OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT CALCULATION COVER SHEET			1. QA: QA Page: 1 Of: 22
2. Calculation Title Disposable Canister Waste Acceptance Criteria			
3. Document Identifier (including Revision Number) CAL-WPS-SE-000007 REV 00			
4. Total Attachments Three (3)	5. Attachment Numbers – Number of pages in each I-1; II-4; III-11		
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9. Remarks			

Revision History

10. Revision No.	11. Description of Revision
00	Initial issue.

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TABLES

1. PURPOSE

The purpose of this calculation is to provide the bases for defining the preclosure limits on radioactive material releases from radioactive waste forms to be received in disposable canisters at the Monitored Geologic Repository (MGR) at Yucca Mountain. Specifically, this calculation will provide the basis for criteria to be included in a forthcoming revision of the Waste Acceptance System Requirements Document (WASRD) that limits releases in terms of non-isotope-specific canister release dose-equivalent source terms. These criteria will be developed for the Department of Energy spent nuclear fuel (DSNF) standard canister, the Multicanister Overpack (MCO), the naval spent fuel canister, the High-Level Waste (HLW) canister, the plutonium can-in-canister, and the large Multipurpose Canister (MPC). The shippers of such canisters will be required to demonstrate that they meet these criteria before the canisters are accepted at the MGR.

The Quality Assurance program is applicable to this calculation. The work reported in this document is part of the analysis of DSNF and is performed using procedure AP-3.12Q, *Calculations*. The work done for this analysis was evaluated according to procedure QAP-2-0, *Control of Activities,* which has been superseded by AP-2.21Q, *Quality Determinations and Planning for Scientific, Engineering, and Regulatory Compliance Activities*. This evaluation determined that such activities are subject to the requirements of DOE/RW/0333P, *Quality Assurance Requirements and Description* (DOE 2000). This work is also prepared in accordance with the development plan titled *Design Basis Event Analyses on DOE SNF and Plutonium Can-In-Canister Waste Forms* (CRWMS M&O 1999a) and *Technical Work Plan For: Department of Energy Spent Nuclear Fuel Work Packages* (CRWMS M&O 2000d). This calculation contains no electronic data applicable to any electronic data management system.

2. METHOD

The calculations described in this document are performed using equations solved in Excel 97 spreadsheets. Performing the calculations in spreadsheets is advantageous since the calculations are easily understood and they can easily be checked. In Sections 2.1, 2.2, 2.3, and 2.5, the general equations that form the basis for the WASRD criteria are presented. These equations have been used for calculating offsite doses (in rem) from source terms (measured in curies).

In Section 2.5, the equations in Sections 2.1, 2.2, and 2.3 are used to develop the basis for limiting the canister radioactive material released in terms of a "canister release dose-equivalent source term" with units of rem/canister. The canister release dose-equivalent source term is insensitive to specific radionuclides released and represents a limit at the point of release, as described in Section 2.5.

Only inhalation and air submersion doses are considered in this calculation (Assumption 3.7). The potential doses from ingestion, water immersion, and contaminated soil are assumed to be negligible in comparison to the combined inhalation and air submersion dose to the receptors at the assumed site boundary. It is assumed that site boundary receptor locations will be evacuated shortly after the postulated event, thus precluding these source term pathways. Submersion doses include doses to the skin, extremities, and to the lens of the eye.

2.1 SOURCE TERMS

The amount of the j[th] isotope in the waste form released to the environment by a hypothetical canister drop and breach event (on a per-canister basis) is calculated using Equation (1) (DOE 1994, p. 1-2):

$$ST_j = MAR_j \times DR_j \times ARF_j \times RF_j \times LPF_j \qquad (1)$$

where:

- ST_j - the amount of the j[th] isotope in the waste form that is released to the environment per canister breached (Ci/canister)
- MAR_j - the material-at-risk of the j[th] isotope in the waste per canister (Ci/canister)
- DR_j - the fraction of the j[th] isotope in the material-at-risk that is affected by a hypothetical canister drop and breach event (i.e., the damage ratio) (unitless)
- ARF_j - the airborne release fraction of the j[th] isotope applicable to the hypothetical canister drop and breach event (unitless)
- RF_j - the respirable fraction of the j[th] isotope applicable to the hypothetical canister drop and breach event (unitless)
- LPF_j - the leakpath factor (LPF) of the j[th] isotope applicable to the hypothetical canister drop and breach event (unitless).

Note that it is necessary to identify each specific LPF for use in deriving the equations in Section 2.5, where ST_j will only consider $LPF_{j,canister}$ (defined below). The other LPF factors defined below are considered in determining the canister release dose-equivalent source term criteria:

$$LPF_j = LPF_{j,canister} \times LPF_{j,cask} \times LPF_{j,facility} \times LPF_{j,HEPA} \qquad (2)$$

where:

- $LPF_{j,canister}$ - the leakpath factor of the j[th] isotope applicable to the canister; i.e., the fraction of radioactive material transported from the canister to the cavity of a shipping cask, a waste package, the facility, or to the environment (unitless). This factor is selected by the waste shippers in determining their canister release and is not used in determining the canister release dose-equivalent source term.
- $LPF_{j,cask}$ - the leakpath factor of the j[th] isotope applicable to the cask; i.e., the fraction of radioactive material transported from the cask to the facility or the environment (unitless). In this analysis, this factor has a value of one if the hypothetical canister drop and breach event does not involve a cask; otherwise a value of 0.1 is used (taking credit for cask or sealed disposal container [DC] retention) (Assumption 3.8).
- $LPF_{j,facility}$ - the leakpath factor of the j[th] isotope applicable to the facility; i.e., the fraction of radioactive material transported from the facility to the environment (unitless). In this analysis, this factor has a value of one (Assumption 3.8).

$LPF_{j,HEPA}$ - the leakpath factor of the jth isotope applicable to the high-efficiency particulate air (HEPA) filters; i.e., the fraction of radioactive material transported through the HEPA filter to the environment (unitless). In this analysis, this factor has a value of one; i.e., no credit is taken for the waste handling building HEPA system (Assumption 3.4).

2.2 INHALATION AND SUBMERSION DOSE

The inhalation dose to an individual from each isotope in the source term from the canistered waste is derived from Regulatory Guide 1.109, Section C.2:

$$D_{j,k}^{inh} = ST_j \times \frac{\chi}{Q} \times BR \times conv \times DCF_{j,k}^{inh} \qquad (3)$$

The air submersion dose is calculated using Equation (4). Note that the source term, ST_j, has been modified by dividing out the respirable fraction (*RF*) in Equation (4) since the air submersion dose should not be modified by the fraction of the source material that is respirable:

$$D_{j,k}^{sub} = \frac{ST_j}{RF_j} \times \frac{\chi}{Q} \times conv \times DCF_{j,k}^{sub} \qquad (4)$$

where for Equations (3) and (4):

$D_{j,k}^{inh}$ - radiation dose from the j^{th} isotope of the canistered waste to the k^{th} organ due to inhalation (rem)

$D_{j,k}^{sub}$ - radiation dose from the j^{th} isotope of the canistered waste to the k^{th} organ due to air submersion (rem)

k - organ index, where organs are gonads, breast, lungs, red marrow, bone surface, thyroid, remainder, and effective (whole body) (unitless)

$\frac{\chi}{Q}$ - atmospheric dispersion factor (s/m^3)

BR - breathing rate (m^3/s)

$DCF_{j,k}^{inh}$ - the inhalation dose conversion factor of the j^{th} isotope for the k^{th} organ (Sv/Bq)

$DCF_{j,k}^{sub}$ - the submersion dose conversion factor of the j^{th} isotope for the k^{th} organ [(Sv m^3)/(Bq s)]

conv - DCF unit conversion factor: 3.7×10^{12} (rem Bq)/(Ci Sv) = 3.7×10^{10} (Bq)/(Ci) x 100 (rem/Sv) (Eckerman et al. 1988, p. 121).

2.3 DDE, CDE, CEDE, TEDE, SDE, AND LDE

The canister radioactive material release events are all assumed to be Category 2 Design Basis Events (DBEs) (Assumption 3.2). The dose measures applicable to Category 2 DBEs at the MGR are defined as follows (10 CFR 20.1003):

Deep-Dose Equivalent (DDE): applies to external whole-body exposure and is equal to the dose equivalent at a tissue depth of 1 cm.

Committed Dose Equivalent (CDE): the dose equivalent to an individual organ or tissue that is received from an intake of radioactive material by an individual during the 50-year period following the intake.

Committed Effective Dose Equivalent (CEDE): the sum of the products of the weighting factors applicable to each of the body organs or tissues that are irradiated and the committed dose equivalent to these organs or tissues, commonly referred to as the whole body dose.

Total Effective Dose Equivalent (TEDE): the sum of the deep-dose equivalent (for external exposures) and the committed effective dose equivalent (for internal exposures).

Skin Dose Equivalent (SDE): applies to the dose to the skin due to the air submersion pathway; the occupational dose limits include an annual shallow dose equivalent to the skin (or to any extremity) limit of 50 rem (10 CFR 20.1003).

Lens Dose Equivalent (LDE): applies to the external exposure of the lens of the eye and is taken as the dose equivalent at a tissue depth of 0.3 centimeters.

The TEDE and the CDE + DDE dose measures, ignoring the ingestion dose pathway (Assumption 3.7) are calculated using Equations (5) and (6) (10 CFR 20):

$$TEDE = CEDE + DDE = \sum_j D^{inh}_{j,effective} + \sum_j D^{sub}_{j,effective} \tag{5}$$

$$CDE_k + DDE = \sum_j D^{inh}_{j,k} + \sum_j D^{sub}_{j,effective} \quad \text{where } k \neq \text{effective} \tag{6}$$

where:

$TEDE$	-	total effective dose equivalent (rem)
$CEDE$	-	committed effective dose equivalent (rem)
DDE	-	deep dose equivalent (rem)
CDE_k	-	committed dose equivalent to the kth organ (rem)

The SDE is calculated using Equation (7) (10 CFR 20):

$$SDE = \sum_j D^{sub}_{j,skin} \tag{7}$$

where:

SDE	-	dose to the skin (skin dose equivalent) (rem)
$D^{sub}_{j,skin}$	-	dose from the jth isotope to the skin from air submersion (rem)

2.4 DISCUSSION OF LDE, SUBMERSION AND INHALATION DCFs

Submersion doses include the SDE and the LDE. In this calculation it is assumed that SDE is negligible and is bounded by the TEDE (Assumption 3.10). The doses to the skin and extremities are only due to the submersion pathway. The SDE is calculated using the dose conversion factors (DCFs) for skin reported in Federal Guidance Report Number 12 (Eckerman and Ryman 1993, Table III.1, pp. 57-73). However, the LDE cannot be calculated using the DCFs for lens of the eye because of a lack of lens of the eye DCF data. Instead, methodology presented in NUREG-1567 (NRC 2000, Section 9.5.2.2) is used to calculate the LDE. The NUREG-1567 methodology states that compliance with the LDE limit is achieved if the sum of the SDE and the TEDE does not exceed 0.15 Sv (15 rem). Therefore, the LDE is calculated by summing the SDE and TEDE.

Table 1 presents a comparison of the inhalation DCFs and the air submersion DCFs for radionuclides typically found in commercial spent nuclear fuel (SNF) as well as DSNF (Eckerman and Ryman 1993 [Table III.1, pp. 57-73], Eckerman et al. 1988 [p. 121; Table 2.1, pp. 121-153 and 182], CRWMS M&O 1999d [Attachment III]). This table sorts the DCFs by radionuclide (according to contribution percentage to a total DCF [the total DCF is a summation of the individual DCFs in each column]) as well as by inhalation effective DCFs, air submersion effective DCFs, and air submersion skin DCFs. In this table the air submersion DCFs were divided by a breathing rate of 3.33E-4 m3/s (ICRP 1975, p. 346) to make the units for the inhalation and air submersion DCFs equitable. A comparison of the DCFs in Table 1 on a per-radionuclide basis demonstrates that the inhalation dose DCFs (and, therefore, dose) are several orders of magnitude greater than the air submersion DCFs. Therefore, the SDE will be several orders of magnitude smaller than the TEDE dose and the LDE will have approximately the same order of magnitude as the TEDE. In accordance with the NUREG-1567 LDE limit rule, the dose limit of 15 rem to the lens of the eye (the LDE) will not be exceeded because the TEDE is limited to 5 rem and the LDE is limited to 15 rem. Therefore, this examination of the DCFs demonstrates that the SDE will be negligible and will be bounded by the TEDE.

Table 1. Comparison of Inhalation and Adjusted Air Submersion Dose Conversion Factors (Sv/Bq)

Isotope	Inhalation Effective DCFs[1]	Percent of sum of DCFs	Isotope	Air Submersion Effective DCFs[2]	Percent of sum of DCFs	Isotope	Air Submersion Skin DCFs[2]	Percent of sum of DCFs
Ac-227	1.81E-03	35.43%	Co-60	3.78E-10	24.22%	Co-60	4.35E-10	17.27%
Th-229	5.80E-04	11.35%	Sn-126	2.32E-10	14.82%	Sn-126	3.92E-10	15.56%
Th-232	4.43E-04	8.67%	Nb-94	2.31E-10	14.80%	Ru-106	3.27E-10	12.98%
Pa-231	3.47E-04	6.79%	Cs-134	2.27E-10	14.55%	Nb-94	2.86E-10	11.34%
U-232	1.78E-04	3.48%	Eu-154	1.84E-10	11.80%	Cs-134	2.84E-10	11.26%
Np-237	1.46E-04	2.86%	Cs-137	8.18E-11	5.24%	Eu-154	2.49E-10	9.87%
Cm-245	1.23E-04	2.41%	Sb-125	6.07E-11	3.88%	Cs-137	1.32E-10	5.23%
Cm-246	1.22E-04	2.39%	Cm-247	4.50E-11	2.88%	Sb-125	7.96E-11	3.16%
Am-241	1.20E-04	2.35%	Ru-106	3.12E-11	2.00%	Cm-247	5.38E-11	2.13%
Am-243	1.19E-04	2.33%	U-235	2.16E-11	1.38%	Cl-36	4.41E-11	1.75%
Pu-239	1.16E-04	2.27%	Cm-243	1.77E-11	1.13%	Kr-85	3.96E-11	1.57%
Pu-240	1.16E-04	2.27%	Cm-245	1.19E-11	0.76%	Cm-243	2.94E-11	1.17%
Am-242m	1.15E-04	2.25%	Th-229	1.15E-11	0.74%	Sr-90	2.76E-11	1.10%
Cm-247	1.12E-04	2.19%	Eu-155	7.48E-12	0.48%	U-235	2.59E-11	1.03%
Pu-242	1.11E-04	2.17%	Am-243	6.55E-12	0.42%	Cd-113m	2.55E-11	1.01%
Pu-238	1.06E-04	2.07%	Pa-231	5.17E-12	0.33%	Th-229	1.62E-11	0.64%
Th-230	8.80E-05	1.72%	Np-237	3.09E-12	0.20%	Cm-245	1.61E-11	0.64%
Cm-243	8.30E-05	1.62%	Am-241	2.46E-12	0.16%	Eu-155	1.02E-11	0.40%
Cm-244	6.70E-05	1.31%	I-129	1.14E-12	0.07%	Am-243	8.26E-12	0.33%
U-233	3.66E-05	0.72%	Ra-226	9.46E-13	0.06%	Tc-99	8.23E-12	0.33%
U-234	3.58E-05	0.70%	Kr-85	3.57E-13	0.02%	Pa-231	7.33E-12	0.29%

(Continued)

Table 1. Comparison of Inhalation and Adjusted Air Submersion Dose Conversion Factors (Sv/Bq) (Continued)

Isotope	Inhalation Effective DCFs[1]	Percent of sum of DCFs	Isotope	Air Submersion Effective DCFs[2]	Percent of sum of DCFs	Isotope	Air Submersion Skin DCFs[2]	Percent of sum of DCFs
U-236	3.39E-05	0.66%	Pb-210	1.69E-13	0.01%	Np-237	4.62E-12	0.18%
U-235	3.32E-05	0.65%	Ac-227	1.12E-13	0.01%	Am-241	3.84E-12	0.15%
U-238	3.20E-05	0.63%	Am-242m	9.52E-14	0.01%	I-129	3.30E-12	0.13%
Sm-147	2.02E-05	0.40%	Cl-36	6.70E-14	0.00%	Cs-135	2.72E-12	0.11%
Cm-242	4.67E-06	0.09%	Th-230	5.23E-14	0.00%	Pm-147	2.44E-12	0.10%
Pb-210	3.67E-06	0.07%	U-233	4.89E-14	0.00%	Ra-226	1.44E-12	0.06%
Ra-226	2.32E-06	0.05%	U-232	4.26E-14	0.00%	Se-79	1.11E-12	0.04%
Pu-241	2.23E-06	0.04%	Th-232	2.62E-14	0.00%	Ac-227	9.86E-13	0.04%
Ra-228	1.29E-06	0.03%	U-234	2.29E-14	0.00%	C-14	7.30E-13	0.03%
Cd-113m	4.13E-07	0.01%	Sr-90	2.26E-14	0.00%	Am-242m	4.08E-13	0.02%
Sr-90	3.51E-07	0.01%	Cd-113m	2.08E-14	0.00%	Pb-210	3.84E-13	0.02%
Ru-106	1.29E-07	0.00%	Cm-242	1.71E-14	0.00%	U-232	1.78E-13	0.01%
Nb-94	1.12E-07	0.00%	U-236	1.50E-14	0.00%	U-233	1.37E-13	0.01%
Zr-93	8.67E-08	0.00%	Cm-244	1.47E-14	0.00%	Th-230	1.35E-13	0.01%
Eu-154	7.73E-08	0.00%	Pu-238	1.47E-14	0.00%	Cm-242	1.29E-13	0.01%
Co-60	5.91E-08	0.00%	Pu-240	1.43E-14	0.00%	Nb-93m	1.29E-13	0.01%
I-129	4.69E-08	0.00%	Cm-246	1.34E-14	0.00%	U-234	1.28E-13	0.01%
Sn-126	2.69E-08	0.00%	Nb-93m	1.33E-14	0.00%	Pu-238	1.23E-13	0.00%
Cs-134	1.25E-08	0.00%	Pu-239	1.27E-14	0.00%	Pu-240	1.18E-13	0.00%
Eu-155	1.12E-08	0.00%	Pu-242	1.20E-14	0.00%	Cm-244	1.17E-13	0.00%
Pm-147	1.06E-08	0.00%	U-238	1.02E-14	0.00%	U-236	1.07E-13	0.00%
Cs-137	8.63E-09	0.00%	Tc-99	4.86E-15	0.00%	Cm-246	1.05E-13	0.00%
Sm-151	8.10E-09	0.00%	Pm-147	2.08E-15	0.00%	Th-232	1.03E-13	0.00%
Nb-93m	7.90E-09	0.00%	Cs-135	1.70E-15	0.00%	Pu-242	9.82E-14	0.00%
Cl-36	5.93E-09	0.00%	H-3	9.94E-16	0.00%	U-238	8.74E-14	0.00%
Pd-107	3.45E-09	0.00%	Se-79	9.10E-16	0.00%	Pu-239	5.59E-14	0.00%
Sb-125	3.30E-09	0.00%	C-14	6.73E-16	0.00%	Sm-151	5.71E-16	0.00%
Se-79	2.66E-09	0.00%	Pu-241	2.18E-16	0.00%	Pu-241	3.51E-16	0.00%
Tc-99	2.25E-09	0.00%	Sm-151	1.08E-16	0.00%	Fe-55	0.00E+00	0.00%
Cs-135	1.23E-09	0.00%	Fe-55	0.00E+00	0.00%	H-3	0.00E+00	0.00%
Ni-63	8.39E-10	0.00%	Ni-59	0.00E+00	0.00%	Ni-59	0.00E+00	0.00%
Fe-55	7.26E-10	0.00%	Ni-63	0.00E+00	0.00%	Ni-63	0.00E+00	0.00%
C-14	5.64E-10	0.00%	Pd-107	0.00E+00	0.00%	Pd-107	0.00E+00	0.00%
Ni-59	3.58E-10	0.00%	Ra-228	0.00E+00	0.00%	Ra-228	0.00E+00	0.00%
H-3	1.73E-11	0.00%	Sm-147	0.00E+00	0.00%	Sm-147	0.00E+00	0.00%
Kr-85	0.00E+00	0.00%	Zr-93	0.00E+00	0.00%	Zr-93	0.00E+00	0.00%

[1] Eckerman and Ryman 1993

[2] Eckerman et al. 1988; these air submersion DCFs have been divided by a breathing rate of 3.33E-4 m3/s.

2.5 CANISTER RELEASE DOSE-EQUIVALENT SOURCE TERMS

The WASRD criterion that will limit canister radioactive material releases is derived in this calculation as a canister release dose-equivalent source term (with units of rem/canister) rather than an isotopic-specific radioactive material release limit (with units of curies/canister). The term "canister release dose-equivalent source term" is used to differentiate it from the actual dose limit for a receptor located at the site boundary as defined by the regulations discussed in the following paragraph. The WASRD criterion limits the dose at the point of canister release located within a controlled facility where no public receptors are present.

The canister release dose-equivalent source terms are determined by back-calculation from the regulatory limits provided in *Revised Interim Guidance Pending Issuance of New U. S. Nuclear Regulatory Commission (NRC) Regulations (Revision 01, July 22, 1999), for Yucca Mountain, Nevada* (Dyer 1999) (Assumption 3.1), which implements proposed 10 CFR 63 Part 111.B.2 (64 FR 8640, Part 111.B.2). For Category 2 DBEs (only Category 2 DBEs are considered, as discussed in Assumption 3.2) the TEDE offsite dose limit to be applied to Equation (5) is 5 rem (per event) (Dyer 1999) and the CEDE + DDE dose limit to be applied to Equation (6) is 50 rem (per event) (Dyer 1999). The approach used to determine the effective and maximum organ source terms uses these two equations and divides them into two parts: one part that involves MGR-related parameters and a second part related to the canister and its contents. New terms are then defined for each equation that are common to both parts of the equations. These terms are then used as the WASRD criteria. Thus, Equations (5) and (6) can be rewritten as:

$$5\,rem \geq TEDE = CEDE + DDE = \sum_j D^{inh}_{j,effective} + \sum_j D^{sub}_{j,effective} \tag{8}$$

$$50\,rem \geq CDE_k + DDE = \sum_j D^{inh}_{j,k} + \sum_j D^{sub}_{j,effective} \quad \text{where } k \neq \text{effective} \tag{9}$$

From Equations (3) and (4) the radiation doses from canistered waste due to inhalation and submersion (excluding the BR and χ/Q) can be defined as:

$$RD^{inh}_{eff} = \sum_j \left(ST_j \times conv \times DCF^{inh}_{j,eff}\right) \tag{10}$$

$$RD^{sub}_{eff} = \sum_j \left(ST_j \times conv \times DCF^{sub}_{j,eff}\right) \tag{11}$$

and

$$RD^{inh}_{k} = \sum_j \left(ST_j \times conv \times DCF^{inh}_{j,k}\right) \tag{12}$$

where:

RD^{inh}_{eff}	-	effective radiation dose from canistered waste due to inhalation, summed over all isotopes (rem/canister)
RD^{sub}_{eff}	-	effective radiation dose from the canistered waste due to air submersion, summed over all isotopes (rem m^3/s canister)
RD^{inh}_{k}	-	radiation dose from canistered waste based on organ index (k) due to inhalation (rem/canister)
ST_j	-	source term of the j^{th} isotope in the waste form (Ci/canister)
$DCF^{inh}_{j,eff}$	-	the effective inhalation dose conversion factor of the j^{th} isotope (Sv/Bq)
$DCF^{inh}_{j,k}$	-	the inhalation dose conversion factor of the j^{th} isotope for the k^{th} organ (Sv/Bq)

$DCF^{sub}_{j,eff}$ - the effective submersion dose conversion factor of the j[th] isotope [(Sv m^3)/(Bq s)]

conv - DCF unit conversion factor: 3.7 x 10^{12} (rem Bq)/(Ci Sv) = 3.7 x 10^{10} (Bq)/(Ci) x 100 (rem/Sv) (Eckerman et al. 1988, p. 121)

j - isotope index (unitless)

k - organ index (unitless).

By combining Equations (3) and (4) with Equations (10) through (12), introducing several new factors, and substituting into Equations (8) and (9), the following equations are derived:

$$5\,rem \geq \left(RD^{inh}_{eff} \times n_{canister} \times S \times LPF_{j,MGR} \times \chi/Q \times BR\right) + \left(RD^{sub}_{eff} \times n_{canister} \times S \times LPF_{j,MGR} \times \chi/Q\right) \quad (13)$$

$$50\,rem \geq \left(RD^{inh}_{k} \times n_{canister} \times S \times LPF_{j,MGR} \times \chi/Q \times BR\right) + \left(RD^{sub}_{eff} \times n_{canister} \times S \times LPF_{j,MGR} \times \chi/Q\right) \quad (14)$$

where:

S - safety factor (unitless)

$n_{canister}$ - number of canisters involved in the bounding hypothetical canister drop and breach event (unitless)

$LPF_{j,MGR}$ - the leakpath factor of the j[th] isotope applicable to the MGR-related parameters i.e., $LPF_{j,cask}$, $LPF_{j,facility}$, and $LPF_{j,HEPA}$ (unitless).

Four parameters in these equations are associated with the MGR: the atmospheric dispersion factor (χ/Q), the leakpath factor ($LPF_{j,MGR}$) and two added factors ($n_{canister}$ and a safety factor, *S*). The number of canisters term, $n_{canister}$, is defined to take into consideration the number of canisters involved in the hypothetical canister drop and breach event. The safety factor, S, provides a safety margin between the regulatory limit and the operating limit.

Equations (13) and (14) can be rewritten to separate the MGR-related parameters from the canister-related parameters as:

$$\frac{5\,rem}{BR\left(n_{canister} \times S \times LPF_{j,MGR} \times \chi/Q\right)} \geq RD^{inh}_{eff} + \frac{RD^{sub}_{eff}}{BR} \quad (15)$$

$$\frac{50\,rem}{BR\left(n_{canister} \times S \times LPF_{j,MGR} \times \chi/Q\right)} \geq RD^{inh}_{k} + \frac{RD^{sub}_{eff}}{BR} \quad (16)$$

Finally, the left-hand terms in Equations (15) and (16) are defined as:

$$\frac{5\,rem}{BR\left(n_{canister} \times S \times LPF_{j,MGR} \times \chi/Q\right)} = TEDE_{canister} \quad (17)$$

$$\frac{50\,rem}{BR\left(n_{canister} \times S \times LPF_{j,MGR} \times \chi/Q\right)} = \left(CDE_k + DDE\right)_{canister} \tag{18}$$

where:

$TEDE_{canister}$ - canister release dose-equivalent source term based on the 5-rem TEDE limit (rem/canister)

$\left(CDE_k + DDE\right)_{canister}$ - canister release dose-equivalent source term based on the 50-rem (CDE+DDE) limit (rem/canister).

Equations (17) and (18) will be solved to obtain the canister release dose-equivalent source term criteria for each of the canisters considered in this calculation. After substituting terms from Equations (17) and (18), Equations (15) and (16) can be rewritten as:

$$TEDE_{canister} \geq RD_{eff}^{inh} + \left(RD_{eff}^{sub}/BR\right) \text{ (rem/canister)} \tag{19}$$

and

$$\left(CDE_k + DDE\right)_{canister} \geq RD_k^{inh} + \left(RD_{eff}^{sub}/BR\right) \text{ (rem/canister)} \tag{20}$$

Equations (19) and (20) are used by the waste shipper to determine if the canister radioactive material release is within the canister release dose-equivalent source term criteria for a hypothetical canister drop and breach event. The methodology for performing this analysis is described with an accompanying sample calculation in Attachment III. Therefore, the allowable dose-equivalent source terms (with units of rem per canister) resulting from a canister breach at the MGR are defined as the $TEDE_{canister}$ and the $\left(CDE_k + DDE\right)_{canister}$. Because of differences in dose conversion factors between the whole body and maximum organ for inhalation and submersion, both limits are provided to ensure that regulatory requirements are met in establishing the canister release dose-equivalent source terms.

3. ASSUMPTIONS

3.1 The approach used to determine canister release dose-equivalent source terms is based on performing a back-calculation from the regulatory site boundary dose limits. *Basis:* This approach will allow for the calculation of a canister release dose-equivalent source term (calculated using MGR-related parameters) such that compliance to the WASRD criteria can be demonstrated using calculations that use fuel/canister-specific parameters. *Usage:* This assumption is used in the derivation (in Section 2.5) of the methodology used to calculate the canister release dose-equivalent source term criteria equations.

3.2 The canister radioactive material release event scenarios are all assumed to be Category 2 DBEs. *Basis:* Event sequence frequencies for postulated scenarios for the current

MGR design were calculated in *Preliminary Selection of MGR Design Basis Events* (CRWMS M&O 1999e). Frequencies were used to categorize event sequences as either Category 1 or Category 2. Event sequences with a scenario frequency less than once per million years are considered to be beyond design basis events and screened out from further consideration. Design basis events involved with the handling of canisters or DCs that contain canisters have been designated as Category 2 DBEs. *Usage:* This assumption is used in developing (in Section 2.5) the methodology used to establish the canister release dose-equivalent source terms. Since the postulated event sequences are assumed to be Category 2 DBEs (CRWMS M&O 1999e), the Category 2 regulatory limits were used in the methodology presented in Section 2.5.

3.3 In determining $n_{canister}$, the maximum number of canisters involved in the bounding hypothetical canister drop event for each fuel type (as determined in Assumption 3.9) are assumed to fail. *Basis:* This is a conservative assumption that will provide for restrictive canister radioactive material releases. *Usage:* This assumption is used in the canister release dose-equivalent source term calculations in Attachment II, as outlined in Table 2.

3.4 No credit is taken for the hot cell or the waste handling building HEPA system. *Basis:* According to the *Repository Safety Strategy* (CRWMS M&O 2000a, Section 5.3, Table 5-2), the waste handling building HEPA system will provide only defense-in-depth for Category 2 DBEs. Therefore no credit for this mitigating system can be taken in a licensing-basis calculation. If the HEPA system was upgraded to a Quality Level 1 (QL-1) safety system and credit was taken, the canister release dose-equivalent source terms would increase by at least a factor of 100. Particulate reductions of up to 3E-04 are possible with HEPA systems, but current NRC precedence limits reductions to 1E-02. *Usage:* This assumption is used in the canister release dose-equivalent source term calculations in Attachment II.

3.5 A distance of 11 km is assumed as the nearest point of public access from the waste handling building for purposes of a dose receptor point. *Basis*: This is a conservative assumption that will not require confirmation because the distance between the waste handling building and the nearest point of public access on the proposed Land Withdrawal Boundary (to the West) is 11.65 kilometers (DTN: MO0001YMP00001.000). Other points on the proposed Land Withdrawal Boundary which are closer to the waste handling building are on either the Nevada Test Site or Nellis Air Force Base property where public access is prohibited (DTN: MO0001YMP00001.000). *Usage*: This assumption is used throughout this calculation.

3.6 A safety factor (*S*) of 1.0 is assumed for this calculation. *Basis:* The waste suppliers will include conservatism in their canister equivalent-dose calculations to cover the uncertainties in their input parameters. *Usage:* This assumption is used in the canister release dose-equivalent source term calculations in Attachment II. No safety factors have been included the calculations to establish the canister release dose-equivalent source term criteria since the margins for uncertainties have been considered in each parameter defined in Equations (17) and (18).

3.7 Only inhalation and air submersion doses are considered in calculating offsite doses; the potential doses from ingestion, water immersion, and contaminated soil (groundshine) are negligible. *Basis*: Category 2 design basis events result in acute releases over a period of a few hours and the doses from these pathways may be controlled by interdiction as needed, thus precluding these source term pathways. This assumption has minimal impact on the calculation results and requires no further confirmation. *Usage:* This assumption is used in the derivation of canister radioactive material source term equations in Section 2.

3.8 An LPF of 1.0 is assumed in this calculation for the waste handling building and the hot cell within the waste handling building. No credit is taken for radionuclide retention in either the hot cell or the waste handling building. Using an LPF of 1.0 for the hot cell and waste handling building implies taking no credit for source term reduction mechanisms such as gravitational settling, plate out, or operation of the waste handling building ventilation system (i.e., HEPA filtration of the source term per Assumption 3.4 before it is released to the environment). An LPF of 0.1 is assumed for cask retention during cask handling in the waste handling building. *Basis: Leakpath Factors for Radionuclide Releases from Breached Confinement Barriers* (CRWMS 2000b, Table 8, page 32) recommends the use of 0.02 for LPF_{cask} instead of 0.1; the use of 0.1 instead of 0.02 is considered reasonable and conservative for this calculation. *Usage:* This assumption is used in the canister release dose-equivalent source term calculations in Attachment II.

3.9 It is assumed that the canisters and canister combinations shown in Table 2 are those that may be potentially involved in a hypothetical canister drop event. The following canisters and canister combinations are considered:

- Department of Energy Spent Nuclear Fuel (DSNF) 18-inch diameter canisters
- DSNF 24-inch diameter canisters
- Multicanister Overpack (MCO)
- MCOs loaded in a cask or DC with HLW canisters
- HLW canisters
- Immobilized plutonium canisters loaded in a cask or DC with HLW canisters
- DSNF 18-inch diameter canister loaded in a cask or DC with HLW canisters
- DSNF 24-inchdiameter canister loaded in a cask or DC with HLW canisters
- Naval spent fuel canisters and MPCs.

Basis: These combinations are based on the system description document for the canister transfer system canisters to be received at the MGR (CRWMS M&O 2000c, Section 1.2.1) as well as design documents for the various waste packages to be used at the MGR (CRWMS M&O 2000e, Section 6; CRWMS M&O 2000f, Section 6) and transportation cask specifications and capacities (DOE 2001, Section 7.1). This calculation is only applicable to these canister combinations. This calculation must be revised or another calculation performed, if necessary, to incorporate any changes to these canister types and combinations. *Usage:* This assumption is used in the canister release dose-equivalent source term calculations in Attachment II.

Table 2. Maximum Number of Canisters by Canister Type and Location[1]

Hypothetical Canister Drop Event Location	DSNF 18" dia.	DSNF 24" dia.	MCO	MCO/HLW	HLW	Pu/HLW	DSNF 18" dia/ HLW	DSNF 24" dia/ HLW	Naval Spent Fuel and MPCs
Carrier Bay	9	5	4	3/1, 2/2, 1/3	5	1/4	1/5	N/A[2]	1
DC Handling System	1	1	2	2/2	5	1/4	1/5	1/4, 2/3	1
Canister Transfer System	1	1	1	1	1	1	1	1	1

1 The combination nomenclature indicates the mix of canister types; 3/1 in the MCO/HLW column indicates 3 MCOs and 1 HLW canister in the same cask.

2 N/A: Not Applicable; at this time it is not anticipated that HLW will be mixed with DSNF 24-inch diameter canisters in transportation casks.

3.10 It is assumed that SDE is negligible and is bounded by the TEDE. *Basis:* As demonstrated in Section 2.4, the SDE is typically several orders of magnitude smaller than the TEDE dose. *Usage:* This assumption is used in the derivation of canister radioactive material source term equations in Section 2.

4. COMPUTER SOFTWARE AND MODEL USAGE

4.1 SOFTWARE INFORMATION

No software routines, macros, or models, as defined by AP-SI.1Q, are used in this analysis. Microsoft Excel spreadsheets using existing functions in Excel were used to multiply and divide applicable terms for dose equations and respirable fractions and is considered appropriate for this application. The spreadsheets used in this calculation have no specific version; they are explicitly coupled with this calculation and its documentation. No changes can be made to the spreadsheets without a revision of this calculation document or the production of a separate calculation that documents the changes.

The checking process provides verification that the results documented in Attachments II and III are correct for the input data contained therein.

The spreadsheets used in this calculation were developed in Excel 97 SR-2 under the Windows 95 operating system on an IBM-compatible personal computer. The spreadsheets used herein have been developed to function under Excel 97 on a personal computer platform with the Windows 95 operating system. Execution of the spreadsheets under a different version of Excel, on a different computing platform, and/or with a different operating system may impact the veracity of their results. In accordance with AP-SI.1Q, Rev. 2, ICN 4, Section 2.1.1, Excel SR97-2 is an exempt software product.

4.2 SPREADSHEET INFORMATION

This calculation uses Excel spreadsheets to generate canister release source terms (Attachment II). The Excel spreadsheets contained in Attachment II are described as follows:

- Table II-1 - Calculation of canister release source terms in the carrier bay. The calculations performed in this sheet involve dividing the applicable regulatory limit (i.e., TEDE or CDE+DDE) by the product of multiplying the number of canisters by the applicable LPFs by the BR by the X/Q and the safety factor.

- Table II-2 – Calculation of canister release source terms in the DC handling system. The calculations performed in this sheet involve dividing the applicable regulatory limit (i.e., TEDE or CDE+DDE) by the product of multiplying the number of canisters by the applicable LPFs by the BR by the X/Q and the safety factor.

- Table II-3 - Calculation of canister release source terms in the canister transfer system. The calculations performed in this sheet involve dividing the applicable regulatory limit (i.e., TEDE or CDE+DDE) by the product of multiplying the number of canisters by the applicable LPFs by the BR by the X/Q and the safety factor.

This calculation also uses Excel spreadsheets to generate canister release source terms (Attachment III) as an example calculation. The Excel spreadsheets contained in Attachment III are described as follows:

- Table III-1 - Lists the material at risk (MAR) in Savannah River Site (SRS) HLW canisters (no calculations).

- Tables III-2 and III-3 - DCFs for isotopes contained in the SRS HLW canisters (no calculations).

- Table III-4 – Calculation of the airborne release fraction. The pulverized fraction (PULF) and deposition factor are multiplied.

- Table III-5 – Calculation of the pulverization factor (PULF) for SRS HLW. Five numbers are multiplied to produce the PULF.

- Table III-6 – SRS HLW canister inhalation dose. The potential radiological dose is multiplied by the inhalation DCF, the airborne release fraction (ARF), and a conversion factor for determination of the canister source term for each organ and isotope.

- Table III-7 – SRS HLW canister submersion dose. The potential radiological dose is multiplied by the submersion DCF, the ARF, and a conversion factor for determination of the canister source term for each organ and isotope.

5. CALCULATIONS

5.1 CALCULATION DESCRIPTION

The purpose of this calculation is to provide the bases for defining the preclosure canister release dose-equivalent source terms for all radioactive waste forms to be received in disposable canisters at the MGR. This calculation will provide the basis for criteria to be used in the WASRD that specifies the dose-equivalent source terms for radioactive material releases from disposable multi-element canisters that result from a hypothetical canister drop and breach event. These criteria will be developed for the DSNF standard canister, the Multicanister Overpack (MCO), the naval spent fuel canister, the HLW canister, and the plutonium can-in-canister.

5.2 INPUT DATA

5.2.1 Canister Quantities

As discussed in Assumption 3.9, the number and types of canisters that are assumed in a hypothetical canister drop event (such as a crane drop event) in the three areas of the waste handling building are provided in Table 2. These areas include the Carrier Bay, Canister Transfer System, and the Disposal Container Handling System. It should be noted that during canister handling activities, the canisters will be prevented from dropping onto another canister through engineered features such as gates and covers.

5.2.2 Leakpath Factor

An LPF of 1.0 is used in this calculation for the waste handling building and the hot cell inside the waste handling building (Assumptions 3.4 and 3.8). Using an LPF of 1.0 implies taking no credit for source term reduction mechanisms such as gravitational settling or operation of the waste handling building ventilation system (i.e., HEPA filtration of the source term before it is released to the environment). An LPF of 0.1 is used in this calculation to credit the barrier provided by a cask in the event that canisters inside a cask are involved in a hypothetical canister drop and breach event, such as in the cask handling area (Assumption 3.8).

5.2.3 Atmospheric Dispersion Factors

The atmospheric dispersion factor (χ/Q) used in this calculation was extracted from *Calculations of Acute and Chronic "Chi/Q" Dispersion Estimates for a Surface Release* (CRWMS M&O 1999b, Table 3, page 11). The interpolated 11-kilometer (Assumption 3.5) Acute Sector 99.5% χ/Q value used is 2.17E-05 s/m^3.

5.2.4 Breathing Rate

An adult breathing rate of 3.33×10^{-4} m^3/s was used for offsite dose calculations. This value is based on the Reference Man breathing rate established by the International Commission on Radiological Protection (ICRP 1975, p. 346) and accepted by the Nuclear Regulatory Commission for accident analysis (NRC 1997, p. 7-7). This breathing rate is based on the volume intake of air for light activity and is considered to be appropriate for hypothetical canister drop and breach event scenarios resulting in short-term ($\leq$ 8-hour) exposures of an individual to radiation at the nearest site boundary.

5.2.5 Safety Factor

The safety factor (S) has a value of 1.0 (Assumption 3.6). The waste suppliers will include conservatism in their canister release dose-equivalent source term calculation to cover uncertainties in their input parameters. Using a value of 1.0 indicates the most conservative safety factor.

5.3 CALCULATION

The purpose of this calculation is to determine the preclosure canister release dose-equivalent source terms for radioactive waste forms to be received in disposable canisters at the MGR. By back-calculating from the effective and maximum organ regulatory dose limits, the desired canister release dose-equivalent source terms can be determined. In this calculation the regulatory limited doses are assumed to be received by an offsite individual at the nearest site boundary from the radionuclide release point (i.e., 11,000 meters for this calculation). The radioactive material release is postulated to occur as a result of a hypothetical canister drop and breach event occurring during the handling of canisters within the waste handling building (such as lifting of canisters by a crane). These doses to individual organs and the whole body are assumed to result from exposure through inhalation and submersion.

5.3.1 Calculation of Canister Release Dose-Equivalent Source Terms

In this section, the equations used to produce canister release dose-equivalent source terms, as described in Section 2 and calculated in Attachment II, are described.

The inhalation source terms are formed by the radionuclides available for release if the engineered barriers (i.e., the canisters) are breached. The inhalation doses are the 50-year committed dose equivalents. A person who inhales the radionuclides suspended in the passing radioactive plume receives the inhalation dose. The air submersion doses result from a person receiving a dose from a passing airborne radioactive cloud. The dispersion of the radioactive material is determined using a site-specific atmospheric dispersion factor.

The LPF is the fraction of airborne material-at-risk that leaves a confinement barrier after the action of depletion mechanisms such as precipitation, gravitational settling of the released particulate material, or agglomeration, through the confinement barrier. Confinement barriers include such barriers as canisters, hot cells, buildings, and/or filters. The waste suppliers will include conservatism in their canister release dose-equivalent source term calculation to cover uncertainties in their input parameters.

The equations for calculating the canister release dose-equivalent source terms were derived in Section 2.5:

$$\frac{5\,rem}{BR\left(n_{canister} \times S \times LPF_{j,MGR} \times \chi/Q\right)} = TEDE_{canister} \tag{17}$$

$$\frac{50\,rem}{BR\left(n_{canister} \times S \times LPF_{j,MGR} \times \chi/Q\right)} = \left(CDE_k + DDE\right)_{canister} \tag{18}$$

As mentioned in Section 2, the allowable doses (in rem) released from a canister into the MGR facility are defined as the $TEDE_{canister}$ and the $\left(CDE_k + DDE\right)_{canister}$ dose-equivalent source terms.

Equations (17) and (18) are used to calculate the canister release dose-equivalent source terms with units of rem/canister. The calculations are presented in Attachment II.

5.3.2 Canister Release Dose-Equivalent Source Term Sample Calculation

The methodology for determining the canister dose-equivalent source terms is described in Attachment III with an accompanying sample calculation.

6. RESULTS

6.1 CANISTER DOSE-EQUIVALENT SOURCE TERMS FOR CANISTER COMBINATIONS

This document may be affected by technical product input information that requires confirmation. Any changes to the document that may occur as a result of completing the confirmation activities will be reflected in subsequent revisions. The status of the technical product input information quality may be confirmed by review of the DIR database.

Table 3 provides the per-canister dose-equivalent source terms calculated for each canister combination as provided in Attachment II. An important factor in the calculations is the number of canisters ($n_{canister}$) involved in the postulated hypothetical canister drop event. The consequences of radioactive material releases from the canisters, and thus, the canister release dose-equivalent source terms determined in this calculation are dependent on the location of the radioactive material release (whether the canisters are in a sealed cask or not) and, by association, the number of canisters involved in the hypothetical canister drop event (Assumption 3.9).

Another important factor in these calculations is the LPF. In this calculation, the LPF is also determined based on where the hypothetical canister drop event is postulated to occur. If the radioactive material release occurs due to a cask drop in the Carrier Bay, an LPF of 0.1 was used to credit the barrier provided by the cask. In the DC Handling System and Canister Transfer System an LPF of 1.0 was used; the canisters are out of the casks and no credit is taken for hot cells or the waste handling building itself (Assumptions 3.4 and 3.8).

Other inputs that may significantly impact the dose results in this calculation include: (1) the assumed location of the restricted area boundary (i.e., 11,000 meters [(Assumption 3.5]), (2) the χ/Q value that was obtained from an MGR calculation, and (3) the safety factor (S) used in the analysis (Assumption 3.6).

6.2 CANISTER RELEASE DOSE-EQUIVALENT SOURCE TERMS

Table 3 lists the canister combinations that were considered in this calculation, the location of the bounding hypothetical drop event, and the most restrictive canister release dose-equivalent source term applicable to the combination as determined from Attachment II. The canister release dose-equivalent source term criteria is shown in Table 4. The criteria in Table 4 was selected for each canister type based on the canister combination release dose-equivalent source terms shown in Table 3. The canister combination that results in the most restrictive (i.e., lowest) dose-equivalent source term sets the criteria for that canister type. For example, from Attachment II calculations, a HLW canister loaded with four other HLW canisters was determined to have a TEDE dose-equivalent source term of 1.38E+08 rem/canister, an MCO loaded with HLW was determined to have a TEDE dose-equivalent source term of 1.73E+08 rem/canister, a DSNF 18-inch diameter canister loaded with HLW was determined to have a TEDE dose-equivalent source term of 1.15E+08 rem/canister, and a DSNF 24-inch diameter canister loaded with HLW was determined to have a TEDE dose-equivalent source term of 1.38E+08 rem/canister. Therefore, for the HLW canister type, the most restrictive TEDE dose-equivalent source term of 1.15E+08 rem/canister was selected as the dose-equivalent source term criteria. This same method was used to select the most restrictive dose-equivalent source term criteria for the DSNF 18-inch diameter canister, the DSNF 18-inch diameter canister, and the MCO canister.

Table 3. Canister Release Dose-Equivalent Source Terms for Canister Combinations

Canister Combination	Number of Canisters in the Hypothetical Canister Drop Event	Bounding Hypothetical Canister Drop Event Location	Canister Release Dose-Equivalent Source Term (rem/canister)	
			$TEDE_{canister}$	$(CDE + DDE)_{canister}$
Single DSNF 18" dia. canister	1	DC Handling System, Canister Transfer System	6.92E+08	6.92E+09
Single DSNF 24" dia. canister	1	DC Handling System, Canister Transfer System	6.92E+08	6.92E+09
MCO	2	DC Handling System	3.46E+08	3.46E+09
MCO/HLW	4	DC Handling System	1.73E+08	1.73E+09
HLW	5	DC Handling System	1.38E+08	1.38E+09
Pu/HLW	5	DC Handling System	1.38E+08	1.38E+09
DSNF 18" dia. HLW	6	DC Handling System	1.15E+08	1.15E+09
DSNF 24" dia. HLW	5	DC Handling System	1.38E+08	1.38E+09
Naval Spent Fuel Canister, MPC	1	DC Handling System, Canister Transfer System	6.92E+08	6.92E+09

Table 4. Canister Release Dose-Equivalent Source Terms

Canister Type	Canister Release Dose-Equivalent Source Term (rem/canister)	
	Effective ($TEDE_{canister}$)	Max Organ [$(CDE + DDE)_{canister}$]
DSNF 18" dia. canister	1.15E+08	1.15E+09
DSNF 24" dia. canister	1.38E+08	1.38E+09
MCO	1.73E+08	1.73E+09
HLW	1.15E+08	1.15E+09
Pu Can-in-Canister	1.38E+08	1.38E+09
Naval Spent Fuel Canister, MPC	6.92E+08	6.92E+09

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7.2 SOURCE DATA

MO0001YMP00001.000. Minimum Distances from Selected Yucca Mountain Project Sites to Public Lands. Submittal date: 01/26/2000.

7.3 CODES, STANDARDS, AND REGULATIONS

Regulatory Guide 1.109, Rev. 1. 1977. *Calculation of Annual Doses to Man from Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance with 10 CFR Part 50, Appendix I.* Washington, D.C.: U.S. Nuclear Regulatory Commission. Readily available.

10 CFR (Code of Federal Regulations) 20. 1999. Energy: Standards for Protection Against Radiation. Readily available.

64 FR (Federal Register) 8640. Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain, Nevada. Proposed rule 10 CFR Part 63. Readily available.

7.4 PROCEDURES

Procedures listed below are retrievable from the OCRWM Program documents database contained in Lotus Notes 4.6 and the Bechtel SAIC Company (BSC) INTRANET.

AP-2.21Q, Rev. 1, ICN 0, BSCN 1. Quality Determinations and Planning for Scientific, Engineering, and Regulatory Compliance Activities.

AP-3.12Q, Rev. 0, ICN 4. Calculations.

AP-SI.1Q, Rev. 3, ICN 01, ECN 01. Software Management.

QAP-2-0, Rev. 5. Control of Activities.

8. ATTACHMENTS

Attachment I	Acronyms
Attachment II	Canister Release Dose-Equivalent Source Term Calculation Spreadsheets
Attachment III	Sample Forward Calculation to Determine Canister Release Dose-Equivalent Source Terms

Attachment I

Acronyms

ARF	Airborne Release Fraction
BR	Breathing Rate
BSC	Bechtel SAIC Company
CDE	Committed Dose Equivalent
CEDE	Committed Effective Dose Equivalent
DBE	Design Basis Event
DC	Disposal Container
DCF	Dose Conversion Factor
DDE	Deep Dose Equivalent
DIRS	Document Input Reference System
DOE	U.S. Department of Energy
DR	Damage Ratio
DSNF	Department of Energy Spent Nuclear Fuel
FR	Federal Register
HEPA	High-Efficiency Particulate Air
HLW	High-Level Waste
LDE	Lens Dose Equivalent
LPF	Leakpath Factor
MAR	Material-at-Risk
MCO	Multicanister Overpack
MGR	Monitored Geologic Repository
MPC	Multipurpose Canister
NRC	U.S. Nuclear Regulatory Commission
PULF	Pulverized Fraction
QL	Quality Level
RF	Respirable Fraction
SDE	Skin Dose Equivalent
SNF	Spent Nuclear Fuel
SRS	Savannah River Site
ST	Source Term
TEDE	Total Effective Dose Equivalent
WASRD	Waste Acceptance System Requirements Document

Attachment II

Canister Release Dose-Equivalent Source Term Calculation Spreadsheets

This attachment contains the Excel 97 spreadsheets used to calculate the canister release dose-equivalent source terms.

Table II-1. Canister Release Dose-Equivalent Source Terms - Carrier Bay										
Canister	No. of Canisters (-)	LPF facility (-)	LPF cask (-)	Breathing Rate (m3/sec)	11,000 m X/Q (sec/m3)	Safety Factor (-)	TEDE Limit (rem)	(CDE+ DDE) Limit (rem)	TEDE Canister (rem/canister)	(CDE+DDE) Canister (rem/canister)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
DSNF 18 in dia.	9	1	0.1	3.33E-04	2.17E-05	1	5	50	7.69E+08	7.69E+09
DSNF 24 in dia.	5	1	0.1	3.33E-04	2.17E-05	1	5	50	1.38E+09	1.38E+10
MCO	4	1	0.1	3.33E-04	2.17E-05	1	5	50	1.73E+09	1.73E+10
MCO/HLW	4	1	0.1	3.33E-04	2.17E-05	1	5	50	1.73E+09	1.73E+10
HLW	5	1	0.1	3.33E-04	2.17E-05	1	5	50	1.38E+09	1.38E+10
Pu/HLW	5	1	0.1	3.33E-04	2.17E-05	1	5	50	1.38E+09	1.38E+10
DSNF 18 in dia./HLW	6	1	0.1	3.33E-04	2.17E-05	1	5	50	1.15E+09	1.15E+10
DSNF 24 in dia./HLW	N/A	1	0.1	3.33E-04	2.17E-05	1	5	50	N/A	N/A
Naval, MPC	1	1	0.1	3.33E-04	2.17E-05	1	5	50	6.92E+09	6.92E+10

Method: TEDE Canister (rem/canister) is calculated by the following:

Rem/Canister = [TEDE Limit, Sec. 2.5]/[(No. Canisters, Assumption 3.9)*(LPF Facility, Assumption 3.8)*(LPF Cask, Assumption 3.8)*
(Breathing Rate, Section 5.2.4)*(X/Q, Section 5.2.3)*(Safety Factor, Section 5.2.5)]

(9) = (7)/[(1) x (2) x (3) x (4) x (5) x (6)]

Method: (CDE+DDE)canister (rem/canister) is calculated by the following:

Rem/Canister = [CDE+DDE) Limit, Sec. 2.5]/[(No. Canisters, Assumption 3.9)*(LPF Facility, Assumption 3.8)*(LPF Cask, Assumption 3.8)*
(Breathing Rate, Section 5.2.4)*(X/Q, Section 5.2.3)*(Safety Factor, Section 5.2.5)]

(10) = (8)/[(1) x (2) x (3) x (4) x (5) x (6)]

References: CRWMS M&O 2000e, Section 6; CRWMS M&O 2000f, Section 6; DOE 2001, Section 7.1

Table II-2. Canister Release Dose-Equivalent Source Terms - DC Handling System										
Canister	No. of Canisters (-) (1)	LPF facility (-) (2)	LPF cask (-) (3)	Breathing Rate (m3/sec) (4)	11,000 m X/Q (sec/m3) (5)	Safety Factor (-) (6)	TEDE Limit (rem) (7)	(CDE+ DDE) Limit (rem) (8)	TEDE Canister (rem/canister) (9)	(CDE+DDE) Canister (rem/canister) (10)
DSNF 18 in dia.	1	1	N/A	3.33E-04	2.17E-05	1	5	50	6.92E+08	6.92E+09
DSNF 24 in dia.	1	1	N/A	3.33E-04	2.17E-05	1	5	50	6.92E+08	6.92E+09
MCO	2	1	N/A	3.33E-04	2.17E-05	1	5	50	3.46E+08	3.46E+09
MCO/HLW	4	1	N/A	3.33E-04	2.17E-05	1	5	50	1.73E+08	1.73E+09
HLW	5	1	N/A	3.33E-04	2.17E-05	1	5	50	1.38E+08	1.38E+09
Pu/HLW	5	1	N/A	3.33E-04	2.17E-05	1	5	50	1.38E+08	1.38E+09
DSNF 18 in dia./HLW	6	1	N/A	3.33E-04	2.17E-05	1	5	50	1.15E+08	1.15E+09
DSNF 24 in dia./HLW	5	1	N/A	3.33E-04	2.17E-05	1	5	50	1.38E+08	1.38E+09
Naval, MPC	1	1	N/A	3.33E-04	2.17E-05	1	5	50	6.92E+08	6.92E+09

Method: TEDE Canister (rem/canister) is calculated by the following:

Rem/Canister = [TEDE Limit, Sec. 2.5]/[(No. Canisters, Assumption 3.9)*(LPF Facility, Assumption 3.8)*(LPF Cask, Assumption 3.8)*
(Breathing Rate, Section 5.2.4)*(X/Q, Section 5.2.3)*(Safety Factor, Section 5.2.5)]

(9) = (7)/[(1) x (2) x (3) x (4) x (5) x (6)]

Method: (CDE+DDE)canister (rem/canister) is calculated by the following:

Rem/Canister = [CDE+DDE) Limit, Sec. 2.5]/[(No. Canisters, Assumption 3.9)*(LPF Facility, Assumption 3.8)*(LPF Cask, Assumption 3.8)*
(Breathing Rate, Section 5.2.4)*(X/Q, Section 5.2.3)*(Safety Factor, Section 5.2.5)]

(10) = (8)/[(1) x (2) x (3) x (4) x (5) x (6)]

References: CRWMS M&O 2000e, Section 6; CRWMS M&O 2000f, Section 6; DOE 2001, Section 7.1

Table II-3. Canister Release Dose-Equivalent Source Terms - Canister Transfer System										
Canister	No. of Canisters (-)	LPF facility (-)	LPF cask (-)	Breathing Rate (m3/sec)	11,000 m X/Q (sec/m3)	Safety Factor (-)	TEDE Limit (rem)	(CDE+ DDE) Limit (rem)	TEDE Canister (rem/canister)	(CDE+DDE) Canister (rem/canister)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
DSNF 18 in dia.	1	1	N/A	3.33E-04	2.17E-05	1	5	50	6.92E+08	6.92E+09
DSNF 24 in dia.	1	1	N/A	3.33E-04	2.17E-05	1	5	50	6.92E+08	6.92E+09
MCO	1	1	N/A	3.33E-04	2.17E-05	1	5	50	6.92E+08	6.92E+09
HLW	1	1	N/A	3.33E-04	2.17E-05	1	5	50	6.92E+08	6.92E+09
Naval, MPC	1	1	N/A	3.33E-04	2.17E-05	1	5	50	6.92E+08	6.92E+09

Method: TEDE Canister (rem/canister) is calculated by the following:

Rem/Canister = [TEDE Limit, Sec. 2.5]/[(No. Canisters, Assumption 3.9)*(LPF Facility, Assumption 3.8)*(LPF Cask, Assumption 3.8)*(Breathing Rate, Section 5.2.4)*(X/Q, Section 5.2.3)*(Safety Factor, Section 5.2.5)]

(9) = (7)/[(1) x (2) x (3) x (4) x (5) x (6)]

Method: (CDE+DDE)canister (rem/canister) is calculated by the following:

Rem/Canister = [CDE+DDE) Limit, Sec. 2.5]/[(No. Canisters, Assumption 3.9)*(LPF Facility, Assumption 3.8)*(LPF Cask, Assumption 3.8)*(Breathing Rate, Section 5.2.4)*(X/Q, Section 5.2.3)*(Safety Factor, Section 5.2.5)]

(10) = (8)/[(1) x (2) x (3) x (4) x (5) x (6)]

References: CRWMS M&O 2000e, Section 6; CRWMS M&O 2000f, Section 6; DOE 2001, Section 7.1

Attachment III

Sample Forward Calculation to Determine Canister Release Dose-Equivalent Source Terms

The purpose of this attachment is to provide the waste producer the methodology for determining the canister release dose-equivalent source terms for radioactive material released from a breached canister (with units of rem/canister) that is not isotope-specific. These dose-equivalent source terms can then be compared to the criteria in Table 4 (i.e., the canister release dose-equivalent source terms) for that waste form. This example assumes a hypothetical canister breach event involving a vitrified high-level waste form produced at the Department of Energy's Savannah River Site (SRS). However, the general approach is applicable to all waste forms.

The SRS HLW canister has the potential to be tipped over during handling operations in the waste handling building. This sample calculation involves the breach of a single SRS HLW canister. All inputs for this sample calculation were obtained from *DOE High-Level Vitrified Waste Dose Calculation* (CRWMS M&O 1999c).

Equations (19) and (20) were derived in Section 2.5. These equations are used to determine the canister release dose-equivalent source terms for radioactive material released during any hypothetical canister breach event. They are solved to determine if the canister contents meet the criteria established for that canister (these criteria are presented in Table 4):

$$TEDE_{canister} \geq RD_{eff}^{inh} + \left(RD_{eff}^{sub}/BR\right) \text{ rem/canister)} \quad (19)$$

and

$$\left(CDE_k + DDE\right)_{canister} \geq RD_k^{inh} + \left(RD_{eff}^{sub}/BR\right) \text{ (rem/canister)} \quad (20)$$

where

$TEDE_{canister}$	-	canister release dose-equivalent source term based on the 5-rem TEDE limit (rem/canister)
$\left(CDE_k + DDE\right)_{canister}$	-	canister release dose-equivalent source term based on the 50-rem (CDE+DDE) limit (rem/canister)
RD_{eff}^{inh}	-	effective radiation dose from canistered waste due to inhalation summed over all isotopes (rem/canister)
RD_{eff}^{sub}	-	effective radiation dose from the canistered waste due to air submersion summed over all isotopes (rem m^3/s canister)
RD_k^{inh}	-	radiation dose from canistered waste based on organ index (k) due to inhalation (rem/canister)
BR	-	breathing rate (m^3/s)
k	-	organ index (unitless).

In order to determine if a hypothetical canister breach event can meet the canister release dose-equivalent source term criteria, the values for the right-hand sides of Equations (19) and (20) must be determined. The terms on the right-hand sides of these equations were defined in Section 2.5 as:

$$RD_{eff}^{inh} = \sum_{j}\left(ST_j \times conv \times DCF_{j,eff}^{inh}\right) \tag{10}$$

$$RD_{eff}^{sub} = \sum_{j}\left(ST_j \times conv \times DCF_{j,eff}^{sub}\right) \tag{11}$$

and

$$RD_{k}^{inh} = \sum_{j}\left(ST_j \times conv \times DCF_{j,k}^{inh}\right) \tag{12}$$

where

ST_j	-	source term of the j^{th} isotope in the waste form (Ci/canister)
$DCF_{j,eff}^{inh}$	-	the effective inhalation dose conversion factor of the j^{th} isotope (Sv/Bq)
$DCF_{j,k}^{inh}$	-	the inhalation dose conversion factor of the j^{th} isotope for the k^{th} organ (Sv/Bq)
$DCF_{j,eff}^{sub}$	-	the effective submersion dose conversion factor of the j^{th} isotope [(Sv m^3)/(Bq s)]
$conv$	-	DCF unit conversion factor: 3.7×10^{12} (rem Bq)/(Ci Sv) = 3.7×10^{10} (Bq)/(Ci) x 100 (rem/Sv) (Eckerman et al. 1988, p. 121)
j	-	isotope index (unitless)
k	-	organ index (unitless).

The curies of the j^{th} isotope in the wasteform released to the environment following a hypothetical canister breach event is calculated using the following equation provided in Section 2.1:

$$ST_j = MAR_j \times DR_j \times ARF_j \times RF_j \times LPF_j \tag{1}$$

where

ST_j	- the amount of the j^{th} isotope in the waste form that is released to the environment per canister breached (Ci/canister)
MAR_j	- the material-at-risk of the j^{th} isotope in the waste per canister (Ci/canister)
DR_j	- the fraction of the j^{th} isotope in the material-at-risk that is affected by the hypothetical radioactive material release event (i.e., the damage ratio) (unitless)

ARF_j - the airborne release fraction of the j[th] isotope applicable to the hypothetical radioactive material release event (unitless)

RF_j - the respirable fraction of the j[th] isotope applicable to the hypothetical radioactive material release event (unitless)

LPF_j - the leakpath factor of the j[th] isotope applicable to the hypothetical radioactive material release event (unitless); in this calculation, this is the LPF_j associated with the canister

j - isotope index (unitless).

Inputs required for this example calculation involving an SRS HLW canister include the following:

- SRS high-level post-irradiated isotopic concentrations. The isotopic concentrations (the material at risk [MAR]) used in this analysis are provided in Table III-1 (CRWMS M&O 1999c, page III-1).

- Inhalation and air submersion dose conversion factors (DCFs) from Federal Guidance Report 11 (Eckerman et al. 1988) and Federal Guidance Report 12 (Eckerman and Ryman 1993), respectively. The Sv/Bq to rem/Ci unit conversion factor is taken from Federal Guidance Report 11. A listing of the inhalation and air submersion DCFs used in this analysis is provided in Tables III-2 and III-3, respectively.

- An adult breathing rate (BR) of 3.33E-4 m^3/s (20 l/min). This breathing rate is used for inhalation dose calculations (ICRP 1975, page 346).

- The SRS HLW canister height of 118 in. (Shaw 1999, Table 2.2). For the hypothetical SRS HLW canister breach event used in this example, this height is assumed to be the distance the canister travels from the upright position to the horizontal position following a tip-over of the canister. This height is used to calculate the particulate formation. The breach is considered non-mechanistic; the height is only needed to determine the airborne release fraction (ARF) and respirable fraction (RF). This value does not require confirmation because this calculation is intended only as an example of how to calculate the curie content of a canister to determine compliance with the specific criteria established for a particular waste form.

- The damage ratio (DR) and leakpath factor (LPF), both of which are assumed to be 1.0 for this example. However, the waste producer may provide a defensible basis for reducing these ratios. It should be noted that the use of values of 1.0 for these values is conservative and limits the allowable rem/canister value (i.e., limits the MAR).

- The formation of particulates from an impact breach of a HLW canister is based on *Airborne Release Fractions at Non-Reactor Nuclear Facilities* (ANSI/ANS-5.10 1998, page 15). The fraction of respirable airborne particulates (or PULF) formed following an impact of HLW can be estimated as reported in this industry standard. The results in this standard are based on empirical measurements of impact tests on UO_2, ceramic, and glass simulated waste forms. These measurements were used to develop a method to estimate the fractions of HLW vitrified glass that could be released as airborne particulates (the ARF) and fraction of airborne particulates that are respirable (the RF). In this example the PULF is calculated as depicted in Table III-4. The PULF is adjusted for deposition inside the canister and the ARF is calculated as depicted in Table III-5. Since only respirable-sized particulates are included in the PULF, the RF is 1.0. Approaches for selecting the ARF and RF may differ for other waste forms;

they are dependent on the amount of material pulverized. The waste provider may select other methods for calculating the values for the RF and the ARF, including values obtained from Department of Energy Handbooks.

The curies of radioactive material released are calculated using Equation (1). Table III-1 provides the MAR used in this calculation. Equations (10), (11), and (12) are used to convert the curies released to units of rem/canister for inhalation and air submersion using the dose conversion factors (found in Tables III-2 and III-3) and the Sv/Bq-to-rem conversion factor (3.7E+12 [rem Bq]/[Ci Sv]). The results of these calculations are presented in Tables III-6 and III-7. Table III-6 provides, in bolded text, the total calculated equivalent dose (in units of rem/canister) that will result in both an effective (RD_{eff}^{inh}) and a maximum organ (RD_k^{inh}) (in this case, bone surface) inhalation dose. Table III -7 provides, in bolded text, the total calculated equivalent dose (in units of [rem m^3]/[s canister]) that will result in an effective submersion dose (RD_{eff}^{sub}).

From these tables the following results are obtained:

RD_{eff}^{inh} = 1.09E+07 rem/canister (Table III -6, column 9)

RD_k^{inh} = 1.80E+08 rem/canister (Table III -6, column 6)

and

RD_{eff}^{sub} = 6.62E-02 rem m^3/s canister (Table III -7, column 9).

The HLW canister release dose-equivalent source terms are obtained from Table 4:

$TEDE_{canister}$ = 1.15E+08 rem/canister

$(CDE_k + DDE)_{canister}$ = 1.15E+09 rem/canister.

Using Equations (19) and (20) that define the criteria:

$$TEDE_{canister} \geq RD_{eff}^{inh} + \left(RD_{eff}^{sub}/BR\right) \text{ (rem/canister)} \quad (19)$$

and

$$(CDE_k + DDE)_{canister} \geq RD_k^{inh} + \left(RD_{eff}^{sub}/BR\right) \text{ (rem/canister)} \quad (20)$$

and the adult breathing rate of 3.33E-4 m^3/s (ICRP 1975, page 346), the following results are seen:

$RD_{eff}^{inh} + \left(RD_{eff}^{sub}/BR\right)$ (rem/canister) = 1.09E+07 rem/canister + [(6.62E-02 rem m^3/s canister)/(3.33E-4 m^3/s)]

$$= 1.09E+07 \text{ rem/canister}$$

and

$$RD_k^{inh} + \left(RD_{eff}^{sub} / BR\right) \text{ (rem/canister)} = 1.80E+08 \text{ rem/canister} + [(6.62E-02 \text{ rem m}^3\text{/s canister})/(3.33E-4 \text{ m}^3\text{/s})]$$

$$= 1.80E+08 \text{ rem/canister.}$$

Therefore:

$$1.15E+08 \text{ rem/canister} \geq 1.09E+07 \text{ rem/canister}$$

and

$$1.15E+09 \text{ rem/canister} \geq 1.80E+08 \text{ rem/canister.}$$

Thus, this example demonstrates that a breached SRS HLW canister meets the criteria established for the HLW canister.

By comparing the rem/canister values to the criteria through this type of calculation, the waste form provider can determine if the curie content of a canister is in compliance with the specific criteria established for that waste form as presented in Table 4.

Because of the unique nature of each waste form, other waste form-specific examples can be provided, if requested, by the waste provider.

Attachment III: Sample Forward Calculation to Determine Canister Release Dose-Equivalent Source Terms

Table III-1. SRS HLW Curies per Canister

Isotope	SRS HLW
Ac-227	0.00E+00
Am-241	2.28E+01
Am-242m	0.00E+00
Am-243	0.00E+00
Cd-113m	0.00E+00
Ce-144	1.16E+02
Cm-243	0.00E+00
Cm-244	8.89E+01
Co-60	8.80E+01
Eu-154	4.14E+02
Eu-155	2.40E+02
Np-237	0.00E+00
Pa-231	0.00E+00
Pm-147	6.46E+03
Pu-238	1.43E+03
Pu-239	1.29E+01
Pu-240	8.70E+00
Pu-241	1.32E+03
Th-228	0.00E+00
U-232	0.00E+00
I-129	0.00E+00
Cs-134	6.28E+01
Cs-137	3.87E+04
Ru-106	7.40E+01
Sr-90	4.28E+04
Y-90	4.28E+04

Reference: *DOE High-Level Vitrified Waste Dose Calculation* (CRWMS M&O 1999c, page III-1)

Table III-2. Inhalation DCFs (Sv/Bq)

	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Isotope	Gonads	Breast	Lungs	Red Marrow	Bone Surface	Thyroid	Remainder	Effective
Ac-227	3.96E-04	6.66E-08	1.54E-03	2.57E-03	3.21E-02	3.59E-08	1.47E-03	1.81E-03
Am-241	3.25E-05	2.67E-09	1.84E-05	1.74E-04	2.17E-03	1.60E-09	7.82E-05	1.20E-04
Am-242m	3.21E-05	1.38E-09	4.20E-06	1.69E-04	2.12E-03	5.64E-10	7.48E-05	1.15E-04
Am-243	3.26E-05	1.52E-08	1.78E-05	1.73E-04	2.17E-03	8.29E-09	7.74E-05	1.19E-04
Cd-113m	3.32E-08	3.32E-08	4.09E-07	3.32E-08	3.32E-08	3.32E-08	1.30E-06	4.13E-07
Ce-144	1.93E-09	1.97E-09	7.91E-07	2.67E-08	4.54E-08	1.88E-09	1.03E-07	1.01E-07
Cm-243	2.07E-05	6.29E-09	1.94E-05	1.18E-04	1.47E-03	3.83E-09	5.76E-05	8.30E-05
Cm-244	1.59E-05	1.04E-09	1.93E-05	9.38E-05	1.17E-03	1.01E-09	4.78E-05	6.70E-05
Co-60	4.76E-09	1.84E-08	3.45E-07	1.72E-08	1.35E-08	1.62E-08	3.60E-08	5.91E-08
Eu-154	1.17E-08	1.55E-08	7.92E-08	1.06E-07	5.23E-07	7.14E-09	1.13E-07	7.73E-08
Eu-155	3.56E-10	6.14E-10	1.19E-08	1.43E-08	1.52E-07	2.40E-10	1.11E-08	1.12E-08
Np-237	2.96E-05	1.69E-08	1.61E-05	2.62E-04	3.27E-03	1.34E-08	2.34E-05	1.46E-04
Pa-231	6.90E-09	8.79E-09	7.47E-04	6.97E-04	8.70E-03	7.64E-09	2.87E-07	3.47E-04
Pm-147	1.88E-14	3.60E-14	7.74E-08	8.16E-09	1.02E-07	1.98E-14	5.89E-09	1.06E-08
Pu-238	2.80E-05	1.00E-09	3.20E-04	1.52E-04	1.90E-03	9.62E-10	7.02E-05	1.06E-04
Pu-239	3.18E-05	9.22E-10	3.23E-04	1.69E-04	2.11E-03	9.03E-10	7.56E-05	1.16E-04
Pu-240	3.18E-05	9.51E-10	3.23E-04	1.69E-04	2.11E-03	9.05E-10	7.56E-05	1.16E-04
Pu-241	6.82E-07	3.06E-11	3.18E-06	3.36E-06	4.20E-05	1.24E-11	1.31E-06	2.23E-06
Th-228	1.35E-06	1.35E-06	6.91E-04	1.12E-04	1.37E-03	1.34E-06	3.44E-06	9.23E-05
U-232	8.00E-08	8.06E-08	1.48E-03	4.06E-06	6.42E-05	7.85E-08	3.11E-06	1.78E-04
I-129	8.69E-11	2.09E-10	3.14E-10	1.40E-10	1.38E-10	1.56E-06	1.18E-10	4.69E-08
Cs-134	1.30E-08	1.08E-08	1.18E-08	1.18E-08	1.10E-08	1.11E-08	1.39E-08	1.25E-08
Cs-137	8.76E-09	7.84E-09	8.82E-09	8.30E-09	7.94E-09	7.93E-09	9.12E-09	8.63E-09
Ru-106	1.38E-08	1.37E-08	1.04E-06	1.37E-08	1.37E-08	1.37E-08	1.69E-08	1.29E-07
Sr-90	2.64E-09	2.64E-09	2.86E-06	3.36E-07	7.27E-07	2.64E-09	5.73E-09	3.51E-07
Y-90	9.52E-12	9.52E-12	9.31E-09	2.79E-10	2.78E-10	9.52E-12	3.87E-09	2.28E-09

Reference: *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion* (Eckerman et al. 1988)

Table III-3. Air Submersion DCFs (Sv m^3/Bq s) [includes contribution of implicit daughters]

	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Isotope	**Gonads**	**Breast**	**Lungs**	**Red Marrow**	**Bone Surface**	**Thyroid**	**Remainder**	**Effective**	**Skin**
Ac-227	3.75E-17	4.45E-17	3.38E-17	2.94E-17	1.04E-16	3.65E-17	3.18E-17	3.74E-17	3.28E-16
Am-241	8.58E-16	1.07E-15	6.74E-16	5.21E-16	2.87E-15	7.83E-16	6.34E-16	8.18E-16	1.28E-15
Am-242m	3.80E-17	6.01E-17	1.72E-17	1.72E-17	7.94E-17	2.95E-17	1.94E-17	3.17E-17	1.36E-16
Am-243	2.19E-15	2.61E-15	1.92E-15	1.55E-15	7.47E-15	2.09E-15	1.79E-15	2.18E-15	2.75E-15
Cd-113m	7.17E-18	8.76E-18	5.93E-18	5.01E-18	2.10E-17	6.76E-18	5.63E-18	6.94E-18	8.48E-15
Ce-144	2.73E-15	3.13E-15	2.64E-15	2.51E-15	5.44E-15	2.75E-15	2.53E-15	2.77E-15	8.57E-14
Cm-243	5.77E-15	6.68E-15	5.50E-15	5.00E-15	1.50E-14	5.76E-15	5.19E-15	5.88E-15	9.79E-15
Cm-244	6.90E-18	1.33E-17	7.08E-19	1.46E-18	8.82E-18	4.19E-18	1.81E-18	4.91E-18	3.91E-17
Co-60	1.23E-13	1.39E-13	1.24E-13	1.23E-13	1.78E-13	1.27E-13	1.20E-13	1.26E-13	1.45E-13
Eu-154	6.00E-14	6.81E-14	5.99E-14	5.87E-14	9.43E-14	6.15E-14	5.75E-14	6.14E-14	8.29E-14
Eu-155	2.49E-15	2.95E-15	2.22E-15	1.85E-15	8.09E-15	2.41E-15	2.07E-15	2.49E-15	3.39E-15
Np-237	1.04E-15	1.26E-15	9.02E-16	7.69E-16	3.20E-15	9.94E-16	8.50E-16	1.03E-15	1.54E-15
Pa-231	1.71E-15	1.99E-15	1.62E-15	1.52E-15	3.64E-15	1.70E-15	1.54E-15	1.72E-15	2.44E-15
Pm-147	7.48E-19	9.56E-19	5.45E-19	4.46E-19	2.18E-18	6.75E-19	5.26E-19	6.93E-19	8.11E-16
Pu-238	6.56E-18	1.27E-17	1.06E-18	1.68E-18	9.30E-18	4.01E-18	1.99E-18	4.88E-18	4.09E-17
Pu-239	4.84E-18	7.55E-18	2.65E-18	2.67E-18	9.47E-18	3.88E-18	2.86E-18	4.24E-18	1.86E-17
Pu-240	6.36E-18	1.23E-17	1.09E-18	1.65E-18	9.26E-18	3.92E-18	1.96E-18	4.75E-18	3.92E-17
Pu-241	7.19E-20	8.67E-20	6.48E-20	5.63E-20	2.19E-19	6.98E-20	6.09E-20	7.25E-20	1.17E-19
Th-228	9.12E-17	1.09E-16	8.33E-17	7.32E-17	2.64E-16	8.88E-17	7.84E-17	9.20E-17	1.50E-16
U-232	1.55E-17	2.32E-17	9.84E-18	8.99E-18	3.86E-17	1.29E-17	1.00E-17	1.42E-17	5.92E-17
I-129	4.83E-16	6.66E-16	2.14E-16	1.64E-16	1.10E-15	3.86E-16	2.30E-16	3.80E-16	1.10E-15
Cs-134	7.40E-14	8.43E-14	7.37E-14	7.19E-14	1.20E-13	7.57E-14	7.06E-14	7.57E-14	9.45E-14
Cs-137	2.67E-14	3.05E-14	2.65E-14	2.58E-14	4.38E-14	2.73E-14	2.54E-14	2.73E-14	4.39E-14
Ru-106	1.07E-14	1.23E-14	1.03E-14	9.65E-15	2.46E-14	1.08E-14	9.79E-15	1.09E-14	1.32E-14
Sr-90	7.78E-18	9.49E-18	6.44E-18	5.44E-18	2.28E-17	7.33E-18	6.11E-18	7.53E-18	9.20E-15
Y-90	1.89E-16	2.20E-16	1.77E-16	1.62E-16	4.44E-16	1.87E-16	1.68E-16	1.90E-16	6.24E-14

Reference: *External Exposure to Radionuclides in Air, Water, and Soil, Exposure-to-Dose Coefficients for General Application, Based on the 1987 Federal Radiation Protection Guidance* (Eckerman and Ryman 1993)

Table III-4. Estimation of Particulate Formation during an SRS HLW Canister Drop DBE

Pulverization Factor: The formation of particulates is described in *Airborne Release Fractions at Non-Reactor Nuclear Facilities* (ANS 1998, page 15).

PULF = EPF*A*d*g*h
PULF = (1) * (0.0002) * (2.75) * (980.7) * (300) * (1.0E-07)
PULF = 1.62E-05

EPF = energy partion factor (unitless)	where	EPF =	1 for HLW
A = correlation coefficient [cm^3/J]	where	A =	0.0002 cm^3/J
d = specimen density (g/cm^3)	where	d =	2.75 gm/cm^3
g = gravitational acceleration (cm^2/s)	where	g =	980.7 cm/s^2
h = height of free-fall (cm)	where	h =	300 cm (118 in)

PULF = a[cm^3/J]*d[g/cm^3]*g[cm/s^2]*h[cm]*1.0E-07[J/dyne-cm]*[dyne-cm-s^2/g-cm^2]
PULF = dimensionless

Table III-5. Calculation of the Airborne Release Fraction (ARF)

Isotopic Group	PULF	Deposition Factor (Note 1)	Airborne Release Fraction (ARF)
	(1)	(2)	(1)*(2)
All	1.62E-05	1.00E+00	1.62E-05

Note 1: A factor of 1.0 indicates no deposition.

Table III-6. SRS HLW Canister Radioactive Material Release Resulting in an Inhalation Dose (rem/canister)

(1) Isotope	(2) Gonad	(3) Breast	(4) Lung	(5) R Marrow	(6) B Surface	(7) Thyroid	(8) Remainder	(9) Effective
Ac-227	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Am-241	4.44E+04	3.64E+00	2.51E+04	2.38E+05	2.96E+06	2.18E+00	1.07E+05	1.64E+05
Am-242m	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Am-243	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cd-113m	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ce-144	1.34E+01	1.37E+01	5.49E+03	1.85E+02	3.15E+02	1.31E+01	7.15E+02	7.01E+02
Cm-243	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cm-244	8.46E+04	5.54E+00	1.03E+05	4.99E+05	6.23E+06	5.38E+00	2.54E+05	3.57E+05
Co-60	2.51E+01	9.69E+01	1.82E+03	9.06E+01	7.11E+01	8.54E+01	1.90E+02	3.11E+02
Eu-154	2.90E+02	3.84E+02	1.96E+03	2.63E+03	1.30E+04	1.77E+02	2.80E+03	1.92E+03
Eu-155	5.12E+00	8.82E+00	1.71E+02	2.05E+02	2.18E+03	3.45E+00	1.59E+02	1.61E+02
Np-237	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pa-231	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pm-147	7.27E-03	1.39E-02	2.99E+04	3.16E+03	3.95E+04	7.66E-03	2.28E+03	4.10E+03
Pu-238	2.40E+06	8.56E+01	2.74E+07	1.30E+07	1.63E+08	8.24E+01	6.01E+06	9.08E+06
Pu-239	2.46E+04	7.12E-01	2.49E+05	1.31E+05	1.63E+06	6.97E-01	5.84E+04	8.96E+04
Pu-240	1.66E+04	4.95E-01	1.68E+05	8.80E+04	1.10E+06	4.71E-01	3.94E+04	6.04E+04
Pu-241	5.39E+04	2.42E+00	2.51E+05	2.66E+05	3.32E+06	9.80E-01	1.04E+05	1.76E+05
Th-228	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
U-232	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
I-129	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cs-134	4.89E+01	4.06E+01	4.44E+01	4.44E+01	4.14E+01	4.17E+01	5.23E+01	4.70E+01
Cs-137	2.03E+04	1.82E+04	2.04E+04	1.92E+04	1.84E+04	1.84E+04	2.11E+04	2.00E+04
Ru-106	6.11E+01	6.07E+01	4.61E+03	6.07E+01	6.07E+01	6.07E+01	7.49E+01	5.72E+02
Sr-90	6.77E+03	6.77E+03	7.33E+06	8.61E+05	1.86E+06	6.77E+03	1.47E+04	8.99E+05
Y-90	2.44E+01	2.44E+01	2.39E+04	7.15E+02	7.12E+02	2.44E+01	9.92E+03	5.84E+03
Totals	2.65E+06	2.57E+04	3.56E+07	1.51E+07	**1.80E+08**	2.56E+04	6.62E+06	**1.09E+07**

Method: Columns (2) through (9) = Table III-1, Ci/can * Table III-2, Inhalation DCF Columns (2) through (9) * ARF (Table III-5) * Conversion Factor

Example: Lung Dose from Am-241 = (2.28E+1 Ci/Can [Table III-1]) * (1.84E-5 Sv/Bq [Table III-2]) * (1.62E-5 [Table III-5]) * (3.7E+12 [rem/Bq]/[Ci Sv]) = 2.51E+4

RD_k^{inh} = max organ dose from above Table, Column 6, bone surface = 1.80E+08 rem/canister

RD_{eff}^{inh} = effective inhalation dose from above Table, Column 9 = 1.09E+07 rem/canister

Table III-7. SRS HLW Canister Radioactive Material Release Resulting in an Air Submersion Dose (rem m^3/s canister)

(1) Isotope	(2) Gonad	(3) Breast	(4) Lung	(5) R Marrow	(6) B Surface	(7) Thyroid	(8) Remainder	(9) Effective	(10) Skin
Ac-227	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Am-241	1.17E-06	1.46E-06	9.20E-07	7.11E-07	3.92E-06	1.07E-06	8.65E-07	1.12E-06	1.75E-06
Am-242m	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Am-243	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cd-113m	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ce-144	1.89E-05	2.17E-05	1.83E-05	1.74E-05	3.78E-05	1.91E-05	1.76E-05	1.93E-05	5.95E-04
Cm-243	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cm-244	3.67E-08	7.08E-08	3.77E-09	7.77E-09	4.69E-08	2.23E-08	9.63E-09	2.61E-08	2.08E-07
Co-60	6.48E-04	7.32E-04	6.53E-04	6.48E-04	9.38E-04	6.69E-04	6.32E-04	6.64E-04	7.64E-04
Eu-154	1.49E-03	1.69E-03	1.48E-03	1.45E-03	2.34E-03	1.52E-03	1.43E-03	1.52E-03	2.05E-03
Eu-155	3.58E-05	4.24E-05	3.19E-05	2.66E-05	1.16E-04	3.46E-05	2.97E-05	3.58E-05	4.87E-05
Np-237	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pa-231	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pm-147	2.89E-07	3.70E-07	2.11E-07	1.73E-07	8.43E-07	2.61E-07	2.03E-07	2.68E-07	3.14E-04
Pu-238	5.62E-07	1.09E-06	9.08E-08	1.44E-07	7.96E-07	3.43E-07	1.70E-07	4.18E-07	3.50E-06
Pu-239	3.74E-09	5.83E-09	2.05E-09	2.06E-09	7.31E-09	3.00E-09	2.21E-09	3.27E-09	1.44E-08
Pu-240	3.31E-09	6.41E-09	5.68E-10	8.59E-10	4.82E-09	2.04E-09	1.02E-09	2.47E-09	2.04E-08
Pu-241	5.68E-09	6.85E-09	5.12E-09	4.45E-09	1.73E-08	5.52E-09	4.81E-09	5.73E-09	9.25E-09
Th-228	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
U-232	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
I-129	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cs-134	2.78E-04	3.17E-04	2.77E-04	2.70E-04	4.51E-04	2.85E-04	2.65E-04	2.85E-04	3.55E-04
Cs-137	6.18E-02	7.06E-02	6.14E-02	5.98E-02	1.02E-01	6.31E-02	5.88E-02	6.31E-02	1.02E-01
Ru-106	4.74E-05	5.45E-05	4.56E-05	4.28E-05	1.09E-04	4.78E-05	4.34E-05	4.83E-05	5.85E-05
Sr-90	1.99E-05	2.43E-05	1.65E-05	1.39E-05	5.84E-05	1.88E-05	1.57E-05	1.93E-05	2.36E-02
Y-90	4.84E-04	5.64E-04	4.54E-04	4.15E-04	1.14E-03	4.79E-04	4.31E-04	4.87E-04	1.60E-01
Totals	6.49E-02	7.40E-02	6.44E-02	6.27E-02	1.07E-01	6.62E-02	6.16E-02	**6.62E-02**	2.89E-01

Method: Columns (2) through (10) = Table III-1, Ci/can * Table III-3, Submersion DCF Columns (2) through (10) * ARF (Table III-5) * Conversion Factor

Example: Lung Dose from Am-241 = (2.28E+1 Ci/Can [Table III-1]) * (6.74E-16 Sv m^3/Bq s [Table III-3]) * (1.62E-5 [Table III-5]) * (3.7E+12 [rem/Bq]/[Ci Sv]) = 9.20E-7 rem m^3/s

RD_{eff}^{sub} = effective submersion dose from above Table, Column 9, 6.62E-02 rem/canister