-lived." These short-lived radionuclides are typically not expected to be detected with bioassay sampling frequencies of one year or six months, and can usually be considered unmonitored radionuclides. In addition, there are some "long-lived" radionuclides whose half-lives were greater than 100 days that were not detected by the gross bioassay methods. These were included in the short-lived radionuclides assessed by air concentration data, as discussed below. This document refers to radionuclides with half-lives greater than or equal to 100 days as "long-lived."

AIR SAMPLING

LBNL performed air sampling in locations where accidental releases of airborne radioactivity were likely (UCRL 1964; LBL 1981b). LBNL also maintained permanently installed air samplers that operated continuously in various locations. The air samples were changed weekly in locations of moderate experimental activity and daily in locations of intense experimental activity. These air samples were also called breathing-zone (BZ) air samples, but were actually work area air samples.

The limitations of work area air sampling were recognized in the early days at LBNL. Air samplers did not normally reflect general room area atmosphere, but only a closely circumscribed volume near the sampling head (Thaxter 1955). Lawrence Berkeley National Laboratory (LBL 1981b) noted:

> *Our air samples are not good representative samples of breathing air. Air currents are so unpredictable that air even a few inches away from a person's nose can be quite different from that which he breathes. Air samples give only a rough idea of an individual's exposure, and for that reason, any radioactivity detected should be taken seriously, even if only a small fraction of MPC.*

There was general guidance on the placement of air samplers that indicates (LBL 1981b):

> *Generally, the sampler should be downwind from the potential source(s) of radioactivity, and close to where the people are working. Often this is impossible to achieve with a fixed sampler location, but it is good to keep the ideals in mind when working out some practical location. In many cases, the best location will be at the principal exhaust from the room. In typical labs this will be the hood(s).*

Guidance on air sampler placement was provided in the early days at LBNL (LBL 1951):

> *Keep the Filter Queen close to the scene of radioactive operations such as gloved boxes and hoods. When radioactive operations are moved to another place in the room the Filter Queen should be moved accordingly.*

In addition (LBL 1981b),

> *Air samplers serve a dual purpose. Besides supplying a record of "breathing zone" air quality, air samplers can also serve as a detector of "spills". Sometimes a "hot" air sample is observed before their direct detection of surface contamination. Also, the sensitivity is sufficient to detect small leakages, enabling corrective measures to be taken to avoid future larger spills.*

A 1953 memorandum, "Sampling Methods and Requirements for Estimating Airborne Radioparticulate Hazards" (Thaxter 1953), indicated that because LBNL was a research facility, technical contamination was not tolerated as it could invalidate weeks of research. LBNL vigorously sought to achieve no airborne contamination. It used high efficiency exhaust air cleaning in enclosures. Nuisance contamination levels were lower by several orders of magnitude than permissible levels on the health bases. This operational philosophy is reflected in the monthly summary air sample reports that listed BZ locations whose monthly average air concentrations were greater than or equal to 1% of the maximum permissible concentration (MPC) discussed below. A review of this monthly summary air sample data indicated very few air sample locations that had monthly average air concentrations greater than or equal to 1% of the MPC.

BZ samples were collected for various locations at LBNL. There are monthly summary reports that list BZ locations that were greater than or equal to 1% of the MPC for alpha and beta emitters. There are also computer printouts of air concentration data for the LBNL BZ air sampling locations. These BZ air concentration data were collected as part of the LBNL Dual Data Entry Phase I and II BZ data effort. The available computer printouts of air concentration data for LBNL from site data capture efforts was not as complete as the monthly summary report data that listed BZ locations that were greater than or equal to 1% of the MPC for alpha and beta emitters. As a result, the monthly summary report data was used as the primary source for the air sampling data. The use of the monthly summary report data also saved considerable time in data entry. The computer printout BZ air concentration data was used to fill in missing data from the monthly summary reports. The LBNL Dual Data Entry Phase I effort consisted of compiling a database of the monthly summary air sample reports that listed BZ locations whose monthly average air concentrations were greater than or equal to 1% of the MPC. This data ranged from 1962 through 1987, and was the majority of the air sample data used. Earlier monthly air sample summary reports, from 1962 through mid-1963, did not report monthly average air concentrations. There were computer printouts of monthly average air concentrations data for 1962 and 1963 that were used to determine the annual average air concentrations for these years. There were also some missing monthly air sample reports in the mid to late 1980's. The LBNL Dual Data Entry Phase II effort consisted of compiling a database of available monthly air sample report data from computer printouts for 1962 through August 1963, December 1984, and 1993. This data was used to fill in data for unavailable years or months from the LBNL Dual Data Entry Phase I effort. Details of the air sample data used in the assessment are provided in Attachment B.

A statistical reduction of these air sample data determined the 95th-percentile annual average air concentration based on the annual average air concentrations of all sample locations (ORAUT 2017b). It should be noted that LBNL performed continuous 24-hour air sampling, typically on a daily or weekly basis. The 95th-percentile annual average air concentrations from the Oak Ridge Associated Universities Team (ORAUT 2017b) were multiplied by 4.2 (168/40 hours) to adjust for a 40-hour work-week exposure. The factor 4.2 represents the upper bound adjustment assuming weekly air sampling. The 95th-percentile annual average air concentrations adjusted for continuous 24-hour air sampling are shown in Table 1 below. These BZ data can be used to determine the internal dose from unmonitored and missed doses associated with gross alpha, beta, and gamma radionuclides for an LBNL worker.

The 95th-percentile annual average air concentrations are considered bounding values. Multiplying all 24-hour air samples by 4.2 to adjust for a 40-hour work-week exposure provides a positive bias in the 95th-percentile annual average air concentrations. Also, as mentioned earlier, is that most of the research at LBNL has been short term, typically on the order of weeks. It is unlikely that a worker would have been continuously exposed to these air concentration levels of radionuclides in the workplace for an entire year. In addition, the monthly summary report data used from 1963 through 1987 only contained air sampling locations that had monthly average air concentrations greater than or equal to 1% of the reference MPC. These reported results corresponded to, at most, only a few percent of the total number of air samples taken for any year. These unreported air sample locations from 1963 through 1987 were filled in with censored air concentration values equal to 1% of the reference MPC. These unreported results corresponded to, at least, approximately 97% of the total number of air samples taken for any year. It should also be noted that LBNL reported monthly average air concentrations in computer printouts of air concentration data that were less than 1% of the reference MPC censoring limit.

A description of the model used to determine the 95th-percentile annual average air concentrations in Table 1 is presented in Attachment B.

The extension of the 1987 air concentration data through 1992 and the 1993 air concentration data for later years is a reasonable assumption. Over time, the number of air sampling locations decreased at LBNL. Attachment B provides information on the numbers of air samples assumed for 1964 through 1987. In addition, a 1994 memorandum indicated that if the risk was low and sample results were continually negative, the sampling was to be discontinued. Over the previous 12 months, the number of sampled locations decreased for this reason (Schoonover 1994).

Air samples were typically counted 72 hours after removal to allow for decay of the short-lived radon and thoron progeny (Peck 1964). There was no decay correction originally applied to these air samples. All BZ radionuclide air concentrations used in the dose reconstruction methodology were decay-corrected back 72 hours. The list of radionuclides with half-lives less than 20 hours, along with their decay-corrected average air concentrations, is shown in Table 2.

Table 1. 95th-Percentile Alpha and Beta/Gamma Annual Air Concentrations.

Year	95th-Percentile Alpha Annual Air Concentration (pCi/m^3)	95th-Percentile Beta/Gamma Annual Air Concentration (pCi/m^3)
1962	0.0235	17.226
1963	0.0190	20.703
1964	0.0378	4.200
1965	0.0392	4.200
1966	0.0168	4.200
1967	0.0220	4.200
1968	0.0267	4.200
1969	0.0195	4.200
1970	0.0336	4.200
1971	0.0092	4.200
1972	0.0305	4.200
1973	0.0084	4.200
1974	0.0266	4.302
1975	0.0132	4.200
1976	0.0084	4.200
1977	0.0087	5.157
1978	0.0112	4.200
1979	0.0084	4.200
1980	0.0119	4.200
1981	0.0138	4.200
1982	0.0265	4.200
1983	0.0084	4.200
1984	0.0207	6.475
1985	0.0084	4.200
1986	0.0084	4.200
1987	0.0087	4.200a
1993	0.0071b	0.133c

a. 1987 beta/gamma air concentration can be extended through 1992.
b. 1993 alpha air concentration can be extended for 1988 and later years.
c. 1993 beta/gamma air concentration can be extended for later years.

Short-lived radionuclide activities that are decay-corrected back 72 hours, such as those in Table 2, cannot be produced at levels to maintain the continuous exposures without leaving significant field contamination in the work areas.

Based on the above, short-lived radionuclides with half-lives less than 12.7 hours were excluded from the potential unmonitored radionuclides. The excluded short-lived radionuclides were:

1. Gamma emitters:
   Carbon-11, ^{60}Cu, ^{63}Zn, ^{104}Ag, ^{224}Ac, ^{99m}Tc, ^{127}Cs, ^{62}Zn, ^{175}Ta.

2. Beta emitters:
   Indium-112, ^{239}U, ^{49}Sc, ^{68}Ga, ^{18}F, ^{149}Nd, ^{195}Ir, ^{228}Ac, ^{127}Te, ^{212}Pb, ^{42}K.

Table 2. Radionuclides with T1/2 Less than 20 Hours.

Radionuclide	Emitter	Half-Life	Beta Branching Fraction/Photon Yield	Decay-Corrected Annual Average Air Concentration (pCi/m^3)[a]
In-112	Beta	14.97 min	0.44	6.79E+87
U-239	Beta	23.45 min	1	1.17E+56
Sc-49	Beta	57.2 min	1	2.26E+23
Ga-68	Beta	67.71 min	1	6.69E+19
F-18	Beta	109.77 min	1	2.94E+12
Nd-149	Beta	1.728 hr	1	1.46E+13
Ir-195	Beta	2.5 hr	1	1.95E+09
Ac-228	Beta	6.16 hr	0.997	1.39E+04
Te-127	Beta	9.35 hr	1	8.73E+02
Pb-212	Beta	10.64 hr	1	4.57E+02
K-42	Beta	12.36 hr	1	2.38E+02
Cu-64	Beta	12.701 hr	0.39	5.47E+02
Nb-90	Beta	14.6 hr	1	1.28E+02
Na-24	Beta	15 hr	1	1.17E+02
Zr-97	Beta	16.9 hr	1	8.04E+01
Pt-197	Beta	18.3 hr	1	6.42E+01
C-11	Gamma	20.39 min	2.43E-06	1.01E+70
Cu-60	Gamma	23.7 min	1.99E+00	1.52E+55
Zn-63	Gamma	38.47 min	1.73E-01	1.52E+35
Ag-104	Gamma	69.2 min	3.06E+00	8.44E+18
Ac-224	Gamma	2.78 hr	6.72E-01	3.90E+08
Tc-99m	Gamma	6.015 hr	5.12E-02	3.29E+05
Cs-127	Gamma	6.25 hr	9.17E-01	1.34E+04
Zn-62	Gamma	9.186 hr	8.98E-01	1.07E+03
Ta-175	Gamma	10.5 hr	1.28E+00	3.81E+02
Y-86	Gamma	14.74 hr	3.20E+00	3.88E+01
Br-76	Gamma	16.2 hr	1.73E+00	5.29E+01
Zr-86	Gamma	16.5 hr	1.21E+00	7.17E+01
Co-55	Gamma	17.54 hr	1.31E+00	5.50E+01

a. Air concentrations are also corrected for beta branching fraction of photon yield.

Please refer to Attachment C for more details on the short-lived radionuclide exclusions.

METHOD FOR ASSESSING INTERNAL DOSE

The method for assessing the internal dose from gross alpha, beta, and gamma bioassay results is presented below. This method is a demonstration of the concept. The final method would be incorporated into an internal dose reconstruction tool for efficiency purposes. This method would apply for 1962 and later.

It should also be noted that the International Commission on Radiological Protection 68 (ICRP 1995) dose conversion factor (DCF) and half-life data were obtained from Rad Toolbox versions 2.0 and 3.0. As a result, there might be some differences in radionuclide half-lives in this document. The current radionuclide data will be incorporated into the dose reconstruction implementation tool.

An example dose reconstruction is provided following this section to demonstrate the concept presented in this section for assessing gross alpha, beta, and gamma bioassay results below the minimum detectable activity (MDA). Tables 4, 6, 8, and 9 below provide intake rates based on the highest 95th-percentile alpha and beta/gamma annual air concentrations for 1967 through 1971 (i.e., 1970) employment period assumed for the example. Using the highest 95th-percentile alpha and beta/gamma annual air concentrations for the 1967 through 1971 example dose reconstruction is an overestimating efficiency measure used for demonstration purposes of the concept presented below.

Gross Alpha Bioassay Results

Table 3 lists alpha-emitting radionuclides at LBNL with half-lives greater than 100 days, along with their branching fractions.

Table 3. Long-Lived (T1/2 >100 days) Alpha Radionuclide Branching Fractions.

Radionuclide	Alpha Branching Fractions
Am-241	1
Am-243	1
Cf-249	1
Cf-250	0.9992
Cf-252	0.9691
Cm-242	1
Cm-243	0.9971
Cm-244	1
Cm-245	1
Cm-246	0.9997
Cm-248	0.9174
Es-253	1
Es-254	1
Np-237	1
Pa-231	1
Pu-236	1
Pu-238	1
Pu-239	1
Pu-240	1
Pu-242	1
Pu-244	0.9988
Th-228	1
Th-229	1
Th-230	1
Th-232	1
Ac-227	0.0138

The bioassay would be assessed for missed dose for each long-lived alpha-emitting radionuclide. The alpha branching fraction (Table 3) must be included when determining the sample activity or MDA for a given radionuclide when starting with a gross result. The reported urine sample value is divided by the branching fraction; the MDA is divided by the branching fraction and a factor of 2 for the missed dose adjustment.

The calculated intake rates from the gross alpha bioassay result are then tabulated for all of the radionuclides based on the solubility type that yielded the largest dose.

Missed dose assumes a constant exposure to a theoretical missed intake that may or may not have occurred. By considering all of the available data, bioassay detection limits and workplace air sampling data, a more accurate upper bound of the potential non-detected internal exposure can be estimated. Therefore, the air sampling data, typically being more sensitive, should be used to limit the missed dose associated with a hypothetical intake associated with the detection limit. To do this, the calculated missed intake rates associated with the bioassay data, for each radionuclide, are compared to the intake rates determined from the BZ air monitoring data (see Table 4). The annual alpha intake rates based on BZ data for each of these radionuclides were determined by assuming the highest 95th-percentile annual air concentration (i.e., 1970) in Table 1 for the assumed exposure period of 1967 through 1971 in the example dose reconstruction presented below. The more limiting intake rate between the bioassay and BZ data is used to calculate the missed dose to the organ of interest. Air sampling data shall not be used to limit intakes based on positive bioassay data. The doses from all of the radionuclides are then compared to each other, and the radionuclide with the largest dose to the organ of interest is assigned.

Table 4. Long-Lived (T1/2 >100 days) Alpha Radionuclide Intake Rates Based on Air Concentration Data.

Radionuclide	Annual Alpha Intake Rate Based on BZ Data (dpm/day)
Am-241	0.49
Am-243	0.49
Cf-249	0.49
Cf-250	0.49
Cf-252	0.51
Cm-242	0.50
Cm-243	0.49
Cm-244	0.49
Cm-245	0.49
Cm-246	0.49
Cm-248	0.53
Es-254	0.49
Np-237	0.49
Pa-231	0.49
Pu-236	0.49
Pu-238	0.49
Pu-239	0.49
Pu-240	0.49
Pu-242	0.49
Pu-244	0.49
Th-228	0.49
Th-229	0.49
Th-230	0.49
Th-232	0.49
Ac-227	35.55

NOTE: These intakes rates are based on the 1970 alpha air concentration in Table 1. This is the highest alpha air concentration for the exposure period of 1967 through 1971 used in the example dose reconstruction presented below.

Gross Beta Bioassay Results

Table 5 lists the long-lived beta-emitting radionuclides used at LBNL with half-lives greater than 100 days, along with their branching fractions.

Table 5. Long-Lived (T1/2 >100 days) Beta Radionuclide Branching Fractions.

Radionuclide	Beta Branching Fractions
Ta-182	1
Tm-170	0.9987
Ca-45	1
Ag-110m	0.9864
Ce-144	1
Bk-249	1
Ru-106	1
Tm-171	1
Cs-134	0.999997
Pm-147	1
Sb-125	1
Tl-204	0.971
Co-60	1
Ra-228	1
Os-194	1
Eu-154	0.9998
Eu-152	0.279
Pu-241	0.99998
Pb-210	0.9999981
Sr-90	1
Cs-137	1
Ni-63	1
Tb-158	0.166
Ho-166m	1
Nb-94	1
Tc-99	1
Cl-36	0.981
Cd-113	1

The bioassay would be assessed for missed dose for each long-lived beta-emitting radionuclide. The beta branching fraction (Table 5) must be included when determining the sample activity or MDA for a given radionuclide when starting with a gross result. The reported urine sample value is divided by the branching fraction; the MDA is divided by the branching fraction and a factor of 2 for the missed dose adjustment.

The calculated intake rates from the gross beta bioassay result are then tabulated for all of the radionuclides based on the solubility type that yielded the largest dose.

Missed dose assumes a constant exposure to a theoretical missed intake that may or may not have occurred. By considering all of the available data, bioassay detection limits and workplace air sampling data, a more accurate upper bound of the potential non-detected internal exposure can be estimated. Therefore, the air sampling data, typically being more sensitive, should be used to limit the missed dose associated with a hypothetical intake associated with the detection limit. To do this, the calculated missed intake rates associated with the bioassay data, for each radionuclide, are compared to the intake rates determined from the BZ air monitoring data (see Table 6).

Table 6. Long-Lived (T1/2 >100 days) Beta Radionuclide Intake Rates Based on Air Concentration Data.

Radionuclide	Annual Beta Intake Rate Based on BZ Data (dpm/day)[a]
Ta-182	62.43
Tm-170	62.39
Ca-45	62.10
Ag-110m	62.67
Ce-144	61.76
Bk-249	61.71
Ru-106	61.66
Tm-171	61.49
Cs-134	61.48
Pm-147	61.44
Sb-125	61.43
Tl-204	63.23
Co-60	61.37
Ra-228	61.37
Os-194	61.37
Eu-154	61.36
Eu-152	219.84
Pu-241	61.33
Pb-210	61.32
Sr-90	61.32
Cs-137	61.32
Ni-63	61.31
Tb-158	369.34
Ho-166m	61.31
Nb-94	61.31
Tc-99	61.31
Cl-36	62.50
Cd-113	61.31

a. These intakes rates are based on the 1970 beta/gamma air concentration in Table 1. This is the highest beta/gamma concentration for the exposure period of 1967 through 1971 used in the example dose reconstruction presented below.

The annual beta intake rates based on BZ data for each of these radionuclides were determined by assuming the highest 95th-percentile annual air concentration (i.e., 1970) in Table 1 for the assumed exposure period of 1967 through 1971 in the example dose reconstruction presented below. The more limiting intake rate between the bioassay and BZ data is used to calculate the missed dose to the organ of interest. Air sampling data shall not be used to limit intakes based on positive bioassay data. The doses from all of the radionuclides are then compared to each other, and the radionuclide with the largest dose to the organ of interest is assigned.

Gross Gamma Bioassay Results

Table 7 lists the long-lived photon-emitting radionuclides used at LBNL with half-lives greater than 100 days, along with their photon yield.

Table 7. Long-Lived (T1/2 >100 days) Gamma Radionuclide Photon Yields.

Radionuclide	Photon Yield (Gammas/Disintegration)
Y-88	1.94
Sn-113	0.0185
Te-123m	0.843
Se-75	1.82
W-181	0.0111
Tm-170	0.0326
Re-184m	0.884
Au-195	0.125
Gd-153	0.535
Zn-65	0.508
Ag-110m	3.21
Pm-143	0.385
Co-57	1.06
Mn-54	1.0
Sm-145	0.128
Pm-144	2.44
Cd-109	0.0361
Hf-172	0.502
Cs-134	2.23
Na-22	0.999
Gd-151	0.158
Rh-101	1.42
Co-60	2.0
Eu-154	1.63
Ba-133	1.36
Eu-152	1.58
Pm-145	0.0283
Bi-207	1.8
Ti-44	1.83
Pt-193	0.211
Ag-108m	2.79
Tb-158	1.04
Al-26	1.03

The bioassay would be assessed for missed dose for each long-lived gamma-emitting radionuclide. The photon yield (listed in Table 7) must be included when determining the sample activity or MDA for a given radionuclide when starting with a gross result. The reported urine sample value is divided by the photon yield; the MDA is divided by photon yield and a factor of 2 for the missed dose adjustment.

The calculated intake rates from the gross gamma bioassay result are then tabulated for all of the radionuclides based on the solubility type that yielded the largest dose.

Missed dose assumes a constant exposure to a theoretical missed intake that may or may not have occurred. By considering all of the available data, bioassay detection limits and workplace air sampling data, a more accurate upper bound of the potential non-detected internal exposure can be estimated. Therefore, the air sampling data, typically being more sensitive, should be used to limit the missed dose associated with a hypothetical intake associated with the detection limit. To do this, the calculated intake rates from bioassay data for each radionuclide are compared to the intake rates determined from the BZ air monitoring data (see Table 8). The annual gamma intake rates based on BZ data for each of these radionuclides were determined by assuming the highest 95th-percentile annual air concentration (i.e., 1970) in Table 1 for the assumed exposure period of 1967 through 1971 in the example dose reconstruction presented below. The more limiting intake rate between the bioassay and BZ data is used to calculate the missed dose to the organ of interest. Air sampling data shall not be used to limit intakes based on positive bioassay data. The doses from all of the radionuclides are then compared to each other, and the radionuclide with the largest dose to the organ of interest is assigned as the final dose.

Table 8. Long-Lived (T1/2 >100 days) Gamma Radionuclide Intake Rates Based on Air Concentration Data.

Radionuclide	Annual Gamma Intake Rate Based on BZ Data (dpm/day)a
Y-88	32.31
Sn-113	3,374.38
Te-123m	74.04
Se-75	34.33
W-181	5,603.86
Tm-170	1,911.87
Re-184m	70.24
Au-195	496.47
Gd-153	115.69
Zn-65	121.82
Ag-110m	19.25
Pm-143	160.50
Co-57	58.50
Mn-54	61.73
Sm-145	481.91
Pm-144	25.24
Cd-109	1,705.45
Hf-172	122.53
Cs-134	27.58
Na-22	61.48
Gd-151	388.55
Rh-101	43.13
Co-60	30.70
Eu-154	37.57
Ba-133	45.07
Eu-152	38.94
Pm-145	2,170.14
Bi-207	34.08
Ti-44	33.60
Pt-193	290.59
Ag-108m	21.99
Tb-158	59.01
Al-26	59.81

a. These intakes rates are based on the 1970 beta/gamma air concentration in Table 1. This is the highest beta/gamma concentration for the exposure period of 1967 through 1971 used in the example dose reconstruction presented below.

Internal Dose from Short-Lived (T1/2 <100 Days) Radionuclides (Including Unmonitored Long-Lived Radionuclides Not Detected by Gross Bioassay Methods)

Table 9 lists radionuclides with a half-life of less than 100 days except for those radionuclides removed earlier due to half-lives shorter than 12.7 hours. These radionuclides, because of their short half-lives, generally are not assumed to be detected by the gross alpha, beta, and gamma bioassay methods due to the typical internal monitoring frequency of one year. Table 9 also includes several long-lived radionuclides not detected by the gross alpha or gross gamma methods.

Table 9. Short-Lived ($T_{1/2}$ <100 days) Radionuclide Intake Rates Based on Air Concentration Data.

Radionuclide	Emission Type	Intake Rate (dpm/day)[a]
Ac-225	Alpha	0.60
Th-227	Alpha	0.55
Es-253	Alpha	0.54
Sm-146[b]	Alpha	0.49
Gd-148[b]	Alpha	0.49
Po-208[b]	Alpha	0.49
Cu-64	Beta	7,990.72
Nb-90	Beta	1,869.55
Na-24	Beta	1,706.70
Zr-97	Beta	1,174.20
Pt-197	Beta	936.81
Ho-166	Beta	394.54
Os-193	Beta	323.47
Ce-143	Beta	278.08
Br-82	Beta	251.99
Sc-48	Beta	192.04
Sm-153	Beta	178.46
Cd-115	Beta	155.91
Y-90	Beta	133.69
As-71	Beta	132.41
Re-186	Beta	114.93
Np-239	Beta	148.22
Au-198	Beta	132.56
Sb-122	Beta	135.68
Au-199	Beta	118.89
Yb-175	Beta	100.70
Lu-177	Beta	83.58
Tb-161	Beta	82.83
Ag-111	Beta	81.04
P-32	Beta	70.91
Os-191	Beta	70.17
Rb-86	Beta	68.54
Th-234	Beta	66.83
P-33	Beta	66.54
Pa-233	Beta	66.22
Ce-141	Beta	65.36
Nb-95	Beta	65.04
Ru-103	Beta	64.64
Hf-181	Beta	64.39
Fe-59	Beta	64.24

Radionuclide	Emission Type	Intake Rate (dpm/day)[a]
Hg-203	Beta	64.11
Sr-89	Beta	63.89
Y-91	Beta	63.53
Sb-124	Beta	63.46
Zr-95	Beta	63.33
W-188	Beta	63.17
Tb-160	Beta	63.10
Ir-192	Beta	66.28
W-185	Beta	63.03
Sc-46	Beta	62.85
S-35	Beta	14.95
Y-86	Gamma	566.46
Br-76	Gamma	771.53
Zr-86	Gamma	1,046.74
Co-55	Gamma	803.57
Rh-100	Gamma	290.59
Ni-57	Gamma	215.53
Sb-119	Gamma	1,392.58
Au-194	Gamma	162.18
Am-240	Gamma	162.74
Br-77	Gamma	195.20
Ga-67	Gamma	134.26
Re-186	Gamma	1,012.77
Ba-128	Gamma	762.77
In-111	Gamma	69.27
Tl-201	Gamma	916.05
Pd-100	Gamma	85.13
Mn-52	Gamma	29.64
Ag-106m	Gamma	20.89
Cs-131	Gamma	93.02
Ba-131	Gamma	58.17
Rh-99	Gamma	44.92
V-48	Gamma	33.39
Te-121	Gamma	69.44
Sr-82	Gamma	111.92
Cr-51	Gamma	672.29
Yb-169	Gamma	44.93
Ag-105	Gamma	48.71
Be-7	Gamma	616.51
Sr-85	Gamma	64.59
Hf-175	Gamma	67.27
Re-183	Gamma	117.92
Co-58	Gamma	62.76
Co-56	Gamma	25.16
Zr-88	Gamma	62.86
Os-185	Gamma	62.37
Fe-55c	Gamma	215.80

Radionuclide	Emission Type	Intake Rate (dpm/day)[a]
Hg-194c	Gamma	248.52
Te-123c	Gamma	77.66

a. These intakes rates are based on the 1970 alpha and beta/gamma air concentrations in Table 1. These are the highest alpha and beta/gamma concentration for the exposure period of 1967 through 1971 used in example dose reconstruction presented below.
b. Long-lived radionuclide not detected by gross alpha method but picked up by air monitoring.
c. Decay energy likely too low for bioassay but might be counted on air sample.

Annual intake rates for each of these radionuclides were determined by assuming the highest 95th-percentile annual air concentration (i.e., 1970) in Table 1 for the assumed exposure period of 1967 through 1971 in the example dose reconstruction presented below. These measured air concentrations were adjusted as appropriate for the emission rate or gamma yield of the detected radiation type.

These intake rates are then multiplied by ICRP (1995) inhalation DCFs, as shown in the example in Tables 24a and 24b, to determine the radionuclide that yields the highest organ committed dose for the beta and gamma emitters. This is an efficiency measure that is used to determine the radionuclide selection. Because the Interactive RadioEpidemiological Program (IREP) cannot accept a 50-year committed dose as input, the intake rate for that particular radionuclide is then run using the Integrated Modules for Bioassay Analysis (IMBA) or the Chronic Annual Dose Workbook (CAD) to determine the annual equivalent internal doses out to the cancer diagnosis date.

Based on these results:

- The dose reconstructor should assign dose from short-lived ($T_{1/2}$ <100 days) **alpha** radionuclides for each year the worker submitted a bioassay sample and the BZ intake rate was not used to assess the dose from the long-lived alpha radionuclide. In the case where the BZ data was used to assess the long-lived alpha radionuclide, the dose from the short-lived alpha radionuclide that results in the largest dose to the organ of interest should be compared to the dose from the long-lived alpha radionuclide. The one that results in the largest dose to the organ of interest should be assigned, but not both (in order not to double count the activity from the BZ data).

- The dose reconstructor should assign dose from short-lived ($T_{1/2}$<100 days) **beta** radionuclides for each year the worker submitted a bioassay sample and the BZ intake rate was not used to assess the dose from the long-lived beta radionuclide. In the case where the BZ data was used to assess the long-lived beta radionuclide, the dose from the short-lived beta radionuclide that results in the largest dose to the organ of interest should be compared to the dose from the long-lived beta radionuclide. The one that results in the largest dose to the organ of interest should be assigned, but not both (in order not to double count the activity from the BZ data).

- The dose reconstructor should assign dose from short-lived ($T_{1/2}$<100 days) **gamma** radionuclides for each year the worker submitted a bioassay sample and the BZ intake rate was not used to assess the dose from the long-lived gamma radionuclide. In the case where the BZ data was used to assess the long-lived gamma radionuclide, the dose from the short-lived gamma radionuclide that results in the largest dose to the organ of interest should be compared to the dose from the long-lived gamma radionuclide. The one that results in the largest dose to the organ of interest should be assigned, but not both (in order not to double count the activity from the BZ data).

The following summarizes the steps to assess internal dose using gross alpha, gross beta, and gross gamma bioassay results below the MDA, and air sampling results at LBNL. Steps for assessing positive bioassay results are also provided, following this section.

Guidance for Assessing Internal Dose Using Gross Alpha, Gross Beta, and Gross Gamma Bioassay Results Below the Minimum Detectable Activity

Alpha Radionuclides:

1. Calculate the dose from long-lived alpha radionuclides.

    a. For each radionuclide, calculate the intake rate and missed dose for each solubility type based on urinalysis data.

    b. For each radionuclide, select the intake rate/solubility type combination yielding the largest internal dose based on urinalysis data.

    c. For each radionuclide, calculate the intake rate based on BZ data.

    d. For each radionuclide, select the smaller of the intake rates based on urinalysis results (step 1.b) and based on the BZ data (step 1.c).

    e. For each radionuclide, calculate the missed dose based on the results of step 1.d.

    f. Select the radionuclide yielding the largest dose in step 1.e.

2. Calculate the dose from short-lived alpha radionuclides.

    a. For each radionuclide, determine the annual intake based on BZ data.

    b. For each radionuclide, select the solubility type that yields the largest DCF for the organ.

c. For each radionuclide, multiply the annual intake by the DCF selected in step 2.b.

d. Select the radionuclide yielding the largest committed dose.

e. Determine the internal dose for the annual intake of the radionuclide yielding the largest committed dose using IMBA or CAD.

3. Dose assignment.

   a. For each year of assumed intake, the urinalysis results yielded the largest dose in step 1.f:

      i. Assign the dose from the long-lived alpha emitter selected in step 1.f, and

      ii. Assign the dose from the short-lived alpha radionuclide selected in step 2.e.

   b. For each year of assumed intake, the BZ intake rate yielded the largest dose from the long-lived alpha radionuclide (step 1.f):

      i. Compare the dose from the short-lived alpha radionuclide that results in the largest dose (from step 2.d) to the dose from the long-lived alpha radionuclide (step 1.f).

      ii. From the results of step 3.b.i, assign only the intake that results in the largest dose to the organ of interest.

Beta Radionuclides:

1. Calculate the dose from long-lived beta radionuclides.

   a. For each radionuclide, calculate the intake rate and missed dose for each solubility type based on urinalysis data.

   b. For each radionuclide, select the intake rate/solubility type combination yielding the largest internal dose based on urinalysis data.

   c. For each radionuclide, calculate the intake rate based on BZ data.

   d. For each radionuclide, select the smaller of the intake rates based on urinalysis results (step 1.b) and based on the BZ data (step 1.c).

   e. For each radionuclide, calculate the missed dose based on the results of step 1.d.

   f. Select the radionuclide yielding the largest dose in step 1.e.

2. Calculate the dose from short-lived beta radionuclides.

   a. For each radionuclide, determine the annual intake based on BZ data.

   b. For each radionuclide, select the solubility type that yields the largest DCF for the organ.

   c. For each radionuclide, multiply the annual intake by the DCF selected in step 2.b.

   d. Select the radionuclide yielding the largest committed dose.

   e. Determine the internal dose for the annual intake of the radionuclide yielding the largest committed dose using IMBA or CAD.

3. Dose assignment.

   a. For each year the urinalysis results yielded the largest dose in step 1.f:

      i. Assign the dose from the long-lived beta emitter selected in step 1.f, and

      ii. Assign the dose from the short-lived beta radionuclide selected in step 2.e.

   b. For each year the BZ intake rate yielded the largest dose from the long-lived beta radionuclide (step 1.f):

      i. Compare the dose from the short-lived beta radionuclide that results in the largest dose (from step 2.d) to the dose from the long-lived beta radionuclide (step 1.f).

      ii. From the results of step 3.b.i, assign only the intake that results in the largest dose to the organ of interest.

<u>Gamma Radionuclides:</u>

1. Calculate the dose from long-lived gamma radionuclides.

   a. For each radionuclide, calculate the intake rate and missed dose for each solubility type based on urinalysis data.

   b. For each radionuclide, select the intake rate/solubility type combination yielding the largest internal dose based on urinalysis data.

   c. For each radionuclide, calculate the intake rate based on BZ data.

d. For each radionuclide, select the smaller of the intake rates based on urinalysis results (step 1.b) and based on the BZ data (step 1.c).

e. For each radionuclide, calculate the missed dose based on the results of step 1.d.

f. Select the radionuclide yielding the largest dose in step 1.e.

2. Calculate the dose from short-lived gamma radionuclides.

a. For each radionuclide, determine the annual intake based on BZ data.

b. For each radionuclide, select the solubility type that yields the largest DCF for the organ.

c. For each radionuclide, multiply the annual intake by the DCF selected in step 2.b.

d. Select the radionuclide yielding the largest committed dose.

e. Determine the internal dose for the annual intake of the radionuclide yielding the largest committed dose using IMBA or CAD.

3. Dose assignment.

a. For each year the urinalysis results yielded the largest dose in step 1.f:

i. Assign the dose from the long-lived gamma emitter selected in step 1.f, and

ii. Assign the dose from the short-lived gamma radionuclide selected in step 2.e.

b. For each year the BZ intake rate yielded the largest dose from the long-lived gamma radionuclide (step 1.f):

i. Compare the dose from the short-lived gamma radionuclide that results in the largest dose (from step 2.d) to the dose from the long-lived beta radionuclide (step 1.f).

ii. From the results of step 3.b.i, assign only the intake that results in the largest dose to the organ of interest.

EXAMPLE: MISSED DOSE RECONSTRUCTION OF LONG- AND SHORT-LIVED ALPHA, BETA, AND GAMMA RADIONUCLIDES

The example presented below is for missed dose for an unknown work location and doses to several organs of interest.

All missed dose calculations based on bioassay are based upon the MDA/2 to calculate the mode value in accordance with Section 3.3.1 in ORAUT (2014).

Table 10. Example Calculation Employment Information.

Employment Period	01/01/1967–12/31/1971
Work Location	Unknown
Internal Monitored Period	01/01/1969–12/31/1971

Table 11. Example Calculation Cancer Information.

Cancer	Date of Diagnosis
Lung	12/31/1975
Bone Surface	12/31/1975
Liver	12/31/1975
Adrenals	12/31/1975

Table 12. Example Calculation Bioassay Information.

Date	Bioassay Results	Gross Alpha MDA (dpm/24 h)	Gross Beta MDA (dpm/24 h)	Gross Gamma MDA (dpm/24 h)
12/31/1969	<MDA	0.2	2	100
12/31/1970	<MDA	0.2	2	100
12/31/1971	<MDA	0.2	2	100

Table 13. Example Calculation Air Concentration Information.

Highest Annual Alpha Air Concentration for 1967–1971	0.0336 pCi/m^3
Highest Annual Beta/Gamma Air Concentration for 1967–1971	4.2 pCi/m^3
Unmonitored Period	01/01/1967–12/31/1968

The highest 95th-percentile alpha air concentration for 1967 through 1971 from Table 1 is 0.0336 pCi/m^3. The highest 95th-percentile beta/gamma air concentration for 1967 through 1971 from Table 1 is 4.2 pCi/m^3. These values will be used to determine the alpha, beta, and gamma annual intake rates based on BZ data in the tables below. This is an overestimating efficiency measure for demonstration purposes. All dose calculations based on the 95th-percentile annual air concentration are applied a constant distribution.

Long-Lived (T1/2 >100 days) Internal Dose, January 1, 1969, Through December 31, 1971

LBNL bioassay monitoring frequencies were typically six months or one year depending on the work. Based on these typical monitoring frequencies, a single bioassay result indicates that the worker had, at most, one year of internal exposure potential before the date of the bioassay sample. Based on the above example, the worker has a potential for intakes from January 1, 1969, through December 31, 1971.

The results of the bioassay and BZ assessments and comparisons based on the gross bioassay methodologies described above are shown in Tables 21a, 21b, 23a, 23b, 24a, and 24b below.

Table 21a provides the missed doses for the long-lived alpha emitters based on urinalysis, and Table 21b provides the limiting doses based on a comparison of the intake rates based on gross alpha urinalysis and the intake rates based on BZ data.

Table 23a provides the missed doses for the long-lived beta emitter based on urinalysis, and Table 23b provides the limiting doses based on a comparison of the intake rates based on gross beta urinalysis and the intake rates based on BZ data.

Table 24a provides the missed doses for the long-lived gamma emitter based on urinalysis, and Table 24b provides the limiting doses based on a comparison of the intake rates based on gross gamma urinalysis and the intake rates based on BZ data.

Tables 14, 15, and 16 provide the summary information from the above tables for the long-lived radionuclide that results in the largest internal doses to the organ of interest based on the comparison of the bioassay intake rate to the BZ intake rate.

Table 14. Alpha Internal Dose Summary (rem), 1969 to 1971.

Organ	Radionuclide	Dose (rem)	Limiting Data
Lung	Ac-227	1.17E+01	BZ
Bone Surface	Ac-227	2.76E+00	BZ
Liver	Ac-227	7.37E-01	BZ
Adrenals	Cm-248	6.80E-04	BZ

Table 15. Beta Internal Dose Summary (rem), 1969 to 1971.

Organ	Radionuclide	Dose (rem)	Limiting Data
Lung	Ra-228	6.80E-01	BZ
Bone Surface	Ra-228	4.15E-01	BZ
Liver	Pb-210	7.87E-02	Bioassay
Adrenals	Tb-158	6.80E-03	BZ

Table 16. Gamma Internal Dose Summary (rem), 1969 to 1971.

Organ	Radionuclide	Dose (rem)	Limiting Data
Lung	Tm-170	1.15E-01	BZ
Bone Surface	Hf-172	1.77E-01	BZ
Liver	Cd-109	1.09E-02	BZ
Adrenals	Hf-172	1.51E-03	BZ

Short-Lived (T1/2 <100 days) Internal Dose, January 1, 1969, Through December 31, 1971

The results of the short-lived internal dose based on BZ assessments described above are shown in Tables 22a, 22b, 25a, and 25b below. Tables 22a and 22b provide the radionuclides that yield the highest committed doses based on BZ data from the short-lived alpha emitters. Tables 25a and 25b provide the radionuclides that yield the highest committed doses based on BZ data from the short-lived beta and gamma emitters. A summary of these results is shown in Table 17a. As previously indicated, IREP cannot accept a 50-year committed dose as input. Therefore, the intake rates for the particular radionuclides are then run using IMBA or CAD to determine the annual equivalent doses to the cancer diagnosis date. The comparison values are based on a single year of intake regardless of the actual intake period because they are for comparison purposes only. Table 17b provides the unmonitored total dose from the start of intake to the date of cancer diagnosis for the alpha-, beta-, and gamma-emitting radionuclides listed in Table 17a.

Table 17a. Short-Lived Internal Committed Dose Summary for Radionuclide Selection (rem), 1969 to 1971.

Organ	Emission Type	Radionuclide	Dose (Rem)
Lung	Alpha	Th-227	2.14E-02
Bone Surface	Alpha	Gd-148	2.99E-01
Liver	Alpha	Gd-148	5.68E-02
Adrenals	Alpha	Po-208	6.29E-05
Lung	Beta	Cu-64	2.68E-03
Bone Surface	Beta	Zr-95	2.39E-03
Liver	Beta	Ir-192	4.04E-04
Adrenals	Beta	Na-24	1.77E-04
Lung	Gamma	Re-186	3.08E-03
Bone Surface	Gamma	Te-123	8.99E-03
Liver	Gamma	Hg-194	2.72E-03
Adrenals	Gamma	Hg-194	3.48E-03

NOTE: Committed doses summarized from Tables 22a, 22b, 25a, and 25b.

Table 17b. Short-Lived Internal Dose Summary (rem), 1969 to 1971.

Organ	Emission Type	Radionuclide	Dose (Rem)
Lung	Alpha	Th-227	6.37E-02
Bone Surface	Alpha	Gd-148	7.06E-02
Liver	Alpha	Gd-148	1.29E-02
Adrenals	Alpha	Po-208	1.88E-04
Lung	Beta	Cu-64	7.92E-03
Bone Surface	Beta	Zr-95	7.11E-03
Liver	Beta	Ir-192	1.25E-03
Adrenals	Beta	Na-24	5.10E-04
Lung	Gamma	Re-186	9.22E-03
Bone Surface	Gamma	Te-123	4.88E-03
Liver	Gamma	Hg-194	1.88E-03
Adrenals	Gamma	Hg-194	2.37E-03

NOTE: Doses determined using IMBA or CAD.

Final Internal Dose, January 1, 1969, Through December 31, 1971

Table 18 summarizes the internal doses to be assigned to the organs of interest based on the comparison of the bioassay and breathing data for short- and long-lived beta- and gamma-emitting radionuclides in Tables 14, 15, 16, and 17b.

Table 18. Internal Dose Summary (rem), 1969 to 1971.

Organ	Emission Type	Intake Assigned	Radionuclide	Dose (Rem)
Lung	Alpha	Long-Lived	Ac-227	1.17E+01
Lung	Alpha	Short-Lived	Not applicable[a]	Not applicable[a]
Bone Surface	Alpha	Long-Lived	Ac-227	2.76E+00
Bone Surface	Alpha	Short-Lived	Not applicable[a]	Not applicable[a]
Liver	Alpha	Long-Lived	Ac-227	7.37E-01
Liver	Alpha	Short-Lived	Not applicable[a]	Not applicable[a]
Adrenals	Alpha	Long-Lived	Cm-248	6.80E-04
Adrenals	Alpha	Short-Lived	Not applicable[a]	Not applicable[a]
Lung	Beta	Long-Lived	Ra-228	6.80E-01
Lung	Beta	Short-Lived	Not applicable[a]	Not applicable[a]
Bone Surface	Beta	Long-Lived	Ra-228	4.15E-01
Bone Surface	Beta	Short-Lived	Not applicable[a]	Not applicable[a]
Liver	Beta	Long-Lived	Pb-210	7.87E-02
Liver	Beta	Short-Lived	Pb-210	1.25E-03
Adrenals	Beta	Long-Lived	Tb-158	6.80E-03
Adrenals	Beta	Short-Lived	Not applicable[a]	Not applicable[a]
Lung	Gamma	Long-Lived	Tm-170	1.15E-01
Lung	Gamma	Short-Lived	Not applicable[a]	Not applicable[a]
Bone Surface	Gamma	Long-Lived	Hf-172	1.77E-01
Bone Surface	Gamma	Short-Lived	Not applicable[a]	Not applicable[a]
Liver	Gamma	Long-Lived	Cd-109	1.09E-02
Liver	Gamma	Short-Lived	Not applicable[a]	Not applicable[a]
Adrenals	Gamma	Long-Lived	Not applicable[b]	Not applicable[b]
Adrenals	Gamma	Short-Lived	Hg-194	2.37E-03

a. Dose from this source term is not applicable as all of the activity associated with the BZ air sampling data are associated with the long-lived radionuclide.

b. Dose from this source term is not applicable as all of the activity associated with the BZ air sampling data are associated with the short-lived radionuclide.

Unmonitored Worker Internal Dose, January 1, 1967, Through December 31, 1968

The internal dose for the period from 1967 to 1968 for unmonitored workers is assessed similarly to the short-lived approach described above, but includes all gross bioassay method radionuclides described above. In addition, there are several alpha emitters determined by separate bioassay methods (Buckley 1969) that are included. These additional alpha emitters are not determined by the LBNL gross alpha procedure. Based on LBNL's bioassay program, if the Energy Employee (EE) was monitored for gross alpha activity only, there would be no potential for exposure to the separate bioassay method radionuclides of Po-210, Ra-226, and uranium. Therefore, these radionuclides were not included in the dose assessment methodology presented above. The additional alpha radionuclides are provided in Table 19 below.

Table 19. Additional Alpha Emitters for Unmonitored Workers, 1967 to 1968.

Separate Bioassay Method Alpha Radionuclides	Annual Alpha Intake Rate Based on BZ Data (dpm/day)	Branching Fraction
Po-210	0.50	1
Ra-226	0.49	1
U-232	0.49	1
U-233	0.49	1
U-234	0.49	1
U-235	0.49	1
U-236	0.49	1
U-238	0.49	1

The results of the internal dose to an unmonitored worker based on the BZ assessments in Tables 4, 6, 8, 9, and 19 above are shown in Tables 26a, 26b, 27a, and 27b. Tables 26a and 26b provides the radionuclides that yield the highest committed doses based on BZ data from the alpha emitters. Tables 27a and 27b provides the radionuclides that yield the highest committed doses based on BZ data from the beta and gamma emitters. A summary of these results is shown in Table 20a. The comparison values are based on a single year of intake regardless of the actual intake period because they are for comparison purposes only. Table 20b provides the internal doses to an unmonitored worker up to the cancer diagnosis dates for the alpha-, beta-, and gamma-emitting radionuclides determined using IMBA or CAD.

Attachment A provides a detailed discussion of the calculation steps supporting the approach discussed above, and the dose results presented in Tables 21a through 27b below.

Table 20a. Unmonitored Worker Internal Committed Dose Summary (rem), 1967 to 1968.

Organ	Emission Type	Radionuclide	Dose (Rem)
Lung	Alpha	Ac-227	4.76E+00
Bone Surface	Alpha	Ac-227	4.11E+02
Liver	Alpha	Ac-227	9.31E+01
Adrenals	Alpha	Ac-227	3.03E-03
Lung	Beta	Ra-228	2.32E-01
Bone Surface	Beta	Ra-228	1.35E+00
Liver	Beta	Pu-241	1.53E-01
Adrenals	Beta	Tb-158	6.52E-03
Lung	Gamma	Tm-170	3.84E-02
Bone Surface	Gamma	Hf-172	6.64E-02
Liver	Gamma	Cd-109	4.47E-02
Adrenals	Gamma	Hg-194	3.48E-03

NOTE: Committed doses summarized from Tables 26b and 27b.

Table 20b. Unmonitored Worker Internal Dose Summary (rem), 1967 to 1968.

Organ	Emission Type	Radionuclide	Dose (Rem)
Lung	Alpha	Ac-227	8.40E+00
Bone Surface	Alpha	Ac-227	2.52E+02
Liver	Alpha	Ac-227	6.60E+01
Adrenals	Alpha	Ac-227	2.08E-03
Lung	Beta	Ra-228	4.37E-01
Bone Surface	Beta	Ra-228	2.21E+01
Liver	Beta	Pu-241	2.03E-02
Adrenals	Beta	Tb-158	6.07E-03
Lung	Gamma	Tm-170	7.70E-02
Bone Surface	Gamma	Hf-172	1.28E-01
Liver	Gamma	Cd-109	8.77E-02
Adrenals	Gamma	Hg-194	1.99E-03

NOTE: Doses determined using IMBA or CAD.

The above example demonstrates the approach for assessing internal dose using bioassay results below the MDA and air concentration data at LBNL. Additional guidance is provided below for completeness for assessing internal dose using positive bioassay results, and internal dose to an unmonitored worker.

Guidance for Assessing Internal Dose Using Positive Bioassay Results Where the Radionuclide is Not Identified

Alpha Radionuclides:

1. Calculate the fitted dose from long-lived alpha radionuclides.

    a. For each radionuclide, calculate the intake and fitted dose for each solubility type based on urinalysis data.

    b. For each radionuclide, select the intake/solubility type combination yielding the largest internal dose based on urinalysis data.

    c. Select the radionuclide yielding the largest dose in step 1.b.

2. Calculate the missed dose from long-lived alpha radionuclides.

    a. Repeat the process used for the alpha emitters.

3. Dose assignment.

    a. Fitted dose is compared to missed dose as appropriate for the case in accordance with the internal dose reconstruction guidance in ORAUT (2014).

Beta Radionuclides:

1. Calculate the fitted dose from long-lived beta radionuclides.

    a. For each radionuclide, calculate the intake and fitted dose for each solubility type based on urinalysis data.

    b. For each radionuclide, select the intake/solubility type combination yielding the largest internal dose based on urinalysis data.

    c. Select the radionuclide yielding the largest dose in step 1.b.

2. Calculate the missed dose from long-lived beta radionuclides.

    a. Repeat the process used for the beta emitters.

3. Dose assignment.

    a. Fitted dose is compared to missed dose as appropriate for the case in accordance with the internal dose reconstruction guidance in ORAUT (2014).

Gamma Radionuclides:

1. Calculate the fitted dose from long-lived gamma radionuclides.

    a. For each radionuclide, calculate the intake and fitted dose for each solubility type based on urinalysis data.

    b. For each radionuclide, select the intake/solubility type combination yielding the largest internal dose based on urinalysis data.

    c. Select the radionuclide yielding the largest dose in step 1.b.

2. Calculate the missed dose from long-lived gamma radionuclides.

    a. Repeat the process used for the gamma emitters.

3. Dose assignment.

    a. Fitted dose is compared to missed dose as appropriate for the case in accordance with the internal dose reconstruction guidance in ORAUT (2014).

Guidance for Assessing Internal Dose Using Positive Bioassay Results Where the Radionuclide is Identified

Alpha Radionuclides:

1. Calculate the fitted dose for the alpha radionuclide.
    a. Calculate the intake rate and fitted dose for each solubility type based on urinalysis data for the radionuclide.
    b. Select the intake rate/solubility type combination yielding the largest internal dose based on urinalysis data for the radionuclide.
2. Calculate the missed dose from long-lived alpha radionuclides.
    a. Repeat the process used for the alpha emitters.
3. Dose assignment.
    a. Fitted dose is compared to missed dose as appropriate for the case in accordance with the internal dose reconstruction guidance in ORAUT (2014).

Beta Radionuclides:

1. Calculate the fitted dose for the beta radionuclide.
    a. Calculate the intake rate and fitted dose for each solubility type based on urinalysis data for the radionuclide.
    b. Select the intake rate/solubility type combination yielding the largest internal dose based on urinalysis data for the radionuclide.
2. Calculate the missed dose from long-lived beta radionuclides.
    a. Repeat the process used for the beta emitters.
3. Dose assignment.
    a. Fitted dose is compared to missed dose as appropriate for the case in accordance with the internal dose reconstruction guidance in ORAUT (2014).

Gamma Radionuclides:

1. Calculate the fitted dose for the gamma radionuclide.

   a. Calculate the intake rate and fitted dose for each solubility type based on urinalysis data for the radionuclide.

   b. Select the intake rate/solubility type combination yielding the largest internal dose based on urinalysis data for the radionuclide.

2. Calculate the missed dose from long-lived gamma radionuclides.

   a. Repeat the process used for the gamma emitters.

3. Dose assignment.

   a. Fitted dose is compared to missed dose as appropriate for the case in accordance with the internal dose reconstruction guidance in ORAUT (2014).

Assessing Internal Dose to an Unmonitored Worker

The method for assessing internal dose to an unmonitored worker at LBNL is detailed in the "Unmonitored Worker Internal Dose, January 1, 1967, through December 31, 1968" section above. The following summarizes the steps to assess internal dose to an unmonitored worker at LBNL.

Alpha Radionuclides:

1. Calculate the dose from both the short-lived and long-lived alpha radionuclides.

   a. For each radionuclide, determine the annual intake based on BZ data.

   b. For each radionuclide, select the solubility type that yields the largest DCF for the organ.

   c. For each radionuclide, multiply the annual intake by the DCF selected in step 1.b.

   d. Select the radionuclide yielding the largest committed dose.

   e. Determine the internal dose for the annual intake of the radionuclide yielding the largest committed dose.

Beta Radionuclides:

1. Calculate the dose from both the short-lived and long-lived beta radionuclides.

   a. For each radionuclide, determine the annual intake based on BZ data.

b. For each radionuclide, select the solubility type that yields the largest DCF for the organ.

c. For each radionuclide, multiply the annual intake by the DCF selected in step 1.b.

d. Select the radionuclide yielding the largest committed dose.

e. Determine the internal dose for the annual intake of the radionuclide yielding the largest committed dose.

Gamma Radionuclides:

1. Calculate the dose from both the short-lived and long-lived beta radionuclides.

   a. For each radionuclide, determine the annual intake based on BZ data.

   b. For each radionuclide, select the solubility type that yields the largest DCF for the organ.

   c. For each radionuclide, multiply the annual intake by the DCF selected in step 1.b.

   d. Select the radionuclide yielding the largest committed dose.

   e. Determine the internal dose for the annual intake of the radionuclide yielding the largest committed dose.

Table 21a. Gross Alpha Method.

Radionuclide	Solubility Type	Intake Rate (dpm/day)	Lung Dose (rem)	Solubility Type	Intake Rate (dpm/day)	Bone Surface Dose (rem)	Solubility Type	Intake Rate (dpm/day)	Liver Dose (rem)	Solubility Type	Intake Rate (dpm/day)	Adrenals Dose (rem)
Am-241	M	9.40	3.78E-01	M	9.40	2.65E+00	M	9.40	4.93E-01	M	9.40	2.27E-03
Am-243	M	9.39	3.45E-01	M	9.39	2.56E+00	M	9.39	4.77E-01	M	9.39	2.25E-03
Cf-249	M	22.16	1.04E+00	M	22.16	9.99E+00	M	22.16	9.89E-01	M	22.16	2.53E-04
Cf-250	M	22.91	1.17E+00	M	22.91	9.39E+00	M	22.91	9.32E-01	M	22.91	1.11E-04
Cf-252	M	26.56	1.65E+00	M	26.56	1.25E+01	M	26.56	1.25E+00	M	26.56	2.82E-03
Cm-242	M	18.04	8.15E-01	M	18.04	4.91E-01	M	18.04	1.62E-01	M	18.04	5.49E-04
Cm-243	M	9.59	4.47E-01	M	9.59	2.67E+00	M	9.59	5.06E-01	M	9.59	2.32E-03
Cm-244	M	9.67	4.47E-01	M	9.67	2.58E+00	M	9.67	4.93E-01	M	9.67	2.21E-03
Cm-245	M	9.39	3.58E-01	M	9.39	2.58E+00	M	9.39	4.81E-01	M	9.39	2.22E-03
Cm-246	M	9.39	3.62E-01	M	9.39	2.60E+00	M	9.39	4.87E-01	M	9.39	2.23E-03
Cm-248	M	10.23	6.59E-01	M	10.23	1.03E+01	M	10.23	1.92E+00	M	10.23	1.30E-02
Es-254	M	32.65	1.80E+00	M	32.65	3.56E+00	M	32.65	3.62E-01	M	32.65	2.16E-04
Np-237	M	3.77	1.13E-01	M	3.77	9.17E-01	M	3.77	3.94E-02	M	3.77	6.50E-04
Pa-231	S	103.13	7.93E+00	M	5.35	2.00E+00	S	103.13	4.42E-03	S	103.13	7.45E-05
Pu-236	S	725.95	5.42E+01	S	725.95	5.49E+00	S	725.95	1.04E+00	S	725.95	1.10E-02
Pu-238	S	524.14	4.06E+01	S	524.14	6.76E+00	S	524.14	1.30E+00	S	524.14	1.31E-02
Pu-239	S	518.05	3.57E+01	S	518.05	6.44E+00	S	518.05	1.24E+00	S	518.05	1.25E-02
Pu-240	S	518.11	3.58E+01	S	518.11	6.45E+00	S	518.11	1.24E+00	S	518.11	1.25E-02
Pu-242	S	518.03	3.26E+01	S	518.03	6.12E+00	S	518.03	1.18E+00	S	518.03	1.19E-02
Pu-244	S	518.65	3.02E+01	S	518.65	5.95E+00	S	518.65	1.15E+00	S	518.65	1.42E-02
Th-228	S	448.37	7.65E+00	S	448.37	1.68E+02	S	448.37	3.26E-01	S	448.37	2.46E-02
Th-229	S	305.30	1.02E+01	S	305.30	1.15E+02	S	305.30	5.75E-01	S	305.30	2.59E-02
Th-230	S	305.27	5.45E+00	S	305.27	1.78E+01	M	9.39	4.77E-01	S	305.27	9.12E-03
Th-232	S	305.26	5.09E+00	S	305.26	1.82E+01	S	305.26	9.94E-02	S	305.26	9.12E-03
Ac-227	S	38661.59	1.27E+04	S	38661.59	3.01E+03	S	38661.59	8.01E+02	S	38661.59	1.71E-01

NOTE: Sample method MDA = 0.2 dpm/sample used to determine intake rate and missed dose based on urinalysis (rem).

Table 21b. Gross Alpha Method (Continued).

Radionuclide	Intake Rate Based on BZ Data (dpm/day)	Lung Dose (rem)	Bioassay or BZ Data	Bone Surface Dose (rem)	Bioassay or BZ Data	Liver Dose (rem)	Bioassay or BZ Data	Adrenals Dose (rem)	Bioassay or BZ Data
Am-241	0.49	1.97E-02	BZ	1.38E-01	BZ	2.57E-02	BZ	1.18E-04	BZ
Am-243	0.49	1.80E-02	BZ	1.34E-01	BZ	2.49E-02	BZ	1.18E-04	BZ
Cf-249	0.49	2.31E-02	BZ	2.21E-01	BZ	2.19E-02	BZ	5.60E-06	BZ
Cf-250	0.49	2.51E-02	BZ	2.01E-01	BZ	2.00E-02	BZ	2.38E-06	BZ
Cf-252	0.51	3.14E-02	BZ	2.39E-01	BZ	2.39E-02	BZ	5.38E-05	BZ
Cm-242	0.50	2.24E-02	BZ	1.35E-02	BZ	4.47E-03	BZ	1.51E-05	BZ
Cm-243	0.49	2.29E-02	BZ	1.37E-01	BZ	2.60E-02	BZ	1.19E-04	BZ
Cm-244	0.49	2.27E-02	BZ	1.31E-01	BZ	2.50E-02	BZ	1.12E-04	BZ
Cm-245	0.49	1.87E-02	BZ	1.35E-01	BZ	2.52E-02	BZ	1.16E-04	BZ
Cm-246	0.49	1.89E-02	BZ	1.36E-01	BZ	2.54E-02	BZ	1.16E-04	BZ
Cm-248	0.53	3.44E-02	BZ	5.40E-01	BZ	1.00E-01	BZ	6.80E-04	BZ
Es-254	0.49	2.72E-02	BZ	5.39E-02	BZ	5.48E-03	BZ	3.26E-06	BZ
Np-237	0.49	1.47E-02	BZ	1.19E-01	BZ	5.12E-03	BZ	8.45E-05	BZ
Pa-231	0.49	3.77E-02	BZ	1.84E-01	BZ	2.10E-05	BZ	3.54E-07	BZ
Pu-236	0.49	3.67E-02	BZ	3.72E-03	BZ	7.05E-04	BZ	7.45E-06	BZ
Pu-238	0.49	3.80E-02	BZ	6.33E-03	BZ	1.22E-03	BZ	1.23E-05	BZ
Pu-239	0.49	3.38E-02	BZ	6.10E-03	BZ	1.17E-03	BZ	1.18E-05	BZ
Pu-240	0.49	3.38E-02	BZ	6.10E-03	BZ	1.18E-03	BZ	1.18E-05	BZ
Pu-242	0.49	3.09E-02	BZ	5.80E-03	BZ	1.12E-03	BZ	1.12E-05	BZ
Pu-244	0.49	2.86E-02	BZ	5.63E-03	BZ	1.09E-03	BZ	1.35E-05	BZ
Th-228	0.49	8.39E-03	BZ	1.85E-01	BZ	3.58E-04	BZ	2.70E-05	BZ
Th-229	0.49	1.65E-02	BZ	1.85E-01	BZ	9.24E-04	BZ	4.17E-05	BZ
Th-230	0.49	8.76E-03	BZ	2.86E-02	BZ	2.49E-02	BZ	1.46E-05	BZ
Th-232	0.49	8.17E-03	BZ	2.92E-02	BZ	1.60E-04	BZ	1.46E-05	BZ
Ac-227	35.55	1.17E+01	BZ	2.76E+00	BZ	7.37E-01	BZ	1.57E-04	BZ
Largest Dose	**Not applicable**	**1.17E+01**	**BZ**	**2.76E+00**	**BZ**	**7.37E-01**	**BZ**	**6.80E-04**	**BZ**
Largest Radionuclide	**Not applicable**	**Ac-227**	**Not applicable**	**Ac-227**	**Not applicable**	**Ac-227**	**Not applicable**	**Cm-248**	**Not applicable**

NOTE: Limiting dose based on comparison of the intake rate based on bioassay in Table 21a to the intake rate based on BZ data (rem).

Table 22a. Gross Alpha Method.

Alpha Radionuclide	Annual BZ Intake Rate (dpm/day)	Lung DCF[a]	Solubility Type	Bone Surface DCF[a]	Solubility Type	Liver DCF[a]	Solubility Type	Adrenals DCF[a]	Solubility Type	Lung Dose[b]	Bone Surface Dose[b]	Liver Dose[b]	Adrenals Dose[b]
Ac-225	0.60	2.000E-01	S	1.037E-01	F	2.778E-02	F	4.074E-05	F	1.986E-02	1.030E-02	2.758E-03	4.045E-06
Th-227	0.55	2.370E-01	S	1.333E-02	M	7.778E-04	M	4.074E-05	M	2.136E-02	1.202E-03	7.010E-05	3.672E-06
Es-253	0.54	6.296E-02	M	1.037E-02	M	1.000E-03	M	1.222E-06	M	5.619E-03	9.255E-04	8.925E-05	1.091E-07
Sm-146	0.49	1.074E-02	M	7.037E-01	M	1.926E-01	M	8.148E-07	M	8.661E-04	5.675E-02	1.553E-02	6.571E-08
Gd-148	0.49	2.185E-02	M	3.704E+00	F	7.037E-01	F	4.815E-06	F	1.762E-03	2.987E-01	5.675E-02	3.883E-07
Po-208	0.49	6.750E-02	M	4.460E-03	F	1.850E-02	F	7.790E-04	F	5.454E-03	3.604E-04	1.495E-03	6.294E-05

a. ICRP (1995) max organ DCF (mrem/pCi).
b. Committed dose to organ from one year of intake based on BZ data (rem).

Table 22b. Summary of Table 22a.

Organ	Emission Type	Largest Radionuclide	Largest Dose (rem)
Lung	Alpha	Th-227	2.14E-02
Bone Surface	Alpha	Gd-148	2.99E-01
Liver	Alpha	Gd-148	5.68E-02
Adrenals	Alpha	Po-208	6.29E-05

Table 23a. Gross Beta Method.

Radionuclide	Solubility Type	Intake Rate (dpm/day)	Lung Dose (rem)	Solubility Type	Intake Rate (dpm/day)	Bone Surface Dose (rem)	Solubility Type	Intake Rate (dpm/day)	Liver Dose (rem)	Solubility Type	Intake Rate (dpm/day)	Adrenals Dose (rem)
Ag-110M	S	1124.29	7.86E-02	S	1124.29	4.31E-03	S	1124.29	1.44E-02	S	1124.29	1.01E-02
Ca-45	M	15.46	4.51E-04	M	15.46	1.00E-04	M	15.46	6.43E-07	M	15.46	6.43E-07
Cd-113	S	1018.80	8.41E-02	S	1018.80	6.92E-04	S	1018.80	1.91E-02	S	1018.80	6.92E-04
Ce-144	S	89598.00	3.55E+01	S	89598.00	1.89E-01	S	89598.00	5.41E-01	S	89598.00	2.19E-02
Cl-36	M	2.14	1.51E-04	M	2.14	1.52E-06	M	2.14	1.52E-06	M	2.14	1.52E-06
Co-60	S	48.16	7.55E-03	S	48.16	3.70E-04	S	48.16	7.72E-04	S	48.16	8.27E-04
Cs-134	F	2.94	4.57E-05	F	2.94	5.16E-05	F	2.94	5.11E-05	F	2.94	5.39E-05
Cs-137	F	2.62	2.94E-05	F	2.62	3.17E-05	F	2.62	3.13E-05	F	2.62	3.24E-05
Eu-152	M	351.53	2.06E-02	M	351.53	3.85E-02	M	351.53	5.51E-02	M	351.53	9.88E-03
Eu-154	M	100.05	1.08E-02	M	100.05	2.67E-02	M	100.05	2.19E-02	M	100.05	2.80E-03
Ho-166M	M	107.00	9.51E-03	M	107.00	2.97E-02	M	107.00	2.52E-02	M	107.00	6.35E-03
Nb-94	S	164.63	3.39E-02	S	164.63	1.08E-03	S	164.63	2.22E-03	S	164.63	2.39E-03
Ni-63	F	4.30	2.76E-06	F	4.30	2.75E-06	F	4.30	2.75E-06	F	4.30	2.75E-06
Os-194	S	303.76	1.61E-01	S	303.76	1.88E-04	S	303.76	1.38E-03	S	303.76	3.07E-04
Pm-147	S	4034.90	1.80E-01	S	4034.90	1.33E-02	S	4034.90	3.56E-03	S	4034.90	2.33E-07
Ru-106	S	63.30	2.99E-02	S	63.30	1.01E-04	S	63.30	1.21E-04	S	63.30	1.29E-04
Sb-125	M	21.04	8.32E-04	M	21.04	1.90E-04	M	21.04	2.81E-05	M	21.04	2.31E-05
Sr-90	F	4.28	4.96E-06	F	4.28	1.51E-03	F	4.28	4.77E-06	F	4.28	4.77E-06
Ta-182	S	2168.20	2.08E-01	S	2168.20	2.40E-03	S	2168.20	3.89E-03	S	2168.20	4.37E-03
Tc-99	M	5.04	2.18E-04	M	5.04	2.82E-07	F	4.53	3.76E-07	M	5.04	2.82E-07
Tl-204	F	4.31	2.73E-06	F	4.31	2.56E-06	F	4.31	2.55E-06	F	4.31	2.55E-06
Tm-170	M	180.16	1.09E-02	M	180.16	2.10E-03	M	180.16	2.84E-04	M	180.16	2.36E-05
Tm-171	M	115.70	6.52E-04	M	115.70	4.35E-03	M	115.70	7.22E-05	M	115.70	6.02E-06
Tb-158	M	509.14	2.75E-02	M	509.14	1.01E-01	M	509.14	4.40E-02	M	509.14	9.37E-03
Ra-228	M	264.82	2.94E+00	M	264.82	1.79E+00	M	264.82	3.95E-02	M	264.82	1.94E-02
Pb-210	F	6.50	2.85E-03	F	6.50	1.86E-01	F	6.50	7.87E-02	F	6.50	2.85E-03
Pu-241	S	5559.11	5.93E-01	S	5559.11	3.64E-01	S	5559.11	7.20E-02	S	5559.11	6.82E-04

NOTE: Sample method MDA = 2 dpm/sample used to determine intake rate and missed dose based on urinalysis (rem).

Table 23b. Gross Beta Method (Continued).

Radionuclide	Intake Rate Based on BZ Data (dpm/day)	Lung Dose (rem)	Bioassay or BZ Data	Bone Surface Dose (rem)	Bioassay or BZ Data	Liver Dose (rem)	Bioassay or BZ Data	Adrenals Dose (rem)	Bioassay or BZ Data
Ag-110M	62.67	4.38E-03	BZ	2.40E-04	BZ	8.03E-04	BZ	5.63E-04	BZ
Ca-45	62.10	4.51E-04	Bio	1.00E-04	Bio	6.43E-07	Bio	6.43E-07	Bio
Cd-113	61.31	5.06E-03	BZ	4.16E-05	BZ	1.15E-03	BZ	4.16E-05	BZ
Ce-144	61.76	2.44E-02	BZ	1.30E-04	BZ	3.73E-04	BZ	1.51E-05	BZ
Cl-36	62.50	1.51E-04	Bio	1.52E-06	Bio	1.52E-06	Bio	1.52E-06	Bio
Co-60	61.37	7.55E-03	Bio	3.70E-04	Bio	7.72E-04	Bio	8.27E-04	Bio
Cs-134	61.48	4.57E-05	Bio	5.16E-05	Bio	5.11E-05	Bio	5.39E-05	Bio
Cs-137	61.32	2.94E-05	Bio	3.17E-05	Bio	3.13E-05	Bio	3.24E-05	Bio
Eu-152	219.84	1.29E-02	BZ	2.41E-02	BZ	3.45E-02	BZ	6.18E-03	BZ
Eu-154	61.36	6.64E-03	BZ	1.64E-02	BZ	1.34E-02	BZ	1.72E-03	BZ
Ho-166M	61.31	5.45E-03	BZ	1.70E-02	BZ	1.44E-02	BZ	3.64E-03	BZ
Nb-94	61.31	1.26E-02	BZ	4.02E-04	BZ	8.28E-04	BZ	8.92E-04	BZ
Ni-63	61.31	2.76E-06	Bio	2.75E-06	Bio	2.75E-06	Bio	2.75E-06	Bio
Os-194	61.37	3.26E-02	BZ	3.80E-05	BZ	2.80E-04	BZ	6.20E-05	BZ
Pm-147	61.44	2.74E-03	BZ	2.03E-04	BZ	5.42E-05	BZ	3.55E-09	BZ
Ru-106	61.66	2.91E-02	BZ	9.86E-05	BZ	1.18E-04	BZ	1.26E-04	BZ
Sb-125	61.43	8.32E-04	Bio	1.90E-04	Bio	2.81E-05	Bio	2.31E-05	Bio
Sr-90	61.32	4.96E-06	Bio	1.51E-03	Bio	4.77E-06	Bio	4.77E-06	Bio
Ta-182	62.43	6.00E-03	BZ	6.90E-05	BZ	1.12E-04	BZ	1.26E-04	BZ
Tc-99	61.31	2.18E-04	Bio	2.82E-07	Bio	3.76E-07	Bio	2.82E-07	Bio
Tl-204	63.23	2.73E-06	Bio	2.56E-06	Bio	2.55E-06	Bio	2.55E-06	Bio
Tm-170	62.39	3.76E-03	BZ	7.28E-04	BZ	9.84E-05	BZ	8.18E-06	BZ
Tm-171	61.49	3.47E-04	BZ	2.31E-03	BZ	3.84E-05	BZ	3.20E-06	BZ
Tb-158	369.34	1.99E-02	BZ	7.32E-02	BZ	3.19E-02	BZ	6.80E-03	BZ
Ra-228	61.37	6.80E-01	BZ	4.15E-01	BZ	9.15E-03	BZ	4.50E-03	BZ
Pb-210	61.32	2.85E-03	Bio	1.86E-01	Bio	7.87E-02	Bio	2.85E-03	Bio
Pu-241	62.67	4.38E-03	BZ	2.40E-04	BZ	8.03E-04	BZ	5.63E-04	BZ
Largest Dose	**Not applicable**	**6.80E-01**	**BZ**	**4.15E-01**	**BZ**	**7.87E-02**	**Bio**	**6.80E-03**	**BZ**
Largest Radionuclide	**Not applicable**	**Ra-228**	**Not applicable**	**Ra-228**	**Not applicable**	**Pb-210**	**Not applicable**	**Tb-158**	**Not applicable**

NOTE: Limiting dose based on comparison of the intake rate based on bioassay in Table 23a to the intake rate based on BZ data (rem).

Table 24a. Gross Gamma Method.

Radionuclide	Solubility Type	Intake Rate (dpm/day)	Lung Dose (rem)	Solubility Type	Intake Rate (dpm/day)	Bone Surface Dose (rem)	Solubility Type	Intake Rate (dpm/day)	Liver Dose (rem)	Solubility Type	Intake Rate (dpm/day)	Adrenals Dose (rem)
Ag-108M	S	14860.83	1.89E+00	S	14860.83	1.04E-01	S	14860.83	3.07E-01	S	14860.83	2.48E-01
Al-26	M	1493.61	1.65E-01	M	1493.61	1.91E-02	M	1493.61	1.18E-02	M	1493.61	1.40E-02
Au-195	S	8916.33	1.35E-01	S	8916.33	2.61E-03	S	8916.33	2.01E-03	S	8916.33	2.13E-03
Ba-133	F	1269.65	1.40E-03	F	1269.65	1.29E-02	F	1269.65	1.13E-03	F	1269.65	2.47E-03
Bi-207	M	677.52	2.16E-02	M	677.52	8.81E-04	M	677.52	1.57E-03	M	677.52	1.84E-03
Cd-109	S	2900720.02	1.71E+02	S	2900720.02	1.27E+00	S	2900720.02	1.85E+01	S	2900720.02	1.49E+00
Co-57	S	2578.60	1.74E-02	S	2578.60	9.56E-04	S	2578.60	1.12E-03	S	2578.60	1.17E-03
Co-60	S	1204.55	1.89E-01	S	1204.55	9.25E-03	S	1204.55	1.93E-02	S	1204.55	2.07E-02
Cs-134	F	65.95	1.02E-03	F	65.95	1.16E-03	F	65.95	1.15E-03	F	65.95	1.21E-03
Eu-152	M	3113.59	1.82E-01	M	3113.59	3.41E-01	M	3113.59	4.88E-01	M	3113.59	8.75E-02
Eu-154	M	3062.77	3.32E-01	M	3062.77	8.17E-01	M	3062.77	6.70E-01	M	3062.77	8.58E-02
Gd-153	M	12307.76	1.59E-01	M	12307.76	2.36E-01	M	12307.76	6.56E-02	M	12307.76	8.42E-03
Hf-172	M	6623.73	4.94E-01	F	1356.15	1.95E+00	M	6623.73	4.04E-02	M	6623.73	8.16E-02
Mn-54	M	1154.03	6.54E-03	M	1154.03	1.70E-03	M	1154.03	2.98E-03	M	1154.03	2.07E-03
Na-22	F	106.35	2.55E-04	F	106.35	6.06E-04	F	106.35	2.59E-04	F	106.35	3.22E-04
Pm-143	S	1006194.81	6.72E+00	S	1006194.81	6.88E-01	S	1006194.81	1.10E+00	S	1006194.81	1.02E+00
Pm-144	S	129257.06	4.36E+00	S	129257.06	3.95E-01	S	129257.06	8.38E-01	S	129257.06	8.05E-01
Pm-145	S	5326963.91	5.28E+01	S	5326963.91	1.13E+01	S	5326963.91	5.88E+00	S	5326963.91	2.17E+00
Pt-193	F	1676.92	2.47E-05	F	1676.92	2.63E-05	F	1676.92	1.49E-04	F	1676.92	1.85E-04
Rh-101	S	3199.58	1.16E-01	S	3199.58	4.58E-03	S	3199.58	5.90E-03	S	3199.58	6.70E-03
Se-75	M	181.95	1.32E-03	M	181.95	3.90E-04	M	181.95	1.61E-03	M	181.95	6.83E-04
Sm-145	M	84808.59	4.39E-01	M	84808.59	1.82E+00	M	84808.59	7.78E-01	M	84808.59	6.88E-02
Sn-113	M	134610.81	3.07E+00	M	134610.81	1.74E-01	M	134610.81	4.75E-02	M	134610.81	5.74E-02
Ti-44	S	11595.34	6.41E+00	S	11595.34	1.50E-01	S	11595.34	2.36E-01	S	11595.34	2.72E-01
Y-88	S	226248.06	4.16E+00	S	226248.06	4.01E-01	S	226248.06	7.61E-01	S	226248.06	8.32E-01
Zn-65	S	4332.45	5.12E-02	S	4332.45	2.20E-02	S	4332.45	1.85E-02	S	4332.45	2.19E-02
Ag-110M	S	17263.39	1.21E+00	S	17263.39	6.62E-02	S	17263.39	2.21E-01	S	17263.39	1.55E-01
Re-184M	M	303.12	1.83E-02	M	303.12	2.31E-04	M	303.12	3.13E-04	M	303.12	3.44E-04
Tm-170	M	276050.94	1.66E+01	M	276050.94	3.22E+00	M	276050.94	4.35E-01	M	276050.94	3.62E-02
Te-123M	M	613.71	2.48E-02	M	613.71	2.36E-02	M	613.71	1.91E-04	M	613.71	2.92E-04
W-181	F	27057.50	2.73E-04	F	27057.50	3.17E-03	F	27057.50	1.04E-03	F	27057.50	4.92E-04

Radionuclide	Solubility Type	Intake Rate (dpm/day)	Lung Dose (rem)	Solubility Type	Intake Rate (dpm/day)	Bone Surface Dose (rem)	Solubility Type	Intake Rate (dpm/day)	Liver Dose (rem)	Solubility Type	Intake Rate (dpm/day)	Adrenals Dose (rem)
Tb-158	M	4067.23	2.20E-01	M	4067.23	8.06E-01	M	4067.23	3.52E-01	M	4067.23	7.49E-02
Gd-151	M	50278.30	3.15E-01	M	50278.30	3.42E-01	M	50278.30	9.00E-02	M	50278.30	1.09E-02

NOTE. Sample method MDA = 100 dpm/sample used to determine intake rate and missed dose based on urinalysis (rem).

Table 24b. Gross Gamma Method (Continued).

Radionuclide	Intake Rate Based on BZ Data (dpm/day)	Lung Dose (rem)	Bioassay or BZ Data	Bone Surface Dose (rem)	Bioassay or BZ Data	Liver Dose (rem)	Bioassay or BZ Data	Adrenals Dose (rem)	Bioassay or BZ Data
Ag-108M	21.99	2.80E-03	BZ	1.54E-04	BZ	4.55E-04	BZ	3.67E-04	BZ
Al-26	59.81	6.62E-03	BZ	7.66E-04	BZ	4.74E-04	BZ	5.63E-04	BZ
Au-195	496.47	7.53E-03	BZ	1.45E-04	BZ	1.12E-04	BZ	1.19E-04	BZ
Ba-133	45.07	4.96E-05	BZ	4.56E-04	BZ	4.01E-05	BZ	8.78E-05	BZ
Bi-207	34.08	1.09E-03	BZ	4.43E-05	BZ	7.88E-05	BZ	9.28E-05	BZ
Cd-109	1705.45	1.00E-01	BZ	7.45E-04	BZ	1.09E-02	BZ	8.74E-04	BZ
Co-57	58.50	3.94E-04	BZ	2.17E-05	BZ	2.55E-05	BZ	2.65E-05	BZ
Co-60	30.70	4.81E-03	BZ	2.36E-04	BZ	4.92E-04	BZ	5.27E-04	BZ
Cs-134	27.58	4.28E-04	BZ	4.84E-04	BZ	4.79E-04	BZ	5.06E-04	BZ
Eu-152	38.94	2.28E-03	BZ	4.27E-03	BZ	6.11E-03	BZ	1.09E-03	BZ
Eu-154	37.57	4.07E-03	BZ	1.00E-02	BZ	8.22E-03	BZ	1.05E-03	BZ
Gd-153	115.69	1.50E-03	BZ	2.22E-03	BZ	6.16E-04	BZ	7.92E-05	BZ
Hf-172	122.53	9.14E-03	BZ	1.77E-01	BZ	7.47E-04	BZ	1.51E-03	BZ
Mn-54	61.73	3.50E-04	BZ	9.08E-05	BZ	1.59E-04	BZ	1.11E-04	BZ
Na-22	61.48	1.47E-04	BZ	3.50E-04	BZ	1.50E-04	BZ	1.86E-04	BZ
Pm-143	160.50	1.07E-03	BZ	1.10E-04	BZ	1.75E-04	BZ	1.63E-04	BZ
Pm-144	25.24	8.52E-04	BZ	7.71E-05	BZ	1.64E-04	BZ	1.57E-04	BZ
Pm-145	2170.14	2.15E-02	BZ	4.61E-03	BZ	2.40E-03	BZ	8.82E-04	BZ
Pt-193	290.59	4.28E-06	BZ	4.56E-06	BZ	2.58E-05	BZ	3.20E-05	BZ
Rh-101	43.13	1.56E-03	BZ	6.18E-05	BZ	7.95E-05	BZ	9.03E-05	BZ
Se-75	34.33	2.49E-04	BZ	7.36E-05	BZ	3.05E-04	BZ	1.29E-04	BZ
Sm-145	481.91	2.49E-03	BZ	1.04E-02	BZ	4.42E-03	BZ	3.91E-04	BZ
Sn-113	3374.38	7.69E-02	BZ	4.36E-03	BZ	1.19E-03	BZ	1.44E-03	BZ
Ti-44	33.60	1.86E-02	BZ	4.33E-04	BZ	6.84E-04	BZ	7.87E-04	BZ
Y-88	32.31	5.94E-04	BZ	5.72E-05	BZ	1.09E-04	BZ	1.19E-04	BZ
Zn-65	121.82	1.44E-03	BZ	6.19E-04	BZ	5.20E-04	BZ	6.15E-04	BZ
Ag-110M	19.25	1.35E-03	BZ	7.38E-05	BZ	2.47E-04	BZ	1.73E-04	BZ
Re-184M	70.24	4.23E-03	BZ	5.36E-05	BZ	7.25E-05	BZ	7.97E-05	BZ
Tm-170	1911.87	1.15E-01	BZ	2.23E-02	BZ	3.01E-03	BZ	2.51E-04	BZ
Te-123M	74.04	2.99E-03	BZ	2.85E-03	BZ	2.30E-05	BZ	3.53E-05	BZ
W-181	5603.86	5.65E-05	BZ	6.57E-04	BZ	2.16E-04	BZ	1.02E-04	BZ
Tb-158	59.01	3.19E-03	BZ	1.17E-02	BZ	5.10E-03	BZ	1.09E-03	BZ

Radionuclide	Intake Rate Based on BZ Data (dpm/day)	Lung Dose (rem)	Bioassay or BZ Data	Bone Surface Dose (rem)	Bioassay or BZ Data	Liver Dose (rem)	Bioassay or BZ Data	Adrenals Dose (rem)	Bioassay or BZ Data
Gd-151	388.55	2.43E-03	BZ	2.65E-03	BZ	6.96E-04	BZ	8.45E-05	BZ
Largest Dose (rem)	**Not applicable**	**1.15E-01**	**BZ**	**1.77E-01**	**BZ**	**1.09E-02**	**BZ**	**1.51E-03**	**BZ**
Largest Radionuclide	**Not applicable**	**Tm-170**	**Not applicable**	**Hf-172**	**Not applicable**	**Cd-109**	**Not applicable**	**Hf-172**	**Not applicable**

NOTE: Limiting dose based on comparison of the intake rate based on bioassay in Table 24a to the intake rate based on BZ data (rem).

Table 25a. Gross Beta and Gross Gamma Methods.

Radionuclide	Emission Type	Annual BZ Intake Rate (dpm/day)	Lung DCF[a] / Solubility Type	Bone Surface DCF[a] / Solubility Type	Liver DCF[a] / Solubility Type	Adrenals DCF[a] / Solubility Type	Lung Dose (rem)[b]	Bone Surface Dose (rem)[b]	Liver Dose (rem)[b]	Adrenals Dose (rem)[b]
Cu-64	Beta	7.99E+03	2.037E-06, S	4.815E-08, F	1.037E-07, F	4.444E-08, F	2.676E-03	6.326E-05	1.362E-04	5.839E-05
Nb-90	Beta	1.87E+03	5.185E-06, S	4.444E-07, M	4.815E-07, M	3.556E-07, M	1.594E-03	1.366E-04	1.480E-04	1.093E-04
Na-24	Beta	1.71E+03	7.037E-07, F	1.111E-06, F	5.556E-07, F	6.296E-07, F	1.975E-04	3.118E-04	1.559E-04	1.767E-04
Zr-97	Beta	1.17E+03	1.037E-05, S	1.630E-06, F	3.259E-07, F	3.519E-07, F	2.002E-03	3.146E-04	6.292E-05	6.793E-05
Pt-197	Beta	9.37E+02	1.704E-07, F	4.815E-08, F	1.741E-07, F	2.185E-07, F	2.624E-05	7.416E-06	2.681E-05	3.366E-05
Ho-166	Beta	3.95E+02	8.519E-06, M	1.444E-07, M	3.111E-07, M	8.519E-09, M	5.526E-04	9.370E-06	2.018E-05	5.526E-07
Os-193	Beta	3.23E+02	8.519E-06, S	1.111E-07, F	9.259E-07, F	1.074E-07, F	4.530E-04	5.909E-06	4.924E-05	5.712E-06
Ce-143	Beta	2.78E+02	1.407E-05, S	2.185E-07, M	6.667E-07, M	5.926E-08, M	6.435E-04	9.991E-06	3.048E-05	2.709E-06
Br-82	Beta	2.52E+02	7.778E-06, M	9.630E-07, F	8.519E-07, M	9.259E-07, M	3.222E-04	3.990E-05	3.529E-05	3.836E-05
Sc-48	Beta	1.92E+02	1.148E-05, S	5.556E-07, S	6.296E-07, S	5.556E-07, S	3.625E-04	1.754E-05	1.988E-05	1.754E-05
Sm-153	Beta	1.78E+02	1.148E-05, M	2.593E-07, M	2.815E-07, M	1.593E-08, M	3.369E-04	7.607E-06	8.259E-06	4.673E-07
Cd-115	Beta	1.56E+02	1.926E-05, S	2.926E-07, F	4.074E-06, F	4.815E-07, F	4.937E-04	7.500E-06	1.044E-04	1.234E-05
Y-90	Beta	1.34E+02	1.889E-05, S	4.074E-07, M	4.074E-07, M	1.481E-08, M	4.152E-04	8.955E-06	8.955E-06	3.256E-07
As-71	Beta	1.32E+02	5.926E-06, M	2.185E-07, M	3.519E-07, M	2.185E-07, M	1.290E-04	4.757E-06	7.660E-06	4.757E-06
Re-186	Beta	1.15E+02	1.852E-05, M	2.111E-07, F	2.667E-07, F	2.037E-07, F	3.499E-04	3.989E-06	5.039E-06	3.849E-06
Np-239	Beta	1.48E+02	1.889E-05, M	1.630E-06, M	1.185E-07, M	4.444E-08, M	4.603E-04	3.971E-05	2.888E-06	1.083E-06
Au-198	Beta	1.33E+02	1.519E-05, S	2.778E-07, F	2.519E-07, F	2.519E-07, F	3.310E-04	6.054E-06	5.489E-06	5.489E-06
Sb-122	Beta	1.36E+02	1.444E-05, M	1.778E-06, F	8.148E-07, F	3.111E-07, F	3.222E-04	3.966E-05	1.818E-05	6.940E-06
Au-199	Beta	1.19E+02	1.778E-05, S	1.222E-07, F	9.630E-08, F	9.630E-08, F	3.475E-04	2.389E-06	1.882E-06	1.882E-06
Yb-175	Beta	1.01E+02	1.593E-05, S	1.185E-06, M	3.296E-08, M	1.407E-08, M	2.637E-04	1.962E-05	5.457E-07	2.330E-07
Lu-177	Beta	8.36E+01	2.704E-05, S	2.741E-06, M	4.074E-08, M	1.778E-08, M	3.715E-04	3.766E-05	5.598E-07	2.443E-07
Tb-161	Beta	8.28E+01	2.593E-05, M	3.185E-06, M	4.444E-07, M	2.185E-08, M	3.531E-04	4.338E-05	6.053E-06	2.976E-07
Ag-111	Beta	8.10E+01	3.407E-05, S	4.074E-07, F	1.296E-05, F	4.074E-07, F	4.540E-04	5.429E-06	1.727E-04	5.429E-06
P-32	Beta	7.09E+01	5.926E-05, M	1.667E-05, F	1.370E-06, F	1.370E-06, F	6.909E-04	1.943E-04	1.598E-05	1.598E-05
Os-191	Beta	7.02E+01	3.704E-05, S	5.556E-07, F	4.444E-06, F	5.185E-07, F	4.273E-04	6.409E-06	5.128E-05	5.982E-06
Rb-86	Beta	6.85E+01	4.074E-06, F	1.481E-05, F	4.074E-06, F	4.074E-06, F	4.591E-05	1.670E-04	4.591E-05	4.591E-05
Th-234	Beta	6.68E+01	1.370E-04, S	1.148E-05, M	1.481E-06, M	1.963E-07, M	1.506E-03	1.262E-04	1.628E-05	2.157E-06
P-33	Beta	6.65E+01	3.556E-05, M	2.778E-06, F	1.963E-07, F	1.963E-07, F	3.890E-04	3.039E-05	2.147E-06	2.147E-06
Pa-233	Beta	6.62E+01	8.519E-05, S	1.185E-05, M	7.407E-07, M	2.667E-07, M	9.274E-04	1.290E-04	8.064E-06	2.903E-06
Ce-141	Beta	6.54E+01	8.889E-05, S	9.630E-06, M	4.444E-06, M	2.370E-07, M	9.552E-04	1.035E-04	4.776E-05	2.547E-06
Nb-95	Beta	6.50E+01	3.000E-05, S	2.667E-06, M	1.815E-06, M	1.222E-06, M	3.208E-04	2.852E-05	1.941E-05	1.307E-05
Ru-103	Beta	6.46E+01	5.556E-05, S	1.593E-06, F	1.556E-06, F	1.593E-06, F	5.904E-04	1.693E-05	1.653E-05	1.693E-05
Hf-181	Beta	6.44E+01	1.037E-04, M	1.778E-04, F	1.333E-06, F	2.667E-06, F	1.098E-03	1.882E-03	1.412E-05	2.823E-05
Fe-59	Beta	6.42E+01	6.296E-05, M	1.111E-05, F	3.259E-05, F	1.111E-05, F	6.650E-04	1.174E-04	3.442E-04	1.174E-04
Hg-203	Beta	6.41E+01	5.185E-05, M	2.407E-06, F	1.963E-06, F	2.333E-06, F	5.465E-04	2.537E-05	2.069E-05	2.459E-05
Sr-89	Beta	6.39E+01	1.407E-04, S	2.519E-05, F	8.148E-07, F	8.148E-07, F	1.478E-03	2.645E-04	8.559E-06	8.559E-06
Y-91	Beta	6.35E+01	1.556E-04, S	8.889E-06, M	8.889E-06, M	1.852E-07, M	1.625E-03	9.284E-05	9.284E-05	1.934E-06
Sb-124	Beta	6.35E+01	1.037E-04, M	2.926E-05, F	5.556E-06, F	3.296E-06, F	1.082E-03	3.053E-04	5.797E-05	3.439E-05

Radionuclide	Emission Type	Annual BZ Intake Rate (dpm/day)	Lung DCF[a] / Solubility Type	Bone Surface DCF[a] / Solubility Type	Liver DCF[a] / Solubility Type	Adrenals DCF[a] / Solubility Type	Lung Dose (rem)[b]	Bone Surface Dose (rem)[b]	Liver Dose (rem)[b]	Adrenals Dose (rem)[b]
Zr-95	Beta	6.33E+01	1.074E-04, S	2.296E-04, F	3.704E-06, F	8.889E-06, F	1.118E-03	2.391E-03	3.857E-05	9.256E-05
W-188	Beta	6.32E+01	1.148E-07, F	4.074E-06, F	1.926E-06, F	5.926E-08, F	1.193E-06	4.232E-05	2.000E-05	6.155E-07
Tb-160	Beta	6.31E+01	1.222E-04, M	4.074E-05, M	1.519E-05, M	3.704E-06, M	1.268E-03	4.226E-04	1.575E-04	3.842E-05
Ir-192	Beta	6.63E+01	1.259E-04, S	5.185E-06, F	3.704E-05, F	8.519E-06, F	1.372E-03	5.651E-05	4.036E-04	9.283E-05
W-185	Beta	6.30E+01	8.889E-08, F	6.296E-07, F	2.963E-07, F	1.148E-08, F	9.212E-07	6.525E-06	3.071E-06	1.190E-07
Sc-46	Beta	6.28E+01	1.111E-04, S	2.444E-06, S	4.815E-06, S	5.185E-06, S	1.148E-03	2.526E-05	4.975E-05	5.358E-05
S-35	Beta	1.49E+01	3.185E-05, M	1.593E-07, F	1.593E-07, F	1.593E-07, F	7.828E-05	3.914E-07	3.914E-07	3.914E-07
Y-86	Gamma	5.66E+02	2.259E-06, S	3.704E-07, M	4.074E-07, M	3.074E-07, M	2.104E-04	3.449E-05	3.794E-05	2.863E-05
Br-76	Gamma	7.72E+02	4.074E-06, M	6.296E-07, F	5.556E-07, F	5.926E-07, F	5.168E-04	7.987E-05	7.047E-05	7.517E-05
Zr-86	Gamma	1.05E+03	2.481E-06, S	1.185E-06, F	3.519E-07, F	4.444E-07, F	4.271E-04	2.040E-04	6.055E-05	7.649E-05
Co-55	Gamma	8.04E+02	4.444E-06, S	2.407E-07, M	2.741E-07, M	2.148E-07, M	5.872E-04	3.181E-05	3.621E-05	2.838E-05
Rh-100	Gamma	2.91E+02	1.148E-06, S	4.444E-07, F	3.704E-07, F	3.593E-07, F	5.485E-05	2.123E-05	1.770E-05	1.716E-05
Ni-57	Gamma	2.16E+02	4.074E-06, M	3.481E-07, F	3.185E-07, M	2.778E-07, M	1.444E-04	1.234E-05	1.129E-05	9.843E-06
Sb-119	Gamma	1.39E+03	1.185E-07, M	5.556E-07, F	3.148E-08, F	1.111E-08, F	2.714E-05	1.272E-04	7.208E-06	2.544E-06
Au-194	Gamma	1.62E+02	1.593E-06, S	2.852E-07, F	2.111E-07, F	2.074E-07, F	4.246E-05	7.604E-06	5.629E-06	5.530E-06
Am-240	Gamma	1.63E+02	3.704E-06, M	4.074E-06, M	7.037E-07, M	2.333E-07, M	9.910E-05	1.090E-04	1.883E-05	6.243E-06
Br-77	Gamma	1.95E+02	6.296E-07, M	1.815E-07, F	1.593E-07, M	1.741E-07, M	2.021E-05	5.824E-06	5.111E-06	5.587E-06
Ga-67	Gamma	1.34E+02	4.815E-06, M	1.296E-06, F	1.963E-07, F	9.259E-08, F	1.063E-04	2.861E-05	4.333E-06	2.044E-06
Re-186	Gamma	1.01E+03	1.852E-05, M	2.111E-07, F	2.667E-07, F	2.037E-07, F	3.084E-03	3.515E-05	4.440E-05	3.392E-05
Ba-128	Gamma	7.63E+02	2.778E-07, F	2.259E-06, F	2.481E-07, F	2.778E-07, F	3.484E-05	2.833E-04	3.112E-05	3.484E-05
In-111	Gamma	6.93E+01	2.815E-06, M	5.185E-07, F	8.148E-07, F	3.333E-07, F	3.206E-05	5.906E-06	9.280E-06	3.797E-06
Tl-201	Gamma	9.16E+02	1.333E-07, F	2.000E-07, F	1.111E-07, F	1.185E-07, F	2.008E-05	3.012E-05	1.673E-05	1.785E-05
Pd-100	Gamma	8.51E+01	8.519E-06, S	1.185E-06, F	8.148E-06, F	2.185E-06, F	1.192E-04	1.659E-05	1.140E-04	3.058E-05
Mn-52	Gamma	2.96E+01	1.148E-05, M	3.481E-06, F	7.778E-06, F	3.222E-06, F	5.595E-05	1.697E-05	3.790E-05	1.570E-05
Ag-106m	Gamma	2.09E+01	6.296E-06, S	2.259E-06, F	1.889E-05, F	5.185E-06, F	2.162E-05	7.759E-06	6.487E-05	1.781E-05
Cs-131	Gamma	9.30E+01	1.148E-07, F	2.407E-07, F	1.037E-07, F	1.074E-07, F	1.756E-06	3.682E-06	1.586E-06	1.643E-06
Ba-131	Gamma	5.82E+01	1.852E-07, F	1.963E-06, F	1.556E-07, F	2.333E-07, F	1.771E-06	1.877E-05	1.488E-06	2.232E-06
Rh-99	Gamma	4.49E+01	1.444E-05, S	1.037E-06, F	8.519E-07, F	8.889E-07, F	1.067E-04	7.659E-06	6.291E-06	6.565E-06
V-48	Gamma	3.34E+01	3.333E-05, M	5.926E-06, F	1.815E-06, M	2.630E-06, F	1.830E-04	3.253E-05	9.963E-06	1.444E-05
Te-121	Gamma	6.94E+01	2.667E-06, M	2.852E-06, F	5.556E-07, M	9.259E-07, F	3.045E-05	3.256E-05	6.343E-06	1.057E-05
Sr-82	Gamma	1.12E+02	1.519E-04, S	3.593E-05, F	2.778E-06, F	3.593E-06, F	2.794E-03	6.611E-04	5.111E-05	6.611E-05
Cr-51	Gamma	6.72E+02	3.259E-07, S	8.519E-08, F	5.185E-08, F	5.556E-08, F	3.603E-05	9.416E-06	5.731E-06	6.141E-06
Yb-169	Gamma	4.49E+01	6.296E-05, S	1.222E-05, M	6.667E-07, M	5.185E-07, M	4.651E-04	9.029E-05	4.925E-06	3.831E-06
Ag-105	Gamma	4.87E+01	9.630E-06, S	1.556E-06, F	1.556E-05, F	3.296E-06, F	7.713E-05	1.246E-05	1.246E-04	2.640E-05
Be-7	Gamma	6.17E+02	4.444E-07, S	8.148E-08, M	8.519E-08, S	1.000E-07, S	4.505E-05	8.259E-06	8.635E-06	1.014E-05
Sr-85	Gamma	6.46E+01	7.778E-06, S	3.444E-06, F	1.000E-06, S	1.778E-06, F	8.260E-05	3.658E-05	1.062E-05	1.888E-05
Hf-175	Gamma	6.73E+01	1.667E-05, M	3.481E-05, F	1.148E-06, F	2.630E-06, F	1.843E-04	3.851E-04	1.270E-05	2.909E-05
Re-183	Gamma	1.18E+02	5.402E-08, M	6.327E-10, M	4.958E-10, M	4.847E-10, M	1.047E-06	1.227E-08	9.612E-09	9.397E-09
Co-58	Gamma	6.28E+01	2.889E-05, S	1.185E-06, M	2.259E-06, M	2.370E-06, S	2.981E-04	1.223E-05	2.331E-05	2.446E-05
Co-56	Gamma	2.52E+01	7.407E-05, S	4.074E-06, M	8.148E-06, M	8.519E-06, S	3.064E-04	1.685E-05	3.371E-05	3.524E-05
Zr-88	Gamma	6.29E+01	3.444E-05, S	5.185E-05, F	8.148E-06, F	2.074E-05, F	3.560E-04	5.359E-04	8.421E-05	2.143E-04
Os-185	Gamma	6.24E+01	1.704E-05, S	4.074E-06, F	1.889E-05, F	7.037E-06, F	1.747E-04	4.178E-05	1.937E-04	7.216E-05

Radionuclide	Emission Type	Annual BZ Intake Rate (dpm/day)	Lung DCF[a] / Solubility Type	Bone Surface DCF[a] / Solubility Type	Liver DCF[a] / Solubility Type	Adrenals DCF[a] / Solubility Type	Lung Dose (rem)[b]	Bone Surface Dose (rem)[b]	Liver Dose (rem)[b]	Adrenals Dose (rem)[b]
Fe-55	Gamma	2.16E+02	9.630E-07, F	6.667E-06, F	7.778E-06, F	9.630E-07, F	3.417E-05	2.365E-04	2.760E-04	3.417E-05
Hg-194	Gamma	2.49E+02	5.185E-05, F	8.519E-05, F	6.667E-05, F	8.519E-05, F	2.119E-03	3.481E-03	2.724E-03	3.481E-03
Te-123	Gamma	7.77E+01	4.444E-06, M	7.037E-04, F	1.444E-06, F	5.556E-06, F	5.675E-05	8.986E-03	1.844E-05	7.094E-05

a. ICRP (1995) max organ DCF (mrem/pCi).
b. Committed dose to organ from one year of intake based on BZ data (rem).

Table 25b. Summary of Table 25a.

Organ	Emission Type	Largest Radionuclide	Largest Dose (rem)
Lung	Beta	Cu-64	2.68E-03
Bone Surface	Beta	Zr-95	2.39E-03
Liver	Beta	Ir-192	4.04E-04
Adrenals	Beta	Na-24	1.77E-04
Lung	Gamma	Re-186	3.08E-03
Bone Surface	Gamma	Te-123	8.99E-03
Liver	Gamma	Hg-194	2.72E-03
Adrenals	Gamma	Hg-194	3.48E-03

Table 26a. Unmonitored Worker Alpha Method.

Alpha Radionuclide	Annual BZ Intake Rate (dpm/day)	Lung DCF[a]	Solubility Type	Bone Surface DCF[a]	Solubility Type	Liver DCF[a]	Solubility Type	Adrenals DCF[a]	Solubility Type	Lung Dose (rem)[b]	Bone Surface Dose (rem)[b]	Liver Dose (rem)[b]	Adrenals Dose (rem)[b]
Ac-225	0.60	2.000E-01	S	1.037E-01	F	2.778E-02	F	4.074E-05	F	1.986E-02	1.030E-02	2.758E-03	4.045E-06
Th-227	0.55	2.370E-01	S	1.333E-02	M	7.778E-04	M	4.074E-05	M	2.136E-02	1.202E-03	7.010E-05	3.672E-06
Es-253	0.54	6.296E-02	M	1.037E-02	M	1.000E-03	M	1.222E-06	M	5.619E-03	9.255E-04	8.925E-05	1.091E-07
Sm-146	0.49	1.074E-02	M	7.037E-01	M	1.926E-01	M	8.148E-07	M	8.661E-04	5.675E-02	1.553E-02	6.571E-08
Gd-148	0.49	2.185E-02	M	3.704E+00	F	7.037E-01	F	4.815E-06	F	1.762E-03	2.987E-01	5.675E-02	3.883E-07
Po-208	0.49	6.750E-02	M	4.460E-03	F	1.850E-02	F	7.790E-04	F	5.454E-03	3.604E-04	1.495E-03	6.294E-05
Am-241	0.49	8.889E-02	M	4.074E+00	M	2.481E-01	M	6.667E-03	M	7.168E-03	3.285E-01	2.001E-02	5.376E-04
Am-243	0.49	8.148E-02	M	4.074E+00	M	2.444E-01	M	7.037E-03	M	6.571E-03	3.285E-01	1.971E-02	5.675E-04
Cf-249	0.49	9.630E-02	M	6.296E+00	M	4.444E-01	M	1.222E-04	M	7.765E-03	5.077E-01	3.584E-02	9.856E-06
Cf-250	0.49	1.037E-01	M	2.741E+00	M	2.185E-01	M	2.444E-05	M	8.373E-03	2.213E-01	1.764E-02	1.974E-06
Cf-252	0.51	1.259E-01	M	1.259E+00	M	1.222E-01	M	2.704E-04	M	1.050E-02	1.050E-01	1.019E-02	2.255E-05
Cm-242	0.50	9.259E-02	M	7.037E-02	M	1.852E-02	M	8.889E-05	M	7.564E-03	5.749E-03	1.513E-03	7.262E-06
Cm-243	0.49	1.000E-01	M	2.778E+00	M	2.037E-01	M	4.074E-03	M	8.089E-03	2.247E-01	1.648E-02	3.296E-04
Cm-244	0.49	9.630E-02	M	2.222E+00	M	1.778E-01	M	3.074E-03	M	7.768E-03	1.793E-01	1.434E-02	2.480E-04
Cm-245	0.49	8.519E-02	M	4.074E+00	M	2.481E-01	M	7.037E-03	M	6.869E-03	3.285E-01	2.001E-02	5.675E-04
Cm-246	0.49	8.519E-02	M	4.074E+00	M	2.519E-01	M	7.037E-03	M	6.871E-03	3.286E-01	2.032E-02	5.676E-04
Cm-248	0.53	1.556E-01	M	1.519E+01	M	9.259E-01	M	2.926E-02	M	1.367E-02	1.335E+00	8.139E-02	2.572E-03
Es-254	0.49	1.111E-01	M	3.407E-01	M	3.074E-02	M	1.444E-05	M	9.028E-03	2.769E-02	2.498E-03	1.174E-06
Np-237	0.49	6.296E-02	M	2.481E+00	M	3.704E-02	M	3.185E-03	M	5.077E-03	2.001E-01	2.987E-03	2.569E-04
Pa-231	0.49	2.667E-01	S	1.630E+01	M	1.037E-03	M	4.074E-05	M	2.150E-02	1.314E+00	8.363E-05	3.285E-06
Pu-236	0.49	1.630E-01	S	1.185E+00	M	2.444E-01	M	2.074E-03	M	1.317E-02	9.576E-02	1.975E-02	1.676E-04
Pu-238	0.49	1.889E-01	S	3.370E+00	M	7.037E-01	M	5.926E-03	M	1.523E-02	2.718E-01	5.675E-02	4.779E-04
Pu-239	0.49	1.741E-01	S	3.704E+00	M	7.778E-01	M	6.296E-03	M	1.404E-02	2.987E-01	6.272E-02	5.077E-04
Pu-240	0.49	1.741E-01	S	3.704E+00	M	7.778E-01	M	6.296E-03	M	1.404E-02	2.987E-01	6.272E-02	5.077E-04
Pu-242	0.49	1.593E-01	S	3.556E+00	M	7.407E-01	M	6.296E-03	M	1.284E-02	2.867E-01	5.973E-02	5.077E-04
Pu-244	0.49	1.481E-01	S	3.519E+00	M	7.407E-01	M	6.296E-03	M	1.196E-02	2.841E-01	5.981E-02	5.083E-04
Th-228	0.49	7.778E-01	S	1.037E+00	M	4.444E-02	M	2.852E-03	M	6.291E-02	8.388E-02	3.595E-03	2.307E-04
Th-229	0.49	1.000E+00	S	1.037E+01	M	4.815E-01	M	3.407E-02	M	8.064E-02	8.363E-01	3.883E-02	2.748E-03
Th-230	0.49	1.481E-01	S	5.556E+00	M	7.037E-02	M	5.926E-03	M	1.195E-02	4.480E-01	5.675E-03	4.779E-04
Th-232	0.49	2.852E-01	S	5.556E+00	M	8.519E-02	M	1.630E-02	M	2.300E-02	4.480E-01	6.869E-03	1.314E-03
Ac-227	35.55	8.148E-01	S	7.037E+01	F	1.593E+01	F	5.185E-04	F	4.763E+00	4.113E+02	9.309E+01	3.031E-03
Po-210	0.50	6.296E-02	M	3.481E-03	F	1.444E-02	F	5.926E-04	F	5.154E-03	2.850E-04	1.182E-03	4.851E-05
Ra-226	0.49	6.296E-02	M	3.333E-02	M	4.815E-04	M	1.111E-04	M	5.077E-03	2.688E-03	3.883E-05	8.960E-06
U-232	0.49	5.556E-01	S	3.704E-01	F	3.704E-02	F	8.519E-03	F	4.480E-02	2.987E-02	2.987E-03	6.870E-04
U-233	0.49	1.556E-01	S	4.444E-02	F	5.556E-03	F	1.481E-03	F	1.254E-02	3.584E-03	4.480E-04	1.195E-04
U-234	0.49	1.519E-01	S	4.074E-02	F	5.556E-03	F	1.444E-03	F	1.225E-02	3.285E-03	4.480E-04	1.165E-04
U-235	0.49	1.333E-01	S	4.074E-02	F	5.185E-03	F	1.333E-03	F	1.075E-02	3.285E-03	4.181E-04	1.075E-04

Alpha Radionuclide	Annual BZ Intake Rate (dpm/day)	Lung DCF[a]	Solubility Type	Bone Surface DCF[a]	Solubility Type	Liver DCF[a]	Solubility Type	Adrenals DCF[a]	Solubility Type	Lung Dose (rem)[b]	Bone Surface Dose (rem)[b]	Liver Dose (rem)[b]	Adrenals Dose (rem)[b]
U-236	0.49	1.370E-01	S	4.074E-02	F	5.185E-03	F	1.333E-03	F	1.105E-02	3.285E-03	4.181E-04	1.075E-04
U-238	0.49	1.259E-01	S	3.704E-02	F	4.815E-03	F	1.259E-03	F	1.015E-02	2.987E-03	3.883E-04	1.015E-04

a. ICRP (1995) max organ DCF (mrem/pCi).
b. Committed dose to organ from one year of intake based on BZ data (rem)

Table 26b. Summary of Table 26a.

Organ	Emission Type	Largest Radionuclide	Largest Dose (rem)
Lung	Alpha	Ac-227	4.76E+00
Bone Surface	Alpha	Ac-227	4.11E+02
Liver	Alpha	Ac-227	9.31E+01
Adrenals	Alpha	Ac-227	3.03E-03

Table 27a. Unmonitored Worker Beta and Gamma Methods.

Radionuclide	Emission Type	Annual BZ Intake Rate (dpm/day)	Lung DCF[a] / Solubility Type	Bone Surface DCF[a] / Solubility Type	Liver DCF[a] / Solubility Type	Adrenals DCF[a] / Solubility Type	Lung Dose (rem)[b]	Bone Surface Dose (rem)[b]	Liver Dose (rem)[b]	Adrenals Dose (rem)[b]
Cu-64	Beta	7.99E+03	2.037E-06, S	4.815E-08, F	1.037E-07, F	4.444E-08, F	2.676E-03	6.326E-05	1.362E-04	5.839E-05
Nb-90	Beta	1.87E+03	5.185E-06, S	4.444E-07, M	4.815E-07, M	3.556E-07, M	1.594E-03	1.366E-04	1.480E-04	1.093E-04
Na-24	Beta	1.71E+03	7.037E-07, F	1.111E-06, F	5.556E-07, F	6.296E-07, F	1.975E-04	3.118E-04	1.559E-04	1.767E-04
Zr-97	Beta	1.17E+03	1.037E-05, S	1.630E-06, F	3.259E-07, F	3.519E-07, F	2.002E-03	3.146E-04	6.292E-05	6.793E-05
Pt-197	Beta	9.37E+02	1.704E-07, F	4.815E-08, F	1.741E-07, F	2.185E-07, F	2.624E-05	7.416E-06	2.681E-05	3.366E-05
Ho-166	Beta	3.95E+02	8.519E-06, M	1.444E-07, M	3.111E-07, M	8.519E-09, M	5.526E-04	9.370E-06	2.018E-05	5.526E-07
Os-193	Beta	3.23E+02	8.519E-06, S	1.111E-07, F	9.259E-07, F	1.074E-07, F	4.530E-04	5.909E-06	4.924E-05	5.712E-06
Ce-143	Beta	2.78E+02	1.407E-05, S	2.185E-07, M	6.667E-07, M	5.926E-08, M	6.435E-04	9.991E-06	3.048E-05	2.709E-06
Br-82	Beta	2.52E+02	7.778E-06, M	9.630E-07, F	8.519E-07, M	9.259E-07, M	3.222E-04	3.990E-05	3.529E-05	3.836E-05
Sc-48	Beta	1.92E+02	1.148E-05, S	5.556E-07, S	6.296E-07, S	5.556E-07, S	3.625E-04	1.754E-05	1.988E-05	1.754E-05
Sm-153	Beta	1.78E+02	1.148E-05, M	2.593E-07, M	2.815E-07, M	1.593E-08, M	3.369E-04	7.607E-06	8.259E-06	4.673E-07
Cd-115	Beta	1.56E+02	1.926E-05, S	2.926E-07, F	4.074E-06, F	4.815E-07, F	4.937E-04	7.500E-06	1.044E-04	1.234E-05
Y-90	Beta	1.34E+02	1.889E-05, S	4.074E-07, M	4.074E-07, M	1.481E-08, M	4.152E-04	8.955E-06	8.955E-06	3.256E-07
As-71	Beta	1.32E+02	5.926E-06, M	2.185E-07, M	3.519E-07, M	2.185E-07, M	1.290E-04	4.757E-06	7.660E-06	4.757E-06
Re-186	Beta	1.15E+02	1.852E-05, M	2.111E-07, F	2.667E-07, F	2.037E-07, F	3.499E-04	3.989E-06	5.039E-06	3.849E-06
Np-239	Beta	1.48E+02	1.889E-05, M	1.630E-06, M	1.185E-07, M	4.444E-08, M	4.603E-04	3.971E-05	2.888E-06	1.083E-06
Au-198	Beta	1.33E+02	1.519E-05, S	2.778E-07, F	2.519E-07, F	2.519E-07, F	3.310E-04	6.054E-06	5.489E-06	5.489E-06
Sb-122	Beta	1.36E+02	1.444E-05, M	1.778E-06, F	8.148E-07, F	3.111E-07, F	3.222E-04	3.966E-05	1.818E-05	6.940E-06
Au-199	Beta	1.19E+02	1.778E-05, S	1.222E-07, F	9.630E-08, F	9.630E-08, F	3.475E-04	2.389E-06	1.882E-06	1.882E-06
Yb-175	Beta	1.01E+02	1.593E-05, S	1.185E-06, M	3.296E-08, M	1.407E-08, M	2.637E-04	1.962E-05	5.457E-07	2.330E-07
Lu-177	Beta	8.36E+01	2.704E-05, S	2.741E-06, M	4.074E-08, M	1.778E-08, M	3.715E-04	3.766E-05	5.598E-07	2.443E-07
Tb-161	Beta	8.28E+01	2.593E-05, M	3.185E-06, M	4.444E-07, M	2.185E-08, M	3.531E-04	4.338E-05	6.053E-06	2.976E-07
Ag-111	Beta	8.10E+01	3.407E-05, S	4.074E-07, F	1.296E-05, F	4.074E-07, F	4.540E-04	5.429E-06	1.727E-04	5.429E-06
P-32	Beta	7.09E+01	5.926E-05, M	1.667E-05, F	1.370E-06, F	1.370E-06, F	6.909E-04	1.943E-04	1.598E-05	1.598E-05
Os-191	Beta	7.02E+01	3.704E-05, S	5.556E-07, F	4.444E-06, F	5.185E-07, F	4.273E-04	6.409E-06	5.128E-05	5.982E-06
Rb-86	Beta	6.85E+01	4.074E-06, F	1.481E-05, F	4.074E-06, F	4.074E-06, F	4.591E-05	1.670E-04	4.591E-05	4.591E-05
Th-234	Beta	6.68E+01	1.370E-04, S	1.148E-05, M	1.481E-06, M	1.963E-07, M	1.506E-03	1.262E-04	1.628E-05	2.157E-06
P-33	Beta	6.65E+01	3.556E-05, M	2.778E-06, F	1.963E-07, F	1.963E-07, F	3.890E-04	3.039E-05	2.147E-06	2.147E-06
Pa-233	Beta	6.62E+01	8.519E-05, S	1.185E-05, M	7.407E-07, M	2.667E-07, M	9.274E-04	1.290E-04	8.064E-06	2.903E-06
Ce-141	Beta	6.54E+01	8.889E-05, S	9.630E-06, M	4.444E-06, M	2.370E-07, M	9.552E-04	1.035E-04	4.776E-05	2.547E-06
Nb-95	Beta	6.50E+01	3.000E-05, S	2.667E-06, M	1.815E-06, M	1.222E-06, M	3.208E-04	2.852E-05	1.941E-05	1.307E-05
Ru-103	Beta	6.46E+01	5.556E-05, S	1.593E-06, F	1.556E-06, F	1.593E-06, F	5.904E-04	1.693E-05	1.653E-05	1.693E-05
Hf-181	Beta	6.44E+01	1.037E-04, M	1.778E-04, F	1.333E-06, F	2.667E-06, F	1.098E-03	1.882E-03	1.412E-05	2.823E-05
Fe-59	Beta	6.42E+01	6.296E-05, M	1.111E-05, F	3.259E-05, F	1.111E-05, F	6.650E-04	1.174E-04	3.442E-04	1.174E-04
Hg-203	Beta	6.41E+01	5.185E-05, M	2.407E-06, F	1.963E-06, F	2.333E-06, F	5.465E-04	2.537E-05	2.069E-05	2.459E-05
Sr-89	Beta	6.39E+01	1.407E-04, S	2.519E-05, F	8.148E-07, F	8.148E-07, F	1.478E-03	2.645E-04	8.559E-06	8.559E-06
Y-91	Beta	6.35E+01	1.556E-04, S	8.889E-06, M	8.889E-06, M	1.852E-07, M	1.625E-03	9.284E-05	9.284E-05	1.934E-06
Sb-124	Beta	6.35E+01	1.037E-04, M	2.926E-05, F	5.556E-06, F	3.296E-06, F	1.082E-03	3.053E-04	5.797E-05	3.439E-05
Zr-95	Beta	6.33E+01	1.074E-04, S	2.296E-04, F	3.704E-06, F	8.889E-06, F	1.118E-03	2.391E-03	3.857E-05	9.256E-05
W-188	Beta	6.32E+01	1.148E-07, F	4.074E-06, F	1.926E-06, F	5.926E-08, F	1.193E-06	4.232E-05	2.000E-05	6.155E-07

Radionuclide	Emission Type	Annual BZ Intake Rate (dpm/day)	Lung DCF[a] / Solubility Type	Bone Surface DCF[a] / Solubility Type	Liver DCF[a] / Solubility Type	Adrenals DCF[a] / Solubility Type	Lung Dose (rem)[b]	Bone Surface Dose (rem)[b]	Liver Dose (rem)[b]	Adrenals Dose (rem)[b]
Tb-160	Beta	6.31E+01	1.222E-04, M	4.074E-05, M	1.519E-05, M	3.704E-06, M	1.268E-03	4.226E-04	1.575E-04	3.842E-05
Ir-192	Beta	6.63E+01	1.259E-04, S	5.185E-06, F	3.704E-05, F	8.519E-06, F	1.372E-03	5.651E-05	4.036E-04	9.283E-05
W-185	Beta	6.30E+01	8.889E-08, F	6.296E-07, F	2.963E-07, F	1.148E-08, F	9.212E-07	6.525E-06	3.071E-06	1.190E-07
Sc-46	Beta	6.28E+01	1.111E-04, S	2.444E-06, S	4.815E-06, S	5.185E-06, S	1.148E-03	2.526E-05	4.975E-05	5.358E-05
S-35	Beta	1.49E+01	3.185E-05, M	1.593E-07, F	1.593E-07, F	1.593E-07, F	7.828E-05	3.914E-07	3.914E-07	3.914E-07
Ta-182	Beta	6.24E+01	1.963E-04, S	4.815E-06, M	3.630E-06, S	4.074E-06, S	2.015E-03	4.942E-05	3.725E-05	4.182E-05
Tm-170	Beta	6.24E+01	1.222E-04, M	2.370E-05, M	3.185E-06, M	2.667E-07, M	1.254E-03	2.431E-04	3.267E-05	2.735E-06
Ca-45	Beta	6.21E+01	5.926E-05, M	1.037E-05, M	1.185E-07, M	1.185E-07, M	6.050E-04	1.059E-04	1.210E-06	1.210E-06
Ag-110m	Beta	6.27E+01	1.407E-04, S	1.407E-05, F	1.556E-04, F	3.630E-05, F	1.450E-03	1.450E-04	1.603E-03	3.740E-04
Ce-144	Beta	6.18E+01	8.148E-04, S	1.259E-04, M	3.704E-04, M	5.185E-06, M	8.274E-03	1.279E-03	3.761E-03	5.265E-05
Bk-249	Beta	6.17E+01	4.074E-05, M	1.519E-02, M	1.037E-03, M	2.889E-07, M	4.133E-04	1.541E-01	1.052E-02	2.931E-06
Ru-106	Beta	6.17E+01	9.630E-04, S	3.111E-05, F	3.111E-05, F	3.148E-05, F	9.762E-03	3.154E-04	3.154E-04	3.191E-04
Tm-171	Beta	6.15E+01	1.148E-05, M	8.519E-05, M	1.407E-06, M	1.185E-07, M	1.161E-04	8.612E-04	1.423E-05	1.198E-06
Cs-134	Beta	6.15E+01	3.148E-05, F	3.556E-05, F	3.519E-05, F	3.704E-05, F	3.182E-04	3.594E-04	3.556E-04	3.744E-04
Pm-147	Beta	6.14E+01	9.259E-05, S	1.889E-04, M	5.185E-05, M	1.185E-09, M	9.354E-04	1.908E-03	5.238E-04	1.197E-08
Sb-125	Beta	6.14E+01	8.148E-05, M	1.000E-04, F	8.519E-06, F	4.444E-06, F	8.230E-04	1.010E-03	8.604E-05	4.489E-05
Tl-204	Beta	6.32E+01	1.296E-06, F	1.185E-06, F	1.185E-06, F	1.185E-06, F	1.348E-05	1.232E-05	1.232E-05	1.232E-05
Co-60	Beta	6.14E+01	3.556E-04, S	1.815E-05, S	3.704E-05, S	4.074E-05, S	3.588E-03	1.831E-04	3.737E-04	4.111E-04
Ra-228	Beta	6.14E+01	2.296E-02, M	1.333E-01, M	5.926E-03, M	5.926E-04, M	2.317E-01	1.345E+00	5.979E-02	5.979E-03
Os-194	Beta	6.14E+01	1.259E-03, S	2.259E-05, F	2.963E-04, F	2.370E-05, F	1.271E-02	2.279E-04	2.990E-03	2.392E-04
Eu-154	Beta	6.14E+01	2.407E-04, M	1.000E-03, M	8.148E-04, M	1.000E-04, M	2.429E-03	1.009E-02	8.220E-03	1.009E-03
Eu-152	Beta	2.20E+02	1.481E-04, M	4.815E-04, M	6.667E-04, M	1.148E-04, M	5.355E-03	1.740E-02	2.410E-02	4.150E-03
Pu-241	Beta	6.13E+01	7.778E-04, S	7.407E-02, M	1.519E-02, M	1.333E-04, M	7.843E-03	7.470E-01	1.531E-01	1.345E-03
Pb-210	Beta	6.13E+01	5.185E-04, F	1.333E-01, F	1.111E-02, F	5.185E-04, F	5.228E-03	1.344E+00	1.120E-01	5.228E-03
Sr-90	Beta	6.13E+01	2.333E-03, S	1.704E-03, F	2.778E-06, F	2.778E-06, F	2.352E-02	1.718E-02	2.801E-05	2.801E-05
Cs-137	Beta	6.13E+01	2.259E-05, F	2.444E-05, F	2.407E-05, F	2.481E-05, F	2.278E-04	2.464E-04	2.427E-04	2.502E-04
Ni-63	Beta	6.13E+01	4.815E-06, M	1.889E-06, F	1.889E-06, F	1.889E-06, F	4.854E-05	1.904E-05	1.904E-05	1.904E-05
Tb-158	Beta	3.69E+02	1.444E-04, M	1.185E-03, M	5.185E-04, M	1.074E-04, M	8.771E-03	7.197E-02	3.149E-02	6.522E-03
Ho-166m	Beta	6.13E+01	2.815E-04, M	1.741E-03, M	1.444E-03, M	3.556E-04, M	2.837E-03	1.755E-02	1.456E-02	3.584E-03
Nb-94	Beta	6.13E+01	5.926E-04, S	2.148E-05, S	4.444E-05, S	4.815E-05, S	5.973E-03	2.165E-04	4.480E-04	4.853E-04
Tc-99	Beta	6.13E+01	8.889E-05, M	1.259E-07, F	1.667E-07, F	1.259E-07, F	8.960E-04	1.269E-06	1.680E-06	1.269E-06
Cl-36	Beta	6.25E+01	1.444E-04, M	1.444E-06, F	1.444E-06, F	1.444E-06, F	1.484E-03	1.484E-05	1.484E-05	1.484E-05
Cd-113	Beta	6.13E+01	2.222E-04, S	8.148E-05, F	2.296E-03, F	8.148E-05, F	2.240E-03	8.213E-04	2.315E-02	8.213E-04
Y-86	Gamma	5.66E+02	2.259E-06, S	3.704E-07, M	4.074E-07, M	3.074E-07, M	2.104E-04	3.449E-05	3.794E-05	2.863E-05
Br-76	Gamma	7.72E+02	4.074E-06, M	6.296E-07, F	5.556E-07, F	5.926E-07, F	5.168E-04	7.987E-05	7.047E-05	7.517E-05
Zr-86	Gamma	1.05E+03	2.481E-06, S	1.185E-06, F	3.519E-07, F	4.444E-07, F	4.271E-04	2.040E-04	6.055E-05	7.649E-05
Co-55	Gamma	8.04E+02	4.444E-06, S	2.407E-07, M	2.741E-07, M	2.148E-07, M	5.872E-04	3.181E-05	3.621E-05	2.838E-05
Rh-100	Gamma	2.91E+02	1.148E-06, S	4.444E-07, F	3.704E-07, F	3.593E-07, F	5.485E-05	2.123E-05	1.770E-05	1.716E-05
Ni-57	Gamma	2.16E+02	4.074E-06, M	3.481E-07, F	3.185E-07, M	2.778E-07, M	1.444E-04	1.234E-05	1.129E-05	9.843E-06
Sb-119	Gamma	1.39E+03	1.185E-07, M	5.556E-07, F	3.148E-08, F	1.111E-08, F	2.714E-05	1.272E-04	7.208E-06	2.544E-06
Au-194	Gamma	1.62E+02	1.593E-06, S	2.852E-07, F	2.111E-07, F	2.074E-07, F	4.246E-05	7.604E-06	5.629E-06	5.530E-06

Radionuclide	Emission Type	Annual BZ Intake Rate (dpm/day)	Lung DCF[a] / Solubility Type	Bone Surface DCF[a] / Solubility Type	Liver DCF[a] / Solubility Type	Adrenals DCF[a] / Solubility Type	Lung Dose (rem)[b]	Bone Surface Dose (rem)[b]	Liver Dose (rem)[b]	Adrenals Dose (rem)[b]
Am-240	Gamma	1.63E+02	3.704E-06, M	4.074E-06, M	7.037E-07, M	2.333E-07, M	9.910E-05	1.090E-04	1.883E-05	6.243E-06
Br-77	Gamma	1.95E+02	6.296E-07, M	1.815E-07, F	1.593E-07, M	1.741E-07, M	2.021E-05	5.824E-06	5.111E-06	5.587E-06
Ga-67	Gamma	1.34E+02	4.815E-06, M	1.296E-06, F	1.963E-07, F	9.259E-08, F	1.063E-04	2.861E-05	4.333E-06	2.044E-06
Re-186	Gamma	1.01E+03	1.852E-05, M	2.111E-07, F	2.667E-07, F	2.037E-07, F	3.084E-03	3.515E-05	4.440E-05	3.392E-05
Ba-128	Gamma	7.63E+02	2.778E-07, F	2.259E-06, F	2.481E-07, F	2.778E-07, F	3.484E-05	2.833E-04	3.112E-05	3.484E-05
In-111	Gamma	6.93E+01	2.815E-06, M	5.185E-07, F	8.148E-07, F	3.333E-07, F	3.206E-05	5.906E-06	9.280E-06	3.797E-06
Tl-201	Gamma	9.16E+02	1.333E-07, F	2.000E-07, F	1.111E-07, F	1.185E-07, F	2.008E-05	3.012E-05	1.673E-05	1.785E-05
Pd-100	Gamma	8.51E+01	8.519E-06, S	1.185E-06, F	8.148E-06, F	2.185E-06, F	1.192E-04	1.659E-05	1.140E-04	3.058E-05
Mn-52	Gamma	2.96E+01	1.148E-05, M	3.481E-06, F	7.778E-06, F	3.222E-06, F	5.595E-05	1.697E-05	3.790E-05	1.570E-05
Ag-106m	Gamma	2.09E+01	6.296E-06, S	2.259E-06, F	1.889E-05, F	5.185E-06, F	2.162E-05	7.759E-06	6.487E-05	1.781E-05
Cs-131	Gamma	9.30E+01	1.148E-07, F	2.407E-07, F	1.037E-07, F	1.074E-07, F	1.756E-06	3.682E-06	1.586E-06	1.643E-06
Ba-131	Gamma	5.82E+01	1.852E-07, F	1.963E-06, F	1.556E-07, F	2.333E-07, F	1.771E-06	1.877E-05	1.488E-06	2.232E-06
Rh-99	Gamma	4.49E+01	1.444E-05, S	1.037E-06, F	8.519E-07, F	8.889E-07, F	1.067E-04	7.659E-06	6.291E-06	6.565E-06
V-48	Gamma	3.34E+01	3.333E-05, M	5.926E-06, F	1.815E-06, M	2.630E-06, F	1.830E-04	3.253E-05	9.963E-06	1.444E-05
Te-121	Gamma	6.94E+01	2.667E-06, M	2.852E-06, F	5.556E-07, M	9.259E-07, F	3.045E-05	3.256E-05	6.343E-06	1.057E-05
Sr-82	Gamma	1.12E+02	1.519E-04, S	3.593E-05, F	2.778E-06, F	3.593E-06, F	2.794E-03	6.611E-04	5.111E-05	6.611E-05
Cr-51	Gamma	6.72E+02	3.259E-07, S	8.519E-08, F	5.185E-08, F	5.556E-08, F	3.603E-05	9.416E-06	5.731E-06	6.141E-06
Yb-169	Gamma	4.49E+01	6.296E-05, S	1.222E-05, M	6.667E-07, M	5.185E-07, M	4.651E-04	9.029E-05	4.925E-06	3.831E-06
Ag-105	Gamma	4.87E+01	9.630E-06, S	1.556E-06, F	1.556E-05, F	3.296E-06, F	7.713E-05	1.246E-05	1.246E-04	2.640E-05
Be-7	Gamma	6.17E+02	4.444E-07, S	8.148E-08, M	8.519E-08, S	1.000E-07, S	4.505E-05	8.259E-06	8.635E-06	1.014E-05
Sr-85	Gamma	6.46E+01	7.778E-06, S	3.444E-06, F	1.000E-06, S	1.778E-06, F	8.260E-05	3.658E-05	1.062E-05	1.888E-05
Hf-175	Gamma	6.73E+01	1.667E-05, M	3.481E-05, F	1.148E-06, F	2.630E-06, F	1.843E-04	3.851E-04	1.270E-05	2.909E-05
Re-183	Gamma	1.18E+02	5.402E-08, M	6.327E-10, M	4.958E-10, M	4.847E-10, M	1.047E-06	1.227E-08	9.612E-09	9.397E-09
Co-58	Gamma	6.28E+01	2.889E-05, S	1.185E-06, M	2.259E-06, M	2.370E-06, S	2.981E-04	1.223E-05	2.331E-05	2.446E-05
Co-56	Gamma	2.52E+01	7.407E-05, S	4.074E-06, M	8.148E-06, M	8.519E-06, S	3.064E-04	1.685E-05	3.371E-05	3.524E-05
Zr-88	Gamma	6.29E+01	3.444E-05, S	5.185E-05, F	8.148E-06, F	2.074E-05, F	3.560E-04	5.359E-04	8.421E-05	2.143E-04
Os-185	Gamma	6.24E+01	1.704E-05, S	4.074E-06, F	1.889E-05, F	7.037E-06, F	1.747E-04	4.178E-05	1.937E-04	7.216E-05
Fe-55	Gamma	2.16E+02	9.630E-07, F	6.667E-06, F	7.778E-06, F	9.630E-07, F	3.417E-05	2.365E-04	2.760E-04	3.417E-05
Hg-194	Gamma	2.49E+02	5.185E-05, F	8.519E-05, F	6.667E-05, F	8.519E-05, F	2.119E-03	3.481E-03	2.724E-03	3.481E-03
Te-123	Gamma	7.77E+01	4.444E-06, M	7.037E-04, F	1.444E-06, F	5.556E-06, F	5.675E-05	8.986E-03	1.844E-05	7.094E-05
Y-88	Gamma	3.23E+01	3.704E-05, S	1.074E-05, M	1.704E-05, M	1.074E-05, M	1.967E-04	5.705E-05	9.050E-05	5.705E-05
Sn-113	Gamma	3.37E+03	4.815E-05, M	1.222E-05, F	1.148E-06, F	1.593E-06, F	2.671E-02	6.781E-03	6.370E-04	8.836E-04
Te-123m	Gamma	7.40E+01	8.148E-05, M	1.556E-04, F	6.667E-07, F	1.296E-06, F	9.920E-04	1.894E-03	8.116E-06	1.578E-05
Se-75	Gamma	3.43E+01	1.481E-05, M	4.444E-06, F	2.037E-05, F	8.148E-06, F	8.363E-05	2.509E-05	1.150E-04	4.599E-05
W-181	Gamma	5.60E+03	2.037E-08, F	2.370E-07, F	7.778E-08, F	3.704E-08, F	1.877E-05	2.184E-04	7.166E-05	3.412E-05
Tm-170	Gamma	1.91E+03	1.222E-04, M	2.370E-05, M	3.185E-06, M	2.667E-07, M	3.842E-02	7.451E-03	1.001E-03	8.382E-05
Re-184m	Gamma	7.02E+01	1.222E-04, M	1.556E-06, M	2.111E-06, M	2.296E-06, M	1.411E-03	1.796E-05	2.438E-05	2.652E-05
Au-195	Gamma	4.96E+02	3.074E-05, S	5.926E-07, S	4.444E-07, S	4.815E-07, S	2.509E-03	4.837E-05	3.628E-05	3.930E-05
Gd-153	Gamma	1.16E+02	2.630E-05, M	2.111E-04, F	5.556E-05, F	5.926E-06, F	5.002E-04	4.016E-03	1.057E-03	1.127E-04
Zn-65	Gamma	1.22E+02	2.407E-05, S	1.037E-05, S	8.519E-06, S	1.037E-05, S	4.822E-04	2.077E-04	1.706E-04	2.077E-04
Ag-110m	Gamma	1.92E+01	1.407E-04, S	1.407E-05, F	1.556E-04, F	3.630E-05, F	4.454E-04	4.454E-05	4.922E-04	1.149E-04

Radionuclide	Emission Type	Annual BZ Intake Rate (dpm/day)	Lung DCF[a] / Solubility Type	Bone Surface DCF[a] / Solubility Type	Liver DCF[a] / Solubility Type	Adrenals DCF[a] / Solubility Type	Lung Dose (rem)[b]	Bone Surface Dose (rem)[b]	Liver Dose (rem)[b]	Adrenals Dose (rem)[b]
Pm-143	Gamma	1.60E+02	1.370E-05, S	1.000E-05, M	1.630E-05, M	4.444E-06, M	3.616E-04	2.639E-04	4.300E-04	1.173E-04
Co-57	Gamma	5.85E+01	1.370E-05, S	7.407E-07, S	8.889E-07, S	9.259E-07, S	1.318E-04	7.125E-06	8.550E-06	8.906E-06
Mn-54	Gamma	6.17E+01	1.148E-05, M	6.296E-06, F	1.074E-05, F	4.815E-06, F	1.165E-04	6.390E-05	1.090E-04	4.887E-05
Sm-145	Gamma	4.82E+02	1.074E-05, M	4.815E-05, M	2.111E-05, M	1.815E-06, M	8.510E-04	3.815E-03	1.673E-03	1.438E-04
Pm-144	Gamma	2.52E+01	7.037E-05, S	2.815E-05, M	9.630E-05, M	2.963E-05, M	2.920E-04	1.168E-04	3.996E-04	1.230E-04
Cd-109	Gamma	1.71E+03	1.222E-04, S	8.519E-06, F	1.593E-04, F	1.074E-05, F	3.427E-02	2.389E-03	4.466E-02	3.012E-03
Hf-172	Gamma	1.23E+02	1.519E-04, M	3.296E-03, F	4.074E-05, F	1.074E-04, F	3.059E-03	6.640E-02	8.207E-04	2.164E-03
Cs-134	Gamma	2.76E+01	3.148E-05, F	3.556E-05, F	3.519E-05, F	3.704E-05, F	1.428E-04	1.612E-04	1.596E-04	1.680E-04
Na-22	Gamma	6.15E+01	4.815E-06, F	1.148E-05, F	4.815E-06, F	6.296E-06, F	4.867E-05	1.161E-04	4.867E-05	6.364E-05
Gd-151	Gamma	3.89E+02	1.259E-05, M	8.148E-05, F	2.111E-05, F	1.778E-06, F	8.044E-04	5.205E-03	1.349E-03	1.136E-04
Rh-101	Gamma	4.31E+01	7.778E-05, S	8.148E-06, F	5.926E-06, F	6.296E-06, F	5.515E-04	5.778E-05	4.202E-05	4.465E-05
Co-60	Gamma	3.07E+01	3.556E-04, S	1.815E-05, S	3.704E-05, S	4.074E-05, S	1.795E-03	9.161E-05	1.870E-04	2.057E-04
Eu-154	Gamma	3.76E+01	2.407E-04, M	1.000E-03, M	8.148E-04, M	1.000E-04, M	1.487E-03	6.177E-03	5.033E-03	6.177E-04
Ba-133	Gamma	4.51E+01	3.704E-06, F	3.556E-05, F	2.963E-06, F	6.296E-06, F	2.745E-05	2.635E-04	2.196E-05	4.666E-05
Eu-152	Gamma	3.89E+01	1.481E-04, M	4.815E-04, M	6.667E-04, M	1.148E-04, M	9.486E-04	3.083E-03	4.268E-03	7.351E-04
Pm-145	Gamma	2.17E+03	2.630E-05, S	1.519E-04, M	6.667E-05, M	5.556E-06, M	9.383E-03	5.418E-02	2.379E-02	1.982E-03
Bi-207	Gamma	3.41E+01	6.667E-05, M	2.630E-06, M	4.815E-06, M	5.556E-06, M	3.736E-04	1.474E-05	2.698E-05	3.113E-05
Ti-44	Gamma	3.36E+01	1.593E-03, S	2.889E-04, F	2.667E-04, F	2.815E-04, F	8.797E-03	1.596E-03	1.473E-03	1.555E-03
Pt-193	Gamma	2.91E+02	3.000E-08, F	3.185E-08, F	1.815E-07, F	2.222E-07, F	1.433E-06	1.522E-06	8.671E-06	1.062E-05
Ag-108m	Gamma	2.20E+01	4.074E-04, S	2.222E-05, S	1.852E-04, F	5.185E-05, S	1.473E-03	8.035E-05	6.696E-04	1.875E-04
Tb-158	Gamma	5.90E+01	1.444E-04, M	1.185E-03, M	5.185E-04, M	1.074E-04, M	1.401E-03	1.150E-02	5.031E-03	1.042E-03
Al-26	Gamma	5.98E+01	2.259E-04, M	9.630E-05, F	3.704E-05, F	4.444E-05, F	2.222E-03	9.470E-04	3.642E-04	4.371E-04

a. ICRP (1995) max organ DCF (mrem/pCi).
b. Committed dose to organ from one year of intake based on BZ data (rem).

Table 27b. Summary of Table 27a.

Organ	Emission Type	Largest Radionuclide	Largest Dose (rem)
Lung	Beta	Ra-228	2.32E-01
Bone Surface	Beta	Ra-228	1.35E+00
Liver	Beta	Pu-241	1.53E-01
Adrenals	Beta	Tb-158	6.52E-03
Lung	Gamma	Tm-170	3.84E-02
Bone Surface	Gamma	Hf-172	6.64E-02
Liver	Gamma	Cd-109	4.47E-02
Adrenals	Gamma	Hg-194	3.48E-03

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ATTACHMENT A

Overview

The following provides a detailed discussion of the calculation steps supporting the results presented in Tables 19 through 27 above for assessing gross alpha, gross beta, gross gamma bioassay, and alpha and beta/gamma air sampling results. This is presented in *Gross Alpha/Beta, Gross Gamma Bioassay, Alpha and Beta/Gamma Air Sampling Results Spreadsheets* (ORAUT 2017a).

As indicated above, the example is for missed dose for an unknown work location and doses to several organs of interest with the details listed below:

Table A-1. Example Calculation Employment Information.

Employment Period	01/01/1967–12/31/1971
Work Location	Unknown
Internal Monitored Period	01/01/1969–12/31/1971

Table A-2. Example Calculation Cancer Information.

Cancer	Date of Diagnosis
Lung	12/31/1975
Bone Surface	12/31/1975
Liver	12/31/1975
Adrenals	12/31/1975

Table A-3. Example Calculation Bioassay Information.

Date	Bioassay Results	Gross Alpha MDA (dpm/24 h)	Gross Beta MDA (dpm/24 h)	Gross Gamma MDA (dpm/24 h)
12/31/1969	<MDA	0.2	2	100
12/31/1970	<MDA	0.2	2	100
12/31/1971	<MDA	0.2	2	100

Table A-4. Example Calculation Air Concentration Information.

Highest Annual Alpha Air Concentration for 1967–1971	0.0336 pCi/m^3
Highest Annual Beta/Gamma Air Concentration for 1967–1971	4.2 pCi/m^3
Unmonitored Period	01/01/1967–12/31/1968

The following describes the general approach for determining the internal dose from the short-lived and long-lived radionuclides. Refer to Worksheet Descriptions and Example Calculations for detail in determining the doses.

The list of alpha, beta, and gamma emitters are presented in Tables 3, 5, 7, and 9 above.

Radionuclides with Half-Lives Less than 100 Days

Radionuclides with half-lives less than 100 days were considered to be unmonitored, given the typical LBNL bioassay frequencies of one year or six months. These are presented in Table 9 above. The internal doses from these unmonitored radionuclides were assessed based on the following:

1. The LBNL 95th-percentile annual average air concentrations were determined based on a statistical reduction of the LBNL Dual Data Entry Phase I and II BZ data effort.

2. The 95th-percentile annual average air concentrations were converted to an annual intake rate for each radionuclide and adjusted for the following:

    a. Decay-corrected back 72 hours.

    b. An annual breathing rate of 2,400 m^3/yr.

    c. Branching fraction (alpha and beta emitters).

    d. Gamma yield (gamma emitters).

3. The committed dose for each radionuclide from one year of intake was determined by multiplying the annual intake by the highest ICRP (1995) inhalation organ DCF for each organ of interest. This is an efficiency measure used to determine the radionuclide yielding the highest dose.

4. Since the IREP input cannot accept a 50-year committed dose, the intake rate for that particular radionuclide and given bioassay method (i.e., gross alpha, gross beta, or gross gamma) is then run using IMBA or CAD to determine the annual equivalent internal doses out to the cancer diagnosis date.

Radionuclides with Half-Lives Greater than 100 Days

Radionuclides whose half-lives are greater than 100 days were assessed using bioassay results. These are presented in Tables 3, 5, and 7 above. The internal doses based on bioassay results from these monitored radionuclides were assessed based on the following:

1. An intake rate for the assumed internally monitored period of January 1, 1969, through December 31, 1971, was calculated using IMBA, based on a urine bioassay result of 1 dpm/24 hours on December 31, 1971.

2. The internal dose for each radionuclide based on the calculated intake rate and a cancer diagnosis date of December 31, 1975, was determined using IMBA.

3. The solubility types yielding the largest internal dose to the organ of interest for each radionuclide were compiled.

4. The doses for each radionuclide were converted to missed dose based on the following:

   a. Alpha emitters were adjusted for the sample-specific MDA and their branching fraction.

   b. Beta emitters were adjusted for the sample-specific MDA and their branching fraction.

   c. Gamma emitters were adjusted for the sample-specific MDA and their photon yield (gammas/disintegration).

5. The intake rates calculated from bioassay data for each radionuclide were compared to the intake rates determined from the BZ air monitoring data. The more limiting intake rate between the bioassay and BZ data was used to calculate the dose to the organ of interest.

6. The radionuclide yielding the highest internal dose to the organ of interest for the given bioassay method (i.e., gross alpha, gross beta, or gross gamma) was assigned for each year the worker was monitored for intakes.

Input Sources

Intake rates:	IMBA was used to determine the intake rate for each solubility type of the radionuclides with $T_{1/2}$ >100 days, based on monitoring from January 1, 1969, to December 31, 1971, and an assumed urine sample result of 1 dpm/24 hours on December 31, 1971.
Dose:	IMBA was used to determine the internal dose for each radionuclide based on the intake rates derived above and a cancer diagnosis date of December 31, 1975.
Branching Fractions:	Rad Toolbox
Photon Yield Data:	Rad Toolbox
ICRP (1995) Inhalation DCFs:	Rad Toolbox
BZ data:	95^{th}-percentile annual air concentrations were determined based on a statistical reduction of the LBNL Dual Data Entry Phase I and II BZ data effort.

Worksheet Descriptions

The following describes the various worksheets, along with the detailed methodology for the key data in the worksheets:

Breathing Zone Data

1. This worksheet contains the LBNL 95th-percentile annual average air concentrations which were determined based on a statistical reduction of the LBNL Dual Data Entry Phase I and II BZ data effort. These data are presented in Table 1 above.

2. These data were used to determine the annual intake rates for each radionuclide in the "Alpha Breathing Zone Int Rates" and "BG Breathing Zone Intake Rates" worksheets.

3. These data were used to determine the annual intake rate for each radionuclide in the "Unmonitored Alpha Organ Doses" and "Unmonitored BG Organ Doses" worksheets.

Doses Based on Bioassay

1. This worksheet contains the intake rates and doses for the solubility type yielding the highest dose to the organ of interest based on a 1 dpm/24 hour urine sample on December 31, 1971, intake from January 1, 1969, to December 31, 1971, and a cancer diagnosis date of December 31, 1975.

2. These intake rates and doses are referenced in the "Gross Alpha Bio Organ Doses," "Gross Beta Bioassay Organ Doses," and "Gross Gamma Bio Organ Doses" worksheets.

ICRP 68 DCFs

1. The ICRP (1995) Inhalation DCFs were taken from Rad Toolbox. This includes additional radionuclides not used in the "DR Methodology."

2. The DCFs are referenced in the "Unmonitored Alpha Organ Doses" and "Unmonitored BG Organ Doses" worksheets for the specific radionuclides assessed. They reflect the solubility type and DCF yielding the largest dose to the organs assessed. These DCFs are used in Tables 22a, 22b, 25a, 25b, 26a, 26b, 27a, and 27b above.

Alpha Breathing Zone Int Rates

1. This worksheet determines the annual intake rates based on the alpha air concentration data from the "Breathing Zone Data" worksheet. These intake rates are is used in Tables 21b, 22a, 22b, 26a, and 26b above.

2. Columns D through I contain the decay data which are taken from Rad ToolBox.

3. The decay data in columns D through I is referenced in the "Gross Alpha Bio Organ Doses" worksheet.

4. Column C determines the intake rates based on the highest 95th-percentile alpha annual air concentration of 0.0336 pCi/m^3 for 1967 to 1971 from the "Breathing Zone Data" worksheet decay-corrected back 72 hours, adjusted for an annual breathing rate of 2,400 m^3/year, and adjusted for alpha branching fraction in column H.

   The annual intake rate based on BZ data (dpm/day) in column C is determined by the following methods:

   Annual intake rate = Annual air concentration × 2.22 × 2,400 ÷ 365 ÷ *Decay correction factor* ÷ *Branching fraction*

   Where:

   Annual intake rate = annual intake rate based on BZ data (dpm/day) [column C]
   Annual air concentration = 95th-percentile annual air concentration (pCi/m^3) [cell D12]
   2.22 = 2.22 dpm/pCi conversion
   2,400 = 2,400 m^3/year inhalation rate
   365 = 365 days/yea r
   Branching fraction = alpha branching fraction [column H]
   $$Decay\ correction\ factor = e^{-\left(\left[0.693 \div Half\text{-}life\right] \times Decay\ correction\ time\right)}$$

   And:

   Half-life = half-life [column D] converted to hours
   Decay correction time = air sample decay correction time [cell A12]

5. The table is broken into two sections: potential unmonitored alpha and alpha bioassay denoted in column J.

Unmonitored Alpha Organ Doses

Note that the doses in these sections are all based on a single year of exposure regardless of the actual exposure period since only comparisons are being done and all doses are proportional to the intake amount.

1. The worksheet contains the committed internal dose from the alpha radionuclides with half-lives less than 100 days that are assumed not to be detected by the gross alpha bioassay method. These doses are presented in Tables 22a and 22b above. The radionuclide intake rates and solubility types yielding the highest dose to the organ of

interest are then run using IMBA or CAD to determine the annual doses for the 1969 through 1971 monitoring period.

2. Column C lists the annual intake rates based on BZ data determined in column C of the "Alpha Breathing Zone Int Rates" worksheet.

3. Columns L through O determine the committed organ doses assessed from one year of intake for each radionuclide based on the annual BZ intake rates in column C and the organ DCFs in columns D though K.

   The Committed Dose to Organ from one year of intake (rem) in columns L through O for alpha emitters is determined by the following:

   $$\textit{Committed dose} = \textit{Annual intake rate} \times \textit{DCF} \times 365 \div 1{,}000 \div 2.22$$

   Where:

   Committed dose = Committed Dose to Organ from one year of intake (rem) [column L through O]
   Annual intake rate = annual intake rate based on BZ data (dpm/day) [column C]
   2.22 = 2.22 dpm/pCi conversion
   1,000 = 1,000 mrem/rem conversion
   365 = 365 days/year
   DCF = ICRP (1995) inhalation maximum organ DCFs (mrem/pCi) [columns D through K]

Gross Alpha Bio Organ Doses

1. This worksheet determines the intake rate based on gross alpha bioassay and the limiting doses based on a comparison of the intake rate based on bioassay to the intake rate based on BZ data. These doses are summarized in Tables 21a and 21b above.

2. Column AF contains the alpha branching fractions which are taken from the "Alpha Breathing Zone Int Rates" worksheet.

3. Columns D, F, I, K, N, P, S, and U contain the intake rates and doses based on a urine sample result of 1 dpm/sample from the "Doses Based on Bioassay" worksheet.

   The Intake Rate (adjusted for MDA and alpha branching fraction) (dpm/day) in columns E, J, O, and T are determined by the following:

   $$\textit{Intake rate based on bioassay} = \textit{Intake rate (1 dpm/sample)} \times \textit{MDA}/2 \div \textit{Branching fraction}$$

   Where:

Intake rate based on bioassay = intake rate (adjusted for MDA and alpha branching fraction) (dpm/day) [columns E, J, O, and T]
Intake rate (1 dpm/sample) = intake rate based on urine sample result of 1 alpha dpm/sample [columns D, I, N, and S]
MDA = gross alpha bioassay MDA [cell C10]

2 = missed dose divisor
Branching fraction = alpha branching fraction [column AF]

4. Columns E, G, J, L, O, Q, T, and V determine the intake rates and missed doses using the alpha urine sample result of 1 dpm/sample adjusted for the sample-specific MDA in cell C10 and branching fraction in column AF.

   The dose (adjusted for MDA and alpha branching fraction) in columns G. L, Q, and V are determined by the following:

   Dose based on bioassay = Dose (1 dpm/sample) × MDA/2 ÷ *Branching fraction*

   Where:

   Dose based on bioassay = dose (adjusted for MDA and alpha branching fraction) [columns G. L, Q, and V]
   Dose (1 dpm/sample) = dose based on urine sample result of 1 alpha dpm/sample [columns F, K, P, and U]
   MDA = gross alpha bioassay minimum detectable activity [cell C10]
   2 = missed dose divisor
   Branching fraction = alpha branching fraction [column AF]

5. Column W contains the annual intake rates based on BZ data obtained from the "Alpha Breathing Zone Int Rates" worksheet.

6. Columns X through AE determine the more limiting dose based on a comparison of the intake rates based on bioassay to the intake rates based on BZ data. If the annual intake rate based on BZ data in column W is less than the intake rate adjusted for MDA and alpha branching fraction, the dose adjusted for MDA and alpha branching fraction is divided by the ratio of intake rate adjusted for MDA and alpha branching fraction to the annual intake rate based on BZ data in column W. Otherwise, the dose adjusted for MDA and alpha branching fraction is assigned.

   If:

   Annual intake rate < Intake rate based on bioassay

   Where:

Intake rate based on bioassay = columns E, J, O, and T
Annual intake rate = column W

Then:

Dose = *Dose based on bioassay* ÷ *Ratio of Bioassay Intake to BZ Intake*

Where:

Dose based on bioassay = columns G, L, Q, and V
Ratio of Bioassay Intake to BZ Intake = intake rate based on bioassay ÷ annual intake rate

Otherwise:

Dose = *Dose based on bioassay*

Unmonitored Worker 67-68 Alpha Doses

1. The worksheet contains the committed internal doses to an unmonitored worker for 1967 through 1968 from all the alpha radionuclides. These doses are presented in Tables 26a and 26b above. The radionuclide intake rates and solubility types yielding the highest dose to the organ of interest are then run using IMBA or CAD to determine the annual doses for the unmonitored period 1967 through 1968.

2. Column C lists the annual intake rates based on BZ data determined in column C of the "Alpha Breathing Zone Int Rates" worksheet.

3. Columns L through O determine the committed organ doses assessed from one year of intake for each radionuclide based on the annual BZ intake rates in column C and the organ DCFs in columns D though K.

   The committed dose to organ from one year of intake (rem) in columns L through O for alpha emitters is determined by the following:

   Committed dose = *Annual intake rate* × *DCF* × 365 ÷ 1,000 ÷ 2.22

   Where:

   Committed dose = committed dose to organ from one year of intake (rem) [column L through O]
   Annual intake rate = annual intake rate based on BZ data (dpm/day) [column C]
   2.22 = 2.22 dpm/pCi conversion
   1,000 = 1,000 mrem/rem conversion
   365 = 365 days/year

DCF = ICRP (1995) inhalation maximum organ DCFs (mrem/pCi) [columns D through K]

BG Breathing Zone Intake Rates

1. This worksheet determines the beta and gamma annual intake rates based on the air concentration data from the "Breathing Zone Data" worksheet. The table is broken into four sections (denoted in column K): potential unmonitored beta, beta bioassay, potential unmonitored gamma, and gamma bioassay radionuclides. The intake rates from Tables 23b, 24b, 25a, 25b, 27a, and 27b above are used.

2. Columns D through J contain the decay data taken from Rad ToolBox. Column J is the photon yield data, unless noted.

3. The decay data in columns F through J are referenced in the "Gross Beta Bioassay Organ Doses" and "Gross Gamma Bio Organ Doses" worksheets.

4. Column C determines the annual intake rates using the highest 95th-percentile annual air concentration of 4.2 pCi/m^3 for 1967 to 1971 from the "Breathing Zone Data" worksheet, decay-corrected back 72 hours and adjusted for beta branching fraction in column H or photon yield in column J.

   The annual intake rate based on BZ data (dpm/day or γpm/day) in column C is determined by the following methods:

   Beta Emitters:

   Annual intake rate = Annual air concentration × 2.22 × 2,400 ÷ 365 ÷ *Decay correction factor* ÷ *Branching fraction*

   Where:

   Annual intake rate = annual intake rate based on BZ data (dpm/day or γpm/day) [column C]
   Annual air concentration = 95th-percentile annual air concentration (pCi/m^3) [cell D12]
   2.22 = 2.22 dpm/pCi conversion
   2,400 = 2,400 m^3/year inhalation rate
   365 = 365 days/year
   Branching fraction = beta branching fraction [column H]
   $$\textit{Decay correction factor} = e^{-([0.693 \div \textit{Half-life}] \times \textit{Decay correction time})}$$

   And:

Half-life = half-life [column D] converted to hours
Decay correction time = air sample decay correction time [cell A12]

Gamma Emitters:

Annual intake rate = Annual air concentration × 2.22 × 2,400 ÷ 365 ÷ *Decay correction factor ÷ Photon yield*

Where:

Annual intake rate = annual intake rate based on BZ data (dpm/day or γpm/day) [column C]
Annual air concentration = 95th-percentile annual air concentration (pCi/m^3) [cell D12]
2.22 = 2.22 dpm/pCi conversion
2,400 = 2,400 m^3/year inhalation rate
365 = 365 days/year
Photon yield = Photon yield [column J]

$$Decay\ correction\ factor = e^{-([0.693 \div Half\text{-}life] \times Decay\ correction\ time)}$$

And:

Half-life = half-life [column D] converted to hours
Decay correction time = air sample decay correction time [cell A12]

Unmonitored BG Organ Doses

1. The worksheet determines the committed internal doses for beta and gamma radionuclides with half-lives less than 100 days that are assumed not to be detected by the gross beta and gross gamma bioassay methods. These doses are presented in Tables 25a and 25b above. The radionuclide intake rates and solubility types yielding the highest dose to the organ of interest are then run using IMBA or CAD to determine the annual doses for the 1969 through 1971 monitoring period.

2. Column C lists the annual intake rates based on BZ data determined in column C of the "BG Breathing Zone Intake Rates" worksheet.

3. Columns L through O determine the committed dose for the organs assessed from one year of intake for each radionuclide based on the annual BZ intake rates in column C and the organ DCFs in columns D though K.

   The Committed Dose to Organ from one year of Intake (rem) in columns L through O for beta and gamma emitters is determined by the following:

Committed dose = Annual intake rate × DCF x 365 ÷ 1,000 ÷ 2.22

Where:

Committed dose = Committed Dose to Organ from one year of Intake (rem) [column L through O]
Annual intake rate = annual intake rate based on BZ data (dpm/day or γpm/day) [column C]
2.22 = 2.22 dpm/pCi conversion
1,000 = 1,000 mrem/rem conversion
365 = 365 days/year
DCF = ICRP (1995) inhalation maximum organ DCFs (mrem/pCi) [columns D through K]

Gross Beta Bio Organ Doses

1. This worksheet determines the intake rate based on gross beta bioassay and the limiting doses based on a comparison of the intake rate based on bioassay to the intake rate based on BZ data. These doses are summarized in Tables 23a and 23b above.

2. Column AF contains the beta branching fractions which are taken from the "BG Breathing Zone Intake Rates" worksheet.

3. Columns D, F, I, K, N, P, S, and U contain the intake rates and doses based on a urine sample result of 1 dpm/sample from the "Doses Based on Bioassay" worksheet.

4. Columns E, G, J, L, O, Q, T, and V determine the intake rates and missed doses using the beta urine sample result of 1 beta dpm/sample adjusted for the sample-specific MDA in cell C10 and branching fraction in column AF.

   a. The Intake Rate (adjusted for MDA and beta branching fraction) (dpm/day) in columns E, J, O, and T are determined by the following:

      *Intake rate based on bioassay = Intake rate (1 dpm/sample) × MDA/*2 ÷ *Branching fraction*

      Where:

      Intake rate based on bioassay = Intake Rate (adjusted for MDA and beta branching fraction) (dpm/day) [columns E, J, O, and T]
      Intake rate (1 dpm/sample) = Intake Rate based on urine sample result of 1 beta dpm/sample [columns D, I, N, and S]
      MDA = gross beta bioassay MDA [cell C10]

2 = missed dose divisor
Branching fraction = beta branching fraction [column AF]

b. The dose (adjusted for MDA and beta branching fraction) in columns G, L, Q, and V is determined by the following:

*Dose based on bioassay = Dose (1 dpm/sample) × MDA/*2 *÷ Branching fraction*

Where:

*Dose based on bioassa*y = Dose (adjusted for MDA and beta branching fraction) [columns G, L, Q, and V]
Dose (1 dpm/sample) = Dose based on urine sample result of 1 beta dpm/sample [columns F, K, P, and U]
MDA = gross beta bioassay MDA [cell C10]
2 = missed dose divisor
Branching fraction = beta branching fraction [column AF]

5. Column W contains the annual intake rates based on BZ data obtained from column C the "BG Breathing Zone Intake Rates" worksheet.

6. Columns X through AE determine the more limiting dose based on a comparison of the intake rates based on bioassay to the intake rates based on BZ data. If the annual intake rate based on BZ data in column W is less than the intake rate adjusted for MDA and beta branching fraction, the dose adjusted for MDA and beta branching fraction is divided by the ratio of intake rate adjusted for MDA and beta branching fraction to the annual intake rate based on BZ data in column W. Otherwise, the dose adjusted for MDA and beta branching fraction is assigned.

If:

Annual intake rate < Intake rate based on bioassay

Where:

Intake rate based on bioassay = columns E, J, O, and T
Annual intake rate = column W

Then:

Dose = Dose based on bioassay ÷ Ratio of Bioassay Intake to BZ Intake

Where:

Dose based on bioassay = columns G, L, Q, and V

Ratio of Bioassay Intake to BZ Intake = Intake rate based on bioassay ÷ Annual intake rate

Otherwise:

Dose = Dose based on bioassay

Gross Gamma Bio Organ Doses

1. This worksheet determines the intake rate based on gross gamma bioassay and the limiting doses based on a comparison of the intake rate based on bioassay to the intake rate based on BZ data. These doses are summarized in Tables 24a and 24b above.

2. Column AF contains the photon yield which are taken from the "BG Breathing Zone Intake Rates" worksheet.

3. Columns D, F, I, K, N, P, S, and U contain the intake rates and doses based on a urine sample result of 1 dpm/sample from the "Doses Based on Bioassay" worksheet.

4. Columns E, G, J, L, O, Q, T, and V determines the intake rates and missed doses using the gamma urine sample result of 1 γpm/sample adjusted for the sample-specific MDA in cell C10, and photon yield in column AJ.

   a. The Intake Rate (adjusted for MDA and γ yield) (dpm/day) in columns E, J, O, and T are determined by the following:

      Intake rate based on bioassay = Intake rate (1 γpm/sample) × MDA/2 ÷ Photon yield

      Where:

      Intake rate based on bioassay = Intake Rate (adjusted for MDA and γ yield) (dpm/day) [columns E, J, O, and T]
      Intake rate (1 dpm/sample) = Intake Rate based on urine sample result of 1 γpm/sample [columns D, I, N, and S]
      MDA = gross gamma bioassay MDA [cell C10]
      2 = missed dose divisor
      Photon yield = Photon yield [column AF]

   b. The Dose (adjusted for MDA and γ yield) in columns G. L, Q, and V are determined by the following:

      Dose based on bioassay = Dose (1 dpm/sample) × MDA/2 ÷ Photon yield

      Where:

Dose based on bioassay = Dose (adjusted for MDA and γ yield) [columns G, L, Q, and V]
Dose (1 dpm/sample) = Dose based on gamma urine sample result of 1 γpm/sample [columns F, K, P, and U]
MDA = gross gamma bioassay MDA [cell C10]
2 = missed dose divisor
Photon yield = Photon yield [column AF]

5. Column W contains the annual intake rates based on BZ data obtained from column C of the "BG Breathing Zone Intake Rates" worksheet.

6. Columns X through AE determines the more limiting dose based on a comparison of the intake rates based on bioassay to the intake rates based on BZ data. If the annual intake rate based on BZ data in column W is less than the intake rate adjusted for MDA and photon yield, the dose adjusted for MDA and photon yield is divided by the ratio of intake rate adjusted for MDA and photon yield to the annual intake rate based on BZ data in column W. Otherwise, the dose adjusted for MDA and photon yield is assigned.

If:

Annual intake rate < Intake rate based on bioassay

Where:

Intake rate based on bioassay = columns E, J, O, and T
Annual intake rate = column W

Then:

Dose = Dose based on bioassay ÷ Ratio of Bioassay Intake to BZ Intake

Where:

Dose based on bioassay = columns G, L, Q, and V
Ratio of Bioassay Intake to BZ Intake = Intake rate based on bioassay ÷ Annual intake rate

Otherwise:

Dose = Dose based on bioassay

Unmonitored Worker BG Doses 67-68

1. The worksheet contains the committed internal doses to an unmonitored worker for 1967 through 1968 from beta and gamma radionuclides. These doses are presented in Table

27a and 27b above. The radionuclide intake rates and solubility types yielding the highest dose to the organ of interest are then run using IMBA or CAD to determine the annual doses for the unmonitored period 1967 through 1968.

2. Column C lists the annual intake rates based on BZ data determined in column C of the "BG Breathing Zone Intake Rates" worksheet.

3. Columns L through O determine the committed dose for the organs assessed from one year of intake for each radionuclide based on the annual BZ intake rates in column C and the organ DCFs in columns D though K.

   The Committed Dose to Organ from one year of Intake (rem) in columns L through O for beta and gamma emitters is determined by the following:

   Committed dose = Annual intake rate × *DCF* × 365 ÷ 1,000 ÷ 2.22

   Where:

   Committed dose = Committed Dose to Organ from one year of Intake (rem) [column L through O]
   Annual intake rate = annual intake rate based on BZ data (dpm/day or γpm/day) [column C]
   2.22 = 2.22 dpm/pCi conversion
   1,000 = 1,000 mrem/rem conversion
   365 = 365 days/year
   DCF = ICRP (1995) inhalation maximum organ DCFs (mrem/pCi) [columns D through K]

Example Calculations

The following provides example calculations for the methods described above in the worksheets:

Alpha Breathing Zone Int Rates

Example for Ac-225

The annual intake rate based on BZ data (dpm/day) in cell C14 is 0.60 dpm/day.

Annual intake rate = Annual air concentration × 2.22 × 2,400 ÷ 365 ÷ *Decay correction factor* ÷ *Branching fraction*

Annual air concentration = 0.0336 pCi/m^3 [cell D12]

2.22 = 2.22 dpm/pCi conversion
2,400 = 2,400 m^3/year inhalation rate

365 = 365 days/year
Branching fraction = 1 [cell H14]
Half-Life = 10 days [cells D10 and E10]
Decay correction time = 72 hours [cell A12]

$$Decay\ correction\ \ factor = e^{-([0.693 \div 10\ \text{days} \times 24\ \text{hours/day}] \times 72\ \text{hours})} = 0.812$$

Annual intake rate = 0.0336 pCi/m^3 × 2.22 dpm/pCi × 2,400 m^3/year ÷ 365 days/year ÷ 0.812 ÷ 1

Annual intake rate = 0.60 dpm/day

Annual intake rate based on BZ data in cell C14 = 0.60 dpm/day.

Unmonitored Alpha Organ Doses

Example for Ac-225

1. The Annual intake rate based on BZ data (dpm/day) in cell C14 is 0.60 dpm/day and is taken from the "Alpha Breathing Zone Int Rates" worksheet validated above.

2. The Committed Dose to Organ from one year of Intake (rem) in cells L14 through O14 are:

Lung =	1.986E-02 rem [cell L14]
Bone surface =	1.030E-02 rem [cell M14]
Liver =	2.758E-03 rem [cell N14]
Adrenals =	4.045E-06 rem [cell O14]

Committed dose = *Annual intake rate* × *DCF* x 365 ÷ 1,000 ÷ 2.22

DCF = 2.000E-01 mrem/pCi [cell D14] (lung)
DCF = 1.037E-01 mrem/pCi [cell F14] (bone surface)
DCF = 2.778E-02 mrem/pCi [cell H14] (liver)
DCF = 4.074E-05 mrem/pCi [cell J14] (adrenals)

Committed dose (lung) = 0.60 dpm/day × 2.000E-01 mrem/pCi × 365 days/year ÷ 1,000 mrem/rem ÷ 2.22 dpm/pCi

Committed dose (lung) = 1.986E-02 rem

Committed dose (bone surface) = 0.60 dpm/day × 1.037E-01 mrem/pCi × 365 days/year ÷ 1,000 mrem/rem ÷ 2.22 dpm/pCi

Committed dose (bone surface) = 1.030E-02 rem

Committed dose (liver) = 0.60 dpm/day × 2.778E-02 mrem/pCi × 365 days/year ÷ 1,000 mrem/rem ÷ 2.22 dpm/pCi

Committed dose (liver) = 2.758E-03 rem

Committed dose (adrenals) = 0.60 dpm/day × 4.074E-05 mrem/pCi × 365 days/year ÷ 1,000 mrem/rem ÷ 2.22 dpm/pCi

Committed dose (adrenals) = 4.045E-06 rem

Gross Alpha Bio Organ Doses

Example for Am-241

The intake rates based on a urine sample result of 1 dpm/sample in cells D13, I13, N13, and S13 are taken from row 77 of the "Doses Based on Bioassay" worksheet.

Intake rate (1 dpm/sample)

Lung =	93.99 dpm/day [cell D13]
Bone surface =	93.99 dpm/day [cell I13]
Liver =	93.99 dpm/day [cell N13]
Adrenals =	93.99 dpm/day [cell S13]

The doses based on a urine sample result of 1 dpm/sample in F13, K13, P13, and U13 are taken from row 77 of the "Doses Based on Bioassay" worksheet.

Dose (1 dpm/sample)

Lung =	3.78E+00 rem [cell F13]
Bone surface =	2.65E+01 rem [cell K13]
Liver =	4.93E+00 rem [cell P13]
Adrenals =	2.27E-02 rem [cell U13]

1. Intake Rates based on bioassay [columns E, J, O, and T]:

   Intake rate based on bioassay = Intake rate (1 dpm/sample) × MDA/2 ÷ Branching fraction

   MDA = 0.2 dpm/sample [cell C10]

   Branching fraction = 1 [cell AF13]

   Intake rate based on bioassay (lung) = 93.99 dpm/day × 0.2 dpm/sample ÷ 2 ÷ 1
   Intake rate based on bioassay (lung) = 9.40 dpm/day [cell E13]

Intake rate based on bioassay (bone surface) = 93.99 dpm/day × 0.2 dpm/sample ÷ 2 ÷ 1
Intake rate based on bioassay (bone surface) = 9.40 dpm/day [cell J13]

Intake rate based on bioassay (liver) = 93.99 dpm/day × 0.2 dpm/sample ÷ 2 ÷ 1
Intake rate based on bioassay (liver) = 9.40 dpm/day [cell O13]

Intake rate based on bioassay (adrenals) = 93.99 dpm/day × 0.2 dpm/sample ÷ 2 ÷ 1
Intake rate based on bioassay (adrenals) = 9.40 dpm/day [cell T13]

2. Doses based on bioassay [columns G. L, Q, and V]:

   The Dose (adjusted for MDA and alpha branching fraction) are:

Lung =	3.78E-01 rem [cell G13]
Bone surface =	2.65E+00 rem [cell L13]
Liver =	4.93E-01 rem [cell Q13]
Adrenals =	2.27E-03 rem [cell V13]

   *Dose based on bioassa*y = *Dose (1 dpm/sample)* × *MDA/*2 ÷ *Branching fraction*

   MDA = 0.2 dpm/sample [cell C10]

   Branching fraction = 1 [cell AF13]

   *Dose based on bioassa*y (lung) = 3.78E+00 rem × 0.2 dpm/sample ÷ 2 ÷ 1
   *Dose based on bioassa*y (lung) = 3.78E-01 rem [cell G13]

   *Dose based on bioassa*y (bone surface) = 2.65E+01 rem × 0.2 dpm/sample ÷ 2 ÷ 1
   *Dose based on bioassa*y (bone surface) = 2.65E+00 rem [cell L13]

   *Dose based on bioassa*y (liver) = 4.93E+00 rem × 0.2 dpm/sample ÷ 2 ÷ 1
   *Dose based on bioassa*y (liver) = 4.93E-01 rem [cell Q13]

   *Dose based on bioassa*y (adrenals) = 2.27E-02 rem × 0.2 dpm/sample ÷ 2 ÷ 1
   *Dose based on bioassa*y (adrenals) = 2.27E-03 rem [cell V13]

3. Annual intake rates based on BZ data [column W]:

   The annual intake rate based on BZ data in cell W13 is 0.49 dpm/day and is taken from cell C20 of the "Alpha Breathing Zone Int Rates" worksheet. The "Alpha Breathing Zone Int Rates" spreadsheet results were previously validated above.

4. Limiting dose based on a comparison of intake rates based on bioassay to intake rates based on BZ Data [columns X, Z, AB, AD]:

The limiting doses based on a comparison of intake rates based on bioassay to intake rates based on BZ data in cells X13, Z13, AB13, and AD13 are:

Lung =	1.97E-02 rem [cell X13]
Bone surface =	1.38E-01 rem [cell Z13]
Liver =	2.57E-02 rem [cell AB13]
Adrenals =	1.18E-04 rem [cell AD13]

The *Annual intake rate* above is 0.49 dpm/day [cell W13].

The *Intake rate based on bioassay* for all organs assessed = 9.40 dpm/day [cells E13, J13, O13, and T13]

Therefore:

Annual intake rate < *Intake rate based on bioassay*
Ratio of Bioassay Intake to BZ Intake = 9.40 dpm/day ÷ 0.49 dpm/day
Ratio of Bioassay Intake to BZ Intake = 19.16

Dose = *Dose based on bioassay* ÷ *Ratio of Bioassay Intake to BZ Intake*

Dose (lung) = 3.78E-01 rem ÷ 19.16
Dose (lung) = 1.97E-02 rem [cell X13]

Dose (bone surface) = 2.65E+00 rem ÷ 19.16
Dose (bone surface) = 1.38E-01 rem [cell Z13]

Dose (liver) = 4.93E-01 rem ÷ 19.16
Dose (liver) = 2.57E-02 rem [cell AB13]

Dose (adrenals) = 2.27E-03 rem ÷ 19.16
Dose (adrenals) = 1.18E-04 rem [cell AD13]

BG Breathing Zone Intake Rates

Beta Example for Cu-64

The annual intake rate based on BZ data (dpm/day) in cell C14 is 7.991E+03 dpm/day.

Annual intake rate = Annual air concentration × 2.22 × 2,400 ÷ 365 ÷ *Decay correction factor* ÷ *Branching fraction*

Annual air concentration = 4.2 pCi/m^3 [cell D12]

2.22 = 2.22 dpm/pCi conversion
2,400 = 2,400 m^3/year inhalation rate
365 = 365 days/year

Branching fraction = 0.39 [cell H14]
Half-Life = 12.701 hours [cells D10 and E10]
Decay correction time = 72 hours [cell A12]

$$\textit{Decay correction factor} = e^{-([0.693 \div 12.701 \text{ hours}] \times 72 \text{ hours})} = 0.01967$$

Annual intake rate = 4.2 pCi/m^3 × 2.22 dpm/pCi × 2,400 m^3/year ÷ 365 days/year ÷ 0.01967 ÷ 0.39

Annual intake rate = 7.991E+03 dpm/day

Annual intake rate based on BZ data (dpm/day) in cell C14 = 7.991E+03 dpm/day.

Gamma Example for Y-86

The annual intake rate based on BZ data (dpm/day) in cell C87 is 5.665E+02 dpm/day.

Annual intake rate = Annual air concentration × 2.22 × 2,400 ÷ 365 ÷ *Decay correction factor* ÷ *Gamma yield*

Annual air concentration = 4.2 pCi/m^3 [cell D12]

2.22 = 2.22 dpm/pCi conversion
2,400 = 2,400 m^3/year inhalation rate
365 = 365 days/year

Gamma Yield = 3.20 [cell J87]
Half-Life = 14.74 hours [cells D87 and E87]
Decay correction time = 72 hours [cell A12]

$$\textit{Decay correction factor} = e^{-([0.693 \div 14.74 \text{ hours}] \times 72 \text{ hours})} = 0.0339$$

Annual intake rate = 4.2 pCi/m^3 × 2.22 dpm/pCi × 2,400 m^3/year ÷ 365 days/year ÷ 0.0339 ÷ 3.20

Annual intake rate = 5.665E+02 dpm/day

Annual intake rate based on BZ data (dpm/day) in cell C87 = 5.665E+02 dpm/day.

Unmonitored BG Organ Doses

Beta Example for Cu-64

1. The annual intake rate based on BZ data (dpm/day) in cell C14 is 7.991E+03 dpm/day and is taken from the "BG Breathing Zone Intake Rates" worksheet validated above.

2. The Committed Dose to Organ from one year of Intake (rem) in cells L14 trough O14 are:

Lung =	2.676E-03 rem [cell L14]
Bone surface =	6.326E-05 rem [cell M14]
Liver =	1.362E-04 rem [cell N14]
Adrenals =	5.839E-05 rem [cell O14]

Committed dose = Annual intake rate × *DCF* × 365 ÷ 1,000 ÷ 2.22

DCF = 2.037E-06 mrem/pCi [cell D14] (lung)
DCF = 4.815E-08 mrem/pCi [cell F14] (bone surface)
DCF = 1.037E-07 mrem/pCi [cell H14] (liver)
DCF = 4.444E-08 mrem/pCi [cell J14] (adrenals)

Committed dose (lung) = 7.991E+03 dpm/day × 2.037E-06 mrem/pCi × 365 days/year ÷ 1,000 mrem/rem ÷ 2.22 dpm/pCi

Committed dose (lung) = 2.676E-03 rem

Committed dose (bone surface) = 7.991E+03 dpm/day x 4.815E-08 mrem/pCi × 365 days/year ÷ 1,000 mrem/rem ÷ 2.22 dpm/pCi

Committed dose (bone surface) = 6.326E-05 rem

Committed dose (liver) = 7.991E+03 dpm/day × 1.037E-07 mrem/pCi × 365 days/year ÷ 1,000 mrem/rem ÷ 2.22 dpm/pCi

Committed dose (liver) = 1.362E-04 rem

Committed dose (adrenals) = 7.991E+03 dpm/day × 4.444E-08 mrem/pCi × 365 days/year ÷ 1,000 mrem/rem ÷ 2.22 dpm/pCi

Committed dose (adrenals) = 5.839E-05 rem

Gamma Example for Y-86

1. The annual intake rate based on BZ data (dpm/day) in cell C59 is 5.665E+02 dpm/day and is taken from the "BG Breathing Zone Intake Rates" worksheet validated above.

2. The Committed Dose to Organ from one year of Intake (rem) in cells L59 through O59 are:

Lung =	2.104E-04 rem [cell L59]
Bone surface =	3.449E-05 rem [cell M59]
Liver =	3.794E-05 rem [cell N59]
Adrenals =	2.863E-05 rem [cell O59]

Committed dose = Annual intake rate × *DCF* × 365 ÷ 1,000 ÷ 2.22

DCF = 2.259E-06 mrem/pCi [cell D59] (lung)
DCF = 3.704E-07 mrem/pCi [cell F59] (bone surface)
DCF = 4.074E-07 mrem/pCi [cell H59] (liver)
DCF = 3.074E-07 mrem/pCi [cell J59] (adrenals)

Committed dose (lung) = 5.665E+02 dpm/day × 2.259E-06 mrem/pCi × 365 days/year ÷ 1,000 mrem/rem ÷ 2.22 dpm/pCi

Committed dose (lung) = 2.104E-04 rem

Committed dose (bone surface) = 5.665E+02 dpm/day × 3.704E-07 mrem/pCi × 365 days/year ÷ 1,000 mrem/rem ÷ 2.22 dpm/pCi

Committed dose (bone surface) = 3.449E-05 rem

Committed dose (liver) = 5.665E+02 dpm/day × 4.074E-07 mrem/pCi × 365 days/year ÷ 1,000 mrem/rem ÷ 2.22 dpm/pCi

Committed dose (liver) = 3.794E-05 rem

Committed dose (adrenals) = 5.665E+02 dpm/day × 3.074E-07 mrem/pCi × 365 days/year ÷ 1,000 mrem/rem ÷ 2.22 dpm/pCi

Committed dose (adrenals) = 2.863E-05 rem

Gross Beta Bioassay Organ Doses

Beta Example for Ag-110m

1. The intakes rates based on a urine sample result of 1 dpm/sample in cells D13, I13, N13, and S13 are taken from row 18 of the "Doses Based on Bioassay" worksheet.

   Intake rate (1 dpm/sample)

Lung =	1109.00 dpm/day [cell D13]
Bone surface =	1109.00 dpm/day [cell I13]
Liver =	1109.00 dpm/day [cell N13]
Adrenals =	1109.00 dpm/day [cell S13]

   The doses based on a urine sample result of 1 dpm/sample in F13, K13, P13, and U13 are taken from row 18 of the "Doses Based on Bioassay" worksheet.

   Dose (1 dpm/sample)

Lung =	7.75E-02 rem [cell F13]
Bone surface =	4.25E-03 rem [cell K13]
Liver =	1.42E-02 rem [cell P13]
Adrenals =	9.96E-03 rem [cell U13]

2. Intake Rates based on bioassay [columns E, J, O, and T]:

   Intake rate based on bioassay = Intake rate (1 dpm/sample) × *MDA/*2 ÷ B*ranching fraction*

   MDA = 2 dpm/sample [cell C10]
   Branching fraction = 0.9864 [cell AF13]

   I*ntake rate based on bioassay* (lung) = 1109.00 dpm/day × 2 dpm/sample ÷ 2 ÷ 0.9864
   I*ntake rate based on bioassay* (lung) = 1124.29 dpm/day [cell E13]

   Intake rate based on bioassay (bone surface) = 1109.00 dpm/day × 2 dpm/sample ÷ 2 ÷ 0.9864
   I*ntake rate based on bioassay* (bone surface) = 1124.29 dpm/day [cell J13]

   Intake rate based on bioassay (liver) = 1109.00 dpm/day × 2 dpm/sample ÷ 2 ÷ 0.9864
   Intake rate based on bioassay (liver) = 1124.29 dpm/day [cell O13]

Intake rate based on bioassay (adrenals) = 1109.00 dpm/day × 2 dpm/sample ÷ 2 ÷ 0.9864
Intake rate based on bioassay (adrenals) = 1124.29 dpm/day [cell T13]

3. Doses based on bioassay [columns G. L, Q, and V]:

The Dose (adjusted for MDA and alpha branching fraction) are:

Lung = 7.86E-02 rem [cell G13]
Bone surface = 4.31E-03 rem [cell L13]
Liver = 1.44E-02 rem [cell Q13]
Adrenals = 1.01E-02 rem [cell V13]

*Dose based on bioassay = Dose (1 dpm/sample) × MDA/*2 ÷ *Branching fraction*

MDA = 2 dpm/sample [cell C10]
Branching fraction = 0.9864 [cell AF13]

Dose based on bioassay (lung) = 7.75E-02 rem × 2 dpm/sample ÷ 2 ÷ 0.9864
Dose based on bioassay (lung) = 7.86E-02 rem [cell G13]

Dose based on bioassay (bone surface) = 4.25E-03 rem × 2 dpm/sample ÷ 2 ÷ 0.9864
Dose based on bioassay (bone surface) = 4.31E-03 rem [cell L13]

Dose based on bioassay (liver) = 1.42E-02 rem × 2 dpm/sample ÷ 2 ÷ 0.9864
Dose based on bioassay (liver) = 1.44E-02 rem [cell Q13]

Dose based on bioassay (adrenals) = 9.96E-03 rem × 2 dpm/sample ÷ 2 ÷ 0.9864
Dose based on bioassay (adrenals) = 1.01E-02 rem [cell V13]

4. Annual intake rates based on BZ data [column W]:

The annual intake rate based on BZ data in cell W13 is 62.67 dpm/day and is taken from cell C62 of the "BG Breathing Zone Intake Rates" worksheet. The "BG Breathing Zone Intake Rates" spreadsheet results were previously validated above.

5. Limiting dose based on a comparison of intake rates based on bioassay to intake rates based on BZ data [columns X, Z, AB, and AD]:

The limiting doses based on a comparison of intake rates based on bioassay to intake rates based on BZ data in cells X13, Z13, Z13, and AD13 are:

Lung = 4.38E-03 rem [cell X13]
Bone surface = 2.40E-04 rem [cell Z13]

Liver = 8.03E-04 rem [cell AB13]
Adrenals = 5.63E-04 rem [cell AD13]

The *Annual intake rate* above is 62.67 dpm/day [cell W13].

The *Intake rate based on bioassay* for all organs assessed = 1,124.29 dpm/day [cells E13, J13, O13, and T13]

Therefore:

Annual intake rate < *Intake rate based on bioassay*
Ratio of Bioassay Intake to BZ Intake = 1,124.29 dpm/day ÷ 62.67 dpm/day
Ratio of Bioassay Intake to BZ Intake = 17.94

Dose = *Dose based on bioassay* ÷ *Ratio of Bioassay Intake to BZ Intake*

Dose (lung) = 7.86E-02 rem ÷ 17.94
Dose (lung) = 4.38E-03 rem [cell X13]

Dose (bone surface) = 4.31E-03 rem ÷ 17.94
Dose (bone surface) = 2.40E-04 rem [cell Z13]

Dose (liver) = 1.44E-02 rem ÷ 17.94
Dose (liver) = 8.03E-04 rem [cell AB13]

Dose (adrenals) = 1.01E-02 rem ÷ 17.94
Dose (adrenals) = 5.63E-04 rem [cell AD13]

Gross Gamma Bio Organ Doses

Gamma Example for Ag-108m

1. The intakes rates based on a urine sample result of 1 dpm/sample in cells D13, I13, N13, and S13 are taken from row 17 of the "Doses Based on Bioassay" worksheet.

   Intake rate (1 dpm/sample)

   Lung = 828.64 dpm/day [cell D13]
   Bone surface = 828.64 dpm/day [cell I13]
   Liver = 828.64 dpm/day [cell N13]
   Adrenals = 828.64 dpm/day [cell S13]

   The doses based on a urine sample result of 1 dpm/sample in F13, K13, P13, and U13 are taken from row 17 of the "Doses Based on Bioassay" worksheet.

Dose (1 dpm/sample)

Lung = 1.06E-01 rem [cell F13]
Bone surface = 5.79E-03 rem [cell K13]
Liver = 1.71E-02 rem [cell P13]
Adrenals = 1.38E-02 rem [cell U13]

2. Intake rates based on bioassay [columns E, J, O, and T]:

*Intake rate based on bioassay = Intake rate (1 dpm/sample) × MDA/*2 *÷ Photon yield*

MDA = 100 dpm/sample [cell C10]
Photon yield = 2.79 [cell AF13]

Intake rate based on bioassay (lung) = 828.64 dpm/day × 100 dpm/sample ÷ 2 ÷ 2.79
Intake rate based on bioassay (lung) = 14,860.83 dpm/day [cell E13]

Intake rate based on bioassay (bone surface) = 828.64 dpm/day × 100 dpm/sample ÷ 2 ÷ 2.79
I*ntake rate based on bioassay* (bone surface) = 14,860.83 dpm/day [cell J13]

Intake rate based on bioassay (liver) = 828.64 dpm/day × 100 dpm/sample ÷ 2 ÷ 2.79
Intake rate based on bioassay (liver) = 14,860.83 dpm/day [cell O13]

Intake rate based on bioassay (adrenals) = 828.64 dpm/day × 100 dpm/sample ÷ 2 ÷ 2.79
Intake rate based on bioassay (adrenals) = 14,860.83 dpm/day [cell T13]

3. Doses based on bioassay [columns G. L, Q, and V]:

The Dose (adjusted for MDA and alpha branching fraction) are:

Lung = 1.89E+00 rem [cell G13]
Bone surface = 1.04E-01 rem [cell L13]
Liver = 3.07E-01 rem [cell Q13]
Adrenals = 2.48E-01 rem [cell V13]

*Dose based on bioassa*y = *Dose (1 dpm/sample) × MDA/*2 *÷ Photon yield*

MDA = 100 dpm/sample [cell C10]
Photon yield = 2.79 [cell AF13]

*Dose based on bioassa*y (lung) = 1.06E-01 rem × 100 dpm/sample ÷ 2 ÷ 2.79
*Dose based on bioassa*y (lung) = 1.89E+00 rem [cell G13]

Dose based on bioassay (bone surface) = 5.79E-03 rem × 100 dpm/sample ÷ 2 ÷ 2.79
Dose based on bioassay (bone surface) = 1.04E-01 rem [cell L13]

Dose based on bioassay (liver) = 1.71E-02 rem × 100 dpm/sample ÷ 2 ÷ 2.79
Dose based on bioassay (liver) = 3.07E-01 rem [cell Q13]

Dose based on bioassay (adrenals) = 1.38E-02 rem × 100 dpm/sample ÷ 2 ÷ 2.79
Dose based on bioassay (adrenals) = 2.48E-01 rem [cell V13]

4. Annual intake rates based on BZ data [column W]:

   The annual intake rate based on BZ data in cell W13 is 21.99 dpm/day and is taken from cell C155 of the "BG Breathing Zone Intake Rates" worksheet. The "BG Breathing Zone Intake Rates" spreadsheet results were previously validated above.

5. Limiting dose based on a comparison of intake rates based on bioassay to intake rates based on BZ Data [columns X, Z, AB, and AD]:

   The limiting doses based on a comparison of intake rates based on bioassay to intake rates based on BZ data in cells X13, Z13, AB13, and AD13 are:

Lung =	2.80E-03 rem [cell X13]
Bone surface =	1.54E-04 rem [cell Z13]
Liver =	4.55E-04 rem [cell AB13]
Adrenals =	3.67E-04 rem [cell AD13]

The *Annual intake rate* above is 21.99 dpm/day [cell W13].
The *Intake rate based on bioassay* for all organs assessed = 14860.83 dpm/day [cells E13, J13, O13, and T13]

Therefore:

Annual intake rate < Intake rate based on bioassay
Ratio of Bioassay Intake to BZ Intake = 14,860.83 dpm/day ÷ 21.99 dpm/day
Ratio of Bioassay Intake to BZ Intake = 675.77
Dose = Dose based on bioassay ÷ Ratio of Bioassay Intake to BZ Intake

Dose (lung) = 1.89E+00 rem ÷ 675.77
Dose (lung) = 2.80E-03 rem [cell X13]

Dose (bone surface) = 1.04E-01 rem ÷ 675.77
Dose (bone surface) = 1.54E-04 rem [cell Z13]

Dose (liver) = 3.07E-01 rem ÷ 675.77
Dose (liver) = 4.55E-04 rem [cell AB13]

Dose (adrenals) = 2.48E-01 rem ÷ 675.77
Dose (adrenals) = 3.67E-04 rem [cell AD13]

ATTACHMENT B

LBNL Air Concentration Data Exposure Model Description

The data used for the statistical reduction of the LBNL air sample data was obtained from the LBNL Dual Data Entry Phase I and II BZ data effort. There were two sets of data entered for the LBNL Dual Data Entry Phase I and II efforts. These two databases were comprised from a number of LBNL air sample reports (LBNL 1963, 1993; LRL-B 1962a, 1962b, 1962c, 1963a, 1963b, 1984).

LBNL monthly summary air sample reports that listed BZ locations that were greater than or equal to 1% of the MPC for the unknown alpha and beta/gamma emitters were entered for the LBNL Dual Data Entry Phase I effort. This available air sample data was from September 1963 through 1987. There was air sample data from 1962 to mid-1963 in this data set that was not monthly average air concentrations data. There were computer printouts of monthly average air concentrations for each air sampling location for 1962 and 1963 that were used to determine the annual average air concentrations for these years. This 1962 and 1963 air sample data were in units of pCi/m^3, and were entered as part of the LBNL Dual Data Entry Phase II effort.

There were also some gaps in the above data. These were missing monthly air sample summary reports in the mid to late 1980's. Computer printouts of LBNL air concentration data for LBNL were used to fill in these gaps. This available data was from December 1984, and January 1993 to June 1993. The December 1984 data were monthly average air concentrations for each air sampling location. The January 1993 to June 1993 data was six months of data for each sampling location. These data were in units of pCi/m^3, and were entered for the LBNL Dual Data Entry Phase II effort.

It should be noted that this exposure model for the LBNL air sample data assumed censored values for non-reported zero or negative air sample data, as explained in the data discussions below.

It should also be noted that a majority of the air sample data was censored for 1964 through 1987 since these data were based on monthly summary air sample reports that listed BZ locations that were greater than or equal to 1% of the MPC. Tables B-1 and B-2 provide the uncensored months, the total number of months, and number of locations for the alpha and beta models sampled. These uncensored months were the air samples results obtained from the monthly air sample summary reports entered in the LBNL Dual Data Entry Phase I effort.

Tables B-5 and B-6 following this section provide details of the available BZ data used from the LBNL Dual Data Entry Phase I and II efforts.

The methods for determining the annual average air concentrations are described below.

1962

For January 1962 through December 1962, there was monthly air sample computer printout data. The annual average air concentrations were determined by the following:

1. "ENV," which were environmental Filter Queen locations, were excluded from the data. The "2 STRM" location was excluded as this was not a building room sample location.

2. Blank alpha and beta/gamma monthly average air concentrations were assigned an average alpha and average beta/gamma air concentration values of 0.001 pCi/m^3 and 0.01 pCi/m^3, respectively. This corresponded to the lowest alpha and beta/gamma monthly average air concentrations reported for any sample location in the data set.

Table B-1. Uncensored Alpha Months, Total Months, and Number of Air Sampling Locations.

Year	Uncensored Alpha Months	Total Months	Number of Air Sampling Locations
1964	26	1,620	135
1965	24	1,608	134
1966	17	1,740	145
1967	22	1,968	164
1968	22	2,028	169
1969	16	1,908	159
1970	20	1,752	146
1971	24	1,560	130
1972	35	1,452	121
1973	20	1,536	128
1974	28	1,416	118
1975	20	1,284	107
1976	8	1,224	102
1977	16	1,176	98
1978	7	1,056	88
1979	6	1,044	87
1980	7	1,092	91
1981	8	1,128	94
1982	14	1,056	88
1983	5	1,020	85
1984	27	972	81
1985	5	948	79
1986	2	948	79
1987	19	948	79

Refer to items 1 and 2 of the September 1963 through 1987 section below for the percent maximum permissible concentration (MPC)/derived concentration guide (DCG) conversions for this period.

3. All unreported air concentrations (i.e., a given month/location combination is not reported) were assigned an average alpha and average beta/gamma air concentration values of 0.001 pCi/$m^3$and 0.01 pCi/m^3, respectively.

4. Any location that was reported at least once in 1962 was assumed to have 12 monthly means for the alpha air concentration and 12 monthly means for the beta/gamma air concentration.

5. The alpha annual average air concentration for each BZ location was determined by averaging the alpha air concentrations for the year. This is the maximum possible mean (MPM) for each location.

6. The beta/gamma annual average air concentration for each BZ location was determined by averaging the beta/gamma air concentrations for the year. This is the MPM for each location.

7. The empirical 95th percentile of the annual alpha MPM for all locations for 1962 was determined.

Table B-2. Uncensored Beta/Gamma Months, Total Months, and Number of Air Sampling Locations.

Year	Uncensored Beta/Gamma Months	Total Months	Number of Air Sampling Locations
1964	26	1,620	135
1965	24	1,608	134
1966	17	1,740	145
1967	22	1,968	164
1968	22	2,028	169
1969	16	1,908	159
1970	20	1,752	146
1971	24	1,560	130
1972	35	1,452	121
1973	20	1,536	128
1974	28	1,416	118
1975	20	1,284	107
1976	8	1,224	102
1977	16	1,176	98
1978	7	1,056	88
1979	6	1,044	87
1980	7	1,092	91
1981	8	1,128	94
1982	14	1,056	88
1983	5	1,020	85
1984	27	972	81
1985	5	948	79
1986	2	948	79
1987	19	948	79

8. The empirical 95th percentile of the annual beta/gamma MPM for all locations for 1962 was determined.

January 1963 Through August 1963

For January 1963 through August 1963, the following was done:

1. Only the room air samples were selected for assessment.

2. Blank alpha and beta/gamma monthly average air concentrations were assigned average alpha and average beta/gamma air concentration values of 0.001 pCi/m^3 and 0.01 pCi/m^3, respectively. This corresponded to the lowest alpha and beta/gamma monthly average air concentrations reported for any sample location in the data set.

3. All unreported air concentrations (i.e., a given month/location combination was not reported) were assigned an average alpha and average beta/gamma air concentration values of 0.001 pCi/m^{3}and 0.01 pCi/m^3, respectively.

4. Any location that was reported at least once in January 1963 through August 1963 was assumed to have eight monthly means for the alpha air concentration and eight monthly means for the beta/gamma air concentration.

5. The data for January 1963 through August 1963 was merged with the September 1963 through December 1963 data discussed in the section below.

September 1963 Through 1987

The reported September 1963 through 1987 BZ locations that were greater than or equal to 1% of the reference MPC were converted back to a monthly average air concentration. This includes any site specific adjustment factors to the MPC or DCG identified in (LBNL 1963). These are provided in items 2 and 3 below.

1. For each location, year, and month in the main dataset that were referenced to a specific radionuclide percent MPC, the MPC's are changed to the corresponding MPC, as shown in the table below. This was necessary to back calculate to air concentrations for these specific locations.

Table B-3. Filter Queen BZ Locations Referenced to a Radionuclide-Specific Percent MPC.

Year	Month	MPC (pCi/m^3)	Radionuclide	ID[a]
1981	6	70	Natural Uranium	1981-6-18-310
1979	3	300	I-125	1979-3-74-363-R
1979	4	6	Am-241	1979-4-50-307W
1980	5	6	Cm-243	1980-5-70A-129-3
1980	5	6	Cm-243	1980-5-70A-129-1
1980	5	6	Cm-243	1980-5-70A-145-2
1980	5	6	Cm-243	1980-5-70A-129-2
1980	5	6	Cm-243	1980-5-70A-129-4
1980	5	6	Cm-243	1980-5-70A-145-1

a. Identifier consisting of year and month, and building, room, and location.

2. Alpha percent MPC/DCG conversion to average monthly air concentrations in pCi/m^3:

   a. September 1963 through December 1970:

      Alpha average monthly air concentration = Alpha % MPC × 0.4 pCi/m^3/100

      Where:

      0.4 pCi/m^3 = Unknown alpha MPC (LBNL 1963).

b. January 1971 through February 1979:

Alpha average monthly air concentration = Alpha % MPC × (0.4 pCi/m^3/2)/100

Where:

0.4 pCi/m^3 = unknown alpha MPC (LBNL 1963)
2 = Unknown alpha MPC adjustment factor (LBNL 1963).

c. March 1979 through December 1987:

Alpha average monthly air concentration = Alpha % MPC × (0.6 pCi/m^3/3)/100

Where:

0.6 pCi/m^3 = Unknown alpha MPC (ERDA 1975).
3 = Unknown alpha MPC adjustment factor (LBNL 1963).

3. Beta/gamma percent MPC/DCG conversion to average monthly air concentrations in pCi/m^3:

a. September 1963 through February 1979:

Beta/gamma average monthly air concentration = Beta/Gamma % MPC × 100 pCi/m^3/100

Where:

100 pCi/m^3 = Unknown beta/gamma MPC (LBNL 1963).

b. March 1979 through December 1987:

Beta/gamma average monthly air concentration = Beta/Gamma % MPC × (300 pCi/m^3/3)/100

Where:

300 pCi/m^3 = Unknown beta/gamma MPC (ERDA 1975).
3 = Unknown beta/gamma MPC adjustment factor (LBNL 1963).

Those BZ locations that were not reported were assumed to have a censored air concentration limit equal to 1% of the reference MPC/DCG including site-specific adjustment factors in items 1 and 2 above. This corresponds to an average alpha air concentration value of 0.004 pCi/m^3 for September 1963 to 1970 and 0.002 pCi/m^3 for 1971 to 1987. This corresponds to an average beta/gamma air concentration value of 1 pCi/m^3 for September 1963 to 1987.

The number of Filter Queen locations sampled per year are listed in Table B-4 below. Before 1971, the number of locations sampled were obtained from the annual summary reports that existed for those years. For 1971 and later, the number of locations sampled per year was based on counting the number of Filter Queen locations excluding any hood and exhaust Filter Queen locations in the monthly air sample computer printouts.

Table B-4. Filter Queen BZ Locations Sampled.

Year	Number of Locations	Reference
1964	135	LBNL 1963
1965	134	LBNL 1963
1966	145	LBNL 1963
1967	164	LBNL 1963
1968	169	LBNL 1963
1969	159	LBNL 1963
1970	146	LBNL 1963
1971	130	LRL-B 1971
1972	121	LRL-B 1973a
1973	128	LRL-B 1973b
1974	118	LRL-B 1974
1975	107	LRL-B 1975
1976	102	LRL-B 1976
1977	98	LRL-B 1977
1978	88	LRL-B 1978
1979	87	LRL-B 1979
1980	91	LRL-B 1980
1981	94	LRL-B 1981
1982	88	LRL-B 1982
1983	85	LRL-B 1983
1984	81	LRL-B 1984
1985	79	LRL-B 1985
1986	79[a]	Not applicable
1987	79[a]	Not applicable
1993	78	LBNL 1993

a. No data available for this year. 1985 number of air sampling locations assumed.

For each year the annual average air concentration was determined by the following:

1. A matrix of the number of sampling locations times 12 months was created. For example, in 1970 there were 146 sampling locations. The matrix would consist of 146 × 12 = 1752 elements.

2. Each annual matrix was filled in with reported air concentration results that were 1% or greater of the reference MPC/DCG. When no alpha result is reported for a given month,

an average alpha air concentration value of 0.004 pCi/m^3 for September 1963 to 1970 and 0.002 pCi/m^3 for 1971 to 1987 were substituted. When no beta result is reported for a given month, an average beta air concentration value of 1 pCi/m^3 for September 1963 to 1987 was substituted.

3. The alpha annual average air concentration for each BZ location was determined by averaging the alpha air concentrations for the year. This is the MPM for each location.

4. The beta/gamma annual average air concentration for each BZ location was determined by averaging the beta/gamma air concentrations for the year. This is the MPM for each location.

5. The empirical 95th percentile of the annual alpha MPM for all locations for all years was determined.

6. The empirical 95th percentile of the annual beta MPM for all locations for all years was determined.

December 1984

The December 1984 monthly gap data was determined by the following method and was merged with the above data:

1. Only the room Filter Queen, and charcoal samples for gaseous activity were selected.

2. Results where either the alpha result is ≥0.002 pCi/m^3 or the beta result is ≥1 pCi/m^3 were selected. These values corresponded to 1% or greater of the reference MPCs used for the data above.

3. Alpha results that were not reported for charcoal filter results that only measure beta/gamma activity from gaseous samples were assigned a value of 0.002 pCi/m^3.

4. This data for the December 1984 monthly gap was merged with the data for September 1963 to 1987 discussed in the previous section.

January 1993 Through June 1993

The January 1993 to June 1993 air concentration data listed six months of data for each Filter Queen sampling location. The 1993 annual average air concentration was determined by the following method:

1. Only the room Filter Queen locations were selected.

2. Alpha and beta/gamma results that were less than or equal to zero were assumed to be equal to the minimum non-zero results for the alpha and beta/gamma results reported in the data set, respectively.

3. The alpha annual average air concentration (the MPM) for each BZ location was determined by averaging the alpha air concentrations for the year.

4. The beta/gamma annual average air concentration (the MPM) for each BZ location was determined by averaging the beta/gamma air concentrations for the year.

5. The empirical 95th percentile of the annual alpha MPM for all locations was determined.

6. The empirical 95th percentile of the annual beta/gamma MPM for all locations was determined.

Table B-5. Alpha BZ Data Details.

Year	Uncensored Positive Results[a]	Uncensored Zero Results	Censored Negative Results	Censored Null Results[b]	Censored Unreported Results[c]	Censored Unavailable Results[d]	Total Months	Number of Air Sampling Locations	Units
1962	1066	0	0	711	1463	0	3240	270	pCi/m^3
1963	858	0	0	330	1020	0	2208	184	Percent MPC/ pCi/m^3
1964	17	0	0	8	1595	0	1620	135	Percent MPC
1965	18	0	0	6	1584	0	1608	134	Percent MPC
1966	9	0	0	8	1723	0	1740	145	Percent MPC
1967	11	0	0	11	1946	0	1968	164	Percent MPC
1968	17	1	0	4	2006	0	2028	169	Percent MPC
1969	9	2	0	5	1892	0	1908	159	Percent MPC
1970	15	0	0	5	1732	0	1752	146	Percent MPC
1971	20	1	0	3	1536	0	1560	130	Percent MPC
1972	27	8	0	0	1417	0	1452	121	Percent MPC
1973	8	11	0	1	1516	0	1536	128	Percent MPC
1974	16	7	0	5	1388	0	1416	118	Percent MPC
1975	8	12	0	0	1264	0	1284	107	Percent MPC
1976	5	3	0	0	1216	0	1224	102	Percent MPC
1977	7	9	0	0	1160	0	1176	98	Percent MPC
1978	5	1	0	1	1049	0	1056	88	Percent MPC
1979	4	2	0	0	1038	0	1044	87	Percent MPC
1980	7	0	0	0	1085	0	1092	91	Percent MPC
1981	6	2	0	0	1120	0	1128	94	Percent MPC
1982	11	2	0	1	1042	0	1056	88	Percent MPC
1983	4	1	0	0	1015	0	1020	85	Percent MPC
1984	13	14	0	5	940	0	972	81	Percent MPC/ pCi/m^3
1985	2	1	0	2	390	553	948	79	pCi/m^3
1986	1	1	0	0	77	869	948	79	Percent MPC

Year	Uncensored Positive Results[a]	Uncensored Zero Results	Censored Negative Results	Censored Null Results[b]	Censored Unreported Results[c]	Censored Unavailable Results[d]	Total Months	Number of Air Sampling Locations	Units
1987	11	8	0	0	376	553	948	79	Percent MPC
1993[e]	581	579	193	Not applicable	Not applicable	Not applicable	Not applicable	78	pCi/m^3

a. Uncensored results were reported positive results for any year or reported zero results in the monthly summary report data for 1963 through 1987, and the 1993 individual air sample data.
b. Null results were blank entries in the reported data for the sampling location.
c. Unreported results were locations that were not sampled every month in the 1962 through August 1963 computer printout data. Unreported results were locations that were not reported in the monthly summary report data for September 1963 through 1987, because they were below the percent MPC reporting limit.
d. Unavailable results were monthly summary report air sample information that were not available for 1985 through 1987.
e. 1993 was an average of the January to June individual (i.e., daily or weekly) air sample results.

Table B-6. Beta/Gamma BZ Data Details.

Year	Uncensored Positive Results[a]	Uncensored Zero Results	Censored Negative Results	Censored Null Results[b]	Censored Unreported Results[c]	Censored Unavailable Results[d]	Total Months	Number of Air Sampling Locations	Units
1962	1773	0	0	4	1463	0	3240	270	pCi/m^3
1963	1183	0	0	5	1020	0	2208	184	Percent MPC/ pCi/m^3
1964	7	0	0	18	1595	0	1620	135	Percent MPC
1965	5	0	0	19	1584	0	1608	134	Percent MPC
1966	6	0	0	11	1723	0	1740	145	Percent MPC
1967	10	0	0	12	1946	0	1968	164	Percent MPC
1968	3	12	0	7	2006	0	2028	169	Percent MPC
1969	3	8	0	5	1892	0	1908	159	Percent MPC
1970	2	13	0	5	1732	0	1752	146	Percent MPC
1971	16	6	0	2	1536	0	1560	130	Percent MPC
1972	32	3	0	0	1417	0	1452	121	Percent MPC
1973	16	4	0	0	1516	0	1536	128	Percent MPC
1974	24	4	0	0	1388	0	1416	118	Percent MPC
1975	15	4	0	1	1264	0	1284	107	Percent MPC
1976	7	1	0	0	1216	0	1224	102	Percent MPC
1977	14	2	0	0	1160	0	1176	98	Percent MPC
1978	5	2	0	0	1049	0	1056	88	Percent MPC
1979	4	2	0	0	1038	0	1044	87	Percent MPC
1980	7	0	0	0	1085	0	1092	91	Percent MPC
1981	6	2	0	0	1120	0	1128	94	Percent MPC
1982	7	7	0	0	1042	0	1056	88	Percent MPC
1983	2	3	0	0	1015	0	1020	85	Percent MPC
1984	24	5	3	0	940	0	972	81	Percent MPC/ pCi/m^3
1985	4	1	0	0	390	553	948	79	pCi/m^3
1986	1	1	0	0	77	869	948	79	Percent MPC

Year	Uncensored Positive Results[a]	Uncensored Zero Results	Censored Negative Results	Censored Null Results[b]	Censored Unreported Results[c]	Censored Unavailable Results[d]	Total Months	Number of Air Sampling Locations	Units
1987	8	11	0	0	376	553	948	79	Percent MPC
1993[e]	688	114	548	Not applicable	Not applicable	Not applicable	Not applicable	78	pCi/m^3

a. Uncensored results were reported positive results for any year or reported zero results in the monthly summary report data for 1963 through 1987, and the 1993 individual air sample data.
b. Null results were blank entries in the reported data for the sampling location.
c. Unreported results were locations that were not sampled every month in the 1962 through August 1963 computer printout data. Unreported results were locations that were not reported in the monthly summary report data for September 1963 through 1987, because they were below the percent MPC reporting limit.
d. Unavailable results were monthly summary report air sample information that were not available for 1985 through 1987.
e. 1993 was an average of the January to June individual (i.e., daily or weekly) air sample results.

ATTACHMENT C

Short-Lived Radionuclide Exclusions

LBNL air samples were typically counted 72 hours after removal to allow for decay of the short-lived radon and thoron daughters (Peck 1964). There was no decay correction applied to these air samples when the results were reported.

To determine if short-lived nuclides are plausible when assigning doses based on air samples, the BZ air concentrations from the dose reconstruction (DR) methodology were decay-corrected back 72 hours to the assumed time of collection stop. Short-lived for this purpose is defined as having a half-life less than 20 hours. The radionuclides along with their decay-corrected average air concentrations are shown in Table C-1.

Table C-1. Radionuclides with Half-Lives Less than 20 Hours.

Radionuclide	Half-Life	Decay-Corrected Annual Average Air Concentration (pCi/m^3)
In-112	14.97 m	6.79E+87
U-239	23.45 m	1.17E+56
Sc-49	57.2 m	2.26E+23
Ga-68	67.71 m	6.69E+19
F-18	109.77 m	2.94E+12
Nd-149	1.728 h	1.46E+13
Ir-195	2.5 h	1.95E+09
Ac-228	6.16 h	1.39E+04
Te-127	9.35 h	8.73E+02
Pb-212	10.64 h	4.57E+02
K-42	12.36 h	2.38E+02
Cu-64	12.701 h	5.47E+02
Nb-90	14.6 h	1.28E+02
Na-24	15 h	1.17E+02
Zr-97	16.9 h	8.04E+01
Pt-197	18.3 h	6.42E+01
C-11	20.39 m	1.01E+70
Cu-60	23.7 m	1.52E+55
Zn-63	38.47 m	1.52E+35
Ag-104	69.2 m	8.44E+18
Ac-224	2.78 h	3.90E+08
Tc-99m	6.015 h	3.29E+05
Cs-127	6.25 h	1.34E+04
Zn-62	9.186 h	1.07E+03
Ta-175	10.5 h	3.81E+02
Y-86	14.74 h	3.88E+01
Br-76	16.2 h	5.29E+01
Zr-86	16.5 h	7.17E+01
Co-55	17.54 h	5.50E+01

The external doses based on air submersion assessment indicates radionuclides with half-lives up to around six hours yield unrealistically high doses and would likely exceed the monthly administrative external dose limits for a worker. This data is presented in Table C-2.

Table C-2. External Doses Based on Air Submersion.

Emission Type	Radionuclide	Annual Breathing Zone Air Concentration (pCi/m^3)	FGR No. 12a Air Submersion Dose Coefficient (Sv per Bq s m-3)	Annual Dose Rate (rads/yr)	Monthly Dose (rads)	Over Monthly Dose Limit	Half-Life	Branching Fraction/ Photon Yield
Beta	In-112	6.79E+87	2.60E-15	3.43E+83	2.86E+82	Yes	14.97 m	0.44
Beta	U-239	1.17E+56	2.17E-15	4.94E+51	4.11E+50	Yes	23.45 m	1
Beta	Sc-49	2.26E+23	1.93E-16	8.48E+17	7.06E+16	Yes	57.2 m	1
Beta	Ga-68	6.69E+19	4.58E-14	5.96E+16	4.97E+15	Yes	67.71 m	1
Beta	F-18	2.94E+12	4.90E-14	2.80E+09	2.33E+08	Yes	109.77 m	1
Beta	Nd-149	1.46E+13	1.81E-14	5.13E+09	4.28E+08	Yes	1.728 h	1
Beta	Ir-195	1.95E+09	2.32E-15	8.82E+04	7.35E+03	Yes	2.5 h	1
Beta	Ac-228	1.39E+04	4.78E-14	1.29E+01	1.08E+00	Yes	6.16 h	0.997
Beta	Te-127	8.73E+02	2.42E-16	4.11E-03	3.42E-04	No	9.35 h	1
Beta	Pb-212	4.57E+02	6.87E-15	6.11E-02	5.09E-03	No	10.64 h	1
Beta	K-42	2.38E+02	1.46E-14	6.76E-02	5.63E-03	No	12.36 h	1
Beta	Cu-64	5.47E+02	9.10E-15	9.69E-02	8.08E-03	No	12.701 h	0.39
Beta	Nb-90	1.28E+02	2.17E-13	5.41E-01	4.51E-02	No	14.6 h	1
Beta	Na-24	1.17E+02	2.13E-13	4.85E-01	4.04E-02	No	15 h	1
Beta	Zr-97	8.04E+01	9.02E-15	1.41E-02	1.18E-03	No	16.9 h	1
Beta	Pt-197	6.42E+01	1.01E-15	1.26E-03	1.05E-04	No	18.3 h	0.44
Gamma	C-11	1.01E+70	4.89E-14	9.58E+66	7.99E+65	Yes	20.39 m	2.43E-06
Gamma	Cu-60	1.52E+55	1.98E-13	5.87E+52	4.90E+51	Yes	23.7 m	1.99E+00
Gamma	Zn-63	1.52E+35	5.32E-14	1.57E+32	1.31E+31	Yes	38.47 m	1.73E-01
Gamma	Ag-104	8.44E+18	1.32E-13	2.17E+16	1.81E+15	Yes	69.2 m	3.06E+00
Gamma	Ac-224	3.90E+08	9.00E-15	6.82E+04	5.69E+03	Yes	2.78 h	6.72E-01
Gamma	Tc-99m	3.29E+05	5.89E-15	3.77E+01	3.14E+00	Yes	6.015 h	5.12E-02
Gamma	Cs-127	1.34E+04	1.93E-14	5.04E+00	4.20E-01	Yes	6.25 h	9.17E-01
Gamma	Zn-62	1.07E+03	2.07E-14	4.31E-01	3.59E-02	No	9.186 h	8.98E-01
Gamma	Ta-175	3.81E+02	4.55E-14	3.37E-01	2.81E-02	No	10.5 h	1.28E+00
Gamma	Y-86	3.88E+01	1.79E-13	1.35E-01	1.13E-02	No	14.74 h	3.20E+00
Gamma	Br-76	5.29E+01	1.34E-13	1.38E-01	1.15E-02	No	16.2 h	1.73E+00
Gamma	Zr-86	7.17E+01	1.28E-14	1.79E-02	1.49E-03	No	16.5 h	1.21E+00
Gamma	Co-55	5.50E+01	9.78E-14	1.05E-01	8.73E-03	No	17.54 h	1.31E+00

a. EPA (1993).

A 1953 memorandum about "Sampling Methods and Requirements for Estimating Airborne Radioparticulate Hazards" (Thaxter 1953) indicated that because LBNL was a research facility, technical contamination was not tolerated as it could invalidate weeks of research. LBNL vigorously sought no airborne contamination. They used high-efficiency exhaust air cleaning in their enclosures. Nuisance contamination levels were lower by several orders of magnitude than permissible levels on the health basis.

Air samples were changed weekly in locations of moderate experimental activity and daily in locations of intense experimental activity at LBNL. Glovebox manifolds and rooms that contained gloveboxes were air sampled. Air samples were surveyed daily to check for hot samples.

High count rate reading air samples were investigated. These investigation air samples are found in various special or investigation air sample reports (LBL 1965, 1967, 1975, 1988, 1995). A limited review of these various special air sample reports indicates that the lowest measured alpha and beta/gamma activities were a small fraction (less than 1%) of the unknown MPC or derived air concentration (DAC). The unknown MPC or DAC was typically used to determine the percent of the MPC or DAC in these investigation air sample reports. Starting in 1971, LBNL used an alpha MPC of 0.2 pCi/m^3 (LBNL 1988) to compare most air concentrations in these special investigations air sample reports. This was a factor of 2 lower than the National Bureau of Standards Handbook 69 (NBS 1959, revised 1963) value of 0.4 pCi/m^3 and a factor of three lower than the ERDA 0524 (ERDA 1975) and DOE 5480 (DOE 1981) values of 0.6 pCi/m^3. LBNL used a beta/gamma MPC of 100 pCi/m^3 throughout. This was a factor of three lower than the ERDAM 0524 and DOE 5480 values of 300 pCi/m^3.

The special investigation air sample data indicates that air samples less than 1% of the MPC or DAC were investigated. The short-lived radionuclides in Table 1 are beta/gamma emitters. One percent of the MPC or DAC results in a beta/gamma air sample investigation limit of 1 pCi/m^3. One reference provides alpha and beta/gamma air sample counting results immediately and after a 48-hour decay period after removal (Patterson 1957). The data indicates that the radon and thoron daughters contribute to an initial count rate approximately 30 to 60 times higher for alpha air samples counted immediately after sample removal. The radon and thoron daughters contribute to an initial count rate approximately three times higher for the beta/gamma air samples counted immediately after sample removal. Accounting for radon/thoron daughter decay, these beta/gamma air samples would read around three pCi/m^3 immediately after removal. The half-life cutoff in the LBNL DR Methodology was around 12 hours. This still included decay-corrected beta emitters on the order of 100 pCi/m^3. This also included decay-corrected gamma emitters on the order of 10 pCi/m^3.

The above indicates that short-lived radionuclide activities decay-corrected back 72 hours, such as those in Table 1, cannot be produced at levels to maintain the continuous exposures without resulting in significant field contamination in the work areas. It is also evident, based on the LBNL air sampling program, that these shorter-lived radionuclides in Table 1 would have been detected and investigated well before reaching these decay-corrected air concentrations levels.

Based on the above, short-lived radionuclides with half-lives less than 12.7 hours were excluded from the potential unmonitored radionuclides.

The short-lived radionuclides excluded were:

1. Gamma emitters:
   Carbon-11, ^{60}Cu, ^{63}Zn, ^{104}Ag, ^{224}Ac, ^{99m}Tc, ^{127}Cs, ^{62}Zn, ^{175}Ta.
2. Beta emitters:
   Indium-112, ^{239}U, ^{49}Sc, ^{68}Ga, ^{18}F, ^{149}Nd, ^{195}Ir, ^{228}Ac, ^{127}Te, ^{212}Pb, ^{42}K.