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Nuclear Risk Assessment 2019 Update for the Mars 2020 Mission Environmental Impact Statement

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Radioisotope Power Systems Launch Safety Project

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ABSTRACT

In the summer of 2020, the National Aeronautics and Space Administration (NASA) plans to launch a spacecraft as part of the Mars 2020 mission. The rover on the proposed spacecraft will use a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) to provide continuous electrical and thermal power for the mission. The MMRTG uses radioactive plutonium dioxide. NASA is preparing a Supplemental Environmental Impact Statement (SEIS) for the mission in accordance with the National Environmental Policy Act. This Nuclear Risk Assessment addresses the responses of the MMRTG option to potential accident and abort conditions during the launch opportunity for the Mars 2020 mission and the associated consequences. This information provides the technical basis for the radiological risks discussed in the SEIS.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
AIC	Accident Initial Condition
AOC	Accident Outcome Condition
BADS	Booster Automatic Destruct System
BOM	Beginning of Mission
CADS	Centaur Automatic Destruct System
CBCF	Carbon Bonded Carbon Fiber
CCAFS	Cape Canaveral Air Force Station
CCB	Common Core Booster
CDS	Command Destruct System
Ci	Curie
DIL	Derived Intervention Limit
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FC	Fueled Clad
FDA	Food and Drug Administration
FEIS	Final Environmental Impact Statement
FGR	Federal Guidance Report
FSAR	Final Safety Analysis Report
FSII	Full Stack Intact Impact
FTS	Flight Termination System
FWPF	Fine Weave Pierced Fabric
GIS	Graphite Impact Shell
GPHS	General Purpose Heat Source
GPHS-RTG	General Purpose Heat Source-Radioisotope Thermoelectric Generator
ICRP	International Commission on Radiological Protection
INSRP	Interagency Nuclear Safety Review Panel
ISA	Interstage Adapter
ISDS	Inadvertent Separation Destruct System
LH_2	Liquid Hydrogen
LO_2	Liquid Oxygen (LOX)
LRE	Liquid Rocket Engine
LV	Launch Vehicle
MET	Mission Elapsed Time
MFCO	Mission Flight Control Officer

Abbreviation	Definition
MLP	Mobile Launch Platform
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
NASA	National Aeronautics and Space Administration
NEPA	National Environmental Policy Act
NRA	Nuclear Risk Assessment
Pb-Te	Lead-Telluride
PLF	Payload Fairing
Pu-238	Plutonium-238
PuO_2	Plutonium Dioxide
ROD	Record of Decision
RP-1	Rocket Propellant 1
RTG	Radioisotope Thermoelectric Generator
SEIS	Supplemental Environmental Impact Statement
Si-Ge	Silicon-Germanium
SLC	Space Launch Complex
SRB	Solid Rocket Booster
SV	Spacecraft (Space Vehicle)
SVII	Space Vehicle Intact Impact
VIF	Vertical Integration Facility

1. INTRODUCTION

In the summer of 2020, the National Aeronautics and Space Administration (NASA) plans to launch a rover to the surface of Mars as part of the Mars 2020 mission. The includes the use of radioactive materials in a single Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) to provide continuous power for the mission. NASA is preparing a Supplemental Environmental Impact Statement (SEIS) for the mission in accordance with the National Environmental Policy Act (NEPA). The SEIS provides information related to updates to the potential environmental impacts associated with the Mars 2020 mission as outlined in the *Final Environmental Impact Statement for the Mars 2020 Mission* (the "2014 FEIS", Reference 1-1) and associated Record of Decision (ROD) issued in January 2015.

The environmental analysis presented in the 2014 FEIS was based on the United States Department of Energy's (DOE's) *Nuclear Risk Assessment for the Mars 2020 Mission Environmental Impact Statement* ("2014 NRA", Reference 1-2). The 2014 NRA was based on the best available information on mission-specific parameters and expendable launch vehicle estimates that NASA provided to DOE in 2013. Since publication of the 2014 FEIS and issuance of the ROD in 2015, NASA has actively advanced the mission. Investments have been made that constitute irrevocable commitment of funds, resources, and decisions, including Mars 2020 rover, payload design, power system fueling, Mars landing site selection, selection of the launch vehicle, and selection of the launch period. This *Nuclear Risk Assessment 2019 Update for the Mars 2020 Mission Environmental Impact Statement* (2019 NRA) includes new and updated information and uses them to address the responses of the proposed MMRTG option to potential accident and abort conditions during the launch opportunity for the Mars 2020 mission and the associated consequences. This information provides the technical basis for the radiological risks for the SEIS.

Mars 2020 mission's science theme is "Seeking Signs of Past Life" and the intent is to explore an astrobiologically relevant ancient environment on Mars to decipher the geologic processes and history, including its past habitability. The overall science objectives of the Mars 2020 mission are summarized below:

- Explore an astrobiologically relevant ancient environment on Mars.
- Assess the biosignature preservation potential within the selected geologic environment and search for potential biosignatures.
- Demonstrate significant technical progress towards the future return of scientifically selected, well-documented samples to Earth.
- Provide a test bed for human spaceflight technologies.

The Mars 2020 mission spacecraft would be launched from Cape Canaveral Air Force Station (CCAFS), Space Launch Complex (SLC) 41. The launch vehicle (LV) for the Mars 2020 mission would be an Atlas V 541, which consists of a Common Core Booster (CCB), four solid rocket boosters (SRBs), and one Centaur III with a 5.4-m diameter payload fairing. NASA has narrowed the launch period to an approximate 20-day launch period opening in July 2020 and closing in August 2020. The planned mission trajectory would place the spacecraft in a heliocentric orbit prior to completion of the second burn of Stage 2. After separation from Stage 2, the spacecraft would be in a heliocentric interplanetary trajectory.

The Mars 2020 rover design uses a MMRTG to provide continuous motive and instrument power and heat to the rover while on the Martian surface. The MMRTG uses the thermal energy from alpha decay of plutonium (primarily plutonium 238 [Pu-238]) to generate electricity and will be provided by DOE. It contains eight General Purpose Heat Source (GPHS) modules and 4.8 kg (10.6 lbs) of plutonium dioxide (PuO_2) in ceramic form, which corresponds to an estimated radioactive inventory of about 59,000 curies (Ci). Safety is an inherent consideration, due to the radioactive nature of this material and the potential for accidents that can threaten the MMRTG and potentially involve PuO_2 release to the environment.

The DOE is responsible for quantifying the risks of its nuclear hardware subjected to the effects of potential launch accidents. The purpose of this document is to provide this information in support of the SEIS for the Mars 2020 mission, being prepared by NASA in accordance with requirements under the NEPA. In 2013, the Launch Approval Process was subject to the requirements of Presidential Directive / National Security Council Memorandum 25 (PD/NSC-25). In 2019, the Launch Approval Process was updated with the issuance of National Security Presidential Memorandum 20 (NSPM-20). The results shown in this 2019 NRA are shown in the format used to support NSPM-20.

The SEIS-supporting assessment presented herein is based in part on 1) spacecraft descriptions, accident environments, and launch vehicle information provided by NASA (Reference 1-1), 2) information regarding accident probabilities provided by NASA (Reference 1-3) and 3) information available from the launch vehicle manufacturer User's Guide (Reference 1-4). The majority of this information has been updated since 2013. The results shown in this 2019 NRA are derived from those presented in the Mars 2020 mission Final Safety Analysis Report (FSAR), which utilized the above updated information.

Section 2 presents a summary of pertinent mission reference design information related to the launch vehicle, spacecraft, mission profile, and radioactive materials. Section 3 provides an overview of the accidents considered in the analysis, their probabilities, and source term estimates. Section 4 summarizes the estimated radiological consequences of accidents and mission risks. Appendix A summarizes the methodology used in developing the nuclear risk assessment.

1.1. References

1-1. National Aeronautics and Space Administration, *Final Environmental Impact Statement for the Mars 2020 Mission,* Science Mission Directorate, NASA, Washington, DC, November 2014.

1-2. D.J. Clayton, J. Bignell, C.A. Jones, D.P. Rohe, G.J. Flores, T.J. Bartel, F. Gelbard, S. Le, C.W. Morrow, D.L. Potter, L.W. Young, N.E. Bixler, and R.J. Lipinski, *Nuclear Risk Assessment for the Mars 2020 Mission Environmental Impact Statement*, SAND2013-10589, Sandia National Laboratories, Albuquerque, NM, January 2014.

1-3. ASCA, Incorporated, *Mars 2020 Mission Updated Launch Accident Probability Data for EIS Risk Assessment,* AR 19-04, Prepared for National Aeronautics and Space Administration, Kennedy Space Center, September 2019.

1-4. United Launch Alliance, *Atlas V Launch Services User's Guide*, United Launch Alliance, Centennial, CO, March 2010.

2. REFERENCE DESIGN INFORMATION

This report section summarizes relevant mission reference design information, including the launch vehicle, spacecraft, MMRTG, launch site, flight safety systems and potential mission timelines.

2.1. Comparison with 2014 NRA

Multiple mission parameters and launch vehicle change have occurred since the 2014 NRA (Reference 2-1). These changes include more details regarding the design of the rover and scientific payload (including instrumentation), the selection of the Mars landing site, the selection of the launch vehicle and refinement of the launch period. The updates are included in the information presented below.

2.2. Mission Description

The Mars 2020 mission plans to launch a robotic rover to a single location on Mars during the July-August 2020 launch opportunity (Reference 2-2). The rover is designed to perform comprehensive science investigations on the planet surface for a mission period of at least one Mars year (where one Mars year is 669 sols, or 687 Earth days). The current planned mission duration necessary to meet the mission objectives is 1.25 Mars years, or 836 sols, and the rover flight system is being developed to enable a surface mission capability of as long as 1.5 Mars years, or 1,003 sols.

The rover will use heat and electricity produced by an MMRTG. The Mars 2020 mission spacecraft would be launched from CCAFS, SLC 41 on an Atlas V 541. The launch opportunity begins July 17, 2020 and ends August 5, 2020. After launch, there will be an approximately 7-month cruise phase en route to Mars.

2.3. Launch Vehicle Description

The LV for the Mars 2020 mission would be an Atlas V 541, as shown in Figure 2-1 (Reference 2-3). Major components include the First Stage (or CCB), with strap-on SRBs, a Second Stage Centaur III, and the Payload Fairing (PLF). The spacecraft is mounted to the Centaur upper stage, housed within the PLF. A three-digit identifier is used to denote the multiple Atlas V launch vehicle configuration possibilities as follows:

- The first digit identifies the diameter class (in meters) of the PLF (4 or 5),
- The second digit indicates the number of SRBs used (0 to 5),
- The third digit indicates the number of Centaur engines (1 or 2).

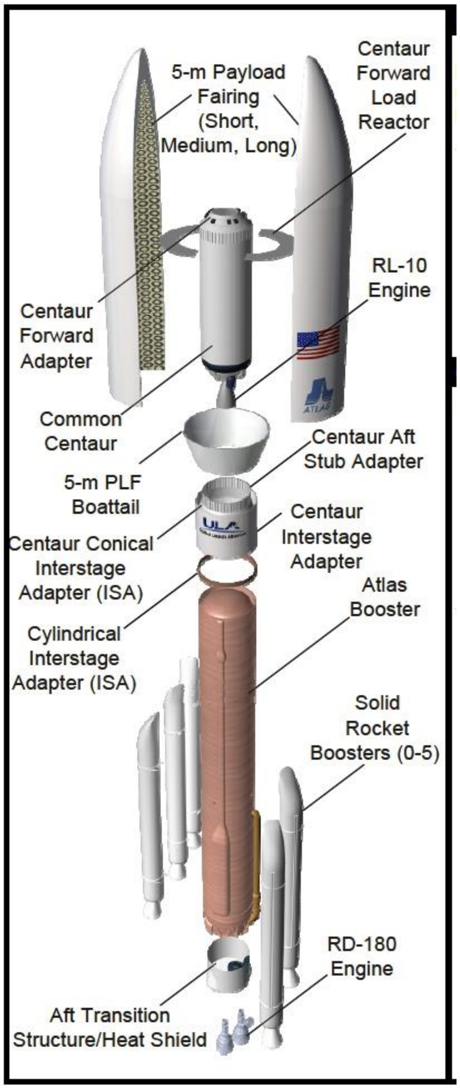

Figure 2-1. Atlas V 5X1 Launch Vehicle (551 shown)

The first stage (or CCB) of the Atlas V 541 is powered by a single RD-180 NPO Energomash engine. The liquid fuel used by the RD-180 engine is Rocket Propellant-1 (RP-1), and the oxidizer is liquid oxygen (LO_2). The total quantity of RP-1 and LO_2 in the CCB is 284,089 kg (626,308 lb). The primary structural material in the CCB is aluminum. Attached to the CCB are four SRB motors, which are approximately 20.05 m (65.7 ft) in length and 156 cm (61.28 in) in diameter. The SRB motors are designated as AJ-60. The mass of the solid propellant in each of these four motors is 42,603 kg (93,839 lb). The SRB case is a composite structure of filament-wound carbon fiber and epoxy.

The second stage of the Atlas V 541 is a single engine Centaur, which is fueled with liquid hydrogen (LH_2) and uses LO_2 as the oxidizer. The total quantity of liquid propellant (LH_2 plus LO_2) is 20,672 kg (45,574 lb). The primary structure of the Centaur fuel tanks is stainless steel. The Centaur's Reaction Control System contains 154 kg (340 lb) of hydrazine propellant for this mission.

The Centaur, spacecraft, and MMRTG are housed within a 5.4 m diameter by 20.7 m (68 ft) tall PLF, which is made from sandwich construction panels with carbon-fiber face sheets and a vented aluminum honeycomb core structure.

The Atlas V Flight Termination System (FTS) provides the capability to destruct the LV and payload if required during non-nominal performance by a secure radio link, and autonomously after detecting an inadvertent vehicle breakup, or unintentional separation of LV stages.

The FTS consists of:

- A Command Destruct System (CDS) that provides the capability for Range Safety to command shutdown of the Centaur and CCB engines and to command destruct of the CCB, connected SRBs, and Centaur stage via a Centaur radio-frequency command system.
- A Centaur Automatic Destruct System (CADS) that provides for automatic Centaur, CCB, and/or connected SRB destruct in the case of inadvertent vehicle breakup or premature stage separation.
- A Booster Automatic Destruct System (BADS) that provides for automatic CCB and connected SRB destruct in the case of inadvertent vehicle breakup or premature stage separation.
- An Inadvertent Separation Destruct System (ISDS) that provides for automatic SRB destruct in the case of inadvertent vehicle breakup or premature SRB separation.

The FTS subsystems, CDS, CADS, BADS, and ISDS are independently initiated and dually redundant destruct systems. The CDS and CADS destruct the launch vehicle, BADS destructs the CCB, and ISDS destructs any SRB that inadvertently separates from the vehicle.

2.4. Spacecraft Description

The Mars 2020 spacecraft consists of four major physical elements: the cruise stage, the aeroshell (heat shield and backshell), the descent stage, and the rover (Reference 2-2). The integrated flight system is shown in its launch configuration in Figure 2-2 and in expanded view in Figure 2-3. There is one MMRTG and it is attached to the back end of the rover. The rover and MMRTG are enclosed within the aeroshell at launch. The current best estimate is that the total mass of the spacecraft after separation from the Centaur will be about 3,866 kg. The cruise and descent stages have propellant tanks which contain a total of about 473 kg of hydrazine.

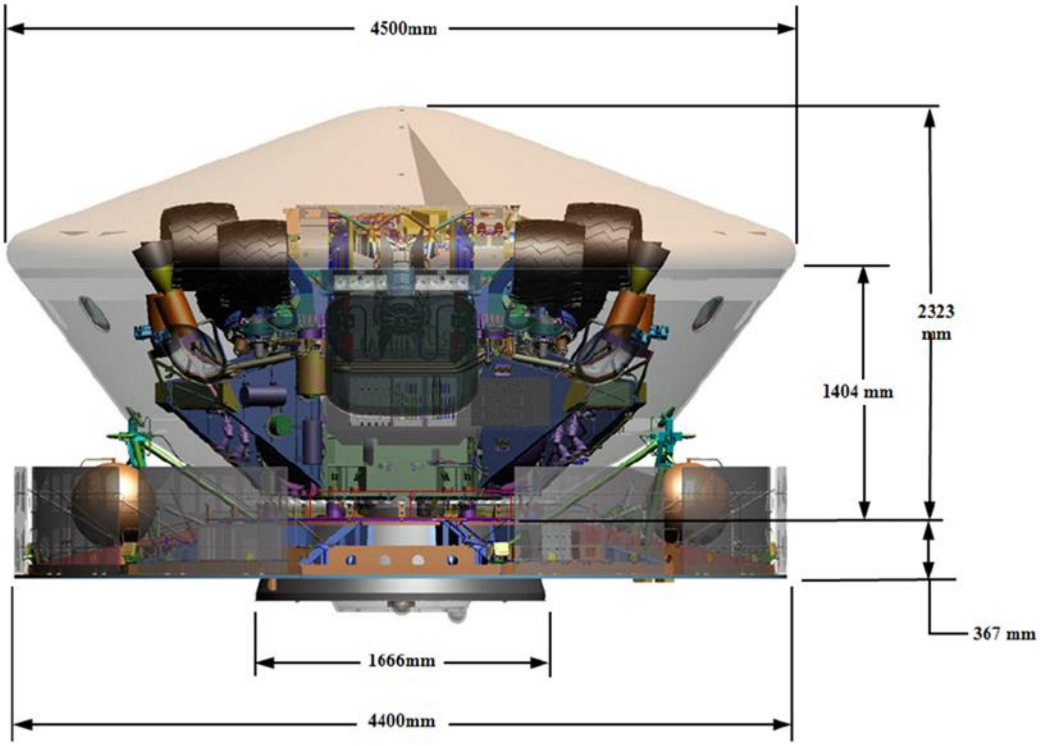

Figure 2-2. Mars 2020 Spacecraft in Launch Configuration

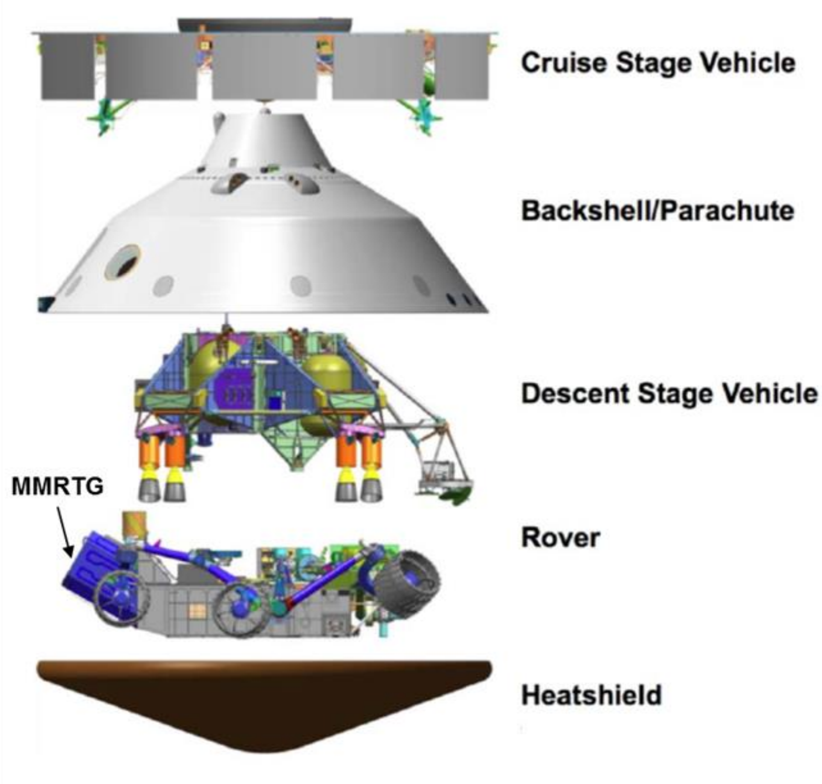

Figure 2-3. Expanded View of Elements in Mars 2020 Space Vehicle Flight System

2.5. Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)

The MMRTG is a PuO_2 fueled thermoelectric generator consisting of two major components: the heat source, consisting of eight Step 2 GPHS modules, and the converter that converts heat to electricity and comprises the remainder of the MMRTG. The two components are independently sealed to maintain an argon environment in the converter chamber and to provide a means to vent helium generated through the radioactive decay of the PuO_2 fuel. This design is intended to protect the thermoelectrics from exposure to the Martian atmosphere, while still allowing for helium venting. The MMRTG uses lead-telluride (Pb-Te) thermoelectrics, which operate at a lower temperature (with average iridium clad temperatures of about 750 °C during Mars 2020 launch conditions), rather than the silicon-germanium (Si-Ge) thermoelectrics used in the General Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG, with iridium clad temperatures of about 1,050 °C) used on earlier NASA missions. Figure 2-4 shows the components of the MMRTG.

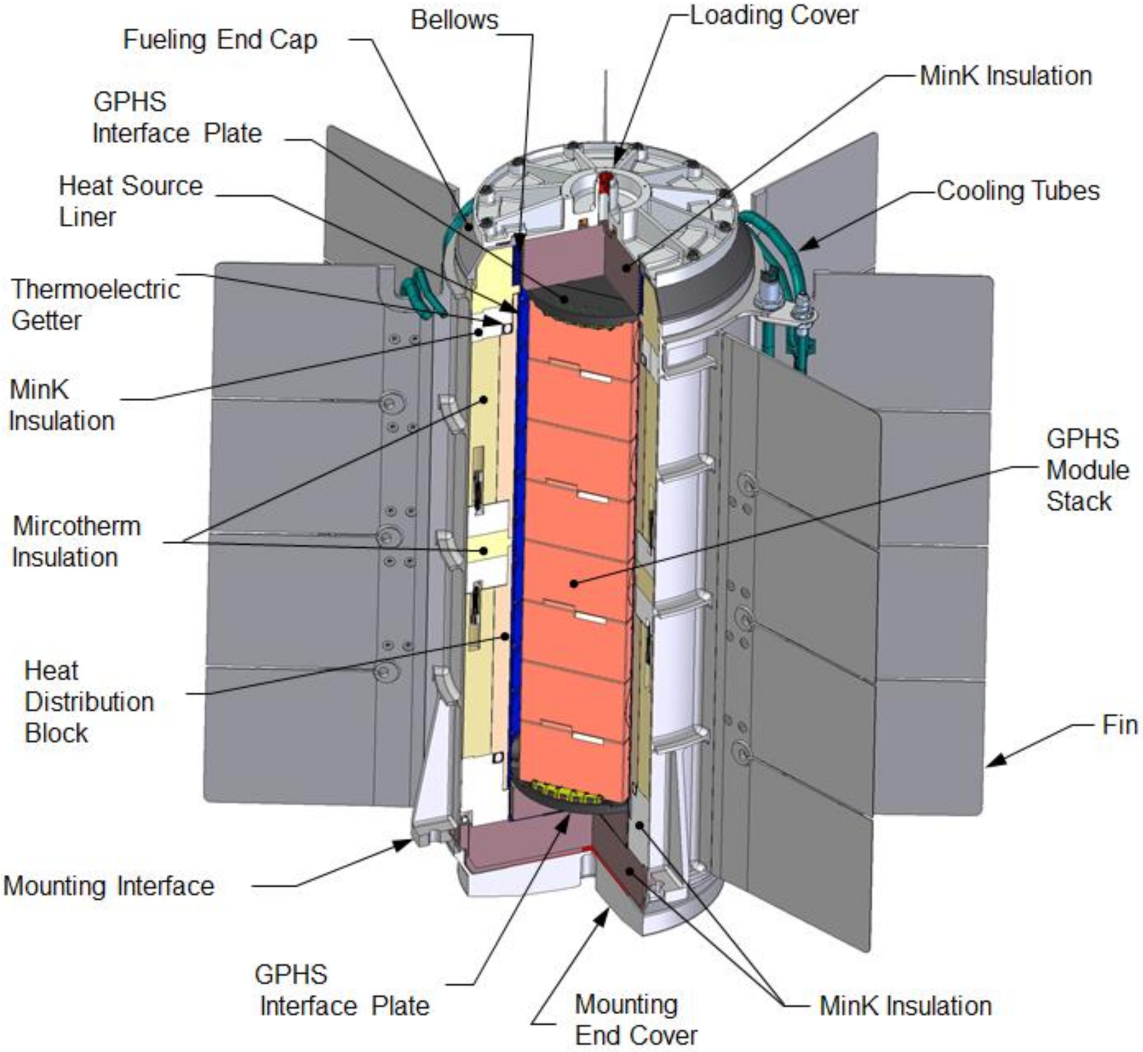

Figure 2-4. Components of the MMRTG

The heat source assembly consists of a stack of eight Step 2 GPHS modules, with two shear buttons between adjacent modules. A cutaway view of a single Step 2 GPHS module is shown in Figure 2-5.

Each module contains four fuel pellets, and each pellet is encapsulated within a vented iridium clad. The encapsulated pellet is called a fueled clad (FC). The iridium cladding is meant to both contain the fuel and help protect it from physical insults, such as ground impacts and impact from LV and spacecraft debris. Each GPHS module contains four FCs enclosed within two cylindrical Fine Weave Pierced Fabric (FWPF) graphite containers, known as Graphite Impact Shells (GISs). Thermal insulators comprised of Carbon Bonded Carbon Fiber (CBCF) graphite surround each GIS. These insulators are designed to provide acceptable iridium temperatures during possible reentry (both during descent and at impact) and to provide some thermal protection against early launch accident fires. Two GISs with thermal insulator discs and sleeves are placed in a rectangular aeroshell to form a GPHS module. The Step 2 GPHS module is the primary heat source structure that provides reentry protection for the FCs. Chamfers, which can be seen in Figure 2-5, are located on the edges of the top face of each Step 2 GPHS module to facilitate module tumbling during reentry of a released module. FWPF graphite lock members are used to facilitate stacking and to resist shear loads due to lateral loading.

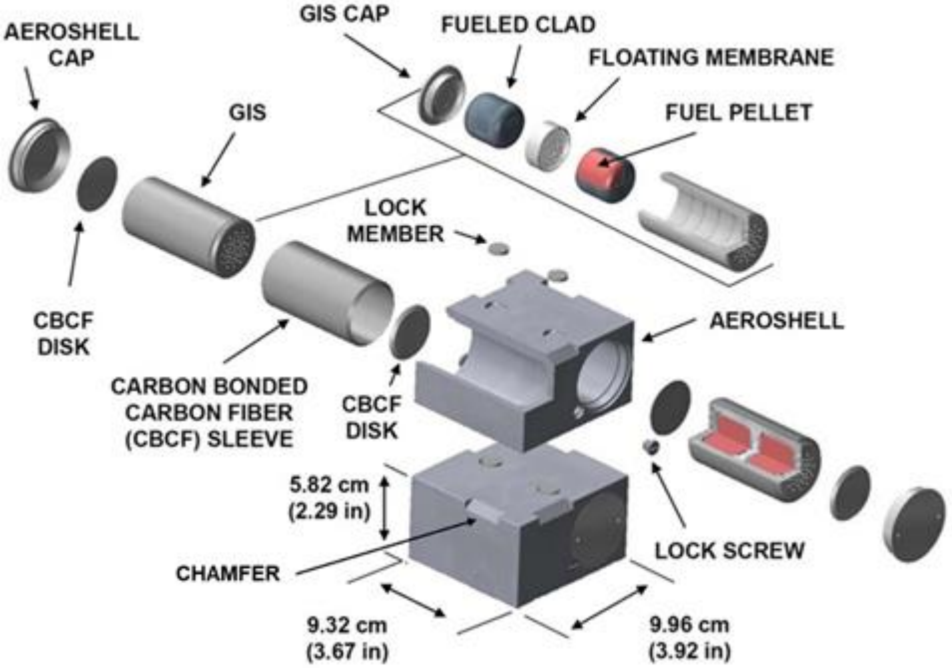

Figure 2-5. Cutaway View of a Step-2 GPHS Module

The FCs each have a thermal inventory of at least 61.0 W per pellet (244 W total per module) at the beginning of mission (BOM). The radioisotope fuel is an isotopic mixture of Pu in the form of the dioxide, PuO_2. The Pu-238 content will be approximately 83.97% by weight of the total Pu at BOM. The specific activity level decreases with time, primarily from the decay of Pu-238, which has a half-life of 87.7 years. The physical form of the fuel is a cylindrical, solid ceramic pellet chamfered and dished at each end. Each pellet is expected to contain approximately 151.3 g of fuel oxide. The nominal activity for the 32 pellets in the eight GPHS modules of the MMRTG is expected to be about 59,000 Ci (14.5 Ci per gram of Pu, all plutonium isotopes included, or 12.2 Ci per gram of oxide fuel). A thermal power reduction of approximately 0.8 percent/year will occur due to alpha decay. A summary of MMRTG properties can be found in Table 2-1.

Table 2-1. MMRTG Properties

Characteristics	Quantity (BOM)
Electrical Power Output	110 W
Nominal Output Voltage	32 V
Weight	44.33 kg without cooling tubes 45.64 with cooling tubes
Dimensions	65.0 cm (25.6 in) overall diameter (fin tip to fin tip) 23.7 cm (9.3 in) case diameter 65.8 cm (25.9 in) overall length 52.8 cm (20.8 in) fin length
Components	**Quantity**
Total GPHS Modules within the MMRTG	8
Total GISs within the MMRTG	16
Total Fuel Pellets within the MMRTG	32
Radiological Properties	**Quantity (BOM)**
Activity Level	59,021 Ci
Fuel Half Life	87.75 yr
Fuel Inventory:	
Pu-238	3,421.9 g
Other Pu Isotopes	653.2 g
Total Pu	4,075.1 g
Other Actinides (Np, U, Am, Th, etc.)	172.6 g
Impurities (Al, B, Cr, Cu, Fe, Pb, etc.)	3.6 g
Oxygen	591.3 g
Total Oxide Fuel	4,842.6 g

2.6. Launch Site Description

Atlas V Launch operations are conducted in the north portion of CCAFS on SLC-41 (Reference 2-2). The launch complex encompasses a land area of about 47 acres. Approximately 10 acres of the launch complex are covered by impermeable surfaces—concrete, asphalt, or buildings. An aerial view of SLC-41 is shown in Figure 2-6. The Atlas V launch pad uses a “clean-pad” launch processing approach whereby the LV is fully integrated off-pad on a Mobile Launch Platform (MLP) in the nearby Vertical Integration Facility (VIF) and the launch pad is used only for launch-day propellant loads and launch countdown.

There are no provisions for spacecraft access at the pad (all final spacecraft access activities, including removal of ordnance safe and arm devices, are made in the VIF). All spacecraft umbilicals needed at the pad are flyaway disconnects that are attached to the MLP. Rollback from the pad to the VIF can be accomplished in 6 hours if LV propellants have not been loaded and within 18 hours if LV propellants must be de-tanked.

Figure 2-6. Atlas V Space Launch Complex 41 Aerial View

2.7. References

2-1. D.J. Clayton, J. Bignell, C.A. Jones, D.P. Rohe, G.J. Flores, T.J. Bartel, F. Gelbard, S. Le, C.W. Morrow, D.L. Potter, L.W. Young, N.E. Bixler, and R.J. Lipinski, *Nuclear Risk Assessment for the Mars 2020 Mission Environmental Impact Statement*, SAND2013-10589, Sandia National Laboratories, Albuquerque, NM, January 2014.

2-2. National Aeronautics and Space Administration, *Final Environmental Impact Statement for the Mars 2020 Mission,* Science Mission Directorate, NASA, Washington, DC, November 2014.

2-3. United Launch Alliance, *Atlas V Launch Services User's Guide*, United Launch Alliance, Centennial, CO, March 2010.

3. ACCIDENT PROBABILITIES AND SOURCE TERMS

The objective of the NRA process is to determine the range and the likelihood of potential accident consequences and, in turn, to determine mission risk for the launch opportunities. The nuclear risk assessment considers: 1) potential accidents associated with the launch, and their probabilities and accident environments; 2) the response of the radioisotope hardware to accident environments with respect to source terms (that portion of the source term that becomes airborne) and their probabilities, and 3) the radiological consequences and mission risks associated with such source terms. The radioactive material inventory of interest, for a single MMRTG, is about 59,000 Ci of primarily Pu-238. The activity includes minor contributions from other related plutonium and actinide radionuclides in the fuel. This section addresses the potential accidents and hardware response; Section 4 addresses potential consequences and risks. The methodology used in developing the accident probabilities, source terms and consequences is presented in Appendix A.

For the purpose of the risk analysis, the Mars 2020 mission is divided into five mission phases on the basis of the mission elapsed time (MET, the time (T) relative to launch), reflecting principal events during the mission as follows:

- Phase 0: Pre-Launch, $T < t_1$, from installation of the MMRTG to just prior to start of the Stage 1 liquid rocket engines (LREs) at t_1.
- Phase 1: Early Launch, $t_1 \leq T < t_x$, from start of Stage 1 LRE(s), to just prior to t_x, where t_x is the time after which there would be no potential for debris or intact vehicle configurations resulting from an accident to impact land in the launch area.
- Phase 2: Late Launch, $t_x \leq T$ when the launch vehicle reaches an altitude of nominally 30,480 m (100,000 ft), an altitude above which reentry heating could occur.
- Phase 3: Suborbital Reentry, from nominally 30,480 m (100,000 ft) altitude to the end of Stage 2 burn 1 and CDS is disabled.
- Phase 4: Orbital Reentry, from end of Stage 2 burn 1 to Stage 2/spacecraft separation.
- Phase 5: Long-Term Reentry, after spacecraft separation until no chance of Earth reentry.

The information on accidents and their probabilities has been based on information presented in Reference 3-1.

3.1. Accidents, Probabilities and Environments

Accidents and their probabilities are developed in terms of Accident Initial Conditions (AICs), defined as the first system-level indication of a launch vehicle failure that could lead to a catastrophic accident or mission failure. An example of an AIC would be a trajectory control malfunction resulting in a launch vehicle deviation from its nominal trajectory. The accident progression after the AIC leads to a range of possible Accident Outcome Conditions (AOCs). An AOC is defined as an event in the accident sequence when the MMRTG might first experience a potentially damaging environment. An example of an AOC would be an FTS action, such as a low altitude CDS or CADS activation, which would be a potential outcome of a trajectory control malfunction.

The AOCs that can result from the AICs are determined to a large degree by the FTS actions that do or do not occur during the accident progression following the AIC. Important FTS considerations affecting the AOCs are as follows:

- <u>CADS</u>: The CADS destructs the Stages 1 and 2 liquid-propellant tanks and the strap on boosters. The CADS is disabled prior to Stage 1/2 separation.
- <u>CDS</u>: The CDS is activated by the Mission Flight Control Officer (MFCO) and destroys the launch vehicle in the same manner as a CADS. The MFCO would likely issue a CDS in case of a trajectory or attitude control malfunction where the launch vehicle deviation from the nominal trajectory violates specific range safety criteria for continuation of a safe launch. If the MFCO response time needed to initiate a CDS is too long, ground impact of the entire vehicle (Full Stack Intact Impact [FSII]) could result. The CDS is disabled at the end of Stage 2 burn 1.

Prelaunch AICs include crane drops, tank failures, and MMRTG loss of cooling. They primarily result in spacecraft impact, but some very low probability scenario results in a second stage or full stack explosion. The Prelaunch AICs generally involve conditions that can be mitigated by systems in place and/or procedures leading to mission abort rather than AOCs that threaten the MMRTG. The $T \geq 0$ AICs include:

- GSE failure during liftoff
- Trajectory and attitude control malfunctions
- Propellant tank failures
- Catastrophic LRE failures affecting either the Stage 1 and 2 engines
- SRB case failure
- Structural failure
- Inadvertent FTS activation or PLF separation
- Staging failure

The AICs identified above can lead to one or more of the following AOCs, denoting conditions of first threat to the MMRTG:

- <u>On-Pad Explosion</u>: This could occur as a result of accidents during Prelaunch or very near the pad just prior to actual liftoff, after completion of the Stage 1 engine health check.
- <u>Low- and High-Altitude FTS</u>: "Low altitude" denotes conditions where impacts are likely to occur on land, while "high altitude" denotes conditions leading to impact on the Atlantic Ocean. The response of the spacecraft to an FTS would depend on the accident environment conditions.
- <u>FSII:</u> The entire launch vehicle stack impacts the ground intact.
- <u>Spacecraft Intact Impact (SVII)</u>: The spacecraft impacts the ground intact.
- <u>Stage 2/Spacecraft (SV):</u> Stage 2/SV combination impacts the ground intact.
- <u>Suborbital reentry</u>: Reentry before orbit achieved, but high enough to consider reentry implications.

- Orbital reentry: Reentry after decay from orbit. Other types of reentry are possible (e.g., prompt), but at a much lower probability.
- Long-term reentry: Reentry after leaving orbit and intersecting the earth again.

The mean accident probabilities for the Mars 2020 AOCs are presented in Table 3-1 (derived from material in Reference 3-1).

Table 3-1. Mars 2020 Mean Accident Probabilities

Mission Phase	Accident Probability
0 (Prelaunch)	1.04E-04
1 (Early Launch)	
On-Pad Explosion	7.92E-05
FSII	1.14E-06
Stage 2/SV	3.01E-05
SVII	1.48E-06
Low Altitude FTS	1.60E-03
Overall Phase 1	1.71E-03
2 (Late Launch)	2.52E-03
3 (Suborbital)	6.82E-03
4 (Orbital)	1.21E-03
5 (Long-Term)	1.43E-04
Overall Mission	1.25E-02

The postulated accident environments associated with potential accidents include blast (explosion overpressure), MMRTG impact on a surface, fragment impact on the MMRTG, thermal (burning liquid propellant and/or solid propellant), and reentry (aerodynamic force and heating). A given accident could involve one or more sequential and/or simultaneously occurring accident environments. The nature and severity of such environments would be a function of the type of accident and the time of occurrence.

3.2. MMRTG Safety Design Features

The response of the MMRTG and its components to accident environments are characterized in terms of the probability of release and source term generated. These in turn are determined by the nature and severity of the accident environments and the design features of the MMRTG and its components. DOE has designed the MMRTG to provide for containment of the PuO_2 fuel to the extent possible during all mission phases, including ground handling, launch, and unplanned events such as reentry, impact, and post-impact situations. Under normal, accident, and post-accident conditions the safety-related design features are intended to:

- Minimize the source term and airborne dispersion of fuel, especially biologically significant, respirable particles.
- Minimize contamination of the air, water, and soil, especially in populated areas.
- Maximize long-term immobilization in the environment (e.g., through use of insoluble fuel forms).

Safety design features of the MMRTG include:

- PuO$_2$ Fuel: The fuel has a high melting temperature (2,400 °C), is nearly insoluble in water, and tends to fracture into largely non-respirable pieces upon impact.
- Iridium Clad: The iridium clad material is chemically compatible with the graphitic components of the aeroshell module and the PuO$_2$ fuel over the operating temperature range of the MMRTG. The iridium has a high melting temperature (2,443 °C) and is ductile at higher temperatures (900 °C).
- Carbon Bonded Carbon Fiber sleeve: The CBCF sleeves provide protection from the heat of reentry from an orbital, suborbital or Earth gravity assist failure and from the heat of launch area fires during an early launch accident.
- GPHS (Step 2) Module Graphitic Components: The GPHS outer aeroshell and GIS are composed of FWPF, a three-dimensional weave carbon-carbon material developed originally for reentry material. The module and its graphitic components are designed to provide reentry and surface impact protection to the fueled clad in case of accidental suborbital or orbital reentry.
- Insulation: The thermal insulation surrounding the GPHS modules helps cushion the modules during impact events and can also provide some protection from the heat of fires.

The MMRTG uses the Step 2 GPHS module in place of the earlier Step 0 module used in the Radioisotope Thermoelectric Generators (RTGs) for the Galileo, Ulysses and Cassini missions, and the Step 1 module used in the RTG for the Pluto New Horizons mission. The MMRTG with 8 GPHS Step 2 modules was on the Mars Science Laboratory Rover, Curiosity. Figure 3-1 shows the progression of changes from the original configuration (Step 0) to Step 2. The Step 0 module did not have any FWPF web between the two GISs, while the Step 1 and 2 modules do. In addition, the Step 2 module has thicker module faces. Both the web and the thicker module faces increase the Step 2 module's strength and improve impact response. Some insight can be gained by examining the safety testing performed on the earlier GPHS-RTG and its components. The GPHS-RTG with 18 GPHS Step 0 modules was used on the Galileo, Ulysses, Cassini missions. Formal safety testing of GPHS-RTG components has established a data base for that design. These safety tests covered responses to the following environments:

- Explosion overpressure
- Fragments
- Impact
- Thermal
- Reentry

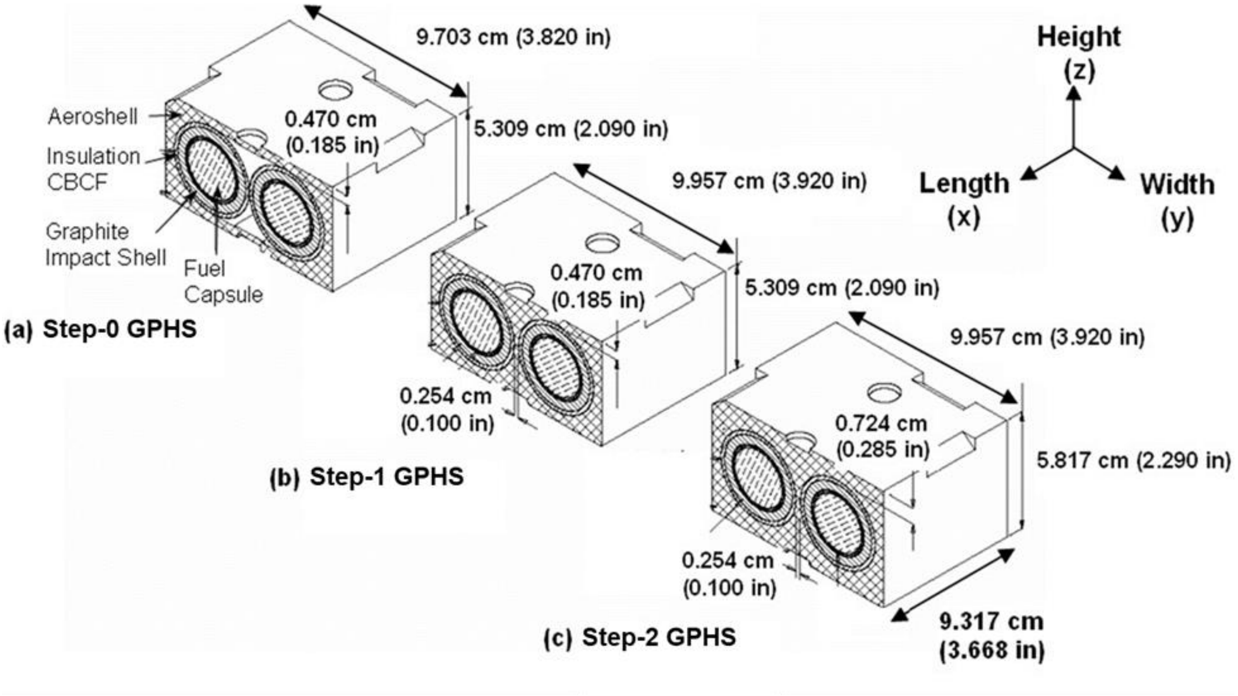

Figure 3-1. Progression of Changes from Step 0 to Step 2 GPHS Modules

3.3. MMRTG Response to Accident Environments

The response of the MMRTG to accident environments is based on consideration of:

- Prior safety testing of the GPHS-RTG and its components
- Modeling of the response of the MMRTG and its components to accident environments using a continuum mechanics code
- A comparison of the MMRTG with the GPHS-RTG
- The types of launch vehicle accidents and their environments also described in the prior section.

This information allows estimates to be made of the probability of release of PuO_2 and the amount of the source term for the range of accident scenarios and environments that could potentially occur during the mission. The protection provided by the aeroshell module, its graphitic components and the iridium clad encapsulating the PuO_2 fuel minimizes the potential for release in accident environments. Potential responses of the MMRTG and its components in accident environments are summarized as follows:

- <u>Explosion Overpressure and Fragments</u>: Liquid propellant explosions from LV destruct and resulting fragments are estimated to result in some MMRTG damage but no fuel release.
- <u>Impact</u>: Fracturing of the GPHS module and its graphitic components under mechanical impact conditions provide energy absorbing protection to the iridium clad. Most impacts of an intact MMRTG or GPHS modules on steel or concrete near the launch pad could result in releases of PuO_2, depending on the impact velocity. Similarly, should Suborbital or Orbital Reentry AOCs lead to GPHS modules impacting rock following reentry, a release could

occur. Ground impact of an intact spacecraft for an early launch accident is expected, since the spacecraft back shell and heat shield prevent breakup during a destruct event. The combined effect of the spacecraft hitting the ground and the MMRTG subsequently being hit by the spacecraft components above it results in a fuel release, depending on the impact velocity and orientation. Larger intact configurations such as FSII and Stage 2/SV intact impact could result in higher source terms for certain orientations in which launch vehicle and/or spacecraft components impact directly onto the MMRTG.

- Thermal: Exposure of released PuO_2 to a liquid propellant fireball environment would be of short duration (nominally 20 s or less). Very minor vaporization of exposed particulate would occur depending on the timing of the ground impact release and the fireball development. The fireball temperature would decrease in temperature to nominally 2,177 ºC in less than 1 s (below which PuO_2 vaporization is negligible) and continue dropping as the fireball expands.

  Exposure of released PuO_2 fuel to the higher-temperature (up to 2,827 ºC), longer-burning (up to 250 s) solid-propellant from SRB fragments could lead to more substantial vaporization of exposed PuO_2. In addition, exposure of a bare (or breached) iridium clad could result in clad degradation either through chemical interactions or melting, resulting in partial vaporization of the PuO_2. The aeroshell graphitic components could be damaged in accident environments, which would allow such an exposure of the iridium clads. In addition, very minor PuO_2 vapor releases from intact aeroshell modules are possible under certain exposure conditions (e.g., underneath large pieces of burning solid propellant). Under such conditions, temperatures inside the module could be high enough to degrade the iridium clads and vaporize some PuO_2, which in turn could permeate through the somewhat porous graphitic materials.

- Reentry: Most suborbital reentries result in intact impact of the spacecraft due to the presence of the spacecraft aeroshell. Most of these impacts occur in water with no release. Land impact can result in source terms that are similar in nature to those from impact near the launch pad, but without the presence of solid propellant fires. Source terms in these cases are similar in nature to those from impact near the launch pad. Reentry from circular orbital decay or long-term reentry will cause breakup of the spacecraft and the MMRTG with subsequent release of the GPHS modules. This will result in some heating and ablation of the surface of the GPHS modules, but no containment failure or release in the air. When these separated components impact land, there is a potential for release from the GPHS module during impact on rock. No release is expected from a water impact or soil impact.

Based on the information presented in this section, the response of the MMRTG to accident environments can be summarized as follows:

- Most launch accidents in Phases 0 and 1 would lead to one of several types of ground impact configurations (i.e., FSII, spacecraft, MMRTG and GPHS modules). Ground impacts of the spacecraft on steel or concrete can lead to a release. For larger impacting configurations, such as an FSII or Stage 2/SV intact impact, larger fuel source terms are expected. Exposure to a liquid propellant fireball could lead to some vaporization of released PuO_2 depending on the relative timing of the impact release and the fireball development. Subsequent exposure of MMRTG hardware and PuO_2 to burning solid propellant could result in larger source terms through melting of the iridium clad and partial vaporization of the PuO_2.

- Nearly all Phase 2 accidents lead to impact of debris in the Atlantic Ocean with no releases. There could be some small in-air releases from blast-driven in-air fragment impacts.
- Phase 3 accidents lead to suborbital reentry and usually ground impact of the intact spacecraft and MMRTG. Some small releases are likely due to impact of the MMRTG by spacecraft hardware. There would be a hydrazine fire with some vaporization. There would be no solid propellant fires or releases due to them.
- Phase 4 and 5 accidents lead to orbital and long-term reentry heating and ground impact environments. The GPHS modules are designed to survive reentry; however, any ground impact on rock could result in releases of PuO_2.

3.4. Source Terms and Probabilities

Since 2013, multiple updates were made to the source term analysis. Changes to the source term modeling approach for the 2019 NRA are based on the Interagency Nuclear Safety Review Panel (INSRP) Safety Evaluation Report recommendations for the 2011 Mars Science Laboratory mission, Mars 2020 INSRP review, NASA and DOE safety testing program data, and the Mars 2020 mission configuration. Additionally, it incorporates lessons learned and modeling data updates derived from a 2014 Antares launch vehicle accident. The analysis also incorporated updated analytical models and computer simulation input parameters, informed by best available knowledge as well as lessons learned from other missions. Models and parameter input updates using the best available information for conducting the nuclear safety analysis include:

- solid propellant fragmentation and trajectory;
- liquid and solid propellant fire environments;
- plutonia release model;
- potential debris impact area;
- blast model information; and
- module and iridium cladding response to impact forces.

The source term computer codes used to simulate the MMRTG response to the potential accident environments were updated since 2013 to include the updated analytical models and computer simulation input parameters. The source term results shown below incorporate these updates.

A summary of the composite accident and source term probabilities by mission phase, along with mean and 99th percentile source terms, are presented in Table 3-2. These results were determined by a Monte Carlo simulation using 100,000 trials or more for each of the various accident scenarios. In these simulations, 100% of the source term was assumed to be airborne, which may be conservative since much of the source term would be trapped by the graphite materials and other debris. Furthermore, simulations show that particles larger than 100 microns would fall to the ground rapidly (generally within a few meters).

Two mean values are displayed: one is based on the average when an accident occurs (including accidents with no release), the other is based on the average considering only non-zero releases. Most accidents do not result in a release; hence the mean source term given an accident is lower than the mean source term given a release.

The 99th percentile source term is obtained by sorting the trials by the total source term. Then the source term for which 1% of the trials are greater is defined as the 99th percentile source term. The 99th percentile source term is the value predicted to be exceeded with a probability of 0.01 (1 in 100), either given an accident, or given a release. In this context, the 99th percentile source term reflects the potential for larger radionuclide source terms at lower probabilities. Some accidents do not result in a release; hence the 99th percentile source term given an accident is lower than the 99th percentile source term given a release. For some launch phases (Phase 2 and Phase 3), the probability of a release is so low that the 99th percentile source term is zero, given an accident.

Table 3-2. Source Term Summary for the MMRTG

Mission Phase	Accident Probability	Conditional Probability of Release	Total Probability of Release	Source Term (Ci)[a]			
				Mean Given an Accident	**Mean Given a Release**	**99th Percentile Accident[c]**	**99th Percentile Release[c]**
0 (Prelaunch)	1.04E-04	6.02E-01	6.26E-05	3.15E+01	5.23E+01	7.51E+02	1.08E+03
1 (Early Launch)							
On-Pad Explosion	7.92E-05	4.07E-01	3.22E-05	5.41E+02	1.33E+03	6.77E+03	1.00E+04
FSII	1.14E-06	7.78E-01	8.84E-07	5.08E+03	6.54E+03	1.96E+04	2.02E+04
Stage 2/SV	3.01E-05	5.30E-01	1.60E-05	1.40E+03	2.65E+03	1.21E+04	1.37E+04
SVII	1.48E-06	5.96E-01	8.82E-07	7.07E+02	1.19E+03	6.09E+03	8.61E+03
Low Altitude FTS	1.60E-03	5.29E-01	8.48E-04	5.75E+02	1.09E+03	4.21E+03	5.55E+03
Overall Phase 1	1.71E-03	5.24E-01	8.98E-04	5.91E+02	1.13E+03	4.64E+03	6.97E+03
2 (Late Launch)	2.52E-03	1.02E-03	2.57E-06	8.14E-02	7.98E+01	-	6.21E+02
3 (Suborbital)	6.82E-03	1.08E-03	7.33E-06	3.99E-01	3.71E+02	-	3.82E+03
4 (Orbital)	1.21E-03	5.46E-02	6.61E-05	2.52E+00	4.61E+01	7.55E+01	4.14E+02
5 (Long-Term)	1.43E-04	5.96E-02	8.52E-06	2.90E+00	4.87E+01	8.50E+01	4.23E+02
Overall Mission[b]	1.25E-02	8.36E-02	1.04E-03	8.18E+01	9.79E+02	2.34E+03	6.29E+03

a. Mean source term and 99th percentile source terms are for all accidents in which a release occurs. 99th percentile accident is the 99th percentile source term given an accident.

b. Overall mission values weighted by total probability of release for each mission phase.

c. The probabilities associated with the 99th percentiles are two orders of magnitude lower than the probabilities shown in the table here for the mean.

Essential features of the results for the MMRTG are as follows:

- Phase 0 (Prelaunch): During the Prelaunch period, prior to ignition of the Stage 1 liquid rocket engine, on-pad accidents could result in a release at a total probability of $6.26x10^{-5}$ (1 in 16,000). The mean source term given an accident is estimated to be 31.5 Ci, the mean source term given a release is estimated to be 52.3 Ci, the 99th percentile given an accident is estimated to be 751 Ci, while the 99th percentile source term given a release is estimated to be 1,080 Ci.

- Phase 1 (Early Launch): During Phase 1 from just prior to ignition to t_x s, after which there would be no potential for land impacts in the launch area, the total probability of release is 8.98×10^{-4} (1 in 1,100). The mean source term given an accident is estimated to be 591 Ci, the mean source term given a release is estimated to be 1,130 Ci, the 99th percentile source term given an accident is estimated to be 4,640 Ci, while the 99th percentile source term given a release is estimated to be 6,970 Ci.
- Phase 2 (Late Launch): In Phase 2 all accidents lead to impact of debris in the Atlantic Ocean. However, there are some very small releases in air from blast-generated debris. The total probability of release is 2.57×10^{-6} (1 in 390,000). The mean source term given an accident is estimated to be 0.0814 Ci, the mean source term given a release is estimated to be 79.8 Ci, the 99th percentile source term given an accident is estimated to be 0 Ci, while the 99th percentile source term given a release is estimated to be 621 Ci.
- Phase 3 (Suborbital Reentry): Accidents during Phase 3 include suborbital reentries. Prior to the attainment of Earth park orbit these conditions could lead to prompt suborbital reentry within minutes. This could result in impacts of the intact spacecraft and MMRTG along the vehicle flight path over the Atlantic Ocean and Africa. Additional suborbital land impacts are possible after crossing over Africa, depending on the mission timeline. Releases are possible should the spacecraft impact land. The total probability of release in Phase 3 is estimated to be 7.33×10^{-6} (or 1 in 140,000). The mean source term given an accident is estimated to be 0.399 Ci, the mean source term given a release is estimated to be 371 Ci, the 99th percentile source term given an accident is estimated to be 0 Ci, while the 99th percentile source term given a release is estimated to be 3,820 Ci.
- Phases 4 (Orbital Reentry): Accidents which occur after attaining park orbit could result in orbital decay reentries from minutes to years after the accident, affecting Earth surfaces between approximately 35° North Latitude and 35° South Latitude. The spacecraft and MMRTG would break apart during reentry, releasing the GPHS modules. The modules would survive reentry but could release fuel, especially if they impact a hard surface such as rock. The total probability of release is estimated to be 6.61×10^{-5} (or 1 in 15,000). The mean source term given an accident is estimated to be 2.52 Ci, the mean source term given a release is estimated to be 46.1 Ci, the 99th percentile source term given an accident is estimated to be 75.5 Ci, while the 99th percentile source term given a release is estimated to be 414 Ci.
- Phase 5 (Long-Term Orbital Reentry): There is a set of reentry accidents which occur after attaining Earth escape. This could result in return to Earth from a heliocentric orbit many years after the accident if the spacecraft misses Mars, affecting Earth surfaces at any latitude. The reentry velocity would be larger than in Phase 4 and the heating environment would be more severe. The total probability of release is estimated to be 8.52×10^{-6} (or 1 in 120,000). The mean source term given an accident is estimated to be 2.90 Ci, the mean source term given a release is estimated to be 48.7 Ci, the 99th percentile source term given an accident is estimated to be 85.0 Ci, while the 99th percentile source term given a release is estimated to be 423 Ci.

3.5. Comparison with 2014 NRA

The changes since 2013 have modified the source term results. A comparison of the accident probabilities and the total probability of release from the 2014 NRA (Reference 3-2) and the 2019

NRA are shown below in Table 3-3. The accident probabilities have increased for accidents during Phase 0 and Phase 5. The accident probabilities have decreased for accidents during Phases 1, 2, 3, and 4. This results in a decrease in the probability of an accident of about 50% for the overall mission for the 2019 NRA relative to the probabilities used in the 2014 NRA. These changes in accident probabilities are a result of launch vehicle updates since 2013.

Table 3-3. Accident Probability and Total Probability of Release 2014 versus 2019 Comparison for the MMRTG

Mission Phase	2014 Accident Probability	2019 Accident Probability	Ratio (2019/ 2014)	2014 Total Probability of Release	2019 Total Probability of Release	Ratio (2019/ 2014)
0 (Prelaunch)	3.28E-05	1.04E-04	3.2	1.07E-05	6.26E-05	5.9
1 (Early Launch)	3.12E-03	1.71E-03	0.5	8.77E-05	8.98E-04	10.2
2 (Late Launch)	3.63E-03	2.52E-03	0.7	7.71E-06	2.57E-06	0.3
3 (Suborbital)	1.31E-02	6.82E-03	0.5	1.48E-05	7.33E-06	0.5
4 (Orbital)	4.66E-03	1.21E-03	0.3	2.61E-04	6.61E-05	0.3
5 (Long-Term)	1.00E-06	1.43E-04	143.0	9.43E-08	8.52E-06	90.3
Overall Mission[a]	2.46E-02	1.25E-02	0.5	3.83E-04	1.04E-03	2.7

a. Overall mission values weighted by total probability of release for each mission phase.

As shown in Table 3-3, comparing the 2014 and 2019 total probabilities of release shows that they have decreased for Phases 2, 3, and 4 and increased for Phases 0, 1, and 5. This results in an increase in the total probability of release for the overall mission by a factor of 2.7 for the 2019 NRA relative to the 2014 NRA. This increase is due to the updated analytical models and computer simulation input parameters discussed above in Section 3.4.

A comparison of the mean source term given a release between the 2014 NRA and the 2019 NRA is shown in Table 3-4. The mean source term given a release has increase in all phases and increased by a factor of 63 for the overall mission for the 2019 NRA relative to the 2014 NRA. This increase is due to the updated analytical models and computer simulation input parameters discussed above in Section 3.4.

Table 3-4. Mean Source Term Given a Release 2014 versus 2019 Comparison for the MMRTG

Mission Phase	2014 Mean Given a Release (Ci)	2019 Mean Given a Release (Ci)	Ratio (2019/ 2014)
0 (Prelaunch)	2.82E-01	5.23E+01	186
1 (Early Launch)	5.90E+01	1.13E+03	19
2 (Late Launch)	1.60E-02	7.98E+01	4,988
3 (Suborbital)	4.16E+01	3.71E+02	9
4 (Orbital)	5.27E-01	4.61E+01	87
5 (Long-Term)	7.73E-01	4.87E+01	63
Overall Mission[a]	1.55E+01	9.79E+02	63

a. Overall mission values weighted by total probability of release for each mission phase.

3.6. References

3-1. ASCA, Incorporated, *Mars 2020 Mission Updated Launch Accident Probability Data for EIS Risk Assessment,* AR 19-04, Prepared for National Aeronautics and Space Administration, Kennedy Space Center, September 2019.

3-2. D.J. Clayton, J. Bignell, C.A. Jones, D.P. Rohe, G.J. Flores, T.J. Bartel, F. Gelbard, S. Le, C.W. Morrow, D.L. Potter, L.W. Young, N.E. Bixler, and R.J. Lipinski, *Nuclear Risk Assessment for the Mars 2020 Mission Environmental Impact Statement*, SAND2013-10589, Sandia National Laboratories, Albuquerque, NM, January 2014.

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4. RADIOLOGICAL CONSEQUENCES, MISSION RISKS AND UNCERTAINTIES

The radiological consequences and mission risks due to the potential PuO_2 releases presented in Section 3 are presented below in Sections 4.1 and 4.2, respectively. Uncertainties in the reported mission health effect risk are discussed in Section 4.3. A comparison with the consequence results from the 2014 NRA is given in Section 4.4. The methodology used in developing estimates for the radiological consequences and mission risks is presented in Appendix A.

4.1. Radiological Consequences

The radiological consequences resulting from the given accident scenarios have been calculated in terms of: 1) maximum individual dose, 2) collective dose, 3) health effects, and 4) land area affected at or above specified levels. The radiological consequences are based on atmospheric transport and dispersion simulations. Biological effects models, based on methods prescribed by the International Commission on Radiological Protection (ICRP), are used to predict the number of incremental latent cancer fatalities over 50 years (health effects) induced following a fuel release accident and assuming no mitigation measures.

Multiple exposure pathways are considered in these types of analysis. The direct pathways include direct inhalation and cloudshine of the released cloud, which could occur over a short duration (minutes to hours). The other exposure pathways result from deposition onto the ground and are calculated over a 50-year exposure period. These pathways include groundshine, ingestion, and additional inhalation from resuspension. A 50-year committed dose period is assumed for PuO_2 that is inhaled or ingested.

The maximum individual dose is the mean (for historical meteorological conditions) maximum (for location) dose delivered to a single individual for a given accident, considering the probability distribution over all release conditions. Collective dose is the sum of the radiation dose received by all individuals exposed to radiation from a given source term in units of "person-rem." Internal doses are determined using age and particle-size dependent dose coefficients based on Federal Guidance Report No. 13 (FGR 13) models (Reference 4-1).

Health effects are estimated on a cancer site-specific basis, as recommended by ICRP for non-uniform exposures such as those from Pu-238, which is primarily an inhalation hazard. Health effects are calculated per exposure pathway using risk coefficients based on the biokinetic and dosimetric models in FGR-13 (Reference 4-1). Contributions to health effects for each cancer site are summed over all exposure pathways for an individual. To estimate the number of health effects for a certain cancer type, individual health effects for each cancer type are multiplied by the number of individuals potentially receiving that cancer.

The total number of health effects is estimated by summing over the types of cancer estimated for the population. This result provides the statistical expectation value of excess latent cancer fatalities induced in the exposed population, which are referred to as health effects. This somewhat overestimates the number of health effects because the same individual cannot die of multiple types of cancer. However, the error is negligible when individual health effect risks are small.

The health effects estimators are based on a linear, no-threshold model relating health effects and effective dose. This means that health effects scale linearly as the dose decreases down to zero, rather than assuming a threshold dose below which there would be no health effects. To estimate the total health effects within the population, the probability of incurring a health effect is estimated for each individual in the exposed population, given a release, and then the probabilities are summed over that population.

The results for land area contaminated are reported in terms of the area contaminated at or above a level of 0.2 μCi/m^2 (the latter being a reference contamination level considered in the risk analyses of previous missions and a former Environmental Protection Agency (EPA) screening level used to determine the need for further action, such as monitoring or cleanup, References 4-2 and 4-3).

The potential for crop contamination is based on the Derived Intervention Limit (DIL), as defined by the Food and Drug Administration (FDA) (Reference 4-3). An average DIL of 2.5 Bq/kg (edible portion of the crop) is assumed. The DIL is converted to a cropland deposition threshold by considering the annual average uptake factor of deposited radionuclides and annual crop yields (kilogram of edible food per square meter of land). The number of square kilometers of cropland that exceeds this value for each crop type is determined from atmospheric transport calculations, cropland location maps, and the average fraction of each crop type within 100 km of the launch site, in Southern Africa or the around the world, depending on the location and extent of the plume.

Since 2013, multiple updates were made to the consequence analysis. Changes to the consequence modeling approach for the 2019 NRA are based on the INSRP Safety Evaluation Report recommendations for the 2011 Mars Science Laboratory mission, the Mars 2020 INSRP review, and the Mars 2020 mission configuration. The analysis also incorporated updated analytical models and computer simulation input parameters, informed by best available knowledge as well as lessons learned from other missions. Models and parameter input updates using the best available information for conducting the nuclear safety analysis include:

- atmospheric transport modeling including:
  - weather data;
  - propellant plume rise;
  - particle tracking in plumes;
- health effects modeling changes, including:
  - age-specific and organ-specific dose coefficients;
  - health effects calculations using organ-specific risk coefficients for Pu-238 and exposure pathways; and
  - use of region-specific crop information.

The consequence computer codes used to simulate the atmospheric transport and dispersion of the released material and the subsequent radiological consequences were updated since 2013 to include the updated analytical models and computer simulation input parameters. The consequence results shown below incorporate these updates.

The safety guidelines in NSPM-20 designate target probabilities for three dose levels to any member of the public. The three dose levels, 25 mrem, 5 rem, and 25 rem, have target probabilities of 0.01 (1 in 100), $1x10^{-4}$ (1 in 10,000) and $1x10^{-5}$ (1 in 100,000), respectively. These levels are shown in Table 4-1. The calculated mean probabilities of exceeding the three dose levels for the overall mission are also shown in Table 4-1. The calculated probabilities may be overestimated as they include all individuals, including workers and spectators, and not just members of the public, as well as assume no mitigating actions are executed. As seen in Table 4-1, the calculated mean probabilities of exceeding the three dose levels are all lower than the safety guidelines, even with the overestimation.

Table 4-1. Overall Mission Mean Exceedance Probabilities for Maximum Individual Dose Levels in the NSPM-20 Safety Guidelines

Maximum Individual Dose Level	Safety Guideline	Mean Exceedance Probability
25 mrem	1.00E-02	3.01E-04
5 rem	1.00E-04	1.28E-05
25 rem	1.00E-05	1.01E-06

A summary of the radiological consequences by mission phase is presented in Table 4-2 and Table 4-3 in terms of the mean and 99th percentile values. Two mean values are displayed: one is based on the average when an accident occurs (including accidents with no release), the other is based on the average considering only non-zero releases. Most accidents do not result in a release; hence the mean consequence given an accident is lower than the mean consequence given a release.

The 99th percentile radiological consequence is obtained by sorting the realizations by the radiological consequence of interest. Then the radiological consequence for which 1% of the realizations are greater is defined as the 99th percentile. The 99th radiological consequence is the value predicted to be exceeded with a probability of 0.01 (1 in 100), either given an accident, or given a release. In this context, the 99th percentile radiological consequence value reflects the potential for larger consequences at lower probabilities. Some accidents do not result in a radiological consequence; hence the 99th percentile consequence given an accident is lower than the mean consequence given a release. For some launch phases (Phase 0, Phase 2 and Phase 3), the probability of a radiological consequence is so low that the 99th percentile consequence is zero.

Table 4-2. Mean Radiological Consequence Summary for the MMRTG

Mission Phase	Accident Probability	Release Probability	Maximum Individual Dose (rem)		Collective Dose (person-rem)		Health Effects		Land Contamination[b] (km^2)		Cropland Intervention[c] (km^2)	
			Given an Accident	Given a Release	Given an Accident	Given a Release	Given an Accident	Given a Release	Given an Accident	Given a Release	Given an Accident	Given a Release
0 (Prelaunch)	1.04E-04	6.26E-05	8.15E-02	1.35E-01	6.99E+02	1.16E+03	1.17E-01	1.95E-01	4.46E+00	7.40E+00	4.58E-04	7.61E-04
1 (Early Launch)												
On-Pad Explosion	7.92E-05	3.22E-05	1.46E-01	3.59E-01	2.86E+03	7.03E+03	4.55E-01	1.12E+00	5.52E+01	1.36E+02	1.00E-02	2.46E-02
FSII	1.14E-06	8.84E-07	9.68E-01	1.24E+00	3.33E+04	4.28E+04	5.41E+00	6.96E+00	5.16E+02	6.64E+02	9.22E-02	1.19E-01
Stage 2/SV	3.01E-05	1.60E-05	2.08E-01	3.92E-01	5.82E+03	1.10E+04	9.04E-01	1.70E+00	1.38E+02	2.60E+02	2.21E-02	4.16E-02
SVII	1.48E-06	8.82E-07	1.12E-01	1.89E-01	2.33E+03	3.92E+03	3.61E-01	6.06E-01	5.22E+01	8.76E+01	9.94E-03	1.67E-02
Low Altitude FTS	1.60E-03	8.48E-04	1.03E-01	1.94E-01	1.63E+03	3.09E+03	2.49E-01	4.70E-01	3.85E+01	7.28E+01	6.75E-03	1.28E-02
Overall Phase 1	1.71E-03	8.98E-04	1.07E-01	2.05E-01	1.78E+03	3.41E+03	2.73E-01	5.22E-01	4.14E+01	7.90E+01	7.23E-03	1.38E-02
2 (Late Launch)	2.52E-03	2.57E-06	4.92E-05	4.82E-02	1.10E-01	1.08E+02	1.70E-05	1.66E-02	2.56E-02	2.51E+01	1.02E-05	1.00E-02
3 (Suborbital)	6.82E-03	7.33E-06	2.54E-03	2.36E+00	1.89E+00	1.75E+03	3.49E-04	3.24E-01	8.15E-02	7.58E+01	5.22E-06	4.86E-03
4 (Orbital)	1.21E-03	6.61E-05	8.64E-02	1.58E+00	4.45E+01	8.16E+02	7.52E-03	1.38E-01	3.21E-01	5.87E+00	3.17E-04	5.80E-03
5 (Long-Term)	1.43E-04	8.52E-06	5.93E-02	9.95E-01	2.45E+01	4.10E+02	4.03E-03	6.77E-02	2.91E-01	4.88E+00	2.89E-04	4.84E-03
Overall Mission[a]	1.25E-02	1.04E-03	2.58E-02	3.09E-01	2.56E+02	3.07E+03	3.94E-02	4.72E-01	5.79E+00	6.93E+01	1.03E-03	1.24E-02

a. Overall mission values weighted by total probability of release for each mission phase.

b. Land area contaminated above a screening level of 0.2 μCi/m^2.

c. Cropland area contaminated above the DIL based on region-specific crops. For Phases 0, 1, and 2 a value of 7.3 μCi/m^2 was used. For Phase 3 a value of 1.4 μCi/m^2 was used. For Phases 4 and 5 a value of 1.8 μCi/m^2 was used.

Table 4-3. 99th Percentile Radiological Consequence Summary for the MMRTG

Mission Phase	Probability of 99th Percentile	Release Probability	Maximum Individual Dose (rem)		Collective Dose (person-rem)		Health Effects		Land Contamination[b] (km^2)		Cropland Intervention[c] (km^2)	
			Given an Accident	Given a Release	Given an Accident	Given a Release	Given an Accident	Given a Release	Given an Accident	Given a Release	Given an Accident	Given a Release
0 (Prelaunch)	1.04E-06	6.26E-07	5.68E-01	2.44E+00	9.71E+03	2.74E+04	1.53E+00	4.63E+00	8.39E+01	1.79E+02	-	-
1 (Early Launch)												
On-Pad Explosion	7.92E-07	3.22E-07	3.20E+00	8.08E+00	7.60E+04	1.28E+05	1.21E+01	2.11E+01	1.59E+03	2.16E+03	3.24E-01	5.77E-01
FSII	1.14E-08	8.84E-09	2.05E+01	2.55E+01	6.63E+05	7.69E+05	1.11E+02	1.30E+02	5.62E+03	6.37E+03	1.65E+00	1.68E+00
Stage 2/SV	3.01E-07	1.60E-07	4.36E+00	6.24E+00	1.06E+05	1.54E+05	1.64E+01	2.20E+01	3.21E+03	4.25E+03	6.70E-01	8.51E-01
SVII	1.48E-08	8.82E-09	2.71E+00	3.60E+00	3.94E+04	6.08E+04	5.87E+00	9.35E+00	9.56E+02	1.36E+03	3.51E-01	4.23E-01
Low Altitude FTS	1.60E-05	8.48E-06	2.26E+00	2.90E+00	2.91E+04	4.13E+04	4.61E+00	6.15E+00	7.67E+02	9.41E+02	2.11E-01	2.68E-01
Overall Phase 1	1.71E-05	8.98E-06	2.30E+00	4.05E+00	3.09E+04	4.99E+04	4.78E+00	7.12E+00	7.84E+02	1.15E+03	2.20E-01	3.17E-01
2 (Late Launch)	2.52E-05	2.57E-08	-	1.25E+00	-	2.37E+03	-	3.87E-01	-	4.07E+02	-	2.67E-01
3 (Suborbital)	6.82E-05	7.33E-08	-	5.51E+01	-	2.21E+04	-	4.10E+00	-	9.69E+02	-	6.54E-02
4 (Orbital)	1.21E-05	6.61E-07	2.53E+00	1.88E+01	4.03E+02	1.42E+04	8.23E-02	2.71E+00	8.58E+00	5.23E+01	-	1.02E-01
5 (Long-Term)	1.43E-06	8.52E-08	5.48E-01	1.86E+01	1.26E+02	7.95E+03	2.07E-02	1.33E+00	9.49E+00	4.09E+01	-	6.83E-02
Overall Mission[a]	1.25E-04	1.04E-05	2.93E-01	5.76E+00	5.16E+03	4.47E+04	7.89E-01	6.79E+00	1.27E+02	1.01E+03	-	2.80E-01

a. Overall mission values weighted by total probability of release for each mission phase.

b. Land area contaminated above a screening level of 0.2 µCi/m^2.

c. Cropland area contaminated above the DIL based on region-specific crops. For Phases 0, 1, and 2 a value of 7.3 µCi/m^2 was used. For Phase 3 a value of 1.4 µCi/m^2 was used. For Phases 4 and 5 a value of 1.8 µCi/m^2 was used.

4.2. Mission Risks

A summary of the mission health effect risk is presented in Table 4-4. For the purpose of this report, health effect risk is defined as the expectation of health effects in a statistical sense (i.e., the product of total probability times the health effects resulting from a release, and then summed over all conditions leading to a release). The health effect risk is determined for each mission phase and the overall mission. Since the health effects resulting from a release equals the sum of the probability of a health effect for each individual in the exposed population, health effect risk can also be interpreted as the total probability of one health effect given the mission (for a health effect risk much less than one).

Table 4-4. Mission Risk Summary for the MMRTG

Mission Phase	Accident Probability	Mean Health Effects, Given an Accident	Mission Risks
0 (Prelaunch)	1.04E-04	1.17E-01	1.22E-05
1 (Early Launch)			
On-Pad Explosion	7.92E-05	4.55E-01	3.60E-05
FSII	1.14E-06	5.41E+00	6.16E-06
Stage 2/SV	3.01E-05	9.04E-01	2.72E-05
SVII	1.48E-06	3.61E-01	5.35E-07
Low Altitude FTS	1.60E-03	2.49E-01	3.99E-04
Overall Phase 1	1.71E-03	2.73E-01	4.69E-04
2 (Late Launch)	2.52E-03	1.70E-05	4.27E-08
3 (Suborbital)	6.82E-03	3.49E-04	2.38E-06
4 (Orbital)	1.21E-03	7.52E-03	9.10E-06
5 (Long-Term)	1.43E-04	4.03E-03	5.77E-07
Overall Mission[a]	1.25E-02	3.94E-02	4.93E-04

a. Overall mission values weighted by accident probability for each mission phase or the sum of each mission phase.

All of the Phase 0, Phase 1 and Phase 2 source terms are in the vicinity of the launch pad. Nearly all of the Phase 3 source terms are within Africa. All of the Phase 4 source terms are between 35° N and 35° S latitude. Phase 5 source terms can occur anywhere on the globe where there is land. As shown in Table 4-4, the overall mission health effect risk for the MMRTG configuration is 4.93×10^{-4}. For the Mars 2020 configuration with an MMRTG, Phase 1 accidents contribute 95% of the health effect risk. The primary AOC contributors to the Phase 1 risk in order of importance are 1) Low Altitude FTS 2) On-Pad Explosion and 3) Stage 2/SV.

Health effect risk contributions to the launch area (defined here as being within 100 km of the launch pad) and global areas are summarized in Table 4-5. The launch area health effect risk for the

MMRTG is 66% of the overall mission risk, and the global area risk is 34%. Launch area health effect risk is 97.5% from accidents during Phase 1. Global risks are also dominated by Phase 1 (90%), resulting from the atmospheric transport of small particles beyond 100 km from the launch pad.

Table 4-5. Mission Risk Contributions by Affected Region for the MMRTG

Mission Phase	Mission Risks		
	Launch Area	Global	Total
0 (Prelaunch)	8.28E-06	3.91E-06	1.22E-05
1 (Early Launch)	3.18E-04	1.50E-04	4.69E-04
2 (Late Launch)	2.99E-08	1.28E-08	4.27E-08
3 (Suborbital)	4.96E-10	2.38E-06	2.38E-06
4 (Orbital)	1.69E-19	9.10E-06	9.10E-06
5 (Long-Term)	1.06E-12	5.77E-07	5.77E-07
Overall Mission[a]	3.26E-04	1.66E-04	4.93E-04

a. Overall mission values are the sum of each mission phase.

Another descriptor used in characterizing risk is the maximum individual risk, presented in Table 4-6. The maximum individual risk is defined in this report to be the risk to the person receiving the maximum individual dose in a given mission phase. It is calculated by multiplying the mean maximum individual dose for each phase by the ratio of the mean health effects over the mean collective dose for each phase and by the probability of an accident. As shown in Table 4-6, the maximum individual health effect risk is below 1 in 10,000,000 for all phases and for the overall mission.

Table 4-6. Maximum Individual Risk for the MMRTG

Mission Phase	Accident Probability	Mean Maximum Individual Dose, Given an Accident (rem)	Mean Health Effects per Collective Dose (rem^{-1})	Maximum Individual Health Effect Risk
0 (Prelaunch)	1.04E-04	8.15E-02	1.68E-04	1.42E-09
1 (Early Launch)	1.71E-03	1.07E-01	1.53E-04	2.81E-08
2 (Late Launch)	2.52E-03	4.92E-05	1.54E-04	1.90E-11
3 (Suborbital)	6.82E-03	2.54E-03	1.85E-04	3.20E-09
4 (Orbital)	1.21E-03	8.64E-02	1.69E-04	1.77E-08
5 (Long Term)	1.43E-04	5.93E-02	1.65E-04	1.40E-09
Overall Mission[a]	1.25E-02	2.58E-02	1.61E-04	5.18E-08

a. Overall mission values weighted by accident probability for each mission phase.

4.3. Uncertainties

The total probability that the consequence level is greater than a threshold c ($\Pr_i(c)$) is denoted by:

$$\Pr_i(c)=\Pr\{\text{Consequence}>c|\text{Release}\}\Pr\{\text{Release}|\text{Accident}_i\}\Pr\{\text{Accident}_i\}$$

The $\Pr\{\text{Accident}_i\}$ is the probability that an accident i has occurred. The $\Pr\{\text{Release}|\text{Accident}_i\}$ represents the probability that, given accident i occurs, PuO_2 is released to the environment. The $\Pr\{\text{Consequence}>c|\text{Release}\}$ is the probability of a consequence greater than c given a release. The uncertainty in the risk values is a function of the uncertainty in the probability of an accident, the probability of a release given an accident, and the probability of a consequence greater than c given a release. An analysis to estimate uncertainties in accident probabilities, source terms, radiological consequences, and mission risks has been performed as part of the Mars 2020 FSAR. The Mars 2020 FSAR analysis shows that the uncertainty in the mission health effect risk is dominated by uncertainties in the launch accident probabilities.

The best estimate of the Mars 2020 mission health effect risk is $4.93\text{x}10^{-4}$. The convolution of the distinct representations of uncertainty leads to a lower and upper 90% uncertainty interval of overall mission health effect risk to be $2.17\text{x}10^{-4}$ and $1.24\text{x}10^{-3}$, respectively. The best estimate of the overall mission exceedance probabilities of the maximum individual dose levels in the NSPM-20 safety guidelines, along with the lower and upper 90% uncertainty intervals are shown in Table 4-7. As seen in Table 4-7, the calculated mean probabilities of exceeding the three dose levels, as well as the lower and upper 90% uncertainty intervals are all lower than the safety guidelines.

Table 4-7. Overall Mission Exceedance Probabilities and Uncertainty Intervals for Maximum Individual Dose Levels in the NSPM-20 Safety Guidelines

Maximum Individual Dose Level	Safety Guideline	Mean Exceedance Probability	Lower 90% Uncertainty Interval	Upper 90% Uncertainty Interval
25 mrem	1.00E-02	3.01E-04	1.30E-04	7.64E-04
5 rem	1.00E-04	1.28E-05	4.70E-06	4.77E-05
25 rem	1.00E-05	1.01E-06	2.60E-07	3.67E-06

4.4. Comparison with 2014 NRA

The updates since 2013 have modified the consequence results. A comparison of the overall mission mean consequence results given a release between the 2014 NRA (Reference 4-5) and the 2019 NRA is given below in Table 4-8. The overall mission mean consequence results given a release have increased for the 2019 NRA relative to the 2014 NRA for all the measures, except for cropland intervention area. In general, consequence measures increase as source terms increase, but the increase is not necessarily one to one. Potential consequences also depend on the particle size distribution of the source term and the surrounding thermal environments. The increase in consequence measures are less than the increase in the overall mission source term for the 2019 NRA (see factor of 63 in Table 3-4) due to the updates to the consequence modeling discussed above in Section 4.1.

Table 4-8. Overall Mission Mean Consequence Given a Release 2014 versus 2019 Comparison for the MMRTG

Overall Mission Consequence Measure[a]	2014 Mean Given a Release	2019 Mean Given a Release	Ratio (2019/ 2014)
Maximum Individual Dose (rem)	1.59E-02	3.09E-01	19.4
Collective Dose (person-rem)	1.26E+02	3.07E+03	24.3
Health Effects	7.59E-02	4.72E-01	6.2
Land Contamination[b] (km^2)	1.94E+00	6.93E+01	35.7
Cropland Intervention[c] (km^2)	3.40E-02	1.24E-02	0.4

a. Overall mission values weighted by total probability of release for each mission phase.

b. Land area contaminated above a screening level of 0.2 $\mu Ci/m^2$.

c. Cropland area contaminated above the DIL based on region-specific crops. For Phases 0, 1, and 2 a value of 7.3 $\mu Ci/m^2$ was used. For Phase 3 a value of 1.4 $\mu Ci/m^2$ was used. For Phases 4 and 5 a value of 1.8 $\mu Ci/m^2$ was used.

The change in risk for each of the consequence measures is equal to the change in the mean given a release and the change in the total probability of release. Recall from Table 3-3, that for the overall mission, the total probability of release increased by a factor of 2.7. A comparison of the risk results from the 2019 NRA and the 2014 NRA shows that the risk of each consequence measure has increased since the 2014 NRA, except for cropland intervention, which stayed about the same. The uncertainties about the risk estimates for the 2014 NRA were presented as within a factor of 25. The health effect risk, cropland intervention risk and maximum individual health effect risk are within the factor of 25. The maximum individual dose risk, collective dose risk and land contamination risk are above the factor of 25. The increases in risk arise from the culmination of the updates to the accident probabilities and the source term and consequence modeling updates described in Sections 3.4 and 4.1.

Table 4-9. Overall Mission Consequence Risk 2014 versus 2019 Comparison for the MMRTG

Overall Mission Consequence Risk[a]	2014 Risk	2019 Risk	Ratio (2019/ 2014)
Maximum Individual Dose (rem)	6.09E-06	3.23E-04	53.0
Collective Dose (person-rem)	4.83E-02	3.20E+00	66.4
Health Effects	2.90E-05	4.93E-04	17.0
Land Contamination[b] (km^2)	7.43E-04	7.24E-02	97.5
Cropland Intervention[c] (km^2)	1.30E-05	1.29E-05	1.0
Maximum Individual Health Effects	3.65E-09	5.18E-08	14.2

a. Overall mission values weighted by total probability of release for each mission phase.

b. Land area contaminated above a screening level of 0.2 $\mu Ci/m^2$.

c. Cropland area contaminated above the DIL based on region-specific crops. For Phases 0, 1, and 2 a value of 7.3 $\mu Ci/m^2$ was used. For Phase 3 a value of 1.4 $\mu Ci/m^2$ was used. For Phases 4 and 5 a value of 1.8 $\mu Ci/m^2$ was used.

4.5. References

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4-4. D. Thompson, *Accidental Radioactive Contamination of Human Food and Animal Feeds: Recommendations for State and Local Agencies*, U.S. Department of Health and Human Services Food and Drug Administration Center for Devices and Radiological Health Rockville, MD, 1998.

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APPENDIX A. RISK ASSESSMENT METHODOLOGY

The Mars 2020 mission spacecraft would use one MMRTG in the baseline configuration to provide electrical power and heat to the science instruments and other spacecraft components. Each MMRTG contains about 4.832 kg of PuO_2, or an estimated 59,000 Ci of radioactivity. The MMRTG would be provided to NASA by the DOE. Due to the radioactive nature of this material, and the potential for accidents involving their release to the environment, DOE is responsible for quantifying the risks associated with potential accidents via a nuclear risk assessment. The purpose of the risk assessment is to provide this information in support of NASA's preparation of the SEIS for the mission in accordance with requirements under the NEPA. This Appendix describes the methodology used to assess the risk. In order to better understand the methodology outlined below, reference should be made to the main text for background information on: 1) mission reference design (Section 2), 2) accidents, probabilities and source terms (Section 3), and 3) radiological consequences, mission risks and uncertainties (Section 4).

A.1. Overview of Methodology

A mission risk assessment typically includes the following steps:

1. Identification of postulated accidents, probabilities, and environments based on consideration of mission reference design information.
2. Evaluation of the response of the MMRTG to accident environments to arrive at source terms, release location, particle size distribution, release spatial configuration, and total probabilities of release. This is done via numerous accident simulations in a Monte Carlo statistical fashion.
3. Environmental transport and dispersion of the released PuO_2 to determine time-integrated concentrations in environmental media (air, soil, and water) as functions of time and space.
4. Exposure pathway modeling to determine the interaction of radioactive concentrations in environmental media (air, soil and water) and people through inhalation, ingestion, and external exposure pathways to arrive at radiological consequences in terms of radiation dose (maximum individual and collective) and health effects. The characterization of radiological consequences is completed using Step 3 results for land area contaminated.
5. Evaluation of mission risks in terms of the expectation of health effects in a statistical sense (i.e., the product of total probability times the health effects resulting from a release, and then summed over all conditions leading to a release). This step uses scaling factors for consequences as a function of released material, as determined in steps 3 and 4, and applying those factors to the source terms determined in Step 2.
6. Evaluation of uncertainties in the reported results for probabilities, source terms, radiological consequences and mission risks.

A.2. Developing Methodology

The consequence risk of a given accident, mission phase or overall mission can be defined as:

$$R = P_{TOT}C \qquad \text{(A-1)}$$

where

R = Risk in terms of expectation of health effects.
P_{TOT} = Total probability of release.
C = Mean consequence measure, given a release.

(Note: Risk defined in this manner can also be interpreted as the total probability of a consequence measure. For simplicity, summations over accident environments, accident scenarios and mission phases have been omitted. As such, the risk identified above could be that for a given accident environment, accident type, mission phase, or overall mission).

The total probability of release, P_{TOT}, is:

$$P_{TOT} = P_{ACC}P_{CON} \tag{A-2}$$

where

P_{ACC} = Probability of an accident (i.e., either for an overall mission phase or a specific type of accident, depending on the type of risk being characterized by R).
P_{CON} = Conditional probability of release given the accident.

The consequence measure, C, can be expressed as:

$$C = Q_{ST}c \tag{A-3}$$

where

Q_{ST} = Mean source term, given a release (Ci).
c = Mean consequence measure per curie of source term.

Risk can now be expressed in terms of four primary factors:

$$R = P_{ACC}P_{CON}Q_{ST}c \tag{A-4}$$

This particular equation can also be used as the basis of an uncertainty analysis. For example, if the uncertainties in each of the four factors on the right are represented by log-normal probability distributions, then the overall uncertainty in the risk, R, can also be represented by a log-normal probability distribution determined by the characteristics of each of the four log-normal distributions on the right.

A.3. Application of Methodology

This section describes the manner in which the methodology outlined in above is applied in order to arrive at the results reported in Sections 3 and 4 of the main text. In applying the methodology outlined above to the Mars 2020 mission, some observations are useful at this point in making a connection between the following factors identified in Equation A-4 affecting mission risk and the information presented in Sections 3 (Accident Probabilities and Source Terms) and 4 (Radiological Consequences and Mission Risks) of the main text:

- Accident Probability, P_{ACC}
- Conditional Probability of Release, P_{CON}
- Mean Source Term, Q_{ST}

- Mean Consequence Measure per curie of source term, c

Characteristics of each of these factors and considerations taken into account in their development for the Mars 2020 mission are summarized below.

Accident Probability, P_{ACC}: For the purpose of the risk analysis, the Mars 2020 mission was divided into six mission phases on the basis of the MET, reflecting principal events during the mission (See Section 3.1):

- Phase 0 (Prelaunch)
- Phase 1 (Early Launch)
- Phase 2 (Late Launch)
- Phase 3 (Suborbital)
- Phase 4 (Orbit)
- Phase 5 (Long-Term)

Accident probabilities, P_{ACC}, are then developed using this information as described in Section 3 of the main text.

- Conditional Probability of Release, P_{CON}, and Mean Source Term, Q_{ST}: For the MMRTG, the conditional probabilities of release, P_{CON}, have been developed by performing a Monte Carlo simulation of possible launch accident sequences. The response of the MMRTG to various accident environments was estimated based on continuum mechanics code modeling for a range of conditions. The mean source term, Q_{ST}, is the total source term amount released. The resulting source terms and probabilities are summarized in Section 3 of the main text.

Mean Consequence Measure per curie of Source Term, c: The mean consequence measure per curie, c, is a rather complex factor and accounts for:

- Particle size distribution of the release: Affects 1) deposition characteristics, 2) inhalability and dose effectiveness, and 3) resuspension characteristics. Three types of particle size distributions have been considered in the analysis: 1) a near vapor type associated with exposure to burning solid propellant, 2) a particulate type associated with pure mechanical source terms, and 3) a blend of the first two types reflecting the modification of an initial mechanical impact source term that is subsequently exposed to burning liquid and/or solid propellant. The particle sizes in the analyses ranged from 0.1 microns to 10 mm physical diameter and were based on fueled clad impact experiments, propellant fire experiments, and detailed mechanical and thermal modeling.
- Vertical plume configuration: Affects the initial dilution, transport and dispersion characteristics. Two types of vertical plume configurations are of interest: 1) the plume resulting from a liquid propellant explosion with its short duration fireball, and 2) the plume resulting from widely scattered burning solid propellant of longer burn durations.
- Meteorology: Affects transport and dispersion of the source term. The location of the source term (launch site or worldwide) determines the type of atmospheric transport and dispersion model and population distribution used in the analysis. Typically, the modeling of

launch area source terms is based on a range of time- and spatially-dependent meteorological conditions representative of the period of launch opportunity. The 2019 NRA analyses sample weather data from several recent years for the months of July and August so as to span the range of possible launch conditions.

- Population distribution: This distribution can be either for: 1) the launch site region or 2) worldwide, depending on the source term location and subsequent atmospheric transport and dispersion characteristics of the source term.
- Dose coefficients: Internal doses are determined using age and particle-size dependent dose coefficients based on FGR 13 models. The maximum individual dose is the maximum dose in units of rem to a single individual. Collective dose is the sum of the radiation dose received by all individuals exposed to radiation from a given source term in units of "person-rem."
- Risk coefficients: The health effects represent incremental cancer fatalities over 50 years induced by source terms. They are calculated on a cancer site-specific basis, as recommended by ICRP for non-uniform exposures such as those from Pu-238, which is primarily an inhalation hazard. Health effects are calculated per exposure pathway using risk coefficients based on the biokinetic and dosimetric models in FGR-13 (Reference 4-1). Contributions to health effects for each cancer site are summed over all exposure pathways for an individual. The health effects estimators are based on a linear, non-threshold model relating health effects and effective dose. This means that health effects decrease as the dose decreases down to zero, rather than assuming a threshold dose below which there would be no health effects. The probability of incurring a health effect is estimated for each individual in the exposed population and then these probabilities are summed over the population, resulting in an estimate of the total health effects in the population.

In terms of the steps identified in Section A.1, the determination of the mean consequence measures per curie of source term, c, requires the combined results of Steps 3 and 4, based on input from Step 2. It should be noted that developing the mean consequence measures per Ci of source term, c, requires summations over particle size groups, meteorological conditions, and the population distribution. The location of the source term (launch site or worldwide) determines the type of atmospheric transport and dispersion model as well as the population distribution used in the analysis.

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