APPENDIX B
EFFECTS OF PLUTONIUM ON THE ENVIRONMENT

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APPENDIX B
EFFECTS OF PLUTONIUM ON THE ENVIRONMENT

B-1 INTRODUCTION

This appendix addresses the potential impacts from a radioactive source containing plutonium (Pu)-238 released to the environment, which could occur in any of the low-probability accidents described in Chapter 4 of this Environmental Impact Statement (EIS). In Alternative 1, the Proposed Action, the Mars 2020 rover would carry one Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) containing approximately 4.8 kilograms (10.6 pounds) of plutonium dioxide (PuO_2) (consisting mostly of Pu-238), with a total activity of about 60,000 curies. Additionally, in Alternative 3, the Mars 2020 rover would include light weight radioisotope heater units (LWRHUs) to keep avionics and communication systems within thermal limits. The rover could include up to 71 LWRHUs, each containing approximately 2.7 grams (0.095 oz) of PuO_2 (consisting mostly of Pu-238), with a total activity of about 33.2 curies. Should 71 LWRHUs be used the total activity would be about 2,400 curies. The health and environmental risks associated with Pu-238 have been previously addressed in the National Aeronautics and Space Administration's (NASA's) EISs for the Galileo, Ulysses, Cassini, Mars Exploration Rovers, New Horizons, and Mars Science Laboratory missions (NASA 1989, NASA 1990, NASA 1995, NASA 1997, NASA 2002b, NASA 2005 and NASA 2006).

Because radiation exposure and its consequences are of interest to the general public, Section B.2 provides information about the nature of radiation and explains basic concepts used to evaluate radiation health effects. Section B.3 discusses the behavior of plutonium in the environment, including how it interacts with the human body.

B-2 RADIOLOGICAL HUMAN HEALTH IMPACTS

This appendix presents numerical information using scientific, or exponential, notation. For example, the number 100,000 can also be expressed as 1×10^5. The number 0.001 can be expressed as 1×10^{-3}. The following chart defines the equivalent numerical notations that may be used in this appendix.

Fractions and Multiples of Units			
Multiple	**Decimal Equivalent**	**Prefix**	**Symbol**
1×10^6	1,000,000	mega-	M
1×10^3	1,000	kilo-	k
1×10^2	100	hecto-	h
1×10	10	deka-	da
1×10^{-1}	0.1	deci-	d
1×10^{-2}	0.01	centi-	c
1×10^{-3}	0.001	milli-	m
1×10^{-6}	0.000001	micro-	μ

B-2.1 NATURE OF RADIATION AND ITS EFFECTS ON HUMANS

What Is Radiation?

Radiation is energy transferred in the form of particles or waves. Globally, human beings are exposed constantly to radiation from the solar system and the Earth's rocks and soil. This radiation contributes to the natural background radiation that always surrounds us. Manmade sources of radiation also exist, including medical and dental x-rays and household smoke detectors.

All matter in the universe is composed of atoms. Radiation comes from the activity of tiny particles within an atom. An atom consists of a positively charged nucleus (central part of an atom) with a number of negatively charged electron particles in various orbits around the nucleus. There are two types of particles in the nucleus: neutrons that are electrically neutral, and protons that are positively charged. Atoms are categorized as different stable elements based on the number of protons in the nucleus. There are more than 100 natural and manmade elements. An element has equal numbers of electrons and protons. When atoms of an element differ in their number of neutrons, they are called isotopes. All elements have three or more isotopes, some or all of which could be unstable.

Unstable isotopes undergo spontaneous change, known as radioactive disintegration or radioactive decay. The process of continuously undergoing spontaneous disintegration is called radioactivity. The radioactivity of a material decreases with time. The time it takes a material to lose half of its original radioactivity is its half-life. An isotope's half-life is a measure of its decay rate. For example, an isotope with a half-life of 8 days will lose one-half of its radioactivity in that amount of time. In 8 more days, one-half of the remaining radioactivity will be lost, and so on. Each radioactive element has a characteristic half-life. The half-lives of various radioactive elements may vary from millionths of a second to billions of years.

As unstable isotopes change into more stable forms, they emit particles and/or energy. An emitted particle may be an alpha particle (a helium nucleus), a beta particle (an electron), or a neutron, with various levels of kinetic energy. Sometimes these particles are emitted in conjunction with gamma rays. The particles and gamma rays are referred to as "ionizing radiation." Ionizing radiation refers to the fact that the radiation can ionize, or electrically charge, an atom by stripping off one or more of its electrons. Gamma rays, even though they do not carry an electric charge, can ionize atoms as they pass through an element by ejecting electrons. Ionizing radiation can cause a change in the chemical composition of many things, including living tissue (organs), which can affect the way they function.

When a radioactive isotope of an element emits a particle, it changes to an entirely different element or isotope, one that may or may not be radioactive. Eventually, a stable element is formed. This transformation, which may take several steps, is known as a decay chain. For example, the isotope plutonium-238, has a half-life of 87.7 years. It emits an alpha particle and becomes the isotope uranium-234, a radioactive isotope with a half-life of 246,000 years. The decay products will build up and eventually die away as time progresses.

Characteristics of various forms of ionizing radiation are briefly described in the following text and in the table below.

Radiation Type	Typical Travel Distance in Air	Barrier
α	Few centimeters	Sheet of paper or skin's surface
β	Few meters	Thin sheet of aluminum foil or glass
γ	Very large	Thick wall of concrete, lead, or steel
n	Very large	Water, paraffin, graphite

Alpha (α) – Alpha particles are the heaviest type of ionizing radiation, consisting of two protons and two neutrons. They can travel only a few centimeters in air. Alpha particles lose their energy almost as soon as they collide with anything. They can be stopped easily by a sheet of paper or by the skin's surface.

Beta (β) – Beta particles, consisting of an electron, are 7,330 times lighter than alpha particles and can travel a longer distance in the air. A high-energy beta particle can travel a few meters in the air. Beta particles can pass through a sheet of paper, but can be stopped by a thin sheet of aluminum foil or glass.

Gamma (γ) – Gamma rays (and x-rays), unlike alpha or beta particles, are waves of pure energy. Gamma rays travel at the speed of light. Gamma radiation is very penetrating and requires a large mass, such as a thick wall of concrete, lead, or steel, to be stopped.

Neutrons (n) – Neutrons produce ionizing radiation indirectly by collision with hydrogen nuclei (protons) and when gamma rays and alpha particles are emitted following neutron capture in matter. A neutron has about one-quarter the weight of an alpha particle. It will travel in the air until it is absorbed in another nucleus. The most prolific source of neutrons is a nuclear reactor.

Radiation Measuring Units

During the early days of radiological experimentation, there was no precise unit for radiation measure. Therefore, a variety of units were used to measure radiation. These units determined the amount, type, and intensity of radiation. Just as heat can be measured in terms of its intensity or effects using units of calories or degrees, amounts of radiation or its effects can be measured in units of curies, radiation absorbed dose (rad), or dose equivalent (roentgen equivalent in man, or rem). The following text summarizes these units.

Curie – The curie, named after scientists Marie and Pierre Curie, describes the intensity of a sample of radioactive material. The decay rate of 1 gram of radium was the original basis of this unit of measure. Because the measured decay rate kept changing slightly as measurement techniques became more accurate, the curie was subsequently defined as exactly 3.7×10^{10} disintegrations (decays) per second.

Radiation Units and Conversions to International System of Units	
1 curie	= 3.7×10^{10} disintegrations per second
	= 3.7×10^{10} becquerels
1 becquerel	= 1 disintegration per second
1 rad	= 0.01 gray
1 rem	= 0.01 sievert
1 gray	= 1 joule per kilogram

Rad – The rad is the unit of measurement for the physical absorption of radiation. The total energy absorbed per unit quantity of tissue is referred to as "absorbed dose" (or simply "dose"). As sunlight heats pavement by giving up an amount of energy to it, radiation similarly gives up energy to objects in its path. One rad is equal to the amount of radiation that leads to the deposition of 0.01 joule of energy per kilogram of absorbing material.

Rem – The rem is a measurement of the dose equivalent from radiation based on its biological effects. The rem is used in measuring effects of radiation on the body. One rem of one type of radiation is presumed to have the same biological effects as one rem of any other kind of radiation. This allows comparison of the biological effects of radionuclides that emit different types of radiation. One-thousandth of a rem is called a millirem.

Person-rem – The term used for reporting the collective dose, the sum of individual doses received in a given time period by a specified population from exposure to a specified radiation source.

The corresponding units of radiation measure in the International System of Units are: becquerel (a measure of source intensity), gray (a measure of absorbed dose), and sievert (a measure of dose equivalent).

An individual may be exposed to ionizing radiation externally (from a radioactive source outside the body) or internally (from ingesting or inhaling radioactive material). The external dose is different from the internal dose because an external dose is delivered only during the actual time of exposure to the external radiation source, while an internal dose continues to be delivered as long as the radioactive source is in the body. The dose from internal exposure is calculated over 50 years following the initial exposure. Both radioactive decay and elimination of the radionuclide by ordinary metabolic processes decrease the dose rate with the passage of time.

B-2.2 RADIATION SOURCES

The average American receives a total of approximately 620 millirem per year from all radiation sources—both natural and manmade—of which approximately 310 millirem per year are from natural sources. Radiation sources can be divided into six different categories: (1) cosmic radiation, (2) terrestrial radiation, (3) internal radiation, (4)

consumer products, (5) medical diagnosis and therapy, and (6) other sources (NCRP 1987, NRC 2011). These categories are discussed in the following paragraphs.

Cosmic Radiation – Cosmic radiation is ionizing radiation resulting from energetic charged particles from space continuously hitting Earth's atmosphere where they create secondary particles and photons (primarily gamma rays and x-rays). These particles, and the secondary particles and photons they create, compose cosmic radiation. Because the atmosphere provides some shielding against cosmic radiation, the intensity of this radiation increases with the altitude above sea level. The average dose to people in the United States from this source is approximately 32 millirem per year.

External Terrestrial Radiation – External terrestrial radiation is radiation emitted from radioactive materials in Earth's rocks and soils. The average individual dose from external terrestrial radiation is approximately 19 millirem per year.

Internal Radiation – Internal radiation results from the human body metabolizing natural radioactive material that has entered the body by inhalation or ingestion. Natural radionuclides in the body include isotopes of uranium, thorium, radium, radon, polonium, bismuth, potassium, rubidium, and carbon. The major contributors to the annual dose equivalent for internal radioactivity are the short-lived decay products of radon, which contribute approximately 229 millirem per year. The average individual dose from other internal radionuclides is approximately 31 millirem per year.

Consumer Products – Consumer products also contain sources of ionizing radiation. In some products, such as smoke detectors and airport x-ray machines, the radiation source is essential to the product's operation. In other products, such as televisions and tobacco, radiation occurs as the products function. The average dose from consumer products is approximately 12 millirem per year.

Medical Diagnosis and Therapy – Radiation is an important diagnostic medical tool and cancer treatment. Nuclear medical procedures result in an average exposure of about 297 millirem per year—a significant increase over the14 millirem per year exposure estimated in the recent past. This increase is due primarily to the expanded use of computed tomography and the use of nuclear medication in therapy. Individual exposures vary widely since not all individuals undergo the same medical procedures.

Other Sources – There are a few additional sources of radiation that contribute minor doses to individuals in the United States. The average dose from nuclear fuel cycle facilities (e.g., uranium mines, mills, and fuel processing plants) and nuclear power plants has been estimated to be less than 1 millirem per year. Radioactive fallout from atmospheric atomic bomb tests, emissions from certain mineral extraction facilities, and transportation of radioactive materials contribute less than 1 millirem per year to the average dose to an individual. Air travel contributes approximately 1 millirem per year to the average dose.

B-2.3 EXPOSURE PATHWAYS

As stated earlier, an individual may be exposed to ionizing radiation both externally and internally. The different ways that could result in radiation exposure to an individual are

called exposure pathways. Each type of exposure is discussed separately in the following paragraphs.

External Exposure – External radiation exposure can result from several different pathways, including exposure to a cloud of radioactive particles passing over the receptor (an exposed individual), standing on ground contaminated with radioactivity, and swimming or boating in contaminated water. If the receptor leaves the source of radiation exposure, the dose rate will be reduced, if not eliminated. Dose from external radiation is based on time spent exposed to a radiation source. The appropriate dose measure is called the effective dose equivalent (EDE).

Internal Exposure – Internal exposure results from a radiation source entering the human body through either inhalation of contaminated air or ingestion of contaminated food or water. In contrast to external exposure, once a radiation source enters the body, it remains there for a period of time that varies, depending on decay and biological half-life.[1] The absorbed dose to each organ of the body is calculated for a period of 50 years following intake. The calculated absorbed dose is called the committed dose equivalent. Various organs have different susceptibilities to damage from radiation. The committed EDE takes these different susceptibilities into account and provides a broad indicator of the health risk to an individual from radiation. The committed EDE is a weighted sum of the committed dose equivalent in each major organ or tissue. The concept of the committed EDE applies only to internal pathways.

B-2.4 RADIATION PROTECTION GUIDES

Several organizations have issued radiation protection guides. Responsibilities of the main radiation safety organizations, particularly those that affect policies in the United States, are summarized in the following text.

International Commission on Radiological Protection (ICRP) – ICRP has responsibility for providing guidance in matters of radiation safety. ICRP's operating policy is to prepare recommendations to address basic principles of radiation protection, leaving the various national protection committees to introduce detailed technical regulations, recommendations, or codes of practice best suited to the needs of their countries.

National Council on Radiation Protection and Measurements – In the United States, this council has responsibility for adapting and providing detailed technical guidelines for implementing ICRP recommendations. The Council consists of expert radiation protection specialists and scientists.

National Research Council and National Academy of Sciences – The National Research Council, which provides science and policy research supporting the National Academy of Sciences, associates the broad science and technology community with the Academy's purposes of furthering knowledge and advising the Federal Government. The Council's Nuclear Radiation Studies Board prepares reports to advise the Federal

[1] Biological half-life is the time for one-half of a radioactive source that has entered the body to be removed from the body by natural processes.

Government on issues related to radiation protection and radioactive materials. The Committee on the Biological Effects of Ionizing Radiation (BEIR), which has issued a number of studies on radiation exposure health conveyances, operates under the Nuclear Radiation Studies Board.

U.S. Environmental Protection Agency (EPA) – EPA has published a series of documents, *Radiation Protection Guidance to Federal Agencies,* used as a regulatory benchmark by a number of Federal agencies to limit public and occupational workforce exposures to the greatest extent possible.

The Interagency Steering Committee on Radiation Standards (ISCORS) – ISCORS technical reports serve as guidance for Federal agencies to assist them in preparing and reporting analysis results and implementing radiation protection standards in a consistent and uniform manner. ISCORS issued a technical report entitled *A Method for Estimating Radiation Risk from TEDE* (DOE 2002). This report provides dose-to-risk conversion factors using total effective dose equivalent (TEDE) to estimate dose. It is recommended for use by DOE personnel and contractors when computing potential radiation risk from calculated radiation dose for comparison purposes. Alternatively, for radiation risk assessments required in risk management decisions, DOE recommends that the radionuclide-specific risk coefficients in EPA's Federal Guidance Report No. 13, *Cancer Risk Coefficients for Environmental Exposure to Radionuclides* (EPA 1999) should be used.

B-2.5 RADIATION EXPOSURE LIMITS

Exposure limits for members of the public and radiation workers are generally consistent with ICRP recommendations. EPA also considers National Council on Radiation Protection and Measurements and ICRP recommendations, and sets specific annual exposure limits (usually less than those recommended by ICRP) in *Radiation Protection Guidance to Federal Agencies* documents. Each regulatory organization then establishes its own set of radiation standards. Examples of exposure limits set by DOE, EPA, and the U.S. Nuclear Regulatory Commission (NRC), for members of the public are shown in Table B-1.

Table B-1. Exposure Limits for Members of the Public

Guidance Criteria (Organization)	Public Exposure Limits at the Site Boundary
40 CFR Part 61 (EPA)	0.01 rem per year (all air pathways)
40 CFR Part 141 (EPA)	0.004 rem per year (drinking water pathways)
DOE Order 5400.5 (DOE)	0.01 rem per year (all air pathways) 0.004 rem per year (drinking water pathway) 0.1 rem per year (all pathway)
10 CFR 20.1301 (NRC)	0.1 rem per year (all pathways)

B-2.6 HEALTH EFFECTS

To provide background information for discussions of radiation exposure impacts, this section explains basic concepts used to evaluate radiation effects.

Radiation can cause a variety of damaging health effects in humans. The most significant effects are induced cancer fatalities. These effects are referred to as "latent cancer fatalities" because the cancer may take many years to develop. In the discussions that follow, all fatal cancers are considered latent; therefore, the terms "latent cancer fatalities" and "fatal cancers" are used interchangeably in this appendix.

The National Research Council's Committee on the BEIR has prepared a series of reports to advise the Federal Government on radiation exposure health consequences. *Health Effects of Exposure to Low Levels of Ionizing Radiation*, BEIR V (NRC 1990), provides current estimates for excess mortality from leukemia and other cancers expected to result from exposure to ionizing radiation.

Models and risk coefficients in BEIR V were derived through analyses of relevant epidemiologic data that included the Japanese atomic bomb survivors, ankylosing spondylitis (spinal arthritis) patients, Canadian and Massachusetts fluoroscopy (breast cancer) patients, New York postpartum mastitis (breast cancer) patients, Israeli tinea capitis (thyroid cancer) patients, and Rochester, New York, thymus (thyroid cancer) patients. Models for leukemia, respiratory cancer, digestive cancer, and other cancers used only the atomic bomb survivor data, although the ankylosis spondylitis patient analysis results were considered. Atomic bomb survivor analyses were based on revised dosimetry, with an assumed relative biological effectiveness of 20 for neutrons, and were restricted to doses less than 400 rad. Estimates of fatal cancer (other than leukemia) risks were obtained by totaling estimates for breast, respiratory, digestive, and other cancers.

The National Council on Radiation Protection and Measurements, based on radiation risk estimates provided in BEIR V and ICRP Publication 60 recommendations (ICRP 1991), estimated the total detriment resulting from low-dose or low-dose-rate exposure to ionizing radiation to be 0.0007 per rem for the general population (NCRP 1993). The total detriment includes fatal and nonfatal cancers, as well as severe hereditary (genetic) effects. The major contribution to the total detriment is from fatal cancer, estimated to be 0.0005 per rem for the general population. The risk estimator breakdowns for the general population are shown in Table B-2. (Risk estimators are lifetime probabilities that an individual would develop a fatal cancer per rem of radiation received.) Nonfatal cancers and genetic effects are less probable radiation exposure consequences.

Table B-2. Nominal Health Risk Estimators Associated with Exposure to 1 Rem of Ionizing Radiation

Exposed Individual	Fatal Cancer [a]	Nonfatal Cancer [b]	Genetic Disorders [b]	Total
Public	0.0005	0.0001	0.00013	0.00073

Source: NCRP 1993.

(a) For fatal cancer, the health effect coefficient is the same as the probability coefficient. When applied to an individual, the unit is the lifetime probability of a cancer fatality per rem of radiation dose. When applied to a population of individuals, the unit is the excess number of fatal cancers per person-rem of radiation dose.

(b) In determining a means of assessing radiation exposure health effects, the ICRP has developed a weighting method for nonfatal cancers and genetic effects.

The EPA, in coordination with other Federal agencies involved in radiation protection, issued the September 1999 Federal Guidance Report No. 13, *Cancer Risk Coefficients for Environmental Exposure to Radionuclides* (EPA 1999). This document is a compilation of risk factors for doses from external gamma radiation and internal intake of radionuclides. Federal Guidance Report No. 13 is the basis of radionuclide risk coefficients used in the EPA *Health Effects Assessment Summary Tables* (EPA 2001) and in computer dose codes, such as the DOE Argonne Residual Radiation code. However, DOE and other agencies regularly conduct dose assessments with models and codes that calculate radiation dose from exposure or intake using dose conversion factors and do not compute risk directly. In these cases, where it is necessary or desirable to estimate risk for comparative purposes (e.g., comparing risk associated with alternative actions), it is common practice to simply multiply the calculated TEDE by a risk-to-dose factor. ISCORS recommends that agencies use a conversion factor of 6×10^{-4} fatal cancers per TEDE (rem) for mortality and 8×10^{-4} cancers per rem for morbidity when making qualitative or semi-quantitative estimates of radiation exposure risk to members of the general public[2] (DOE 2002). The TEDE-to-risk factor provided in *Estimating Radiation Risk from Total Effective Dose Equivalent (TEDE),* ISCORS Technical Report No. 1, is based upon a static population with characteristics consistent with the U.S. population.

The ISCORS report notes that the recommended risk coefficients used with TEDE dose estimates generally produce conservative radiation risk estimates (i.e., they overestimate risk).[3] For the ingestion pathway of 11 radionuclides compared, risks would be overestimated compared with Federal Guidance Report No. 13 values for about 8 radionuclides, and significantly overestimated (by up to a factor of 6) for 4 of the 8. The DOE Office of Environmental Policy and Guidance also compared the risks obtained using the risk conversion factor with the risks in Federal Guidance Report No. 13 for the inhalation pathway, and found a bias toward overestimation of risk, although it was not as severe as for ingestion. For 16 radionuclides/chemical states evaluated, 7 were significantly overestimated (by more than a factor of 2), 5 were significantly underestimated, and the remainder agreed within about a factor of 2. Generally, these differences are within the uncertainty of transport and uptake portions of dose or risk modeling and, therefore, the approach recommended is fully acceptable for comparative assessments. That notwithstanding, it is strongly recommended that, wherever possible, the more rigorous approach with Federal Guidance Report No. 13 cancer risk coefficients be used (DOE 2002).

The values in Table B-2 are "nominal" cancer and genetic disorder probability coefficients. They are based on an idealized population receiving a uniform whole-body dose. Recent EPA studies, based on age-dependent dose coefficients for members of

[2]Such estimates should not be stated with more than 1 significant digit.

[3]This statement presumes that using the radionuclide-specific risk factors in Federal Guidance Report No. 13 would be a more accurate measure of potential risk than multiplying the TEDE by a single average risk factor.

the public, indicate that the product of the effective dose and the probability coefficient could over- or underestimate radiological risk (EPA 1999). In support of risk results provided in Federal Guidance Report No. 13, EPA performed an uncertainty analysis on uniform whole-body exposure effects. The analysis resulted in an estimated nominal risk coefficient increase from 0.051 fatal cancers per gray (0.00051 fatal cancers per rad) to 0.0575 fatal cancers per gray (0.000575 fatal cancers per rad) (EPA 1999a). This result indicates a nominal risk coefficient increase of about 20 percent over that provided in *Risk Estimates for Radiation Protection* (NCRP 1993) for the public.

Based on review of recent EPA reports, ISCORS recommended that a risk factor of 0.0006 fatal cancers per rem be used for estimating risks when using calculated dose (DOE 2002).

Numerical fatal cancer estimates presented in this EIS were obtained using a linear no-threshold extrapolation from the nominal risk estimated for lifetime total cancer mortality. Other methods of extrapolation to the low-dose region could yield higher or lower numerical fatal cancer estimates. Studies of human populations exposed to low doses are inadequate to demonstrate the actual risk level. There is scientific uncertainty about cancer risk in the low-dose region below the range of epidemiologic observation, and the possibility of no risk cannot be excluded (CIRRPC 1992). The National Research Council in its report on the Biological Effects of Ionizing Radiation (BEIR) states that the available scientific information is consistent with a linear dose model for low exposure levels and that, in their judgment, it is unlikely that a threshold exists (NRC 2006). Therefore, the risk factor of 0.0006 fatal cancers per rem was used as the conversion factor for all radiological exposures due to accidents, including those in the low-dose region.

B-2.7 EIS HEALTH EFFECT RISK ESTIMATORS

Health impacts of radiation exposure, whether from external or internal sources, generally are identified as somatic (i.e., affecting the exposed individual) or genetic (i.e., affecting descendants of the exposed individual). Radiation is more likely to produce somatic than genetic effects. The somatic risks of most importance are induced cancers. Except for leukemia, which can have an induction period (time between exposure to the carcinogen and cancer diagnosis) of as little as 2 to 7 years, most cancers have an induction period of more than 20 years.

For uniform irradiation of the body, cancer incidence varies among organs and tissues; the thyroid and skin demonstrate a greater sensitivity than other organs. Such cancers, however, also produce relatively low mortality rates because they are relatively amenable to medical treatment. Because fatal cancer is the most serious effect of environmental and occupational radiation exposures, estimates of cancer fatalities, rather than cancer incidence, are presented in this appendix. The numbers of fatal cancers can be used to compare risks among the various alternatives.

Based on the preceding discussion, the number of fatal cancers to workers and the general public for postulated accidents in which individual doses are less than 20 rem is calculated using a health risk estimator of 0.0006 per person-rem. The risk estimator

associated with total cancer incidence among the public is 0.0008 per person-rem (DOE 2002).

The fatal cancer estimators are used to calculate the statistical expectation of the effects of exposing a population to radiation. For example, if 100,000 people were each exposed to a one-time radiation dose of 100 millirem (0.1 rem), the collective dose would be 10,000 person-rem. The exposed population would then be expected to experience six additional cancer fatalities from the radiation (10,000 person-rem × 0.0006 lifetime probability of cancer fatalities per person-rem = 6 cancer fatalities).

Calculations of the number of excess fatal cancers associated with radiation exposure do not always yield whole numbers. These calculations may yield numbers less than one, especially in environmental impact applications. For example, if a population of 100,000 were exposed to a total dose of only 0.001 rem per person, the collective dose would be 100 person-rem (100,000 persons × 0.001 rem = 100 person-rem). The corresponding estimated number of cancer fatalities would be 0.06 (100 person-rem × 0.0006 cancer fatalities per person-rem = 0.06 cancer fatalities). The 0.06 means that there is 1 chance in 16.6 that the exposed population would experience 1 fatal cancer. In other words, 0.06 cancer fatalities are the *expected* number of deaths that would result if the same exposure situation were applied to many different groups of 100,000 people. In most groups, no person would incur a fatal cancer from the 0.001 rem dose each member received. In a small fraction of the groups, one cancer fatality would result; in exceptionally few groups, two or more cancer fatalities would occur. The *average* expected number of deaths over all the groups would be 0.06 cancer fatalities (just as the average of 0, 0, 0, and 1 is ¼, or 0.25). The most likely outcome is no cancer fatalities.

The same concept is applied to estimate radiation exposure effects on an individual member of the public. Consider the effects of an individual's exposure to a 300-millirem (0.30-rem) annual dose from all natural radiation sources. The probability that the individual would develop a fatal cancer from continuous exposure to this radiation over an average life of 72 years (presumed) is 0.013 (one person × 0.30 rem per year × 72 years × 0.0006 cancer fatalities per person-rem = 0.013). This corresponds to 1 chance in 77.

B-3 EFFECTS OF PLUTONIUM ON THE ENVIRONMENT

B-3.1 INTRODUCTION

The purpose of this section is to describe qualitatively the factors that influence the movement of PuO_2 through the environment and into the human body in the event that there is an accidental release of PuO_2 from the spacecraft's MMRTG or LWRHUs.

B-3.2 CHEMICAL AND PHYSICAL PROPERTIES THAT ARE IMPORTANT FOR BEHAVIOR IN THE ENVIRONMENT AND THE HUMAN BODY

In this section, the following important characteristics are discussed:

- Chemical form;
- Particle size distribution;

- Solubility;
- Half-life; and
- Decay modes.

Chemical Form

In the MMRTG for the Mars 2020 mission, the Pu-238 is present as plutonium dioxide in ceramic form. The predominant risk pathways are those in which this material is released as the result of ground impact and fire. It is therefore assumed that the plutonium remains oxidized. This is important because the chemical form influences the solubility, which, in turn, strongly influences such factors as bioaccumulation and uptake in the human body.

Particle Size Distribution

It is also important to understand the physical form of the material, in particular the particle size distribution, which influences: whether the material will fall to the ground in the immediate vicinity of the accident or will be transported over long distances; the initial deposition and subsequent resuspension of particles in both air and water; solubility in water and in biological fluids; and whether or not the material can be inhaled and where it will be deposited and retained within the human respiratory system. Generally speaking, larger particles have less potential for suspension and resuspension; as the particle size decreases, particles are more easily kept in suspension.

The initial particle size distribution is a function of the conditions of the accident. For example, the launch area source terms could initially be in the form of vapor as a result of exposure to fire. The vapors would contain not only the radionuclides but also various structural materials. The radionuclides would tend to condense with and agglomerate with these other materials, which would then predominantly determine the characteristics of the aerosol. The potential for uptake of inhaled particles is critically dependent on the size of the particles (respirable particles are generally considered to be 10 microns (10 micrometers) or less, although larger sizes can be deposited in the upper respiratory tract).

Solubility

A number of factors affect the solubility of PuO_2 in water. Physical parameters most important to the solubility of PuO_2 are the reactive surface area and oxidation state of plutonium and the water chemistry, including pH, reduction/oxidation potential, and temperature. The mass to surface area ratios of particles affect the reactivity and solubility, with solubility being inversely related to particle size. In general, PuO_2 is insoluble.

Because PuO_2 is so insoluble, movement through the environment depends on physical processes. PuO_2 may be carried into the soil by a number of routes, including the percolation of rainfall and subsequent leaching of particles into the soil, animal burrowing activity, and plowing or other disturbance of the soil by humans. Migration of

the PuO_2 into the soil column is of concern, primarily because of the potential for PuO_2 to reach groundwater aquifers used as drinking water suppliers. Once deposited on soil, however, PuO_2 appears to be extremely stable. Soil profile studies have shown that generally more than 95 percent of the PuO_2 from nuclear weapons fallout remained in the top 5 centimeters (2 inches) of surface soil (in undisturbed areas) for 10 to 20 years following deposition (DOE 1987).

Half-Life

The half-life of Pu-238 is 87.7 years. This half-life is particularly important for chronic exposure pathways (inhalation and ingestion). Over a human lifetime (nominally 70 years), the amount of Pu-238 in the body is reduced by less than a factor of 2 due to radioactive decay.

Decay Modes

Pu-238 is an alpha particle emitter with decay energies of about 5 million electron volts. Its radioactive decay products are also alpha-emitters with about the same decay energy. These alpha particles are what predominantly determine the effects on the human body. Pu-238 can also undergo extremely unlikely spontaneous fission, but with significantly smaller effects.

B-3.3 THE TRANSPORT OF PLUTONIUM OXIDES THROUGH THE ENVIRONMENT

This Section discusses the various ways in which plutonium can be transported through the environment to the point at which it is taken into or irradiates the human body. The modeling for the Mars 2020 mission encompasses both short-term (during plume passage) and long-term (chronic exposure) pathways.

Plutonium is one of the most widely studied elements in terms of chemistry and environmental behavior. Although its chemistry and oxidation states are quite diverse, the element's environmental mobility is very limited (INSRP 1989). The pathways and the generalized behavior of plutonium in the environment are described in the literature (e.g., Aarkrog 1977, Pinder and Doswell 1985, Pinder et al. 1987, Yang and Nelson 1984). The extent and magnitude of potential environmental impacts caused by PuO_2 releases depend on the mobility and availability of PuO_2 and are directly controlled by a number of physical and chemical parameters, including particle size, potential for suspension, deposition and resuspension, solubility, and oxidation state of any dissolved plutonium.

During Plume Passage

The predominant pathway during the passage of the airborne plume is inhalation. The important parameters in this calculation are the rate of dilution of the plume as it travels downwind, the deposition mechanisms that deplete the plume and leave radioactive material on the ground, and the rate of inhalation. All of these parameters and mechanisms are independent of the fact that the radionuclide in question is Pu-238. For example, the small particle sizes arising from agglomeration onto aluminum oxide particles (see Section B.3.2) mean that gravitational settling is not important. It is therefore appropriate to use a standard Gaussian model for the atmospheric dispersion.

Similarly, the small particle size means that, once it is transported to a human receptor, it is inhaled. Work done for previous EISs shows that inhalation of the particles in the passing plume and of resuspended particles are the two most important contributors to the radiation dose accumulated by human receptors.

The other pathway that is potentially important during plume passage is cloud shine—the irradiation of the human body by neutrons and gamma rays emitted by the passing plume of radioactive material. However, because Pu-238 emits predominantly alpha particles, this irradiation pathway is not a significant contributor to doses resulting from potential accidents associated with the Mars 2020 Mission.

Chronic Exposure Pathways

This section considers contributions due to resuspension, ingestion of vegetables, external exposure, seafood ingestion, and contamination of drinking water.

Resuspension

For launch area accidents, the resuspension model used in the analysis starts with an initial resuspension factor that decreases exponentially to a constant long-term resuspension factor (Momeni et al. 1979; Strenge and Bander 1981). For materials deposited after traveling more than 100 kilometers (62 miles) from the source of a release, or released high in the atmosphere, the resuspension factor is at all times typically similar to the long-term resuspension factor (Bennett 1976, UNSCEAR 1982). The work done in previous EISs shows that resuspension is the most significant of the chronic exposure pathways and is comparable to or larger in its effects on humans than is the direct inhalation pathway.

Vegetable Ingestion

Parameters used for estimating the uptake from harvesting and consumption of agricultural products has been measured (Baes et al. 1984, Rupp 1980, Yang and Nelson 1984). These and similar agricultural and food consumption parameters and plutonium ingestion parameters (ICRP 1979) are used as the basis for estimating human doses via ingestion. For example, an analysis of Pu-238 contamination of orange trees shows that a total of only 1 percent of the plutonium actually aerially deposited on the plants would be transported on fruit from field to market during the 12 months following harvesting (Pinder et al. 1987). Most of this plutonium would adhere to the fruit's peel and would be removed prior to ingestion; uptake to the orange itself would be extremely small or nonexistent.

Four mechanisms of vegetable ingestion were taken into account, as described below.

1. ***Initial deposition immediately following the accident:*** The amount initially deposited per curie released depends on non-PuO_2 specific factors such as particle size distribution and characteristics of the vegetation. The predicted amount of radioactive material ingested by humans then depends on assumptions about physical mechanisms and vegetable distribution, such as: the removal half-life for leaf-deposited material, a leaf interception factor, and a vegetable density. Additionally, harvesting (whether continuous, delayed, or crops are destroyed) and

consumption assumptions would affect the predicted amount of radioactive material ingested by humans.

2. ***Continuous redeposition on the vegetables due to resuspension over the first 50 years following the accident:*** The amount ingested by individuals is controlled by the resuspension mechanism (see above), the assumed dry deposition velocity, and assumptions about harvesting and distribution.
3. ***Root uptake:*** This mechanism is, in principle, highly radionuclide and vegetable-specific and depends on such factors as solubility, radionuclide chemistry, and vegetable chemistry. In general, PuO_2 is insoluble and is poorly transported in terrestrial environments. Most forms of plutonium, including PuO_2, are removed from biological pathways by processes such as fixation in soil. Only small amounts of material would be concentrated by biological accumulation into grazing animals and vegetables.
4. ***Rain splashup:*** This mechanism depends in part on the characteristics of the soil and the rainfall.

For Pu-238, radiation doses arising via these pathways are a small fraction of those arising from the inhalation pathways.

External Radiation

External radiation from material deposited on the ground and resuspended material is calculated using standard methods for cloudshine and groundshine. Because Pu-238 is predominantly an alpha emitter, this exposure pathway is relatively unimportant.

Seafood and Fish Pathway

Radiation doses can result from the bioaccumulation of plutonium deposited on the surfaces of inland waters or oceans. The predicted radiation doses arising from this pathway depend on a number of assumptions and physical and chemical processes, including how the deposited radionuclides are diluted in the water, how the radionuclides are partitioned between water and sediment, and how radionuclides are accumulated in different types of fish, crustaceans and mollusks.

In marine and aquatic systems, larger particles would quickly settle to the bottom sediments; smaller silt-size particles may remain in suspension within the water column for extended periods of time. Smaller particles may not even break the water surface (due to surface tension), forming a thin layer on the water surface that is subsequently transported to the shoreline by wind and wave action. Resuspension of smaller particles from the bottom could occur due to physical disturbance of the sediments by wave action and recreational uses of the water bodies (e.g., swimming, boating, and fishing), as well as by the feeding activity of various marine and aquatic species. Particles of PuO_2, as a component of the bottom sediments, may also be transported toward and along the shoreline by wave action and currents in near-shore environments (NASA 1990).

Studies have indicated that bioaccumulation in marine organisms can vary widely depending on the type and population densities of seafood species impacted (e.g.,

freshwater fish, saltwater fish, mollusks), the amount and particle size distribution of radioactive material released, and the deposition area.

PuO_2 entering into a water/sediment system would be preferentially taken out of solution and bound in saturated sediments in amounts on the order of 100,000 times greater than the amounts that would remain in the associated water column (NASA 1990).

Clays, organics, and other anionic constituents tend to bind most of the PuO_2 particles in the sediment column. The binding of PuO_2 usually occurs in the first few centimeters of sediment, greatly reducing the concentration of this constituent with depth.

Overall, the seafood pathway is insignificant for PuO_2. This is due to a combination of considerable dilution in the water, overwhelming partition into sediment, and small bioaccumulation factors.

Contamination of Drinking Water

It is possible that surface water runoff containing PuO_2 could directly contaminate drinking water supplies that originate from surface water bodies, because this type of contamination is primarily due to suspended PuO_2 particles and not from dissolved PuO_2. Filtering the surface water before chemical treatment would reduce the concentration of total plutonium to very low levels (NASA 1990).

B-3.4 TRANSPORT AND DEPOSITION OF RADIONUCLIDES IN THE HUMAN BODY

The International Commission on Radiological Protection (ICRP) has developed accepted models for the distribution of inhaled and ingested radionuclides in the body. The ultimate fate of these radionuclides depends on such factors as particle size distribution, solubility, and chemistry. The ICRP models require knowledge of numerous parameters, most of which are obtained empirically (e.g., there is no theoretical model for determining what fraction of ingested plutonium enters the bloodstream). The required parameters are obtained from animal experiments and, if available, from human studies concerning the effects of nuclear weapons and of nuclear fallout. Of the transuranium elements, plutonium is by far the most widely studied.

PuO_2 that enters the human body by inhalation or ingestion has many possible fates, all of which have been studied in detail (ICRP 1979; ICRP 1986). The inhalation route is found to be approximately 1,000 times as effective as ingestion in transporting plutonium to the blood, due to the short time of residency, the chemical properties of plutonium, and the physiological environment of the gastro-intestinal tract (ICRP 1979).

Ingested PuO_2 would quickly pass through the digestive system and be excreted with only a small quantity being absorbed via the mucosa into the bloodstream. The fractional absorption of PuO_2 is estimated to average about 1 part in 100,000 ingested (ICRP 1979; ICRP 1986) – that is, in ICRP terminology, the f_1 factor for ingestion is 10^{-5}. The fractional absorption is based on the average individual. Note that PuO_2 in the environment could become more soluble with time due to the use of fertilizers in gardening, chlorination in drinking water, and conversion to soluble forms in seawater.

Dietary and physiological factors, such as fasting, dietary calcium deficiency, disease or intake of medications, may also change the fractional absorption (ICRP 1986).

Inhaled PuO_2 would be transported to one or more portions of the respiratory system depending on the particle size. Generally, most particles larger than 5 to 10 microns would be intercepted in the nasopharyngeal region and either expelled or swallowed to pass through the digestive tract; what is not absorbed would then be excreted. Particles smaller than about 5 microns would be transported to and remain in the trachea, bronchi, or deep lung regions. Particles reaching the deep lung would be cleared from the body much more slowly than those not entering the lung. For example, approximate micrometer-size PuO_2 particles would typically be cleared from the pulmonary area of the lung at the rate of 40 percent in the first day, and the remaining 60 percent cleared in 500 days (ICRP 1979). Particles captured in the mucous lining of the upper respiratory tract would be moved more rapidly to the pharynx, where they would be swallowed. Once swallowed, they would behave as if ingested.

Plutonium dioxide remaining in the lung would continuously irradiate lung tissue, and a small fraction would be transported over time directly to the blood or to lymph nodes and then to the blood. The estimated fraction of plutonium transferred directly from pulmonary lung tissues to the blood would be about 1 percent of the amount retained in the lungs, depending on the size distribution of ultra-fine particles. Smaller particles are likely to form over time from larger particles due to the natural fragmentation processes associated with radioactive decay and may also be transferred to the blood. Over a period of years, approximately 15 percent of the PuO_2 initially deposited in the lungs would be transferred to the lymph nodes. Of that, up to 90 percent would likely be retained in the lymph node with a 1,000 day half-life before being transferred to the blood (ICRP 1986). Overall, the PuO_2 f_1 factor for inhalation is the same as that for ingestion, i.e., 10^{-5}.

Once PuO_2 has entered the blood via ingestion or inhalation, it would circulate and be deposited primarily in the liver and skeletal system. It is currently accepted that plutonium transported by the blood is distributed to the following organs: 45 percent in the liver, 45 percent in the skeletal system, 0.035 percent in the testes, and 0.011 percent in the ovaries, with a non-measurable amount crossing the placenta and available for uptake by the fetus. The remaining 10 percent of the activity in the blood is excreted through the kidneys and colon or deposited in other tissues (ICRP 1979, ICRP 1986).

The estimated residence times in the liver, skeletal system, and gonads are quite long. Current estimates for 50 percent removal times for plutonium are 20 years for the liver, 50 years for the skeleton, and permanent retention for the gonads.

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