Defense Threat Reduction Agency
8725 John J. Kingman Road, MS-6201
Fort Belvoir, VA 22060-6201

DTRA-TR-14-022

TECHNICAL REPORT

Skin Dose Assessment Methodology for Military Personnel at McMurdo Station, Antarctica (1962-1979)

June 2014

Prepared by:

McMurdo Station Radiation Dose Assessment
Integrated Project Team

For:

Assistant Secretary of Defense for Health Affairs
and Deputy Assistant Secretary of the Navy for Safety

This page intentionally left blank.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
25-06-2014

2. REPORT TYPE
Technical Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Skin Dose Assessment Methodology for Military Personnel at McMurdo Station, Antarctica (1962-1979)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
McKenzie-Carter, Michael A.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Leidos, Inc., 11951 Freedom Drive, Reston, VA 20190

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Nuclear Technologies Department, Attn: Dr. Paul Blake
Defense Threat Reduction Agency
8725 John J. Kingman Road, Mail Stop 6201
Fort Belvoir, VA 22060-6201

10. SPONSOR/MONITOR'S ACRONYM(S)
DTRA J9-NTSN

11. SPONSORING/MONITORING AGENCY REPORT NUMBER
DTRA-TR-14-022

12. DISTRIBUTION AVAILABILITY STATEMENT
DISTRIBUTION A. Approved for public release: distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This report describes an approach to estimating skin doses for McMurdo Station veterans who were present at McMurdo Station at any time during 1962-1979. This report is based largely on the information contained in an earlier external and internal dose assessment for McMurdo Station veterans (DTRA-TR-12-003). The skin dose assessment methods include the use of high-sided estimates of parameters along with uncertainty factors that lead to upper-bound doses. In addition to reliance on DTRA-TR-12-003, the methodology includes information, parameters, and values contained in applicable Standard Operating Procedures for the Nuclear Test Personnel Review (NTPR) program, and in other widely available reference documents. The report includes two examples demonstrating the skin dose calculations for all exposure pathways, and Appendices containing tables of relevant parameter values.

15. SUBJECT TERMS
McMurdo Station, Veterans, Skin Dose, Radiation Dose Assessment, Nuclear Test Personnel Review Program

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	U	35 Pages	Paul K. Blake, PhD
					19b. TELEPONE NUMBER (*Include area code*) (703) 767-3384

STANDARD FORM 298 (Rev. 8/98)

UNIT CONVERSION TABLE

U.S. customary units to and from international units of measurement*

U.S. Customary Units	Multiply by → / ← Divide by†		International Units
Length/Area/Volume			
inch (in)	2.54	$\times 10^{-2}$	meter (m)
foot (ft)	3.048	$\times 10^{-1}$	meter (m)
yard (yd)	9.144	$\times 10^{-1}$	meter (m)
mile (mi, international)	1.609 344	$\times 10^{3}$	meter (m)
mile (nmi, nautical, U.S.)	1.852	$\times 10^{3}$	meter (m)
barn (b)	1	$\times 10^{-28}$	square meter (m^2)
gallon (gal, U.S. liquid)	3.785 412	$\times 10^{-3}$	cubic meter (m^3)
cubic foot (ft^3)	2.831 685	$\times 10^{-2}$	cubic meter (m^3)
Mass/Density			
pound (lb)	4.535 924	$\times 10^{-1}$	kilogram (kg)
atomic mass unit (AMU)	1.660 539	$\times 10^{-27}$	kilogram (kg)
pound-mass per cubic foot (lb ft^{-3})	1.601 846	$\times 10^{1}$	kilogram per cubic meter (kg m^{-3})
pound-force (lbf avoirdupois)	4.448 222		newton (N)
Energy/Work/Power			
electronvolt (eV)	1.602 177	$\times 10^{-19}$	joule (J)
erg	1	$\times 10^{-7}$	joule (J)
kiloton (kT) (TNT equivalent)	4.184	$\times 10^{12}$	joule (J)
British thermal unit (Btu) (thermochemical)	1.054 350	$\times 10^{3}$	joule (J)
foot-pound-force (ft lbf)	1.355 818		joule (J)
calorie (cal) (thermochemical)	4.184		joule (J)
Pressure			
atmosphere (atm)	1.013 250	$\times 10^{5}$	pascal (Pa)
pound force per square inch (psi)	6.984 757	$\times 10^{3}$	pascal (Pa)
Temperature			
degree Fahrenheit (°F)	[T(°F) − 32]/1.8		degree Celsius (°C)
degree Fahrenheit (°F)	[T(°F) + 459.67]/1.8		kelvin (K)
Radiation			
curie (Ci) (activity of radionuclides)	3.7	$\times 10^{10}$	s^{-1}‡
air exposure (roentgen)	2.579 760	$\times 10^{-4}$	coulomb per kilogram (C kg^{-1})
absorbed dose (rad)	1	$\times 10^{-2}$	J kg^{-1}§
equivalent and effective dose (rem)	1	$\times 10^{-2}$	J kg^{-1}**

* Specific details regarding the implementation of SI units may be viewed at http://www.bipm.org/en/si/.
† Multiply the U.S. customary unit by the factor to get the international unit. Divide the international unit by the factor to get the U.S. customary unit.
‡ The special name for the SI unit of the activity of a radionuclide is the becquerel (Bq). (1 Bq = 1 s^{-1}).
§ The special name for the SI unit of absorbed dose is the gray (Gy). (1 Gy = 1 J kg^{-1}).
** The special name for the SI unit of equivalent and effective dose is the sievert (Sv). (1 Sv = 1 J kg^{-1}).

DTRA-TR-14-022: Skin Dose Assessment Methodology for Military Personnel at McMurdo Station, Antarctica (1962-1979)

Table of Contents

List of Tables

Executive Summary

During 1962–1979, an onsite nuclear power plant (NPP) was operated, and eventually dismantled and decommissioned at McMurdo Station, Antarctica. A radiation dose assessment for U.S. Department of Defense military personnel who were stationed at McMurdo Station from 1962 to 1979 has been accomplished and documented in a previous report (DTRA-TR-12-003). That previous report did not address potential skin doses for these personnel, and to address that need the current report describes an approach to estimating skin doses for McMurdo Station veterans who were present at McMurdo Station at any time during 1962-1979. The methodology is applicable to personnel who were present at McMurdo Station during either a winter-over or during an austral summer period.

The skin dose methodology described in this report is based on the exposure pathways, radiological data, and exposure parameter values identified in DTRA-TR-12-003. The methods include the use of high-sided estimates of parameters along with uncertainty factors that lead to upper-bound doses. Equations for skin doses from three exposure pathways are described: immersion in outdoor air containing radioactive noble gases; ground shine from spilled contaminated soil; and dermal contamination from deposition of suspended contaminated soil on the skin or clothing. In addition to the use of information in DTRA-TR-12-003, the methodology incorporates relevant information, parameters, and values from applicable Standard Operating Procedures for the Nuclear Test Personnel Review program, and in other widely available reference documents.

To illustrate the use of the dose equations, the report includes detailed skin dose calculations for two example scenarios covering all exposure pathways. The first example addresses the potential skin dose for an individual present at McMurdo Station during a winter-over period while the NPP was operational. The upper-bound skin dose for this example is 6.1 mSv (0.61 rem), and is applicable to any skin site. The second example addresses a winter-over period during the time the NPP was being decommissioned. The highest upper-bound skin dose calculated in this example is 182 mSv (18.2 rem), calculated for the neck. Because of the high interception and retention fraction assumed for the neck, the dose calculated for the skin of the neck in the second example will likely bound the potential skin doses for any skin site for all McMurdo Station veterans.

This page intentionally left blank.

Section 1.

Introduction

During 1962–1979, an onsite nuclear power plant (NPP) was built, operated, and eventually dismantled and decommissioned at McMurdo Station, Antarctica. A radiation dose assessment for U.S. Department of Defense military personnel who were stationed at McMurdo Station during Operation Deep Freeze (DF) from 1962 to 1979 was accomplished in DTRA-TR-12-003 (Dunavant et al., 2013). That dose assessment addresses external and internal doses for the whole body, thyroid, and red bone marrow. Subsequent to the publication of DTRA-TR-12-003, the need for potential skin doses for McMurdo veterans was identified. To address that need, an approach to estimating skin doses for McMurdo Station veterans was developed and is described here.

The assessment of skin doses is based on the exposure pathways, radiological data, and exposure parameter values identified in the earlier external and internal dose assessment. The objective of that previous dose assessment was to estimate upper-bound external and internal radiation doses for McMurdo Station support personnel. This objective resulted in the use of high-sided parameter values, selected to represent the top of the range of plausible values. The assessment of skin doses in the present document mirrors the approach of the external and internal dose assessment, and uses high-sided assumptions, models, and parameter values whenever possible that are designed to produce conservative estimates of potential skin doses for McMurdo Station veterans. (Dunavant et al., 2013)

Military personnel were assigned to McMurdo Station for as long as a full winter-over period (from October to November of the following year), or during all or part of an austral summer (October to March). For all DF years, skin doses can be calculated for both winter-over or austral summer periods. (Dunavant et al., 2013)

The methodologies described in Dunavant et al. (2013) include general external exposure pathways for gamma radiation that can result in doses to the skin. The methodologies described in the current report address additional skin-specific exposure pathways that can result in skin doses from both beta and gamma radiation, and that are not addressed in the previous report. The skin-specific exposure pathways, and the applicable Operation DF periods for each pathway, are:

- Immersion in outdoor air containing radioactive noble gases (DF62–DF73 for both winter-over and austral summer personnel)
- Ground shine from contaminated soil spilled on the ground, roads, and loading areas (DF75–DF79 for both winter-over and austral summer personnel)
- Dermal contamination from deposition of suspended contaminated soil on the skin or clothing:
  - During decommissioning, from excavation and removal of backfill at NPP (DF75–DF79 for both winter-over and austral summer personnel).
  - From suspended contaminated soil spilled on roadways or the ship loading areas (DF75–DF79 for both winter-over and for austral summer personnel).

An air immersion skin dose from suspended contaminated soil is also a possible exposure pathway. This pathway was evaluated during preparation of this report and was found to be insignificant (the maximum potential skin dose is less than 0.01 mSv [0.001 rem]).

Specific methods (equations) to calculate skin doses for each of the pathways listed above have been developed using methodologies based on information, parameters, and values contained in DTRA-TR-12-003, in applicable Standard Operating procedures for the Nuclear Test Personnel Review (NTPR) program (DTRA, 2010), and in other widely available reference documents (e.g., USEPA, 1993). These methods and parameter values were developed to estimate the dose to the basal cell layer of the skin between the epidermis and the dermis, at a depth of 70 μm (0.007 cm). Use of this depth as the reference epidermal thickness is consistent with relevant guidance, e.g., ICRU (1997), USEPA (1993), ICRP (2002), and USNRC (2013).

The methods described in the following Sections (2–4) for skin-specific exposure pathways are designed to be relatively simple and straightforward to use for calculating generic high-sided skin dose estimates or high-sided estimates for specific individuals. Specific scenario parameter values required to perform an individual skin dose assessment, such as the specific skin site location on the body, can typically be obtained from veteran input (i.e., the veteran's case file). Uncertainty considerations associated with the doses are discussed in Section 5. Examples of the potential skin doses resulting from the methodologies are provided in Section 6.

Section 2.

Skin Dose from Immersion in Air Containing Radioactive Noble Gases

The reactor at McMurdo Station produced radioactive noble gases during its operation. Releases of Ar-41 are of primary concern for environmental exposures. Air containing Ar-41 was released from the McMurdo Station NPP at concentrations not greater than 370 Bq m^{-3} (1.0×10^4 pCi m^{-3}). All support personnel who were assigned to McMurdo Station while the reactor was operational are assumed to have been exposed to this source of external radiation. (Dunavant et al., 2013)

An estimate of the beta+gamma skin dose for this pathway is based on the information in Section 5.1.3 and Appendix B-1.4 of Dunavant et al. (2013), and is implemented using Equation (1).

$$D_{imm.skin} = C_{NG} \times DC_{NG.Sub} \times F_{wind} \times T_{NG} \quad (1)$$

where

$D_{imm.skin}$	=	Beta+gamma dose to skin (all skin sites) from air immersion (mSv)
C_{NG}	=	Concentration of noble gases at accessible locations (Bq m^{-3})
$DC_{NG.Sub}$	=	Noble gas air submersion dose coefficient for skin (mSv h^{-1} per Bq m^{-3})
F_{wind}	=	Wind direction factor (the fraction of time that the wind was blowing towards the direction of interest) (unitless)
T_{NG}	=	Time duration for submersion in air (h)

For a high-sided default estimate, the method used in Dunavant et al. (2013) for estimating the Ar-41 concentration (C_{NG}) at a veteran's location is used. In that report, the airborne concentration of Ar-41 corresponding to the concentration resulting in the maximum regulatory permissible dose was used (370 Bq m^{-3} [1.0×10^4 pCi m^{-3}]). Use of this value produces a high-sided dose estimate, and also simplifies the calculations because a single dose value is used for all winter-over or austral summer periods.

The value(s) for air submersion dose coefficient(s) for skin ($DC_{NG.Sub}$) are available from Federal Guidance Report (FGR) No. 12 (USEPA, 1993). The default value of 3.64×10^{-7} mSv h^{-1} per Bq m^{-3} for Ar-41 is used, consistent with Dunavant et al. (2013). To ensure a high-sided dose estimate, there is no accounting for any shielding of beta particles afforded by the presence of clothing. To incorporate this clothing shielding, the dose coefficient $DC_{NG.Sub}$ could be modified to reduce the beta fraction by a factor that would account for the shielding effect of the clothing. This factor is estimated to be on the order of 10-50% (DTRA, 2010, ED03). However, this shielding factor is ignored in order to simplify and further high-side the dose calculation for this pathway.

A value of 0.5 is used for the wind direction factor (F_{wind}), as recommended in Dunavant et al. (2013).

The default value for the duration of air submersion (T_{NG}) is 24 h d^{-1} for the entire winter-over or austral summer because noble gases could infiltrate to indoor locations. Using the nominal durations for austral summers (6 months) and winter-overs (14 months) yields T_{NG} values of approximately 4,380 h and 10,220 h for austral summers and winter-overs, respectively. (Dunavant et al., 2013)

Similar to the external dose due to immersion in noble gases described in Dunavant et al. (2013), the estimation of skin dose from this pathway does not require any veteran input – the resulting dose is bounding for all veterans. This means that there will be no exception ratios needed for this pathway in order to calculate a veteran-specific dose for any veteran requests (NDC, 2013).

Section 3.

Skin Dose from Contaminated Soil Groundshine

Personnel could have received skin doses from exposure to residual radiation from bulk contaminated soil spilled onto the ground during transport to the ship loading area or during ship loading. The dose estimate for this pathway is accomplished by using Equations (2) and (3).

$$D_{soil_i} = D(x)_{\beta grnd} \quad (2)$$

$$D(x)_{\beta grnd} = D_{soil.ext} \times R(x,t)_{\beta\gamma} \times M(x) \quad (3)$$

where

D_{soil_i}	=	Beta skin dose to skin site *i* from contaminated soil on the ground (mSv)
$D(x)_{\beta grnd}$	=	Beta dose to skin at height *x* above the ground (mSv)
$D_{soil.ext}$	=	Gamma dose from exposure to contaminated soil on the ground (mSv)
$R(x,t)_{\beta\gamma}$	=	Beta-to-gamma dose ratio at height *x* above an infinite plane source and time *t* following fission (unitless)
$M(x)$	=	Clothing modification factor for skin at height *x* (unitless)

Values for the gamma dose from contaminated soil on the ground ($D_{soil.ext}$) for each DF period are obtained from information in Section 5.1.6 and Appendix B-1.7 and Tables 26 and 27 of Dunavant et al. (2013). Doses for all periods vary only slightly, from 0.03–0.04 mSv (3-4 mrem). These doses are based on the highest level of contamination measured in soil samples in 1978 at McMurdo Station.

Due to the limited ranges and relatively large attenuation of beta particles, beta-to-gamma dose ratios ($R(x,t)_{\beta\gamma}$) are highly dependent on the distance and orientation of the skin site relative to the source, and the presence of shielding material between the source and the skin. In addition, if a mixture of radionuclides is present in the source, the ratio will be subject to variation with time. Consequently, the most useful beta-to-gamma dose ratios for McMurdo Station skin assessments are those in a form where ratios and the degree of shielding afforded by clothing are measured or calculated using the proper orientation and as a function of height and decay time. Ratios in this format were not located for power reactor effluents such as might be encountered by personnel at McMurdo Station. However, values in this form are available from the Nuclear Test Personnel Review (NTPR) Program for mixed fission products at two general sites: the Pacific Proving Ground and the Nevada Test Site (Barss and Weitz, 2006; DTRA, 2010-ED03). The NTPR values were calculated for various heights and post-fission times for an individual standing upright in an infinite planar field of mixed fission product deposition, and they incorporate body self-shielding and a film badge equivalency modification, as described in Appendix A. Corresponding values at the two sites are generally close to each other, in particular the values at a post-fission time of 1 year. The Nevada Test Site 1-year values are slightly higher than the corresponding values at Pacific Proving Ground, thus they are used as the default set for $R(x,t)_{\beta\gamma}$ in this skin dose assessment. The Nevada Test Site 1-year values range from about 164 to 17 for heights from 1 to 200 cm as shown in Appendix A, Table A-1.

The NTS 1-year beta-to-gamma dose ratios are judged to be conservative estimates for use at McMurdo Station for several reasons. For example, the ratios were calculated neglecting certain items to simplify the calculations and to ensure that the ratios are high-sided. These neglected items include self-attenuation of large particles, surface roughness, and various weathering phenomena (Barss and Weitz, 2006). In addition, the NTS ratios were compared to other available sources of beta-to-gamma dose ratios, to ensure that they are reasonably conservative. Survey measurements at various indoor areas at various commercial U.S. reactor facilities showed beta-to-gamma dose ratios ranging from 0.1 to 42 at source-to-detector distances from 15 feet to 3 inches, although most measurements were made at distances of 3-6 inches (Rathbun et al., 1984). And surveys done during general decontamination work at the Chernobyl site resulted in ratios of total dose (beta+gamma) to gamma dose of 2.5–11 measured at "the height of the face" (WHO, 2005). Finally, in the case of a single representative radionuclide, a beta-to-photon ratio of 21 was calculated for a point source of Cs-137 at a distance of 1 m (ORAU, 2012). Based on comparisons of these values with corresponding values from Appendix A, Table A-1, the NTS 1-year ratios represent reasonably conservative values to use for $R(x,t)_{\beta\gamma}$.

Values for the clothing modification factor ($M(x)$), vary from about 0.42 to 0.88 for heights from 1–200 cm above the ground, assuming a covering of "light clothing" such as coveralls (DTRA, 2010-ED03). Values for $M(x)$ also vary up to about ±10% for various time periods up to a year following fission, which is ignored for this analysis (values for post-fission time of 1 year are used as default values). A table of values for various heights and time post-fission is included in Appendix A, Table A-2.

The skin dose from this pathway can also be estimated using the highest level of contamination measured in soil samples in 1978 at McMurdo Station (Dunavant et al., 2013), together with the dose coefficient for exposure to contaminated soil on the ground for skin from FGR Report No. 12 (USEPA, 1993) and appropriate duration parameter values. Doses from this second approach have been estimated and were determined to be lower but comparable to doses calculated using the first approach described above.

To incorporate veteran-specific information into the skin dose calculation from this pathway, the veteran's height and skin sites of interest are needed. Also required is information regarding any clothing that may have covered the skin site(s). This veteran-specific information will determine the values for $R(x,t)_{\beta\gamma}$ and $M(x)$ for use in an individual dose assessment. Heights above the ground for typical skin sites for a "Standard Height" individual (height of 172.7 cm [68 inches]), as well as other parameters discussed in this section, are listed in Appendix A, Table A-3.

Section 4.

Skin Dose from Dermal or Clothing Contamination

The skin dose due to the deposition of contaminated soil onto the skin (dermal contamination) or onto clothing is described in this section. This dose could result from contaminants in soil that are suspended and subsequently deposited directly onto exposed skin or onto clothing. Contaminated soil that was spilled onto the ground, roads, and loading areas at McMurdo Station could become suspended by wind action or through mechanical disturbances (e.g., walking, vehicles), and subsequently deposited onto the skin or clothing. This skin dose would presumably be accrued simultaneously with a dose from inhalation of the suspended soil, as described in Sections 5.2.2, 5.2.3, B-2.2, and B-2.3 of Dunavant et al. (2013).

Skin dose estimates for this pathway are accomplished using the methodology used in the NTPR program (DTRA, 2010-ED04), together with appropriate values from Dunavant et al. (2013). An estimate of the skin dose from dermal contamination due to suspended contaminated soil is accomplished by using Equation (4).

$$D_{dermal_i} = \sum_{1}^{n} \left\{ F_{res_i} \times C_{aero} \times \left(\frac{(\Delta t_{res})^2}{2} + \Delta t_{res} \times \Delta t_{wash} \right) \times DCF_{skin_i} \times ws \times 3600 \right\} \quad (4)$$

where:

D_{dermal_i}	=	Skin dose at skin site *i* from dermal or clothing contamination (mGy)
n	=	Number of days of exposure to suspended contaminated soil (days)
F_{res_i}	=	Effective retention factor for soil contaminants at skin site *i* (unitless)
C_{aero}	=	Concentration of soil contaminants in air (Bq m^{-3})
Δt_{res}	=	Duration of time spent in the area of contaminated soil (h)
Δt_{wash}	=	Time interval from exiting the area of contaminated soil to removal of deposited contaminants from the skin by washing (h)
DCF_{skin_i}	=	Skin dose conversion factor for dermal contact or clothing contamination at skin site *i* (mGy h^{-1} per Bq m^{-2})
ws	=	Wind speed (m s^{-1})
3600	=	Seconds in 1 hour (s h^{-1})

The value of the effective retention factor (F_{res_i}) is dependent on the location of the skin site of interest on the body, because different skin sites exhibit different degrees of interception and retention of material. Using the deterministic values in Table 2 of ED04 (DTRA, 2010), F_{res_i} is calculated as 0.02 × IRF_i/IRF_{fa}, where the interception and retention fraction (IRF_i) is for a specific bare (or uncovered) skin site location *i*, and IRF_{fa} is for the reference site (i.e., bare forearm). The *IRF* value for covered skin (all sites) is 0.04 (DTRA, 2010). See Appendix A, Section A-2 for details of the calculation of F_{res_i}. Values used for calculation of F_{res_i} are shown in Appendix A, Table A-4, and calculated values for IRF_i, IRF_{fa}, and F_{res_i} for various skins sites are tabulated in Appendix A, Table A-5.

The concentration of soil contaminants in air (C_{aero}) is used for both the assessment of skin dose during decommissioning activities and during exposure to soil spilled on the roads. For both estimates, the soil contamination is assumed to consist entirely of Cs-137. For estimates of the potential skin dose during decommissioning, the highest measured concentration of contaminants in air samples during decommissioning of 0.7 Bq m^{-3} (20 pCi m^{-3}) is used for C_{aero}, as determined in Section 5.2.2 of Dunavant et al. (2013). The duration of exposure to suspended contaminated soil during decommissioning (n) is 156 d. (Dunavant et al., 2013)

For dermal or clothing contamination from spilled contaminated soil suspended from roads, two different levels of airborne soil contamination are assumed for the period of exposure, as described in Sections 5.2.3 and B-2.3 of Dunavant et al. (2013). An initial soil concentration is assumed to exist for seven days, after which cleanup of the soil is assumed to result in a lower, residual concentration for the following 420 days for winter-over personnel, and the following 180 days for austral summer personnel. The calculated air concentrations from the initial and residual soil concentrations are approximately 2.4 Bq m^{-3} (65 pCi m^{-3}) and 0.048 Bq m^{-3} (1.3 pCi m^{-3}), respectively. (Dunavant et al., 2013)

Values for the duration of time spent in the area of contaminated soil (Δt_{res}) are veteran-dependent. However a default value for Δt_{res} is available from Section 5.2.3 of Dunavant et al. (2013). The default value for exposure to the initial spilled soil is 10 h d^{-1} for 7 days (70 h) followed by exposure to the residual levels (following cleanup) for 4 h d^{-1} for 420 d (1,680 h) for winter-over personnel, and 4 h d^{-1} for 180 d (720 h) for austral summer personnel. A default value of 4 h for the length of time contaminated soil remains on the skin or clothing is used for Δt_{wash}.

Values for the skin dose conversion factor (DCF_{skin}) were obtained from information in NTPR documentation (DTRA, 2010-ED04). To simplify the calculation, a high-sided default value of 2.68×10^{-7} mGy h^{-1} per Bq m^{-2} is used for all uncovered skin sites (i.e., for dermal contamination), and a value of 1.19×10^{-7} mGy h^{-1} per Bq m^{-2} is used for all covered skin sites (i.e., for clothing contamination). These values were calculated using the nominal time-independent value of 900 rad h^{-1} per Ci m^{-2} (400 rad h^{-1} per Ci m^{-2} for clothing contamination) and a value of 1.1 to adjust for the minimum skin thickness found at different body locations. (DTRA, 2010-ED04)

Suspension of spilled contaminants at McMurdo Station could be due to either wind or mechanical disturbances such as walking or shoveling. Consistent with the analysis in Dunavant et al. (2013), a high degree of suspension due to wind is assumed. The default value for wind speed (ws) of 5.2 m s^{-1} is based on the average speed of wind observations at McMurdo Station (Lazzara, 2006).

To incorporate veteran-specific information into the skin dose calculation from this pathway, the specific skin site(s) is needed. Also required is information regarding the duration of time spent in the area of contaminated soil and how long the contamination remained on the skin or clothing, if available.

Section 5.

Uncertainty Considerations

The dose methodology described herein, especially when used with the high-sided default values, will result in conservative estimates of potential skin doses for McMurdo Station veterans. However, certain parameter values applicable to a specific veteran could exceed the default values. For example, the wind could be blowing towards the veteran's location for greater than 50% of the time, the veteran may have skin layers that are thinner than those assumed, or the veteran may have spent more time near contaminated soil than the default assumptions. In addition, other potential sources of uncertainty exist, including measurement, recording, or data processing errors, and spatial variability in environmental concentrations of contaminants. (Dunavant et al., 2013)

To help ensure that McMurdo Station skin doses are not underestimated, uncertainty factors (UF) are described here for use with the skin dose estimates calculated with the assessment methodology described. Use of a UF with high-sided skin dose estimates to arrive at estimates of upper-bound doses is consistent with the use of a UF with the high-sided external and internal dose estimates for McMurdo Station veterans (Dunavant et al., 2013).

For the purposes of this report, the UF is defined as the ratio of an "upper-bound" dose to the estimated high-sided dose. Neither the "upper-bound" nor the high-sided dose are rigorously calculated, and so the intent of using a UF with the high-sided skin doses is to obtain estimates of upper-bound doses that are not less than the true 95th percentile value for each total skin dose.

For simple skin exposure pathways (air immersion and exposure to contaminated soil on the ground), a UF of 3 is recommended. This is based on the use of the same factor for external doses in the NTPR program (DTRA, 2010). For the more complex exposure pathway of dermal and clothing contamination, UF factors may range from approximately 3 to 14, based on experience with skin dose calculations accomplished for the NTPR program (DTRA, 2010). Because of the use of high-sided methodologies and parameter values described above, the maximum observed UF of 14 is not used, and a UF of 10 is recommended for use with this skin dose exposure pathway for McMurdo Station veterans.

This page intentionally left blank.

Section 6.

Example Skin Dose Calculations

To illustrate the use of the skin dose calculation methods, two examples are provided below. The first example is representative of any McMurdo Station support veteran present at McMurdo Station while the McMurdo Station NPP was operational. The second example is representative of any McMurdo Station support veteran present at McMurdo Station after operation of the McMurdo Station NPP had ceased and decommissioning activities had started.

6.1 Example 1: Winter-over during NPP Operational Period

The first example is for a hypothetical McMurdo Station support veteran who is assumed to have been present at McMurdo Station during the winter-over of DF70. Because the NPP was operational in DF70 and decommissioning had not yet started, the only skin-specific exposure pathway described above that is applicable to this veteran would be immersion in air containing radioactive noble gases. The parameter values used for Example 1 are shown in Table 1. Note that veteran-specific information, including the specific skin site, is not necessary to identify because the only applicable pathway (immersion in air) does not depend on the skin site.

Table 1. Parameter values applicable to Example 1

Exposure Pathway/Parameter	Veteran-specific value	Comment
1. Air immersion pathway (Equation 1)		
C_{NG}	370 Bq m^{-3}	NPP Release concentration for Ar-41 (Table 15, Dunavant et al., 2013)
$DC_{NG.Sub}$	3.64×10^{-7} mSv h^{-1} per Bq m^{-3}	Air submersion dose coefficient for Ar-41 (Table III.1, USEPA, 1993)
F_{wind}	0.5	Dunavant et al. (2013)
T_{NG}	10,220 h	Total for 24 h d^{-1} for 14 months
2. Contaminated soil on the ground	n/a	Decommissioning had not yet started in DF70
3. Dermal and clothing contamination	n/a	Decommissioning had not yet started in DF70

Skin dose from air immersion: Using the default parameter values in Section 2 and the veteran-specific values above, the skin dose from skin-specific pathways for Example 1 is calculated as follows:

$$D_{imm.skin} = 370 \text{ Bq m}^{-3} \times 3.64 \times 10^{-7} \text{mSv h}^{-1} \text{ per Bq m}^{-3} \times 0.5 \times 1.02 \times 10^{4} \text{ h}$$

$$= 0.69 \text{ mSv}$$

The upper-bound skin dose from this pathway is $D_{imm.skin} \times 3 = 2.1$ mSv.

The total skin dose for a veteran's presence during DF70 is the sum of the estimated external whole-body gamma dose and the skin dose estimated above. The calculated total external gamma dose for a veteran who was part of the support personnel during DF70 is 2 mSv (0.2 rem), with an associated upper-bound estimate of 4 mSv (0.4 rem). This upper-bound external dose includes doses from all external gamma sources for DF70 and was obtained from (Dunavant et al., 2013). The upper-bound external dose for a specific veteran would be obtained using NDC Form 6470/20 (NDC, 2013). The total upper-bound skin dose for Example 1 is conservatively estimated to be (4 + 2.1=) 6.1 mSv (0.61 rem) for any skin site. Based on the external doses in Dunavant et al. (2013), the default upper-bound skin dose calculated for any veteran present at McMurdo Station from DF62 through DF74 would not be higher than the 6.1 mSv (0.61 rem) estimated for this example.

6.2 Example 2: Winter-over during Decommissioning Period

The second example of a skin dose calculation is for a hypothetical McMurdo Station support veteran who is assumed to have been present at McMurdo Station during winter-over of DF78. Because the McMurdo Station NPP was no longer operational and decommissioning was in progress in DF78, the applicable skin-specific exposure pathways for this example are exposure to contaminated soil on the ground, and dermal/clothing contamination. The veteran has the following relevant characteristics (assumed to be obtained from veteran input):

- Veteran height is 152 cm (5 feet, 0 inches)
- Three veteran skin cancer sites: face (uncovered), neck (uncovered) and forearm (covered)

Based on the above information from the veteran, the heights of the skin cancers are 141 cm (face), 132 cm (neck), and 87.4 cm (forearm). These were determined by using the veteran's height of 152 cm and ratioing the standard standing heights for his skin sites found in Appendix Table A-3. Note that a below-average height is assumed for this example in order to demonstrate relatively high ground shine doses. The veteran-specific parameter values applicable to the skin dose assessment for Example 2 are shown in Table 2.

Table 2. Parameter values applicable to Example 2

Exposure Pathway/Parameter	Veteran-specific value	Comment
1. Air immersion pathway	n/a	Exposure pathway is not applicable because the NPP was not operating in 1976
2. Contaminated soil on the ground (Equations 2 and 3)		
$D_{soil.ext}$	0.034 mSv (0.004 rem)	Table 26 of Dunavant et al. (2013)
$R(x,t)_{\beta\gamma}$	24.0 (face) 25.0 (neck) 31.1 (forearm)	Interpolated using values in Appendix Table A-1 (t=1 year) and Table A-3
$M(x)$	0.87 (forearm)	Appendix Table A-2; a single layer of clothing is assumed
3. Dermal and clothing contamination (Equation 4)		
F_{res_i}	0.003 (face) 0.3 (neck) 0.008 (covered forearm)	Appendix Section A-2 and Table A-5
$C_{aero_{decom}}$	0.7 Bq m^{-3}	Dunavant et al. (2013)
$C_{aero_{soil}}$	2.4 Bq m^{-3} (first 7 days) 0.048 Bq m^{-3} (next 420 days)	See Section 4
$\Delta t_{res\ decom}$	10 h d^{-1}	Default value for decommissioning; see Section 4
$\Delta t_{res\ soil}$	10 h d^{-1} (first 7 days) 4 h d^{-1} (next 420 days)	Default values for spilled soil; see Section 4
Δt_{wash}	4 h	Default value; see Section 4
n_{decomm} n_{soil}	156 d 7 d (high conc), 420 d (low conc)	Default values; see Section 4

<u>Skin doses from exposure to contaminated soil</u>: Using the default parameter values in Section 3 and the veteran-specific values above, the beta skin doses (D_{soil_i}) from exposure to contaminated soil on the ground for Example 2 are calculated as follows:

$$D_{soil_{face}} = 0.034 \times 24.0 = 0.82 \text{ mSv}$$

$$D_{soil_{neck}} = 0.034 \times 25.0 = 0.85 \text{ mSv}$$

$$D_{soil_{forearm}} = 0.034 \times 31.1 \times 0.87 = 0.92 \text{ mSv}$$

<u>Skin doses from dermal and clothing contamination during decommissioning</u>: Using the default parameter values in Section 4 and the veteran-specific values above, the skin doses from

dermal and clothing contamination during decommissioning for Example 2 are calculated as follows:

$$D_{dermal_{decom\,face}} = \sum_{1}^{156} \left[\begin{matrix} 0.003 \times 0.7\ \text{Bq m}^{-3} \times \left(\frac{(10\ h)^2}{2} + 10\ h \times 4h \right) \times \\ 2.68 \times 10^{-7} \text{mGy h}^{-1} \text{ per Bq m}^{-2} \times 5.2\ \text{m s}^{-1} \times 3600\ \text{s h}^{-1} \end{matrix} \right]$$

$$= 0.148\ \text{mGy}$$

$$D_{dermal_{decom\,neck}} = \sum_{1}^{156} \left[\begin{matrix} 0.3 \times 0.7\ \text{Bq m}^{-3} \times \left(\frac{(10\ \text{h})^2}{2} + 10\ \text{h} \times 4\text{h} \right) \times \\ 2.68 \times 10^{-7} \text{mGy h}^{-1} \text{ per Bq m}^{-2} \times 5.2\ \text{m s}^{-1} \times 3600\ \text{s h}^{-1} \end{matrix} \right]$$

$$= 14.8\ \text{mGy}$$

$$D_{dermal_{decom\,forearm}} = \sum_{1}^{156} \left[\begin{matrix} 0.008 \times 0.7\ \text{Bq m}^{-3} \times \left(\frac{(10\ \text{h})^2}{2} + 10\ \text{h} \times 4\text{h} \right) \times \\ 1.19 \times 10^{-7} \text{mGy h}^{-1} \text{ per Bq m}^{-2} \times 5.2\ \text{m s}^{-1} \times 3600\ \text{s h}^{-1} \end{matrix} \right]$$

$$= 0.175\ \text{mGy}$$

Dermal and clothing contamination from spilled soil: Using the default parameter values in Section 4 and the veteran-specific values above, the skin doses from dermal and clothing contamination due to suspended spilled soil for Example 2 are calculated as follows:

$$D_{dermal_{soil\,face}} = \sum_{1}^{7} \left[\begin{matrix} 0.003 \times 2.4\ \text{Bq m}^{-3} \times \left(\frac{(10\ \text{h})^2}{2} + 10\ \text{h} \times 4\text{h} \right) \times \\ 2.68 \times 10^{-7} \text{mGy h}^{-1} \text{ per Bq m}^{-2} \times 5.2\ \text{m s}^{-1} \times 3600\ \text{s h}^{-1} \end{matrix} \right]$$

$$+ \sum_{8}^{427} \left[\begin{matrix} 0.003 \times 0.048\ \text{Bq m}^{-3} \times \left(\frac{(4\ \text{h})^2}{2} + 4\ \text{h} \times 4\text{h} \right) \times \\ 2.68 \times 10^{-7} \text{mGy h}^{-1} \text{ per Bq m}^{-2} \times 5.2\ \text{m s}^{-1} \times 3600\ \text{s h}^{-1} \end{matrix} \right]$$

$$= 0.030\ \text{mGy}$$

$$D_{dermal_{soil\,neck}} = \sum_{1}^{7}\left[\begin{array}{c} 0.3 \times 2.4\ \text{Bq m}^{-3} \times \left(\frac{(10\ \text{h})^2}{2} + 10\ \text{h} \times 4\text{h}\right) \times \\ 2.68 \times 10^{-7}\text{mGy h}^{-1}\ \text{per Bq m}^{-2} \times 5.2\ \text{m s}^{-1} \times 3600\ \text{s h}^{-1} \end{array}\right]$$

$$+ \sum_{8}^{427}\left[\begin{array}{c} 0.3 \times 0.048\ \text{Bq m}^{-3} \times \left(\frac{(4\ \text{h})^2}{2} + 4\ \text{h} \times 4\text{h}\right) \times \\ 2.68 \times 10^{-7}\text{mGy h}^{-1}\ \text{per Bq m}^{-2} \times 5.2\ \text{m s}^{-1} \times 3600\ \text{s h}^{-1} \end{array}\right]$$

$$= 3.0\ \text{mGy}$$

$$D_{dermal_{soil\,forearm}} = \sum_{1}^{7}\left[\begin{array}{c} 0.008 \times 2.4\ \text{Bq m}^{-3} \times \left(\frac{(10\ \text{h})^2}{2} + 10\ \text{h} \times 4\text{h}\right) \times \\ 1.19 \times 10^{-7}\text{mGy h}^{-1}\ \text{per Bq m}^{-2} \times 5.2\ \text{m s}^{-1} \times 3600\ \text{s h}^{-1} \end{array}\right]$$

$$+ \sum_{8}^{427}\left[\begin{array}{c} 0.008 \times 0.048\ \text{Bq m}^{-3} \times \left(\frac{(4\ \text{h})^2}{2} + 4\ \text{h} \times 4\text{h}\right) \times \\ 1.19 \times 10^{-7}\text{mGy h}^{-1}\ \text{per Bq m}^{-2} \times 5.2\ \text{m s}^{-1} \times 3600\ \text{s h}^{-1} \end{array}\right]$$

$$= 0.036\ \text{mGy}$$

Assuming an equivalency of Gy and Sv (i.e., radiation weighting factor = 1), skin doses from the pathways above are shown in Table 3 for each skin site of Example 2. Also shown in Table 3 are the upper-bound values for the skin-specific pathways, using UF values from Section 5.

Table 3. Summary of skin doses for three skin sites of Example 2

Exposure Pathway	Skin doses for each skin site (mSv)		
	Face	**Neck**	**Forearm**
Skin-specific pathway doses			
• Beta ground shine	0.82	0.85	0.92
• Dermal contamination – decommissioning	0.148	14.8	0.175
• Dermal contamination – spilled soil	0.030	3.0	0.036
Skin-specific total doses	1.00	18.6	1.13
Skin-specific upper-bound doses*	4.2	180	4.9
Whole-body upper-bound external doses†	2.0	2.0	2.0
Total upper-bound skin doses‡	6.2	182	6.9

* Skin-specific upper-bound dose calculated using UF values of 3 and 10 as described in Section 5.

† The default whole body upper-bound external dose is obtained from Dunavant et al. (2013).

‡ Total upper-bound skin dose is the rounded sum of upper-bound doses from ground shine, dermal contamination, and external whole body.

The generic whole-body external dose for a veteran who was part of the support personnel during DF78 was 0.5 mSv (0.05 rem), with an upper-bound estimate of 2 mSv (0.2 rem). This upper-bound external dose includes doses from all external gamma sources for DF78 and was obtained from (Dunavant et al., 2013). The upper-bound external dose for a specific veteran would be obtained using NDC Form 6470/20 (NDC, 2013). Adding the 2 mSv (0.2 rem) external dose to the skin doses (ignoring some overlap in the dose calculations) results in rounded total upper-bound skin doses for Example 2 of 6.2 mSv (0.62 rem), 182 mSv (18.2 rem), and 6.9 mSv (0.69 rem) calculated for the face, neck, and covered forearm, respectively; these values are shown in Table 3. Because of the high interception and retention fraction for the bare neck, the total upper-bound dose calculated for the bare neck in Example 2 likely bound the potential skin doses for any skin site for all McMurdo Station veterans.

Section 7.

References

Barss, N. M. and Weitz, R. L., 2006. "Reconstruction of External Dose from Beta Radiation Sources of Nuclear Weapon Origin." *Health Physics*, Volume 91(4), pp. 379–389. October.

DTRA (Defense Threat Reduction Agency), 2010. *Standard Operating Procedures Manual for Radiation Dose Assessment, Revision 1.3/1.3a*. DTRA-SOP-10-01, Defense Threat Reduction Agency, Fort Belvoir, VA. January 31/March 31.

Dunavant, J.D., Chehata, M., Morris, W.J., Fairchild, G.R., Blake, P.K., 2013. *Upper-Bound Radiation Dose Assessment for Military Personnel at McMurdo Station, Antarctica, between 1962 and 1979*. DTRA-TR-12-003. Defense Threat Reduction Agency, Fort Belvoir, VA. June 1.

ICRU (International Commission on Radiation Units and Measurements), 1997. *Dosimetry of External Beta Rays for Radiation Protection*. ICRU Report 56. Bethesda, MD.

ICRP (International Commission on Radiological Protection), 2002. *Basic Anatomical and Physiological Data for Use in Radiological Protection: Reference Values*. ICRP Publication 89. Ann.ICRP 32 (3-4).

Lazzara, M.A., 2006. *A McMurdo Station, Antarctica Climatology with Special Emphasis on Fog.* Antarctic Meteorological Research Center, University of Wisconsin, Madison, WI. April 1.

NDC (Naval Dosimetry Center), 2013. *McMurdo Station Radiation Dose Assessment Questionnaire*, Form NDC 6470/20. U.S. Naval Dosimetry Center, Bethesda, MD.

ORAU (Oak Ridge Associated Universities), 2012. *Nevada Test Site – Occupational External Dose*, NIOSH Technical Basis/Site Profile document No. ORAUT-TKBS-0008-6, Revision 3, Oak Ridge Associated Universities, November 9.

Rathbun, L.A., Endes, G.W. R., Fox, R.A., Robertson, P.L., Scherpelz, R.I., 1984. *Beta Particle Measurement and Dosimetry Requirements at NRC-Licensed Facilities*, NUREG/CR-3544, U.S. Nuclear Regulatory Commission, Washington, DC. August.

USEPA (United States Environmental Protection Agency), 1993. *External Exposure to Radionuclides in Air, Water, and Soil, Federal Guidance Report No. 12*. EPA 402-R-93-081. U.S. Environmental Protection Agency, Washington, DC. September.

USNRC (United States Nuclear Regulatory Commission), 2013. *Standards for Protection Against Radiation*, Title 10, Part 20 of the Code of Federal Regulations, U.S. Nuclear Regulatory Commission, Rockville, MD. May 20.

WHO (World Health Organization), 2005. *Health Effects of the Chernobyl Accident and Special Health Care Programmes*, Report of the UN Chernobyl Forum Expert Group "Health" (EGH), World Health Organization, Geneva. August 31.

This page intentionally left blank.

Appendix A.
Parameter Values for Skin Dose Assessments

A-1. Parameters used in Contaminated Soil Groundshine Pathway

Beta-to-gamma dose ratios applicable to bare skin exposure of an individual standing upright in an infinite planar field of fission product deposition are shown in Table A-1 (DTRA, 2010, ED03). In deriving the ratios, it was assumed that body self-shielding reduced both 1) the beta dose at any target site on the body by a factor of 0.5 from its free field value, and 2) the gamma dose recorded on a properly worn film badge to a value of 0.7 times its free-field value. Table A-1 values for 1 year after fission are used as default values (shaded in table below).

Table A-1. Beta-to-gamma dose ratios for bare skin exposures to mixed fission products at the Nevada Test Site

Time after Fission	Distance from source plane (cm)							
	1	20	40	80	100	120	160	200
0.5 h	36.0	24.6	18.3	12.4	10.8	9.6	7.6	5.9
1 h	32.2	21.8	16.1	10.8	9.4	8.2	6.4	4.9
2 h	31.6	21.2	15.5	10.3	8.9	7.8	6.1	4.6
4 h	40.1	26.6	19.3	12.7	10.9	9.5	7.3	5.6
6 h	50.5	33.3	24.0	15.7	13.4	11.7	9.0	6.9
12 h	64.7	41.8	29.7	18.7	15.9	13.7	10.2	7.6
1 d	64.2	39.6	26.9	15.9	13.0	10.9	7.7	5.4
2 d	63.4	36.3	23.3	12.7	10.1	8.2	5.4	3.5
3 d	62.0	33.4	20.5	10.7	8.4	6.7	4.2	2.6
1 wk	61.6	30.3	17.5	8.4	6.4	5.0	3.1	1.8
2 wk	64.7	31.9	18.4	8.9	6.8	5.3	3.3	2.0
1 mo	71.6	36.2	21.3	10.7	8.3	6.7	4.3	2.7
2 mo	84.6	41.5	24.3	12.6	10.2	8.5	5.9	3.9
4 mo	89.4	42.2	24.4	13.3	11.1	9.6	7.1	5.0
6 mo	93.4	44.3	26.0	14.6	12.5	11.0	8.5	6.2
9 mo	114.7	56.5	34.3	20.3	17.8	16.0	12.8	9.7
1 y	164.0	84.3	52.9	32.8	29.1	26.5	21.7	16.8
2 y	487.7	260.5	168.1	107.5	96.1	88.1	72.9	57.3

Multiplicative modification factors to account for the presence of clothing over the skin are shown in Table A-2 (DTRA, 2010, ED03). The values were derived assuming that the individual is standing upright on an infinite plane of deposited fission products, wearing a single layer of clothing that is 28 mg cm^{-2} in density-thickness. This density thickness is representative of “coverall” material. For McMurdo Station analyses, values for 1 year after fission are used as default values (shaded in table below).

Table A-2. Modification factors for light clothing

Time after fission	Distance from source plane (cm)							
	1	20	40	80	100	120	160	200
1 h	0.59	0.74	0.80	0.83	0.84	0.86	0.87	0.87
2 h	0.59	0.73	0.79	0.84	0.84	0.85	0.87	0.87
6 h	0.57	0.72	0.78	0.83	0.84	0.85	0.86	0.87
1 d	0.52	0.67	0.73	0.78	0.80	0.81	0.82	0.83
1 wk	0.40	0.54	0.66	0.71	0.72	0.74	0.74	0.78
2 wk	0.40	0.55	0.66	0.71	0.72	0.73	0.77	0.74
1 mo	0.41	0.56	0.67	0.73	0.74	0.75	0.78	0.77
1 y	0.42	0.62	0.78	0.86	0.87	0.87	0.88	0.88

To demonstrate the use of the beta-to-gamma dose ratios applicable to bare skin exposure and the clothing modification factors for covered skin sites, values of these parameters applicable to a representative list of skin sites for a "standard height" individual are shown in Table A-3. The skin site heights listed are based on an individual's height of 172.7 cm (68 in), and are the heights used in the NTPR program (DTRA, 2010). For determining skin site heights for individuals other than those individuals that are 172.7 cm in total height, the "Standard Heights" value should be multiplied by the ratio of the individual's height to the standard height (i.e., standard height for skin site $i \times$ individual's height [cm]/172.7 cm). For McMurdo Station veterans, it is expected that only the "Standing" heights will be used because individuals most likely did not sit in a chair or on the ground while in any potentially-contaminated areas.

Table A-3. Standard Heights and Corresponding Parameter Values

Skin Site	Standard Heights (cm)			Beta-to-gamma Dose Ratio* $[R(x,t)_{\beta\gamma}]$	Clothing Modification Factor† $[M(x)]$
	Standing	Sitting (chair)	Sitting (grnd)		
foot/ankle	1.0	1.0	5.1	163.9	0.42
calf or shin	20.3	20.3	15.2	83.4	0.62
knee	40.6	40.6	15.2	52.4	0.78
hand or mid-thigh	71.1	53.1	15.2	35.5	0.84
waist	99.1	56.5	14.0	29.2	0.87
forearm	99.1	56.5	20.3	29.2	0.87
lower back or stomach	119.4	76.8	34.3	26.6	0.87
upper back, upper arm, or mid-chest	139.7	97.1	54.6	24.1	0.87
neck	149.9	107.3	64.8	22.9	0.88
face, nose, ear, or head	160.0	117.5	74.9	21.7	0.88
top of head	172.7	130.2	87.6	20.1	0.88

* Beta-to-gamma ratios listed in this table are those values applicable to the standing heights.
† Clothing modification factors shown are for a single layer of clothing with density thickness of 28 mg cm^{-2}.

A-2. Parameters Used in Dermal and Clothing Contamination Pathway

The effective retention factor (F_{res}) is calculated as follows:

$$F_{res_i} = CE \times \frac{IRF_i}{IRF_{fa}} \times PS \times EM \times EF \qquad \text{(A-1)}$$

where:

F_{res_i}	=	Effective retention factor for soil contaminants at skin site *i* (unitless)
CE	=	Collection efficiency (unitless)
IRF_i	=	Interception and retention fraction for skin site *i* (unitless)
IRF_{fa}	=	Reference interception and retention fraction for forearm (unitless)
PS	=	Particle size factor (unitless)
EM	=	Moisture factor (unitless)
EF	=	Enrichment factor (unitless)

Values used for parameters in Equation A-1 are shown in Table A-4 (DTRA, 2010, ED04). A discussion of each factor is available in SOP ED04 of DTRA (2010). A summary of the interception and retention fractions (*IRF*), and effective retention factors (F_{res}) for a representative list of uncovered skin sites are shown in Table A-5 (DTRA, 2010, ED04). Furthermore, the values of *IRF* and F_{res} for covered skin (all sites) are 0.04 and 0.008, respectively (DTRA, 2010).

Table A-4. Summary of factors in the calculation of the effective retention factor

Parameter	Value
Collection Efficiency (CE)	0.02
Ratio of site-specific *IRF* to forearm (fa) *IRF* (IRF/IRF_{fa})	See Table A-5
Particle Size Factor (*PS*)	1.0
Moisture Factor (*EM*)	
High humidity, e.g. Pacific Ocean	3.0
Low humidity to dry, e.g., McMurdo Station	1.0
Enrichment Factor (*EF*)	1.0

Table A-5. Interception and retention fractions, and effective retention factors

Uncovered Skin Site	Interception and Retention Fraction (*IRF*)	Effective Retention Factor (F_{res})
foot/ankle	1.5*	0.3
calf or shin	0.1	0.02
knee	0.1	0.02
mid-thigh	0.1	0.02
waist	1.5*	0.3
forearms	0.1	0.02
stomach	0.04	0.008
mid-chest	0.04	0.008
neck	1.5*	0.3
face/head	0.015	0.003
top of head	0.17	0.034

* The foot/ankle, waist, and neck are assumed to represent sites that exhibit enhanced collection and retention of particles.

Using Equation A-1 and the parameter values in the tables above, the calculation of F_{res} for McMurdo Station veterans can be simplified and calculated as follows:

$$F_{res_i} = 0.02 \times \frac{IRF_i}{IRF_{fa}} \qquad \text{(A-2)}$$

$$= 0.2 \times IRF_i$$

Appendix B.
Skin Doses for Standard Height Skin Sites

This Appendix contains the calculated external skin doses for a "standard-height" individual for the skin-specific pathways described in the main report. Doses are shown for all DF periods, for a representative listing of skin sites that are thought to include the most common skin dose requests for McMurdo Station veterans.

This page intentionally left blank.

Table B-1. Standard height external skin doses (mSv) for all applicable exposure pathways and DF* tours

Skin Site	DF62 - DF73 (Operational Period)		DF75 - DF79 (Decommissioning Period)					
	Winter	Summer	Winter			Summer		
				Dermal/Clothing deposition			Dermal/Clothing deposition	
	Immersion†	Immersion	Grnd Shine	Dcom‡	Dsoil‡	Grnd Shine	Dcom‡	Dsoil‡
foot/ankle (covered)	0.686	0.294	2.33	0.175	0.036	1.89	0.175	0.031
calf or shin (covered)	0.686	0.294	1.74	0.175	0.036	1.42	0.175	0.031
knee (covered)	0.686	0.294	1.38	0.175	0.036	1.12	0.175	0.031
hand or mid-thigh (covered)	0.686	0.294	1.01	0.175	0.036	0.819	0.175	0.031
hand or mid-thigh (bare)	0.686	0.294	1.20	0.985	0.20	0.975	0.985	0.17
waist (covered)	0.686	0.294	0.858	0.175	0.036	0.699	0.175	0.031
forearm (covered)	0.686	0.294	0.858	0.175	0.036	0.699	0.175	0.031
lower back or stomach (covered)	0.686	0.294	0.780	0.175	0.036	0.635	0.175	0.031
upper back, upper arm, or chest (covered)	0.686	0.294	0.708	0.175	0.036	0.577	0.175	0.031
neck (covered)	0.686	0.294	0.680	0.175	0.036	0.554	0.175	0.031
neck (bare)	0.686	0.294	0.773	14.8	3.01	0.630	14.8	2.59
face, nose, ear, or head (bare)	0.686	0.294	0.732	0.148	0.030	0.596	0.148	0.026
top of head (bare)	0.686	0.294	0.680	1.67	0.341	0.554	1.67	0.293

* All skin-specific pathway doses during DF 74 are 0 mSv.

† The immersion doses for DF62 Winter tour are slightly lower than what are tabulated here, because the McMurdo Station NPP was operational for only part of the DF62 Winter tour. The full-tour immersion doses (i.e., for DF63-73 Winter) are assigned to DF62 Winter as a conservative simplification.

‡ "Dcom" and "Dsoil" are the doses for dermal contamination (for bare sites) and clothing contamination (for covered sites) during decommissioning and from spilled soil, respectively.

Table B-2. Upper-bound external skin doses[*] from skin-specific exposure pathways for all DF tours

Skin Site	DF62–DF73[†]		DF74[‡]	DF75–DF79	
	Winter	Summer	Winter/Summer	Winter	Summer
foot/ankle (covered)	2.1	0.88	0	9.1	7.7
calf or shin (covered)	2.1	0.88	0	7.3	6.3
knee (covered)	2.1	0.88	0	6.3	5.4
hand or mid-thigh (covered)	2.1	0.88	0	5.1	4.5
hand or mid-thigh (bare)	2.1	0.88	0	15	15
waist (covered)	2.1	0.88	0	4.7	4.2
forearm (covered)	2.1	0.88	0	4.7	4.2
lower back or stomach (covered)	2.1	0.88	0	4.5	4.0
upper back, upper arm, or chest (covered)	2.1	0.88	0	4.2	3.8
neck (covered)	2.1	0.88	0	4.2	3.7
neck (bare)	2.1	0.88	0	180	175
face, nose, ear, or head (bare)	2.1	0.88	0	4.0	3.5
top of head (bare)	2.1	0.88	0	22	21

[*] Upper-bound doses are calculated using uncertainty factors discussed in Section 5.
[†] DF62–DF73 doses shown here are due only to Ar-41 air immersion.
[‡] There were no skin-specific external skin dose pathways during DF74.

Abbreviations, Acronyms, and Unit Symbols

Ar	Argon
Bq	Becquerel
Ci	Curie
cm	Centimeter
Cs	Cesium
d	Day
DF	Deep Freeze
DTRA	Defense Threat Reduction Agency
FGR	Federal Guidance Report
Gy	Gray
h	Hour
ICRP	International Commission on Radiological Protection
m	Meter
µm	Micrometer
mGy	Milligray
mrem	Millirem
mSv	Millisievert
mo	Month
NDC	Naval Dosimetry Center
NPP	Nuclear Power Plant
NTPR	Nuclear Test Personnel Review
ORAU	Oak Ridge Associated Universities
pCi	Picocurie
rad	Rad (unit of absorbed dose)
rem	Roentgen Equivalent Man
s	Second
Sv	Sievert
TR	Technical Report
UF	Uncertainty Factor
USEPA	United States Environmental Protection Agency
USNRC	United States Nuclear Regulatory Commission
WHO	World Health Organization
wk	Week
y	Year