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Health Physics Parameter Analysis for the Mars 2020 Launch

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Prepared by
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Health Physics Parameter Analysis for the Mars 2020 Launch

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Abstract

This report describes research into three health physics parameters used by Launch Safety (LS) for which the appropriate value, distribution, or applicability came into question during preparation of the Mars 2020 LS analysis. These parameters and associated issues include the Dose and Dose Rate Effectiveness Factor (DDREF) and its use in health effects calculations, a methodology for translating projected contamination per unit area into dose to aquatic and terrestrial biota, and plutonium transfer factors for use in ingestion pathway consequence analyses.

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NOMENCLATURE

BCG	Biota Concentration Guide
BEIR	Committee on the Biological Effects of Ionizing Radiation
CR	Concentration Ratio
DDREF	Dose and Dose Rate Effectiveness Factor
DOE	U.S. Department of Energy
DRL	Derived Response Level
EPA	U.S. Environmental Protection Agency
FGR-13	Federal Guidance Report No. 13
FRMAC	Federal Radiological Monitoring and Assessment Center
GSD	Geometric Standard Deviation
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IUR	International Union of Radioecology
LS	Launch Safety
LET	Linear Energy Transfer
Mars 2020 FSAR	Mars 2020 Final Safety Analysis Report
MSL FSAR	Mars Science Laboratory Final Safety Analysis Report
NCRP	National Council on Radiation Protection and Measurements
PNNL	Pacific Northwest National Laboratory
STORM	Sandia-developed Transport of Radioactive Material
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation

1. INTRODUCTION

The nuclear risk analysis in the *Draft Input to the Mars 2020 Final Safety Analysis Report* (Mars 2020 FSAR) [1] includes methods for estimating consequences such as individual doses, population doses, excess latent cancer fatalities (i.e., "health effects"), and land contamination areas that exceed either a dose or activity per unit area. The purpose of this paper is to provide some background on three health physics parameters and associated issues encountered during preparation of the Mars 2020 Launch Safety (LS) analysis. These issues include

- the appropriateness of using a Dose and Dose Rate Effectiveness Factor (DDREF) in health effects calculations,
- an evaluation of potential dose to biota in accordance with the dose limits specified in DOE-STD-1153-2002, and
- a literature review for plutonium-238 transfer factor values and distributions for crops.

A discussion of the decision to assign an uncertainty distribution to the DDREF for use in LS analyses is included in Section 2. The development of a Derived Response Level (DRL) for biota is included in Section 3. Lastly, plutonium-238 transfer factors for crops are discussed in Section 4. Section 5 summarizes the recommended approach for each of the health physics parameters discussed in this report.

2. DOSE AND DOSE RATE EFFECTIVENESS FACTOR (DDREF)

Previous LS analyses estimated the potential excess latent cancer fatalities (i.e., "health effects") resulting from exposure to radiation from several exposure pathways over a 50-year time period. The exposure pathways included external and internal exposure from airborne radioactive material in a passing plume and from radioactivity deposited on the ground. Health effects are estimated on an organ-specific basis for non-uniform irradiation of the body, as recommended by the International Commission on Radiological Protection (ICRP) in Publication 60 [2]. Contributions to an organ dose are summed over all dose pathways for an individual. The number of health effects for a certain cancer type and dose level are estimated by multiplying the individual organ doses by the number of individuals receiving that organ dose and by the cancer risk factor for that organ. The total number of health effects is estimated by summing over the types of cancer. This result provides the statistical expectation value of excess latent cancer fatalities induced in the exposed population. The main exposure pathway potentially resulting from a Mars 2020 launch accident is the intake (inhalation, ingestion) of plutonium-238. Potential radiation exposures from launch accidents are considered to be limited to low dose and low dose rate exposures to high-linear energy transfer (LET) alpha radiation.

ICRP 60 provides a nominal fatality probability coefficient, which is the estimated probability of fatal cancer per unit effective dose. This value is 5×10^{-2} Sv^{-1} for the public and is averaged over age and gender. This coefficient is distributed among the organs to generate organ-specific fatality probability coefficients and is based primarily on data from high dose, high dose rate exposures to Japanese atomic bomb survivors. A DDREF has historically been used in combination with the linear-non-threshold (LNT) model to account for a decrease in effectiveness of low-LET radiation at low doses and dose rates as compared to the high dose, high dose rate data upon which the cancer risk coefficients are based. ICRP 60 considers "low dose" to be less than 0.2 Gy and "low dose rate" to be less than 0.1 Gy per hour. The ICRP 60 nominal fatality probability coefficient for low dose and lose dose rate exposures was calculated by dividing high dose, high dose rate estimates of risk by a DDREF of 2.

The use of the DDREF and its value are a controversial subject in the health physics community. This paper discusses past DDREF recommendations, introduces recent studies that do not support the use of a DDREF, discusses DDREF applicability to high-LET radiation, and ultimately recommends a DDREF uncertainty distribution for use in the Mars 2020 LS analysis.

2.1. History of DDREF Recommendations

2.1.1. Recommendations by ICRP, NCRP, UNSCEAR, and BEIR

The global health physics community follows the recommendations of several scientific organizations, including the ICRP, the National Council on Radiation Protection and Measurements (NCRP), the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), and the Committee on the Biological Effects of Ionizing Radiation (BEIR), a committee of the American National Research Council. Each of these organizations has issued DDREF recommendations.

As mentioned previously, ICRP 60 (1990) recommends a DDREF of 2. The ICRP states that "the choice of this value is somewhat arbitrary and may be conservative." Previous to 1990, UNSCEAR used a DDREF of 2 and 2.5 in 1977, suggested a DDREF of up to 5 in 1986, and recommended 2 to 10 in 1988. BEIR III used a DDREF of 2.25 and BEIR V recommended 2 or more, but applied 2 only in the case of leukemia and 1 for other cancers. In 1992, the NCRP also recommended a dose rate effectiveness factor of 2 [3].

In 2006, UNSCEAR re-evaluated available data using Bayesian analysis and estimated a DDREF of 2 [4]. Also in 2006, the BEIR VII committee performed a Bayesian analysis and yielded a "believable range" of DDREF values to be 1.1 to 2.3, with a median value of 1.5 for solid tumors. A linear-quadratic model was used for leukemia, negating the need for a DDREF. The committee noted that "while it would be possible to use the linear-quadratic model directly, the DDREF adjustment to the linear model is used to conform with historical precedent dictated in part by simplicity of calculations. In the low-dose range of interest, there is essentially no difference between the two," where "two" refers to the linear-quadratic model and the DDREF-adjusted linear model [5].

ICRP 103 was published in 2007, in which the ICRP updated its recommendations based on new scientific data [6]. In this publication, the ICRP maintained its stance on using the LNT model and estimates of cancer risk did not significantly change. Regarding the DDREF, the ICRP stated that "the statistical precision afforded by studies [on protracted exposure] and other uncertainties associated with the inability to adequately control confounding factors do not allow for a precise estimate of DDREF at this time" and that considering past studies by other organizations and "recognising (sic) the broad range of experimental animal data showing reduction in carcinogenic effectiveness and life-shortening following protracted exposures, the Commission finds no compelling reason to change its 1990 recommendations of a DDREF of 2." The ICRP also stressed that "its recommendation to retain an ICRP DDREF summary value of 2 for radiological protection purposes is a broad judgement which embodies elements of both subjectivity and probabilistic uncertainty." The ICRP has currently assigned Task Group 91 to review available information and recommend whether or not to continue using a DDREF [7].

2.1.2. Recommendations by Other Agencies

The U.S. Environmental Protection Agency (EPA) addressed the DDREF in their 1994 publication "Estimating Radiogenic Cancer Risks", also known as the Blue Book [8]. In this document, the EPA review of data available at the time yielded a DDREF between 1 and 3. The EPA ultimately recommended a DDREF of 2 for all organs except the breast, for which a DDREF of 1 was recommended because epidemiological evidence showed that "dose fractionation has little or no effect on risk." Federal Guidance Report No. 13 (FGR-13) [9] was published in 1999 and contains radionuclide-specific cancer risk coefficients based on the EPA's 1994 publication.

The EPA updated its cancer mortality risk estimates in their 2011 publication "EPA Radiogenic Cancer Risk Models and Projections for the U.S. Population" [10]. This study primarily used the BEIR VII models with some modifications. As a result, the EPA now recommends a DDREF of 1.5 for solid tumors, including the breast. A revision of FGR-13 based on this updated guidance is planned, but has not yet been published.

The U.S. Nuclear Regulatory Commission (NRC) does not explicitly address the use of a DDREF in its regulations. However in a staff review of BEIR VII, the NRC stated that it uses a DDREF of 2 based on ICRP 60, NCRP 116, and BEIR V recommendations, and that "changing to a DDREF of 1.5 in the face of considerable statistical uncertainty appears unwarranted at this time, but will be reconsidered again when the ICRP publishes its next set of radiation protection recommendations" [11]. (As mentioned previously, the ICRP continued to recommend a DDREF of 2 in its ICRP 103 report that updates the ICRP 60 recommendations.)

The International Atomic Energy Agency (IAEA) safety standards for radiation protection [12] are based on the recommendations of the ICRP, as decreed by the IAEA Board of Governors in 1960, and as such use a DDREF of 2 [13].

2.2. Recent DDREF Studies

The ICRP and BEIR DDREF estimates are based primarily on a combination of atomic bomb survivor data, animal data, and cellular in vitro studies. Recently, several meta-analyses have been performed on human epidemiological studies involving low dose, low dose rate exposures. Meta-analyses combine the results of individual studies that, by themselves, do not provide the statistical power required to detect the small risks associated with low doses and low dose rates [6].

Two papers published in 2005 and 2007 by Cardis et al. estimated cancer risk among radiation workers in 15 countries [14, 15]. This study concluded that "results suggest that there is a small excess risk of cancer, even at the low doses and dose rates typically received by nuclear workers" [14]. Another study published in 2005 by Krestinina et al. estimated an excess risk of cancer to the Techa River Cohort, who received primarily external gamma exposure from the release of radioactive material into the Techa River from the Mayak nuclear weapons facility [16]. These excess risks indicate that chronic exposures per unit dose have the same risk as acute exposures per unit dose, and would therefore suggest a DDREF closer to 1. ICRP 103 recognized the benefit of studies such as that by Cardis in terms of combining analyses of datasets to help increase statistical power, but contends that "the confidence intervals for the estimated trends in cancer risk with dose were wide" in the Cardis study and that "findings were consistent with risks extrapolated from high-dose, acute exposure data using a DDREF of 2," among other confounding factors [6].

In 2009, Jacob et al. [17] published a meta-analysis of several cancer mortality studies, including those by Cardis and Krestinina. The study concluded that "there is no indication that the excess cancer risk per dose for low-dose-rate, moderate-dose exposures is smaller than for the atomic bomb survivors" and that "cancer risks associated with low-dose-rate, moderate-dose exposures to ionising (sic) radiation may be greater than those published by BEIR VII and the ICRP." A meta-analysis of leukemia risk studies was published by Daniels and Schubauer-Berigan in 2011 in which the estimated excess relative risk of leukemia at low dose, low dose rate appeared to agree with Japanese bomb survivor data [18].

The World Health Organization (WHO) chose not to apply a DDREF in their health risk assessment for the 2011 Fukushima accident, calling it a "prudent choice" based on the Jacob et al. and Daniels and Schubauer-Berigan studies but noting that it was not a unanimous decision among the experts involved in the assessment [19]. UNSCEAR commented on WHO's use of a DDREF of 1 in its 2013 Fukushima report, stating that "this is not incompatible with [UNSCEAR's] estimates of cancer risks" [20].

In 2014, the German Commission on Radiological Protection called for the DDREF to be "abolished" (i.e., the DDREF should be 1) [21]. The primary basis for this recommendation is that there is not "sufficient justification" for the DDREF. They state that "in light of the current level of scientific knowledge and major radiation risk uncertainty, various scientific criteria indicate that such a factor would not be introduced if it were not already in place," but also that "consideration should be given in terms of the extent to which a potential underestimate of the risk of cancer at low doses and low dose rates could be in line with the precautionary principle customary to radiation protection."

2.3. DDREF Applicability to High-LET Radiation

The radionuclide of concern for the Mars 2020 mission is plutonium-238, which represents approximately 99 percent of the total activity of the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG). Plutonium-238 is primarily an alpha-emitter. This is important to note because alpha radiation is high-LET and generally more damaging per unit dose than low-LET radiation, for which the DDREF was created.

In its report for the Mars Science Laboratory Interagency Nuclear Safety Review Panel (MSL INSRP) [22] the Biomedical Environmental Effects (BEES) Working Group effectively recommended a DDREF of 1 for alpha radiation from plutonium-238 based on the previously-discussed Cardis and Krestinina studies and a statement in NCRP Report No. 136 that "…the evidence for linearity is stronger for high LET radiation than with low LET radiation." Because a DDREF of 2 is built into the ICRP's nominal fatal probability coefficient for low dose and low dose rate exposures, the BEES Working Group recommended using twice the ICRP coefficient, essentially undoing the built-in DDREF of 2.

ICRP 60 states in paragraph B113 that with the appropriate choice of radiation weighting factor, the nominal fatal probability coefficients derived from low-LET exposures apply to high-LET radiation. The radiation weighting factor represents the relative biological effectiveness (RBE) of a given radiation type in inducing stochastic effects at low doses. FGR-13 provides further explanation of the ICRP's recommendation, stating that the EPA assumed: "…the RBE for alpha particles is 20, in comparison to low-LET radiation at low doses and dose rates. Where the comparison was made against acute high doses of low-LET radiation, however, a value of 10 was assumed for the alpha particle RBE. Thus the low-LET radiation DDREF of 2 used for these cancers was incorporated implicitly into the RBE value for alpha radiation." In other words, for low dose and dose rate exposures the low-LET risk is reduced by a DDREF and the alpha particle RBE is increased by the same factor. This approach maintains the assumed linearity of dose response for high-LET radiation.

Current LS analyses use ICRP 60-based dose coefficients which assume a radiation weighting factor of 20 for alpha radiation for low dose and dose rate exposures. This is consistent with FGR-13 use of an alpha particle RBE of 20. Thus, LS analyses implicitly account for DDREF and no further adjustment of coefficients is needed for alpha-emitters.

2.4. Recommended DDREF For Use In LS Analyses

Most international organizations and U.S. regulatory agencies recommend a DDREF of 2, although there is increasing dissention in the scientific community as to if this is justified. Because of this, the impact of an uncertain DDREF on LS analyses will be explored. The proposed probability density function for DDREF is provided in Equation (1) and pictured in Figure 2-1, where *x* represents an uncertain value of DDREF and *f(x)* is the probability associated with a value of DDREF. The median of the distribution is 2.00 and the mean is 2.25. The source of this distribution is the uncertainty analysis that accompanies the EPA's 1994 Blue Book [23], which is referenced by FGR-13. A similar distribution is used in the NRC State-of-the-Art Reactor Consequence Analysis (SOARCA) uncertainty analyses [24].

$$
\begin{aligned}
f(x) &= 0.5 \qquad 1 \le x \le 2 \\
f(x) &= 0.5e^{-(x-2)} \qquad x > 2
\end{aligned}
\tag{1}
$$

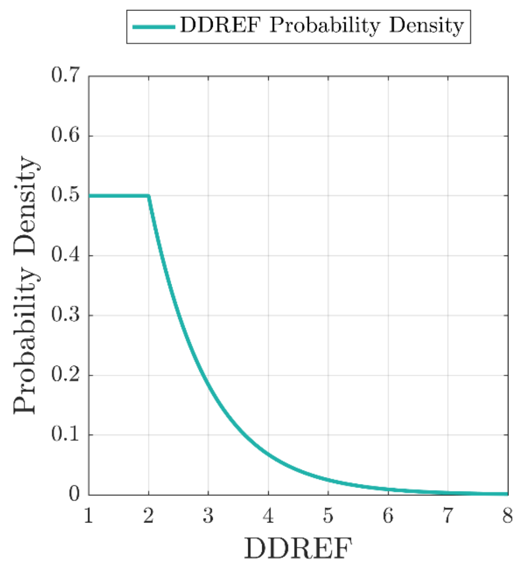

Figure 2-1. DDREF Uncertainty Distribution

Because the ICRP 60 risk coefficients used in LS analyses implicitly include a DDREF of 2, the uncertain DDREF is implemented by multiplying the risk coefficient by 2 and dividing by the sampled DDREF value. The use of tabulated dose and risk coefficients in LS analyses precludes the ability to apply this uncertainty specifically to the alpha particle RBE.

If the risk coefficients are updated to those based on FGR-13, the same approach is used, but noting that the EPA recommends a different DDREF distribution specifically for the breast. At this time an organ-specific DDREF distribution cannot be accommodated in the code used to calculate excess latent cancer fatalities for LS analyses.

3. BIOTA DERIVED RESPONSE LEVEL (DRL) ANALYSIS

DOE-STD-1153-2002, *A Graded Approach for Evaluating Radiation Doses to Aquatic and Terrestrial Biota*, is a technical standard for determining if DOE-specified absorbed dose limits for plants and animals are exceeded [25]. The limits are

- for aquatic animals, 1 rad/d (10 mGy/d)
- for riparian animals, 0.1 rad/d (1 mGy/d)
- for terrestrial plants, 1 rad/d (10 mGy/d), and
- for terrestrial animals, 0.1 rad/d (1 mGy/d).

The standard assumption in the radiation protection field is that "…if man is adequately protected then other living things are also likely to be sufficiently protected" (ICRP 1977; 1991). DOE-STD-1153-2002 says that this assumption is "less appropriate in cases where human access is restricted or pathways exist that are much more important for biota than for humans."

Generally, DOE-STD-1153-2002 describes the screening approach that should be taken to demonstrate compliance with the dose limits for routine DOE operations. The foreword of the document says "these methods (and the Biota Concentration Guides contained in them) are not intended to be used as design criteria, indicators of the severity of accidental releases of radioactive materials, or guides for mitigating the consequences of accidental releases," though later in the document it says that the approach "could be used to provide an indication of long-term "recovery" or health of the population over time following an accident."

DOE-STD-1153-2002 provides Biota Concentration Guides (BCG) to which sampled environmental media are to be compared. The BCGs correspond to the dose limits and are to be interpreted as "an indication that populations of plants and animals could be impacted." BCGs are calculated for the soil and water mediums for terrestrial animals and plants, and the sediment and water mediums for aquatic and riparian animals. The RESRAD-BIOTA code [26] contains BCGs calculated following the guidance in DOE-STD-1153-2002.

Consequence analyses for LS are performed using the Sandia-developed Transport of Radioactive Material (STORM) code. STORM only projects areal radioactive contamination ($\mu Ci/m^2$), not contamination by unit mass of sediment or unit volume of water, which are the units of the available BCGs. This limitation requires a modification to the BCG methods so that they can be calculated per unit area. This per unit area quantity is called a Derived Response Level (DRL) following the Federal Radiological Monitoring and Assessment Center (FRMAC) approach [27]. For use in LS analyses, soil BCGs will be converted to areal DRLs using the following methods for only the terrestrial animal and terrestrial plant because the soil BCGs are more restrictive than the water BCGs for these organisms. Likewise, water BCGs are converted to areal DRLs for only the aquatic animal and riparian animal because they are more restrictive than the sediment BCGs for these organisms.

3.1. Technical Caveats

The following assumptions are inherent in the derivation of the dose coefficients used in calculation of BCGs (stated in DOE-STD-1153-2002, Table 2.2):

- Estimates of the contribution to dose from external radioactive material were made assuming that all of the ionizing radiation was deposited in the organism (i.e., no pass-through and no self-shielding).
- For external exposure to contaminated soil, the source was presumed to be infinite in extent. In the case of external exposure to contaminated sediment and water, the source was presumed to be semi-infinite in extent.
- The source medium to which the organisms are continuously exposed is assumed to contain uniform concentrations of radionuclides.
- Estimates of the contribution to dose from internal radioactive material were conservatively made assuming that all of the decay energy is retained in the tissue of the organism, (i.e., 100% absorption).
- The radionuclides are presumed to be homogeneously distributed in the tissues of the receptor organism.
- A radiation weighing factor of 20 for alpha particles is used in calculating the BCGs for all organism types. This is conservative, especially if nonstochastic effects are most important in determining harm to biota.

These assumptions yield conservative estimates of energy deposition in the organism from external and internal sources of radiation exposure. An additional conservativism of the BCG calculations for terrestrial biota is the assumption that the plant or animal is completely surrounded by soil (i.e., exposure by immersion rather than groundshine).

The BCGs provided by RESRAD-BIOTA (and therefore, the DRLs included in this paper) are intended for "generic screening." A more accurate estimation of potential dose received by biota requires site-specific and organism-specific inputs.

3.2. Soil DRL for Biota

Soil BCGs are provided by RESRAD-BIOTA for plutonium-238 in units of pCi per gram of soil. Soil density and depth are used to convert this mass concentration to an areal DRL in µCi/m^2 as shown in Equation (2):

$$DRL_{area,soil} = BCG_{soil} * d * \rho_{soil} * k \qquad (2)$$

$$\frac{\mu Ci}{m^2} = \frac{pCi}{g_{soil}} * cm * \frac{g_{soil}}{cm^3} * \left(\frac{1\ uCi}{10^6\ pCi} * \frac{100^2\ cm^2}{1\ m^2}\right)$$

where

$DRL_{area,soil}$ = Derived Response Level for soil (μCi/m^2)

BCG_{soil} = Biota Concentration Guide for soil (pCi/g_{soil})

d = Depth of migration in soil (cm)

ρ_{soil} = Soil density (g_{soil}/cm^3)

k = Conversion factor from pCi to μCi and cm^2 to m^2 (10^{-2})

The depth of migration in soil is assumed to be 1 cm for plutonium in this analysis. This is a conservative assumption as plutonium is generally found to migrate no more than 5 cm in undisturbed soil over 10 to 20 years [28, 29]. Soil density is assumed to be 1.6 g_{soil}/cm^3 following the default assumptions used by FRMAC [27].

The DRLs shown in Table 3.2-1 are calculated for terrestrial plants and terrestrial animals using the previously described assumptions. Table 3.2-1 also includes the soil BCGs for these organisms as provided by RESRAD-BIOTA.

Table 3.2-1. Plutonium-238 Areal Soil DRLs for Biota

Organism Type	BCG_{soil} (pCi/g)	$DRL_{area,soil}$ (μCi/m^2)
Terrestrial animal	5270	84
Terrestrial plant	17,500	280

The DRL for the terrestrial animal is the most restrictive (i.e., smaller DRL). Using this approach, a terrestrial animal in an area that is projected to be contaminated to greater than 84 μCi/m^2 would likely receive a dose that exceeds the limit for terrestrial animals as specified by DOE-STD-1153-2002. Note that this DRL is 420 times greater than 0.2 μCi/m^2, which is the activity level at which the Draft Input to the Mars 2020 FSAR reports land contamination. The value 0.2 μCi/m^2 was formerly used by the EPA and in past LS analyses as an activity level above which further action should be considered (such as monitoring and cleanup) [1].

3.3. Water DRL for Biota

Water BCGs are provided by RESRAD-BIOTA for plutonium-238 in units of pCi per liter of water. Equation G.3-25 of the Mars Science Laboratory (MSL) Final Safety Analysis Report (FSAR) [30] relates the concentration of plutonium in water to the surface contamination of a water body, which is desired for this analysis. A key assumption for this approach is that any deposition on inland water or shallow ocean is rapidly transferred to the bottom sediment. Furthermore, dilution due to currents and movement of sediment is neglected. The surface concentration in the sediment is then assumed to equal the ground concentration evaluated from transport analysis. The conversion from water concentration to an areal DRL is shown in Equation (3):

$$DRL_{area,water} = BCG_{water} * d * \rho_{sediment} * K_d * k \quad (3)$$

$$\frac{\mu Ci}{m^2} = \frac{pCi}{L_{water}} * cm * \frac{g_{sediment}}{cm^3} * \frac{ml_{water}}{g_{sediment}} * \left(\frac{1\ L_{water}}{1000\ ml_{water}} * \frac{1\ uCi}{10^6\ pCi} * \frac{100^2\ cm^2}{1\ m^2}\right)$$

where

$DRL_{area,water}$ = Derived Response Level for water (µCi/m^2)

BCG_{water} = Biota Concentration Guide for water (pCi/l_{water})

d = Depth of migration in sediment (cm)

$\rho_{sediment}$ = Sediment density ($g_{sediment}$/cm^3)

K_d = Distribution coefficient, i.e., the ratio of radionuclide in sediment and in water (ml_{water}/$g_{sediment}$)

k = Conversion factor from ml to l, pCi to µCi, and cm^2 to m^2 (10^{-5})

Based on the MSL FSAR, the depth of migration in sediment is assumed to be 1 cm for plutonium. The density of sediment is assumed to be 1 $g_{sediment}$/cm^3. The distribution coefficient is assumed to be 1×10^5 ml_{water}/$g_{sediment}$ for freshwater and 5×10^4 ml_{water}/$g_{sediment}$ for saline water.

The DRLs shown in Table 3.3-1 are calculated for terrestrial plants and terrestrial animals using the previously described assumptions. Table 3.3-1 also includes the water BCGs for these organisms as provided by RESRAD-BIOTA.

Table 3.3-1. Plutonium-238 Areal Water DRLs for Biota

Organism Type	BCG_{water} (pCi/l)	$DRL_{area,water}$ (µCi/m^2)	
		Freshwater	Saline Water
Aquatic animal	176	176	88
Riparian animal	550	550	275

The DRL for the aquatic animal in saline water is the most restrictive (i.e., smallest DRL). Using this approach, an aquatic animal in an area that is projected to be contaminated to greater than 88 µCi/m^2 would likely receive a dose that exceeds the limit for aquatic animals as specified by DOE-STD-1153-2002. Note that this DRL is 440 times greater than 0.2 µCi/m^2, which is the activity level at which the Draft Input to the Mars 2020 FSAR reports land contamination. The value 0.2 µCi/m^2 was formerly used by the EPA and in past LS analyses as an activity level above which further action should be considered (such as monitoring and cleanup) [1].

4. PLUTONIUM TRANSFER FACTORS FOR CROPS

The Draft Input to the Mars 2020 FSAR includes statistical modeling of the consequences due to release of radioactive material from a launch accident. For this statistical modeling, probability distributions for inputs are desired. SAND2017-7381, *Distribution Development for STORM Ingestion Input Parameters* [31], describes the distributions for inputs to ingestion dose calculations, one of which is the crop uptake factor for plutonium. The crop uptake factor is the ratio of activity in the plant over the activity deposited on the ground, i.e., the fraction of activity deposited on the ground that is ultimately consumed by humans. Uptake factors for individual crops take into account the acreage, yield, and radionuclide transfer factor from the soil and/or from the plant surface to the edible portion of a given crop.

Radionuclide transfer factors are quantities that are empirically derived to relate the concentration of radioactivity in soil to concentration in the plant growing in that soil. These quantities are sometimes also called concentration ratios (CR) in the health physics community. Typical transfer factor units for plants are Bq per kg plant per Bq per kg soil. The following literature review was performed in order to develop a transfer factor distribution, which was then used to inform the distribution for the crop uptake factor, as documented in SAND2017-7381 [31].

4.1. Literature Review Results

Two transfer factor compilations, *A Compendium of Transfer Factors for Agricultural and Animal Products* (PNNL-13421, 2003 [32]) and *Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments* (IAEA Technical Report Series No. 472, 2010 [33]), were used as a starting point for determining a plutonium transfer factor and uncertainty. PNNL-13421 is the primary reference for transfer factors in the FRMAC Assessment Manual [27]. IAEA-TRS-472 is also commonly used by FRMAC for non-default ingestion assessments.

4.1.1. PNNL-13421

PNNL-13421 provides plutonium crop transfer factors for leafy vegetables, fruit, root vegetables, and grain. These values are listed in Table 4.1-1. PNNL-13421 provides only transfer factor values, with no associated uncertainties.

Table 4.1-1. Plutonium Transfer Factors available in PNNL-13421

Crop Type	Plutonium Transfer Factor $(Bq/kg_{crop})/(Bq/kg_{soil})$
Leafy vegetables	6.0E-05
Fruit	4.5E-05
Root vegetables	1.1E-03
Grain	8.6E-06

Of the available references used for actinide crop transfer factors in this compendium, no uncertainties are reported except in one reference, ORNL-5786 [34]. This report by Baes et al. is the source for the actinide fruit transfer factors in PNNL-13421. It states that “the [transfer factor] for plutonium appears to be lognormally distributed and reported values range from 10^{-6} to 10^{-2}.”

4.1.2. IAEA-TRS-472

IAEA-TRS-472 provides an extensive list of plutonium transfer factors, particularly for crops. The majority of these transfer factors are geometric mean values accompanied by a geometric standard deviation, minimum, and maximum. A list of the plutonium crop transfer factors from IAEA-TRS-472 is included in Appendix A. IAEA-TECDOC-1616 [35], a supporting document for IAEA-TRS-472, contains a more detailed discussion of the IAEA’s data collection and analysis.

The PNNL and IAEA transfer factors appear to be within at most an order of magnitude of each other given a specific radionuclide and crop type. When performing a direct comparison between the two references, it is important to note that the transfer factors from IAEA are listed for a specific environment (e.g., temperate, tropical, and subtropical), soil group (e.g. sand, loam, clay, and organic), and plant compartment, whereas the PNNL document does not provide such detail.

4.2. Transfer Factor Distributions

There are many sources of variability in transfer factor values, including “the chemical nature of the radionuclide, variations in metabolic and biochemical mechanisms of radionuclide uptake by plants, detoxification mechanisms, hydrological conditions within the soil, and plant available concentrations in soil within the rhizosphere” [33]. Soil specifically can have an important impact on transfer factor variability. For example, “The difference in transfer factors to farm crops for different soils may be one or two orders of magnitude” and “The transfer of both plutonium and americium is lower in loam, organic and calcareous soils” [33]. Table 2 in IAEA-TRS-472 can be consulted if the soil type is known and the decision is made to use soil-specific transfer factors.

Argonne National Laboratory performed an analysis of the parameters used in its RESRAD computer code [36]. RESRAD is used to estimate radiation doses and risks from residual radioactive materials. Plant, meat, and milk transfer factors and bioaccumulation factors are among the parameters used by RESRAD. In the RESRAD analysis, transfer factors were assigned a lognormal distribution, along with a low, base, and high value. The high and low values were selected to be 10 times and 1/10 of, respectively, the base values, citing the following basis:

> *“For cases in which probability information was not available in the two [DandD] reports…selection of the low and high values was based on data from previously searched literature and professional judgments. Note that the low and high values were not the absolute lower bound and upper bound values for a parameter but the values thought to represent a parameter in terms of revealing the potential range of radiation doses under likely conditions.”*

Sheppard and Evenden performed an analysis of the statistical variation of transfer factors in the International Union of Radioecology (IUR) database in 1995 [37]. Many transfer factors in PNNL-13421 and IAEA-TRS-472 come from the IUR database. Sheppard and Evenden state:

> *"Ratios such as CRs have a tendency, formalized by the Central Limit Theorem, to be lognormally distributed. This is also found to be true empirically, and is generally true for the CR values in the IUR database. As a result, GMs and GSDs are appropriate to summarize the data. The GSDs have fortunate attributes: 1) they are unitless and do not change value even if the CR is expressed on a plant wet weight basis, as done in some assessments, and 2) they are directly comparable among elements even though bioavailability varies markedly among the elements. These attributes are especially useful because it is possible to obtain good estimates of GSD from large databases and then apply them to elements or settings where there is a paucity of data."*

Based on analysis of the IUR database, Sheppard and Evenden recommend using a geometric standard deviation of about 6 if information about crops and soil type are not known. Table 1 in Reference [37] by Sheppard and Evenden contains recommended geometric standard deviations to use when more information is known.

4.3. Recommended Plutonium Transfer Factor for use in STORM

Appendix A contains a list of the plutonium crop transfer factors from IAEA-TRS-472 that can be used to develop a distribution for the crop uptake factor. If these transfer factors are considered sufficient, a decision must be made whether or not to use soil-specific mean values, keeping in mind that the mean transfer factor for a given soil is typically derived from very few samples. The literature recommends using a lognormal distribution to represent the uncertainty in transfer factors.

5. CONCLUSIONS

The health physics parameters and associated issues discussed in this paper are planned to be included in the Mars 2020 LS analysis with the exception of dose to biota for the reason described among the following final recommendations:

- A probability distribution function for the DDREF is proposed for use in LS analyses given its uncertainty in the health physics community. The function is

$$f(x) = 0.5 \qquad 1 \le x \le 2$$
$$f(x) = 0.5e^{-(x-2)} \qquad x > 2$$

  where x represents an uncertain value of DDREF and $f(x)$ is the probability associated with a value of DDREF.

- The activity level at which the Draft Input to the Mars 2020 FSAR tabulates land contamination is 0.2 μCi/m^2. This value was formerly used by the EPA and in past LS analyses as an activity level above which further action such as monitoring and cleanup should be considered. The areal soil concentration that would likely cause terrestrial biota to receive a dose that exceeds the dose limits specified in DOE-STD-1153-2002 is estimated to be 84 μCi/m^2, which is 420 times greater than 0.2 μCi/m^2. The areal water concentration that would likely cause aquatic biota to receive a dose that exceeds the limits specified in DOE-STD-1153-2002 is estimated to be 88 μCi/m^2, which is 440 times greater than 0.2 μCi/m^2. Land contamination areas reported at the 0.2 μCi/m^2 contamination level would encompass the terrestrial and aquatic biota values. Using the 0.2 μCi/m^2 contamination level is bounding.

- IAEA-TRS-472 provides plutonium transfer factors for various crops and various environments and soil types. This information can be used to develop a distribution for the crop uptake factor for use in the STORM code. Most references recommend a lognormal distribution for transfer factors. The actual distribution developed for STORM can be found in SAND2017-7381, *Distribution Development for STORM Ingestion Input Parameters* [31].

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APPENDIX A: CROP TRANSFER FACTORS FOR PLUTONIUM

Source: *Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments* (IAEA Technical Report Series No. 472, 2010 [33])

Plant group	Plant compartment	Environment	Soil Group	N	Mean (GM)	GSD	Minimum	Maximum
Cereals	Grain	Temperate	All soil	105	9.50E-06	6.7	2.00E-07	1.10E-03
Cereals	Grain	Temperate	Clay	16	7.40E-06	14.9	2.00E-07	5.10E-04
Cereals	Grain	Temperate	Loam	10	4.90E-06	11	3.50E-07	3.10E-04
Cereals	Grain	Temperate	Organic	2	5.40E-04		2.30E-06	1.10E-03
Cereals	Grain	Temperate	Sand	76	1.00E-05	4.5	5.00E-07	3.60E-04
Cereals	Stems and shoots	Temperate	All soil	10	4.40E-05	16.4	4.40E-07	9.00E-04
Cereals	Stems and shoots	Temperate	Clay	4	2.40E-06	5.5	4.40E-07	2.00E-05
Cereals	Stems and shoots	Temperate	Loam	5	4.50E-04	2	1.50E-04	9.00E-04
Cereals	Stems and shoots	Temperate	Sand	1	4.00E-05			
Grasses	Stems and shoots	Temperate	All soil	2	1.60E-04		5.00E-05	2.70E-04
Herbaceous plants		Temperate	All soil	9	1.20E-04	1.2	2.70E-05	8.30E-04
Herbaceous plants		Temperate	Loam	1	8.80E-05			
Herbaceous plants		Temperate	Organic	1	7.30E-05			
Herbaceous plants		Temperate	Sand	1	1.60E-04			
Herbaceous plants		Temperate	Unspecified	6	1.30E-04	1.5	2.70E-05	8.30E-04
Leafy vegetables	Leaves	Temperate	All soil	13	8.30E-05	2.7	1.00E-05	2.90E-04
Leafy vegetables	Leaves	Temperate	Loam	1	2.80E-04			
Leafy vegetables	Leaves	Temperate	Organic	1	2.70E-05			
Leafy vegetables	Leaves	Temperate	Sand	4	1.10E-04	2.7	2.90E-05	2.90E-04
Leguminous fodder	Stems and shoots	Temperate	All soil	74	4.90E-04	2.2	1.10E-04	2.90E-03
Leguminous fodder	Stems and shoots	Temperate	Clay	16	4.10E-04	1.9	1.20E-04	1.10E-03
Leguminous fodder	Stems and shoots	Temperate	Loam	25	5.80E-04	2.4	1.10E-04	2.90E-03
Leguminous fodder	Stems and shoots	Temperate	Sand	33	4.80E-04	2.2	1.10E-04	2.00E-03
Leguminous vegetables	Seeds and pods	Temperate	All soil	18	6.30E-05	1.4	3.70E-05	1.50E-04
Leguminous vegetables	Seeds and pods	Temperate	Sand	18	6.30E-05	1.4	3.70E-05	1.50E-04
Maize	Grain	Temperate	All soil	1	3.00E-06			
Maize	Stems and shoots	Temperate	All soil	58	5.20E-05	2.7	2.00E-06	3.20E-04
Maize	Stems and shoots	Temperate	Sand	58	5.20E-05	2.7	2.00E-06	3.20E-04
Non-leafy vegetables	Fruits, heads, berries, buds	Temperate	All soil	9	6.50E-05	2.7	6.00E-06	2.00E-04
Non-leafy vegetables	Fruits, heads, berries, buds	Temperate	Loam	8	6.20E-05	2.7	6.00E-06	2.00E-04
Pasture	Stems and shoots	Temperate	All soil	22	5.50E-04	3	6.30E-05	3.90E-03
Pasture	Stems and shoots	Temperate	Clay	5	2.00E-03	1.5	1.20E-03	3.90E-03
Pasture	Stems and shoots	Temperate	Loam	10	3.00E-04	3	6.30E-05	3.30E-03
Pasture	Stems and shoots	Temperate	Organic	1	1.10E-03			

Plant group	Plant compartment	Environment	Soil Group	N	Mean (GM)	GSD	Minimum	Maximum
Pasture	Stems and shoots	Temperate	Sand	5	4.60E-04	1.8	2.10E-04	9.40E-04
Root crops	Leaves	Temperate	All soil	10	1.20E-03	2.5	2.50E-04	4.90E-03
Root crops	Leaves	Temperate	Loam	5	2.20E-03	1.8	1.10E-03	4.90E-03
Root crops	Leaves	Temperate	Organic	1	2.50E-04			
Root crops	Leaves	Temperate	Sand	4	7.70E-04	1.9	3.40E-04	1.60E-03
Root crops	Roots	Temperate	All soil	5	3.90E-04	10	7.00E-05	5.80E-03
Root crops	Roots	Temperate	Sand	4	5.50E-04	10	7.00E-05	5.80E-03
Shrubs		Temperate	Unspecified	2	1.70E-04		6.40E-05	2.70E-04
Tubers	Tubers	Temperate	All soil	87	1.10E-04	5.5	3.80E-06	5.00E-03
Tubers	Tubers	Temperate	Clay	3	3.60E-04	3.7	8.00E-05	9.40E-04
Tubers	Tubers	Temperate	Loam	9	1.50E-04	11	6.20E-06	5.00E-03
Tubers	Tubers	Temperate	Organic	2	4.10E-04		1.30E-05	8.00E-04
Tubers	Tubers	Temperate	Sand	72	1.00E-04	5	3.80E-06	2.00E-03
Woody Trees		Temperate	All soil	10	1.40E-04	2.9	1.30E-06	2.10E-02
Woody Trees		Temperate	Loam	1	8.00E-06			
Woody Trees		Temperate	Organic	1	1.00E-06			
Woody Trees		Temperate	Sand	1	2.00E-05			
Woody Trees		Temperate	Unspecified	7	5.50E-04	2.2	2.80E-05	2.10E-02
Fruits	Coconut milk	Tropical	Unspecified	1	3.20E-05			
Fruits	Fruits	Tropical	Unspecified	2	2.30E-05		1.60E-05	2.90E-05
Non-leafy vegetables	Fruits, heads, berries, buds	Tropical	Unspecified	1	1.70E-05			
Other crops		Tropical	Unspecified	1	6.70E-05			
Leafy vegetables	Leaves	Subtropical	Unspecified	2	1.10E-03		1.90E-04	2.00E-03
Non-leafy vegetables	Fruits	Subtropical	Unspecified	2	8.20E-04		4.30E-04	1.20E-03
Root crops	Roots	Subtropical	Unspecified	2	4.60E-03		5.30E-04	8.60E-03
Tubers	Tubers	Subtropical	Unspecified	6	1.50E-03	2.4	6.20E-04	4.80E-03

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