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Nuclear Risk Assessment for the Mars 2020 Mission Environmental Impact Statement

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Prepared for the U. S. Department of Energy, Office of Space and Defense Power Systems (NE-75)

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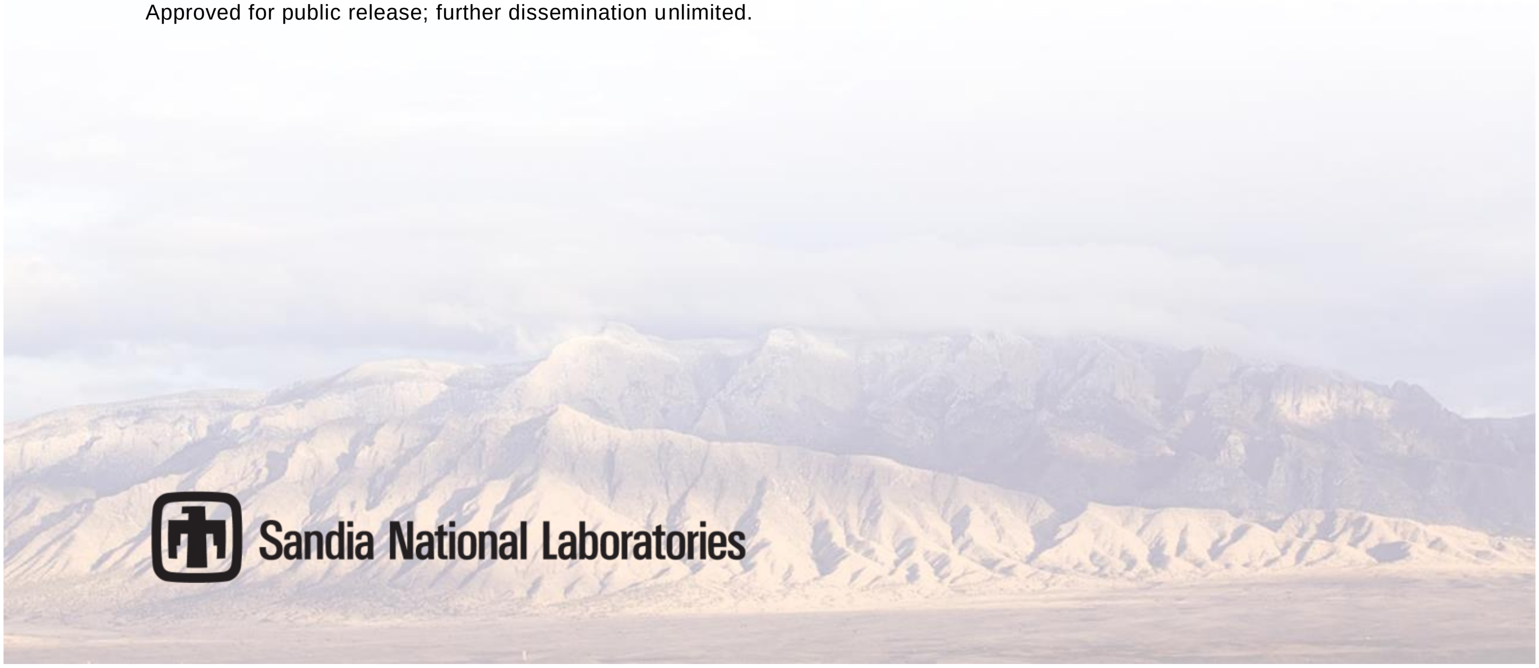

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Nuclear Risk Assessment for the Mars 2020 Mission Environmental Impact Statement

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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. One option for the rover on the proposed spacecraft uses a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) to provide continuous electrical and thermal power for the mission. An alternative option being considered is a set of solar panels for electrical power with up to 80 Light-Weight Radioisotope Heater Units (LWRHUs) for local component heating. Both the MMRTG and the LWRHUs use radioactive plutonium dioxide. NASA is preparing an Environmental Impact Statement (EIS) in accordance with the National Environmental Policy Act. The EIS will include information on the risks of mission accidents to the general public and on-site workers at the launch complex. This Nuclear Risk Assessment (NRA) addresses the responses of the MMRTG or LWRHU options 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 of both options for the EIS.

LIMITATIONS

Launch Vehicle Selection: The assessment presented in this report is based on the Atlas V 551 and the Delta IV Heavy launch vehicles. Since the risks derived from these launch vehicles are believed to bound the risks that would be derived for the Atlas V 541 and Falcon Heavy, respectively, the results are representative of all of the launch vehicles being considered by NASA.

Specific Mission Final Safety Analysis Report (FSAR): This document is being provided in advance of the more detailed FSAR being prepared by DOE and its contractors, as required by (1) DOE Directives and (2) the formal Launch Approval Process established by Presidential Directive/National Security Council Memorandum Number 25 (PD/NSC 25). The results of the specific FSAR could differ from those presented in this document due to the use of more recent information and differing methodologies.

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Acronyms and Abbreviations

ACM	Attitude Control Malfunction
ADS	Automatic Destruct System
AED	Aerodynamic Equivalent Diameter
AIC	Accident Initial Condition
AOC	Accident Outcome Condition
APXS	Alpha-Particle X-ray Spectrometer
BOM	Beginning of Mission
CADS	Centaur Automatic Destruct System
CBC	Common Booster Core
CBCF	Carbon Bonded Carbon Fiber
CCAFS	Cape Canaveral Air Force Station
CCB	Common Core Booster
CDS	Command Destruct System
CFA	Centaur Forward Adapter
Co-57	Cobalt-57
Cm-244	Curium-244
CS	Cruise Stage
CSC	Conical shaped charge
DAN	Dynamic Albedo of Neutrons

DCSS	Delta IV Cryogenic Second Stage
DOE	Department of Energy
EIS	Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
EPDM	Ethylene Propylenediene Monomer
EV	Entry Vehicle
FAP	Fairing Acoustic Protection
FSAR	Final Safety Analysis Report
FSII	Full Stack Intact Impact
FTS	Flight Termination System
FUT	Fixed Umbilical Tower
FWPF	Fine Weave Pierced Fabric
GH_2	Gaseous Hydrogen
GIS	Graphite Impact Shell
GPHS	General Purpose Heat Source
GSE	Ground Support Equipment
ISCORS	Interagency Steering Committee on Radiation Standards
ICRP	International Commission on Radiological Protection
IIP	Instantaneous Impact Point
ILL	Impact Limit Lines
ISDS	Inadvertent Separation Destruct System
LH_2	Liquid Hydrogen
LOC	Launch Operations Center
LO_2	Liquid Oxygen (LOX)
LPI	Lanyard Pull Initiator
LRE	Liquid Rocket Engine
LSC	Linear Shaped Charges
LV	Launch Vehicle
MEOP	Maximum Expected Operating Pressure
MER	Mars Exploration Rover
MET	Mission Elapsed Time
MFCO	Mission Flight Control Officer

MIMOS-II	Miniaturized Mössbauer Spectrometer II
MLP	Mobile Launch Platform
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
MSL	Mars Science Laboratory
MST	Mobile Service Tower
NASA	National Aeronautics and Space Administration
NCRP	National Council on Radiation Protection and Measurements
NEPA	National Environmental Policy Act
NRA	Nuclear Risk Assessment
NRC	Nuclear Regulatory Commission
PA	Payload Adapter
PD/NSC-25	Presidential Directive/National Security Council Memorandum Number 25
PG	Pyrolytic Graphite
PLF	Payload Fairing
PNH	Pluto New Horizons
Pt-30Rh	Platinum-30 rhodium
Pu-238	Plutonium-238
PuO_2	Plutonium dioxide
PVan	Payload Van
RAS	Representative Accident Scenario
RP-1	Rocket Propellant 1
RTG	Radioisotope Thermoelectric Generator
SCBC	Strap-on Common Booster Core
SEB	Support Equipment Building
SLC	Space Launch Complex
SRM	Solid Rocket Motor
SRB	Solid Rocket Booster
SV	Space Vehicle (spacecraft)
SVII	Space Vehicle Intact Impact
TCM	Trajectory Control Malfunction
TVC	Thrust Vector Control
ULA	United Launch Alliance

VAFB	Vandenberg Air Force Base
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. One option for the proposed rover includes the use of radioactive materials in a single Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) to provide continuous power for the mission. An alternative power option being considered is a set of solar panels for electrical power combined with up to 80 Light-Weight Radioisotope Heater Units (LWRHUs) for local component heating. NASA is preparing an Environmental Impact Statement (EIS) for the mission in accordance with the National Environmental Policy Act (NEPA). The EIS includes information on the risks of mission accidents to the general public and on-site workers at the launch complex. This Nuclear Risk Assessment (NRA) addresses the responses of the proposed MMRTG or LWRHU options 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 of both options for the EIS.

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:

Investigation Science Objectives:

a. Explore an astrobiologically relevant ancient environment on Mars.

b. Assess the biosignature preservation potential within the selected geologic environment and search for potential biosignatures.

c. Demonstrate significant technical progress towards the future return of scientifically selected, well-documented samples to Earth.

d. Provide a test bed for human spaceflight technologies.

The Mars 2020 mission spacecraft would be launched from Cape Canaveral Air Force Station (CCAFS), Florida. NASA has not yet selected the launch vehicle for the mission. However, there are four candidate Launch Vehicles (LV) being considered for the Mars 2020 mission based upon the stated launch opportunity, spacecraft mass and mission requirements: the Atlas V 541, the Atlas V 551, the Delta IV Heavy, and the Falcon Heavy (formerly called the Falcon 9 Heavy). The Atlas V, the Delta IV, and the Falcon would be launched from CCAFS Space Launch Complex (SLC) 41, SLC-37, or SLC-40, respectively. The consequences of the Atlas V 541 will be enveloped by those of the Atlas V 551 because the 551 uses an additional solid rocket motor.

For the Falcon Heavy launch vehicle that has no flight history, detailed design and in flight performance data do not exist. Therefore, certain assumptions have been made regarding the vehicle design and number of successful flights prior to the Mars 2020 launch date. These assumptions reflect the expectation that the Falcon Heavy will achieve the degree of success and documented reliability prior to its use for missions carrying radioisotope power sources. Further, it is assumed that, to the first order, the Falcon Heavy accident modes and probabilities are equivalent to the Delta IV Heavy.

There would be one primary launch period of opportunity: July 7, 2020 to August 5, 2020 and one backup in August 2020. If the mission needs to be delayed to 2022, there is a launch opportunity within August and September of 2022. The analyses for the NRA samples weather data from several recent years for the months of July, August, and September so as to span the range of possible launch conditions. In addition, since NASA has not selected the time of launch on a given day, this report assumes a daytime launch. The planned mission trajectory would place the spacecraft in a heliocentric orbit prior to completion of the Stage 2 second burn. After separation from Stage 2, the spacecraft would be in a heliocentric interplanetary trajectory. If the spacecraft fails to intersect Mars, there is a very small but finite probability that it might return to Earth over the next several centuries.

The baseline Mars 2020 rover would use one MMRTG to provide continuous power. The MMRTG would contain eight General Purpose Heat Source (GPHS) modules. The MMRTG would contain 4.8 kg of plutonium dioxide (PuO_2) in ceramic form, with an estimated inventory of 60,000 curies (Ci), due primarily to plutonium-238 (Pu-238), an alpha-emitting radioisotope with a half-life of 87.7 years. An alternative power option is a set of solar panels with up to 80 LWRHUs to provide local component heating. Each LWRHU would contain 2.7 g of PuO_2 with an inventory of nominally 33 Ci. Eighty LWRHUs would have a total inventory of about 2,640 Ci. The MMRTG and LWRHUs would be provided by the U.S. Department of Energy (DOE). Due to the radioactive nature of this material and the potential for accidents resulting in its release to the environment, safety is an inherent consideration in all steps from mission design through launch.

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 EIS for the mission, being prepared by NASA in accordance with requirements under the NEPA. There would also be an independent Launch Approval Process for the mission subject to the requirements of Presidential Directive / National Security Council Memorandum Number 25 (PD/NSC-25), for which DOE would prepare a Final Safety Analysis Report (FSAR).

The EIS-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 1-2) and 3) information available from the launch vehicle manufacturers' User's Guides (References 1-3 through 1-6).

A composite approach has been taken in reporting the results in this report for accident probabilities, airborne portion of potential releases of PuO_2 in case of an accident (source terms), radiological consequences, and mission risks. In the composite approach, the results for the Atlas V 541, the Atlas V 551, the Delta IV Heavy, and the Falcon Heavy would be combined in a probability-weighted manner with equal weight being given to each launch vehicle (25% each). Since the detailed calculations for the Atlas V 551 are being used to represent the Atlas V 541, and since the detailed calculations for the Delta IV Heavy are being used to represent the Falcon Heavy, the net result is that the Atlas V 551 calculations and the Delta IV Heavy calculations will be weighted 50% each. This approach reflects the state of knowledge at this early planning stage in the mission with respect to the candidate launch vehicles being considered for the Mars 2020 mission. Differences in results among the various candidate launch vehicles are not considered to be significant, given the uncertainties in the estimates being made in the nuclear risk assessment.

Section 2.0 presents a summary of pertinent mission reference design information related to the launch vehicle, spacecraft, mission profile, and radioactive materials. Section 3.0 provides an overview of the accidents considered in the analysis, their probabilities, and source term estimates. Section 4.0 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 Science Laboratory Mission, Volume 1, Executive Summary and Chapters 1 through 8*, Science Mission Directorate, NASA, Washington, DC, November 2006.

1-2. ASCA, Incorporated, *Mars 2020 Launch Accident Probability Data for EIS Risk Assessment, Revision Draft*, AR 13-02, Prepared for National Aeronautics and Space Administration, Kennedy Space Center, September 2013.

1-3. United Launch Alliance, *Atlas V Launch Services User's Guide*, United Launch Alliance, Centennial, CO, March 2010.

1-4. United Launch Alliance, *Delta IV Launch Services User's Guide,* United Launch Alliance, Centennial, CO, September 2013.

1-5. Space Exploration Technologies Space Exploration Technologies, *Falcon 9 Launch Vehicle Payload User's Guide*, *Rev 1*, SCM-2008-010-Rev-1, Space Exploration Technologies Corporation (SpaceX), Hawthorne, CA 2009.

1-6. Space Exploration Technologies Space Exploration Technologies, *Falcon Heavy Launch Vehicle Payload User's Guide*, *Rev 0*, Space Exploration Technologies Corporation (SpaceX), Hawthorne, CA 2013.

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2. REFERENCE DESIGN INFORMATION

This report section summarizes relevant mission reference design information, including the conceptual mission, a range of candidate launch vehicles, spacecraft, MMRTG, LWRHU, launch site, flight safety systems and potential mission timelines.

2.1. Mission Description

The purpose of the Mars 2020 mission is to "Seek Signs of Past Life" with the intention to explore an astrobiologically relevant ancient environment on Mars to decipher the geologic processes and history, including its past habitability. The Mars 2020 mission is being designed to have the capability to reach Martian landing sites of interest between 30 degrees North latitude and 30 degrees South latitude. The rover will explore the area landing site and gather imaging, spectroscopy, composition data, and other measurements about selected Martian soils, rocks, and the atmosphere.

The mission would launch from the Cape Canaveral Air Force Station (CCAFS) sometime between July to August 2020. The set of launch vehicles being considered are the Atlas V 551, Atlas V 541, Delta IV Heavy and the Falcon Heavy.

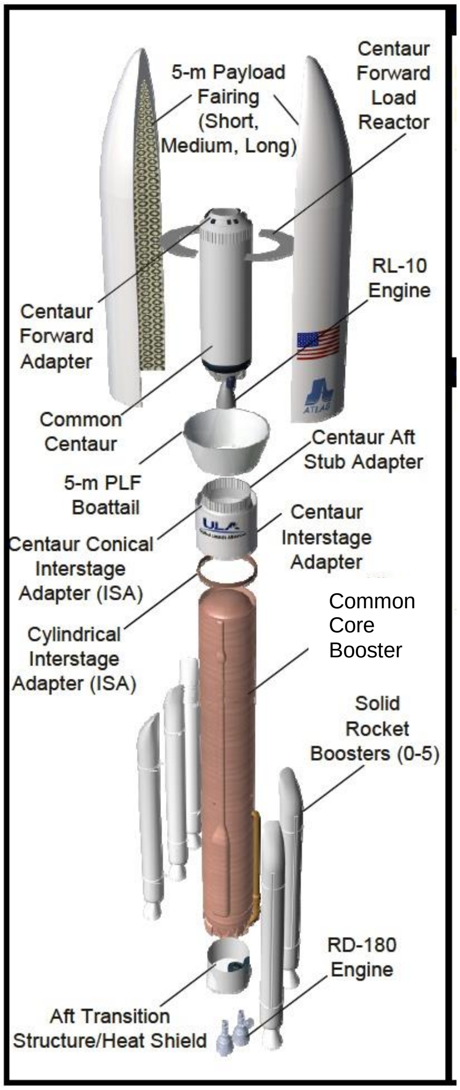
2.2. Launch Vehicle Descriptions

The radioisotope hardware may be used on any of several launch vehicles. For this analysis, two launch vehicles are described and used as representative of the four candidates: the Atlas V 551 and the Delta IV Heavy. The Atlas V 551 risk encompasses the Atlas V 541 risk, and the Delta IV Heavy risk is assumed to approximate the Falcon Heavy risk. The Atlas V, manufactured by United Launch Alliance (ULA) in Denver, CO, is described in Section 2.2.1. The Delta IV, also manufactured by ULA, is described in Section 2.2.2. A general discussion of Flight Termination Systems (FTSs) is provided in Section 2.2.3. Most of these descriptions come directly from the LV user's guides (References 2-1and 2-2) and the Mars Science Laboratory (MSL) EIS (Reference 2-3).

2.2.1. Atlas V Launch Vehicles

An Atlas V 551, with five solid rocket boosters (SRBs), is shown in Figure 2-1 (from Reference 2-1). An Atlas V 541 would have four SRBs (Reference 2-1). Major components include the First Stage, also called the Common Core Booster^{TM} (CCB), with strap-on SRBs, a Second Stage Centaur III, and the Payload Fairing (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).



[Note: The figure shows an Atlas V 551 with five SRBs; the Atlas V 541 would have four SRBs.]

Figure 2-1. Atlas V 551 Launch Vehicle

2.2.1.1 First Stage

The Atlas V booster design departs from the heritage pressure-stabilized monocoque booster tanks of previous Atlas launch vehicles in favor of the larger-diameter, structurally stable CCB. The CCB is 3.81 m (12.5 ft) in diameter and 32.46 m (106.5 ft) in length. The CCB is powered by a single RD-180 Pratt & Whitney/NPO Energomash engine (two nozzles). The RD-180 operates on a staged combustion cycle using liquid oxygen (LO_2, the oxidizer) and Rocket Propellant 1 (RP-1) propellants. The aft tank is RP-1 and the forward tank is LO_2. The total liquid propellant quantity (RP-1 plus LO_2) is 284,089 kg (626,309 lb).

The First Stage avionics are integrated with the Centaur avionics system for guidance, flight control, instrumentation, and sequencing functions. An external equipment pod located on the CCB houses flight termination, data acquisition, pneumatics, and instrumentation systems.

2.2.1.2 Solid Rocket Boosters

The SRB consists of a motor case, insulation, propellant, nozzle, igniter, nose fairing, raceway, and equipment deck. Each SRB is approximately 1.58 m (5.2 ft) in diameter and 20.0 m (65.6 ft) long with a mass of 46,697 kg (102,949 lb). Each SRB carries nominally 43,005 kg (94,809 lb) of propellant and has a burn time of 95 s.

The SRB motor case is a composite structure of filament-wound carbon fiber and epoxy. The case is filament-wound directly over a strip-wound insulation of Kevlar-filled Ethylene Propylenediene Monomer (EPDM) rubber. The case has structural attachment points in the forward and aft cylindrical areas to allow attachment of the booster to the vehicle core. Push off devices called “thrusters,” two forward and one aft, are activated to cause SRB separation. The thrusters also provide the structural attachment of the SRB to the CCB.

2.2.1.3 Second Stage

The Atlas V launch vehicle uses the Centaur III as the Second Stage, with major components consisting of a Pratt & Whitney RL10A-4-2 engine, a two-chamber propellant tank, Centaur Forward Adapter (CFA), and tank insulation. The Centaur has an overall length of 12.68 m (41.6 ft) and carries 20,830 kg (45,922 lb) of liquid hydrogen (LH_2) and LO_2. The RL10A-4-2 engine incorporates electromechanically actuated thrust vector control (TVC).

The pressurized propellant tank structure provides primary structural integrity for the Centaur stage and support for all systems and components. A double-wall, vacuum-insulated common bulkhead separates the propellants. The tank structural integrity is maintained by internal pressurization. The propellant tanks are of a Leak-Before-Burst design. The forward LH_2 tank is designed to a Maximum Expected Operating Pressure (MEOP) of 46.7 psig, and the aft LO_2 tank to an MEOP of 62.7 psig.

The CFA is bolted to the forward tank ring and structurally supports the Payload Adapter (PA) and PLF. The lower segment is an aluminum skin/stringer cylindrical structure 3.05 m (10 ft) in diameter and 0.64 m (2.1 ft) long. The upper segment provides mounting for avionics components, electrical harnesses, and the forward umbilical panel. The PA bolts to the forward ring of the CFA.

2.2.1.4 Payload Fairing

The PLF provides a protective enclosure for the space vehicle during the prelaunch processing operations, vehicle launch, and ascent. The PLF enclosure provides thermal, acoustic, electromagnetic, and environmental protection. The Atlas V 500 series launch vehicles incorporate the 5.4 meter (17.7 ft) diameter PLF, shown in Figure 2-2 (from Reference 2-1). The 5.4 m PLF is available in three lengths: the standard short 20.7 m (68 ft), the non-standard medium 23.4 m (77 ft), and the non-standard long 26.5 m (87 ft). Mars 2020 likely will use the 20.7 m (68 ft) length standard short PLF.

Major components of the fairing include a fixed conical boattail that attaches the PLF to the launch vehicle, a base module that encapsulates the Centaur stage, and a cylindrical module that transitions into a constant radius ogive nose section topped by a spherical nose cap that encapsulates the payload. The PLF cylindrical module and ogive sections provide mounting provisions for various secondary systems. Payload compartment cooling system provisions are contained in the ogive-shaped portion of the fairing. Electrical packages required for the fairing separation system are mounted on the internal surface of the fairing. Fairing Acoustic Protection (FAP) is provided on the 5.4 m PLF to attenuate sound pressure.

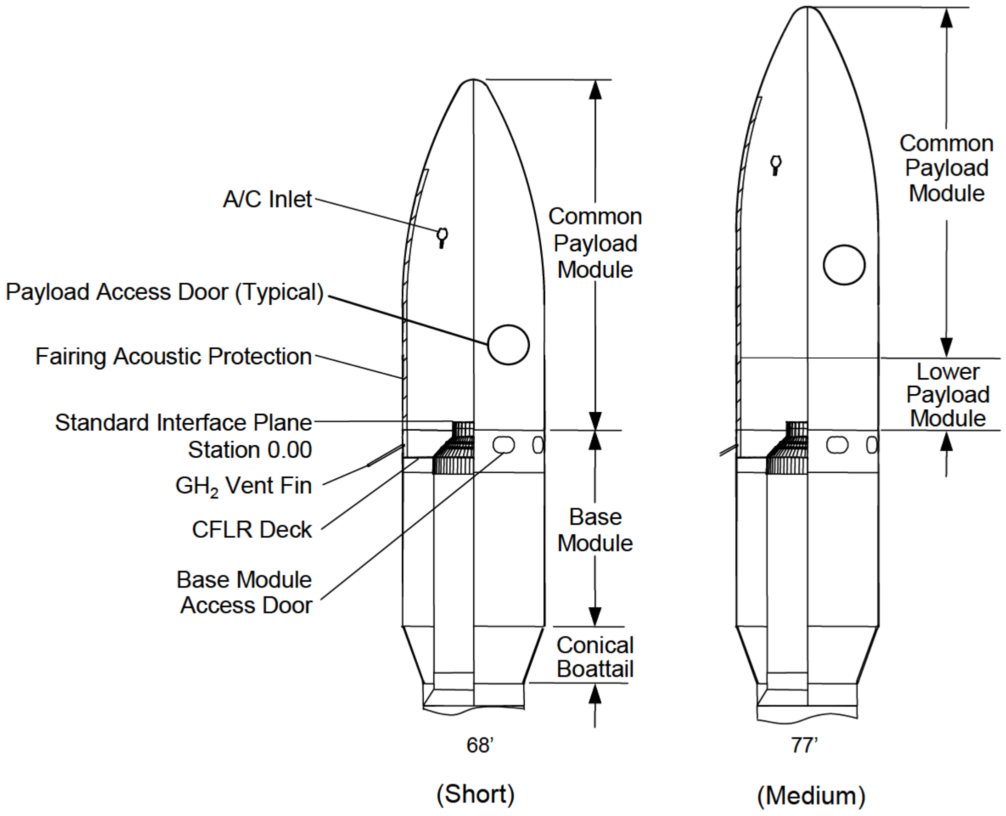


Figure 2-2. Atlas V 5-m Payload Fairings

2.2.2. Delta IV Heavy Launch Vehicle

The Delta IV family of launch vehicles includes 5 configurations: the Delta IV Medium, the Delta IV Medium+ (4,2), the Delta IV Medium+ (5,2), the Delta IV Medium+ (5,4) and the Delta IV Heavy (Reference 2-2). The "+" refers to the addition of Solid Rocket Motors (SRMs), the first number in the parentheses is the fairing diameter, and the second one is the number of SRMs. The Delta IV Heavy is the largest and most powerful among the five Delta IV configurations available and is designed to launch from either the Eastern Range at Cape Canaveral Air Force Station (CCAFS) or Western Range at Vandenberg Air Force Base (VAFB). The Delta IV Heavy Launch Vehicle is divided into two stages. The First Stage consists of a Common Booster Core (CBC) and two Strap-on CBCs (SCBCs, port and starboard), with each powered by a cryogenic RS-68 engine. The Second Stage consists of a Delta IV Cryogenic Second Stage (DCSS) powered by a cryogenic RL-10B-2 engine. The First and Second Stage are connected by the Interstage through the center or core CBC. Both stages are described in more detail in the sections below. Figure 2-3 depicts the Delta IV Heavy First and Second Stages (from Reference 2-2).

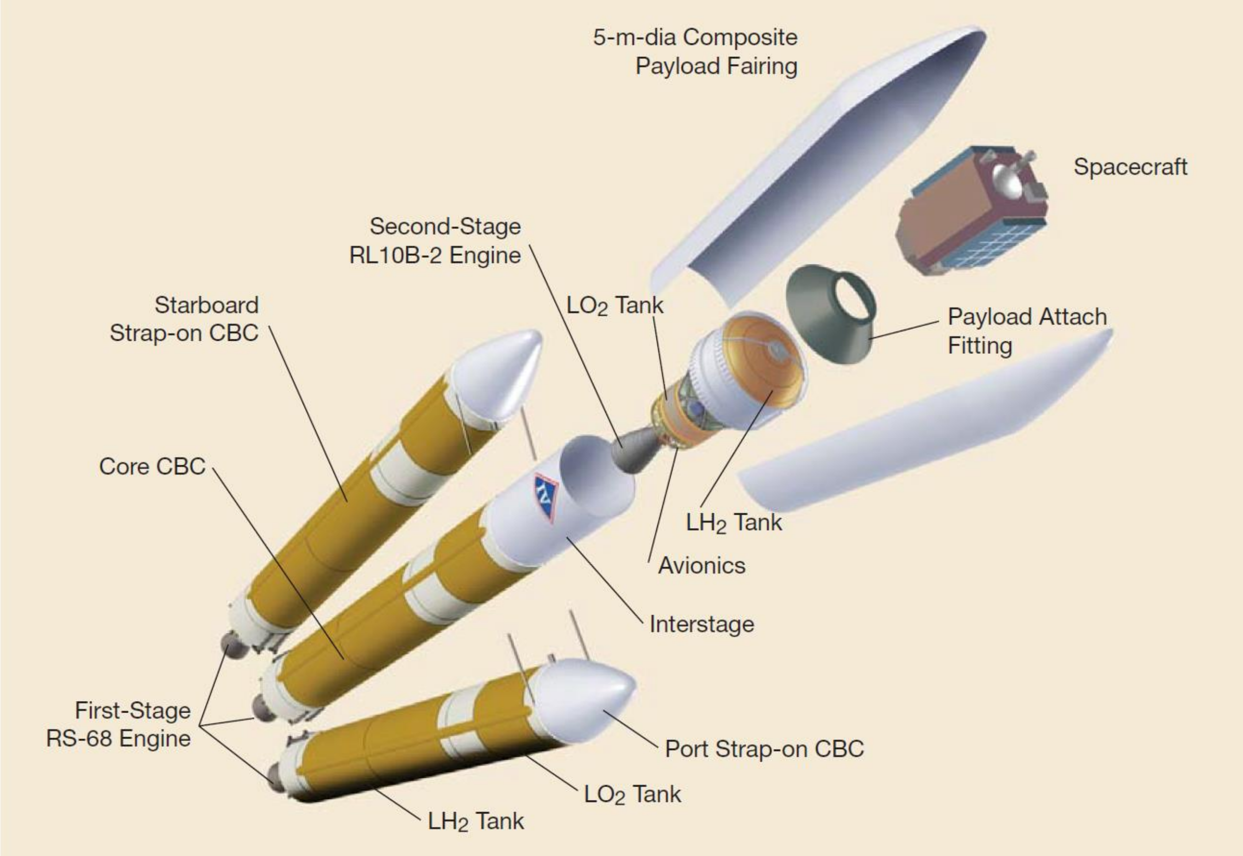


Figure 2-3. Delta IV Heavy Launch Vehicle

2.2.2.1 First Stage

The Delta IV Heavy First Stage consists of a CBC, commonly referred to as the core, main or center CBC, and two SCBCs, with each CBC or SCBC powered by an Aerojet Rocketdyne RS-68A Engine, commonly referred to as Main Engine. The three CBCs primary structures are: engine section, LH_2 fuel tank, Centerbody, and LO_2 oxidizer tank. Additionally, the center CBC has an upper structure which is called the Interstage and connects the First Stage to the Second Stage. The SCBCs upper structure consists of a nose cone which is an aerodynamic fairing.

The CBC has an overall diameter of 5 meters and for the Delta IV Heavy configuration the Interstage consists of a 5 meter diameter cylinder. The CBC and SCBCs use cryogenic propellants for the RS-68A engine. LH_2 is the fuel and LO_2, commonly called LOX, is the oxidizer. The CBCs contain supporting mechanism, including propulsion, mechanical (pneumatics/hydraulics), avionics and ordnance, used in vehicle pre-launch, launch, flight, destruct, staging, separation, and control. The CBCs, upon consuming the propellants and separating, return and impact in the ocean. The propellant inventory in the CBC and the two SCBCs is 202,103 kg (445,560 lb) each.

2.2.2.2 Strap-on Boosters

The SCBCs are essentially identical to the CBC and are attached to the center CBC through hardware designed to provide positive separation and to disconnect the avionics wire harnesses at the proper time during flight. The primary hardware consists of two forward attach strut assemblies and two aft separation attach assemblies. The forward strut assemblies attach the SCBC at the nose cone to the center CBC at the aft end of the Interstage. The aft separation assemblies attach the SCBC to the center CBC at the engine sections.

2.2.2.3 Second Stage

The Delta IV Heavy Launch Vehicle uses a 5-meter diameter Second Stage, commonly referred to as Delta IV Cryogenic Second Stage (DCSS). It consists of LO_2 and LH_2 cryogenic propellant Tanks, Forward and Aft skirts, Intertank, Equipment Shelf, Pratt & Whitney RL10B-2 engine, and support mechanisms. The latter includes the engine propellant supply system, mechanical system, avionics system, and ordnance used for flight, vehicle destruct, staging events and control functions. The 5-m (16.4 ft) long Second Stage uses a Pratt & Whitney RL10B-2 engine burning LO_2 and LH_2. The engine gimbal system uses electromechanical actuators. The propellant inventory is 27,200 kg (60,000 lb) of LO_2 and LH_2, with a burn time of nominally 1125 s.

2.2.2.4 Payload Fairing

The Payload Fairing (PLF) protects the encapsulated payload through the boost flight. There are different PLF options for the Delta IV Heavy. For single manifest missions, there is the 5-m composite fairing in a 19.1 m (62.7 ft) length and the 5-m metallic trisector fairing in a 19.8 m (65 ft) length, which is the baseline for government programs. For dual-manifest missions, the fairing consists of two sections: a 5-m composite bisector fairing and a lower 5-m composite dual-payload canister (DPC). The PLF is designed for payload encapsulation off-pad for safety, security, and to minimize the on-pad time. See Figure 2-4.

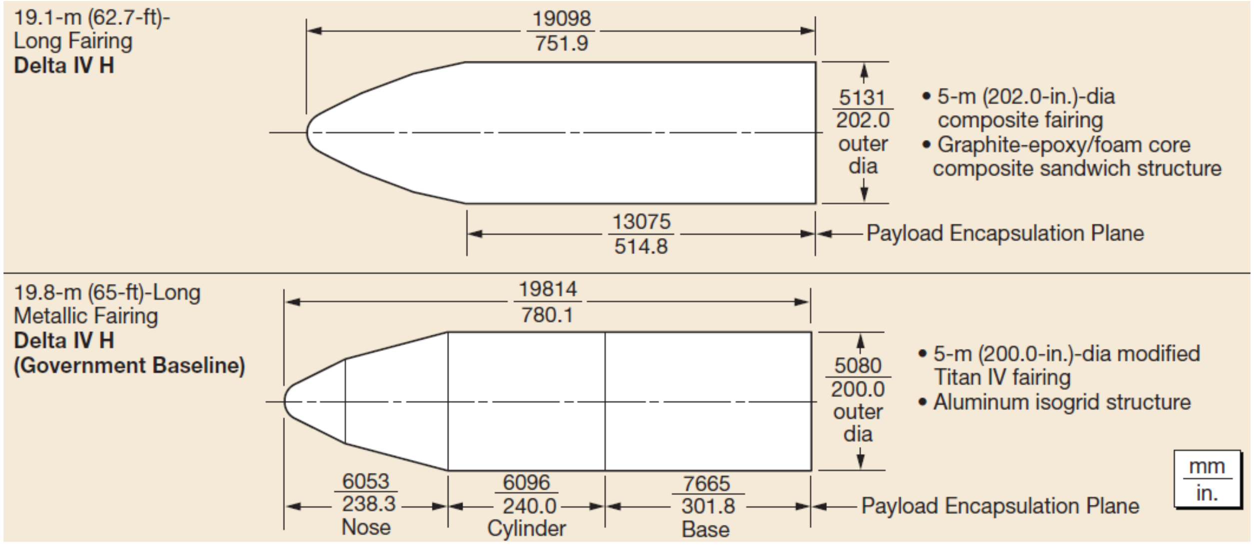


Figure 2-4. Delta IV Heavy 5-m Payload Fairings

2.2.3. Flight Termination Systems

The U.S. Air Force Range Safety organization requires launch vehicles to have a FTS. The purpose of the FTS is to minimize the risk to property damage and personnel safety in the event of a major vehicle malfunction by terminating vehicle thrust and dispersing all tank propellants. For any of the vehicles under consideration, there is one set of FTS ordnance destruct charges activated through either a Command Destruct System (CDS) or an Automatic Destruct System (ADS). The Command Destruct is activated through coded signals sent from the Mission Flight Control Officer’s (MFCO's) ground console to a receiving system onboard the vehicle. The CDS is comprised of the ground signal generation and transmission equipment, the vehicle on-board receiving and decoding equipment, and the destruct ordnance components. In a CDS event, the FTS avionics system onboard the vehicle issues commands to shut down all thrusting engines (First or Second Stage) and signals the guidance computer to stop further vehicle event sequencing, such as stage separation. The FTS avionics system will then initiate destruct ordnance components that will split open the First and Second stage liquid propellant tanks and sends commands to render any strap-on SRBs non-propulsive.

2.2.3.1 Atlas V Flight Termination System

In the FTS for the Atlas V, the ADS uses a breakwire system to sense and automatically destruct the Stage 1 tanks and SRBs, if inadvertent vehicle breakup or premature stage separation occurs. The Centaur is provided with its own ADS, called the Centaur ADS (CADS). The CADS provides the capability to automatically destruct the Stage 1 tanks, SRBs, and Centaur tanks. The ADS and CADS are safed prior to Stage 1 / 2 separation. The CDS provides the capability to shut down the CCB and Centaur engines and destruct the vehicle upon receipt of valid commands from Range Safety. The CDS avionics are located on the CFA. The Atlas V FTS uses a conical shaped charge (CSC) directed at the Centaur common bulkhead between the two tanks, and uses linear shaped charges (LSCs) on the First Stage tanks. In case of an SRB inadvertent separation event, the inadvertent separation destruct system (ISDS) would destruct the separated SRB after a time delay that permits the SRB to fall away from the core prior to activating a linear-shaped charge on the SRB. During a normal SRB staging event, the ISDS is safed.

2.2.3.2 Delta IV Heavy Flight Termination System

The FTS for the Delta IV consists of an ADS comprised of the same destruct ordnance components as in the CDS with the addition of steel cables (or lanyards), lanyard pull initiators (LPIs) and interrupters. These LPIs are located in the engine section of the First Stage core booster and would be routed up to the Second Stage. The interrupters are placed in line between the output of the LPIs and the rest of the ordnance train to protect against inadvertent activation of the LPI on the ground. Mechanically displacing or pulling either lanyard during a vehicle break-up situation initiates the ADS. These lanyards must be cut via explosive cutters (ADS Safing function) prior to Stage 1/2 separation. The Delta IV uses a CSC on the Second Stage LO_2 tank and LSCs on the Second Stage LH_2 and the CBC/SCBC tanks.

The avionics components of the CDS are located on the Second Stage. The destruct ordnance signal passes aft to the First Stage through umbilical disconnects. LSCs are used on the First Stage core booster to split open the liquid propellant tanks as well as the Second Stage LH_2 tank to penetrate the tank skin and cause rapid release of the propellant.

2.3. Spacecraft Description

The Mars 2020 Project is a mission to land a roving science vehicle (rover) on Mars modeled after the successful MSL Curiosity Rover. The Mars 2020 mission would perform scientific investigations relating to habitability with the intent to assemble rock samples of sufficient interest to be stored (cached) for possible return to Earth in a future mission. A surface operation lifetime of hundreds of Martian days (or sols) has been established. The spacecraft would be launched in 2020 onto an Earth-Mars trajectory sometime during the July to August launch opportunities.

The present spacecraft design is a “build to print” of MSL flight system which consists of a Cruise Stage (CS), an aeroshell including the heatshield and backshell, a Descent Stage, and the science rover. The MSL spacecraft, which is the best current estimate of what the Mars 2020 configuration would be, is shown in its launch configuration in Figure 2-5 through Figure 2-8. For the baseline condition, the rover is powered by a single MMRTG, which is attached to the back end. For the alternative option, the electrical power is supplied by solar panels on the rover, and thermal heating is provided by up to 80 LWRHUs located within the rover. The center of mass of the MMRTG is 1.6 m (5.2 ft) above the separation plane between the LV and the spacecraft, also referred to as the space vehicle (SV). The mass of the spacecraft after separation from the second stage is not yet finalized but will be no more than 4,050 kg (8,929 lb). The Cruise Stage has two propellant tanks with a total of up to 70 kg (154 lb) of hydrazine, and the Descent Stage has three propellant tanks with about 389 kg (858 lb) of hydrazine (for descent deceleration), for a combined total of 459 kg (1,012 lb).

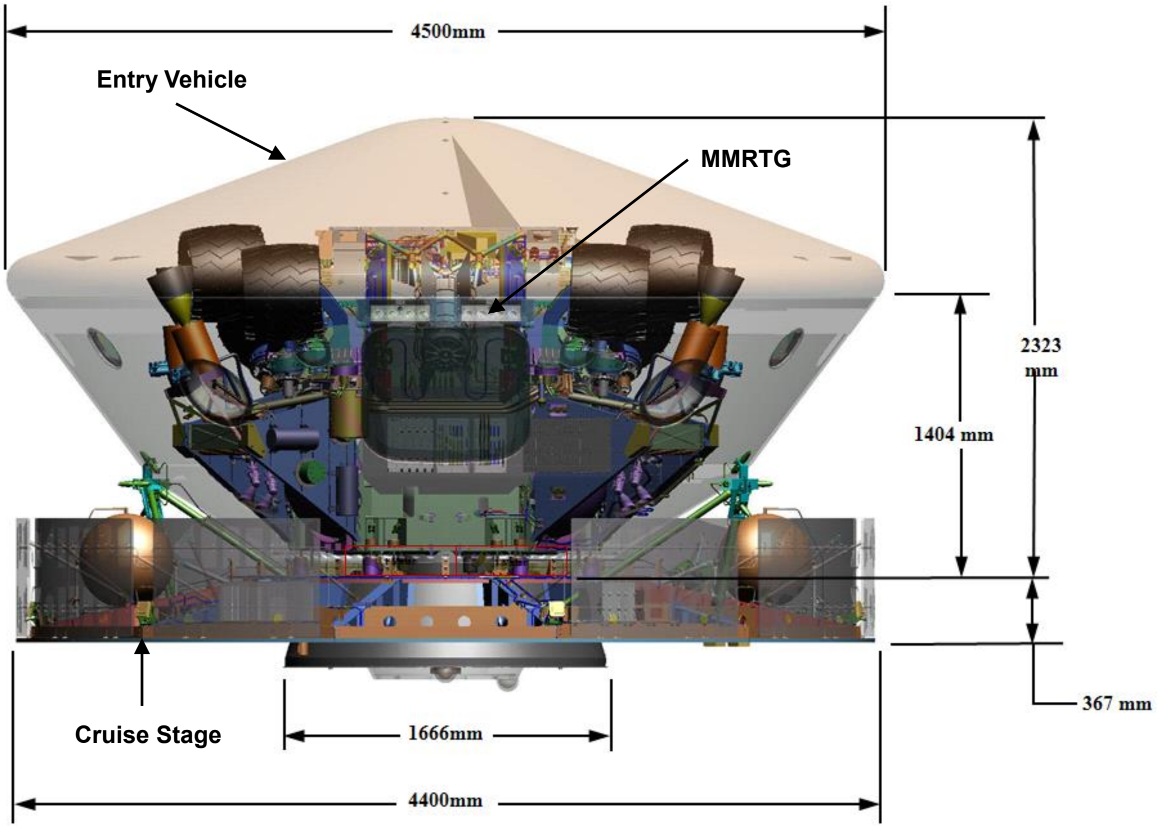


Figure 2-5. MSL Spacecraft

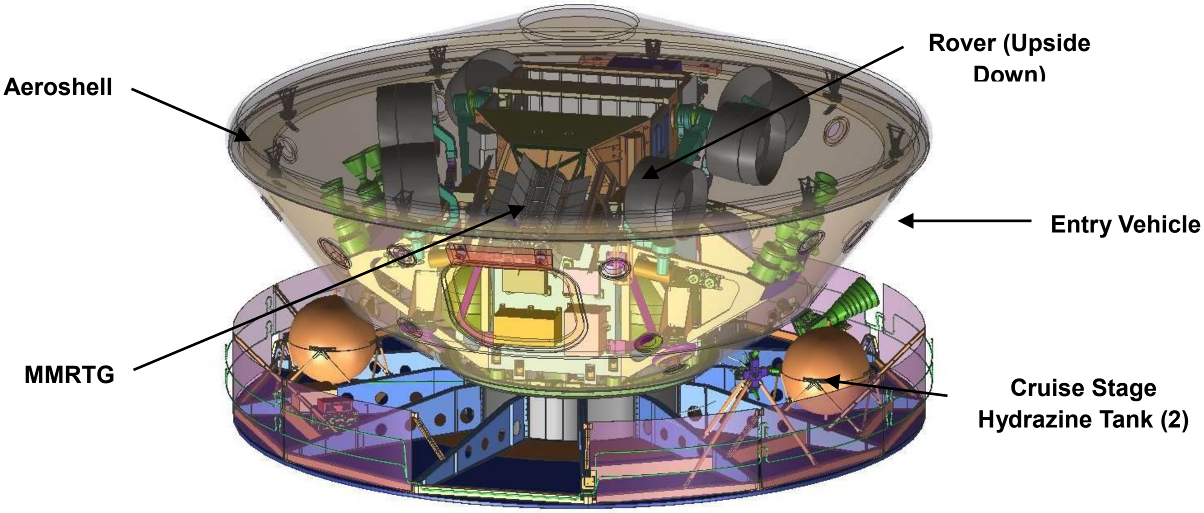


Figure 2-6. MSL Spacecraft Angled View

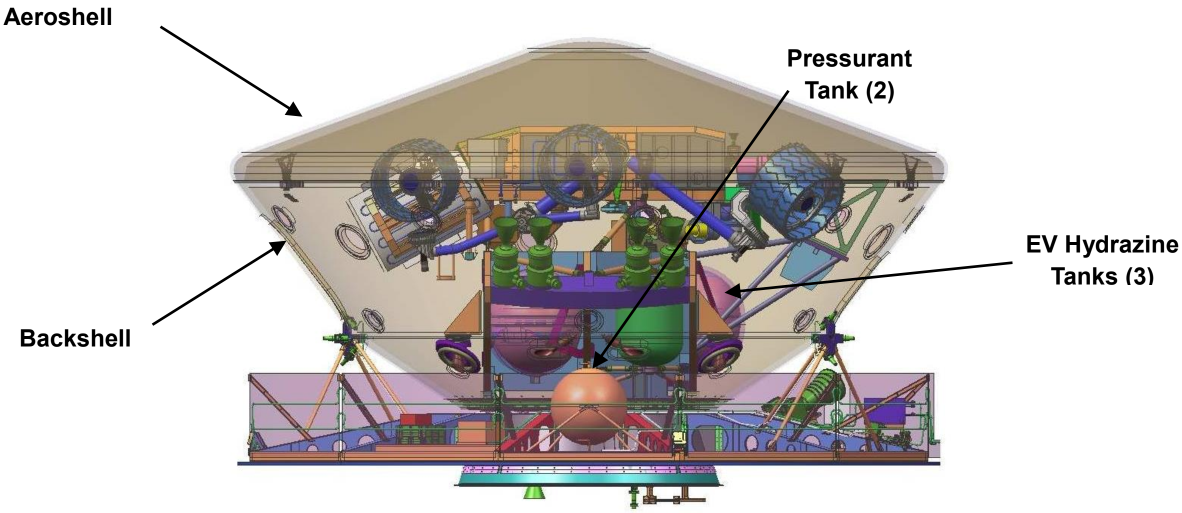


Figure 2-7. MSL Spacecraft Side View

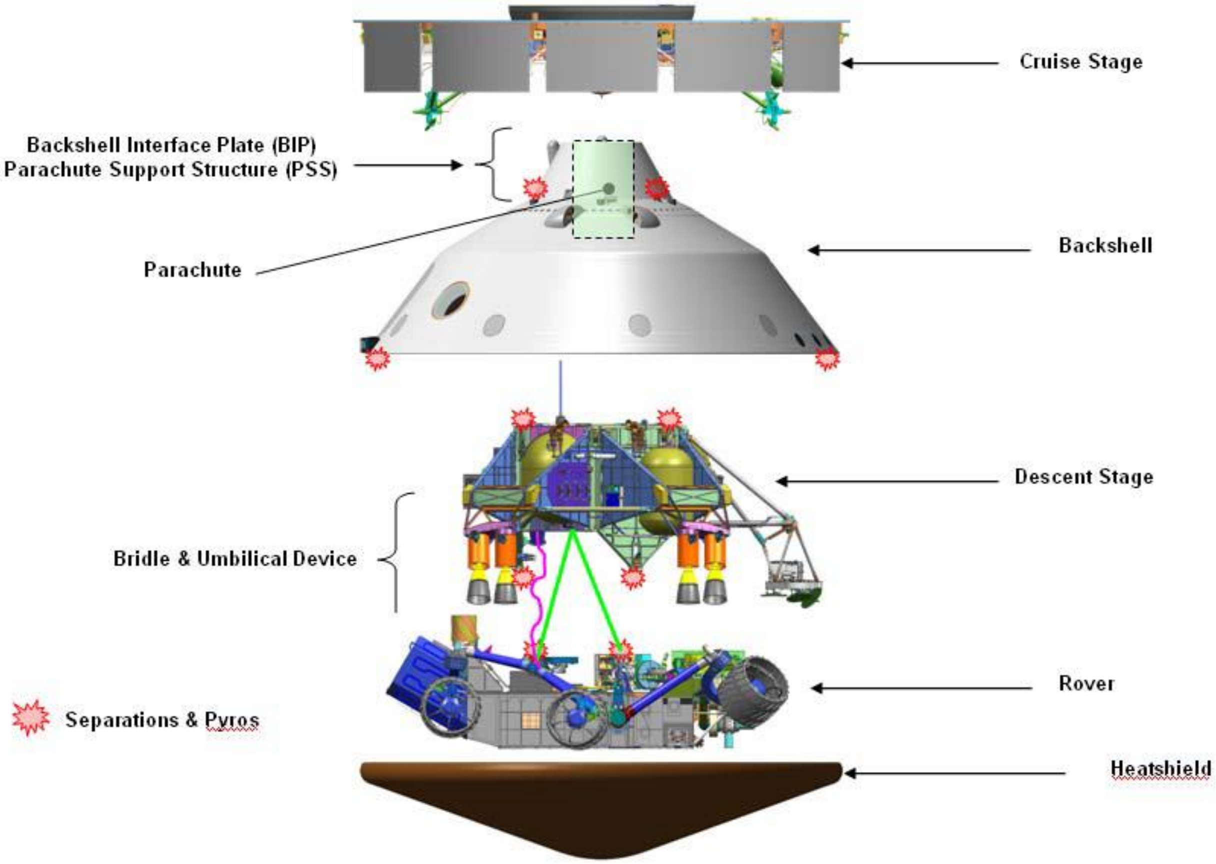


Figure 2-8. Expanded View of the MSL Spacecraft

2.3.1. Cruise Stage

The Cruise Stage provides all the services to support the trip to Mars. This includes 1) communications uplink and downlink to Earth through the onboard Medium- and High-Gain Antennas, 2) power to the EV during cruise via 13 m^2 of solar array, and 3) spacecraft attitude control via a spin stabilized hydrazine propellant system. The Cruise Stage will contain a Heat Rejection System via radiators to rid the spacecraft of heat from the MMRTG. A total of approximately 70 kg of hydrazine are contained in two titanium propellant tanks. Mechanically, the Cruise Stage transfers launch loads from Entry Vehicle to LV spacecraft adapter.

2.3.2. Entry Vehicle

The EV contains the systems necessary to safely enter the Martian atmosphere and deliver the rover to its designated landing site. The EV includes a heatshield and backshell, supersonic/subsonic parachute deployed via a mortar, a Descent Stage, and the rover itself. The maximum diameter of the EV Aeroshell is 4.5 m.

2.3.3. Descent Stage

The Descent Stage provides the propellant needed to guide, slow down, hover and lower the rover onto its designated landing site. The Descent Stage contains three hydrazine tanks and two composite-overwrapped titanium vessel pressurant tanks. The total hydrazine fuel is about 389 kg. The fuel tanks are made from titanium with an elastomeric diaphragm.

Of particular interest are some compact heavy items in the Descent Stage. These include two ejectable cruise balance masses, the six ejectable entry balance masses, and the hip-plane balance mass that are internal to the backshell. The balance masses are constructed from tungsten. Each cruise balance mass weighs about 72 kg while each entry balance mass weighs about 28 kg. Figure 2-9 shows the cruise balance mass. The effect of these compact masses on the MMRTG or LWRHUs during launch accidents has been assessed and included in this analysis.

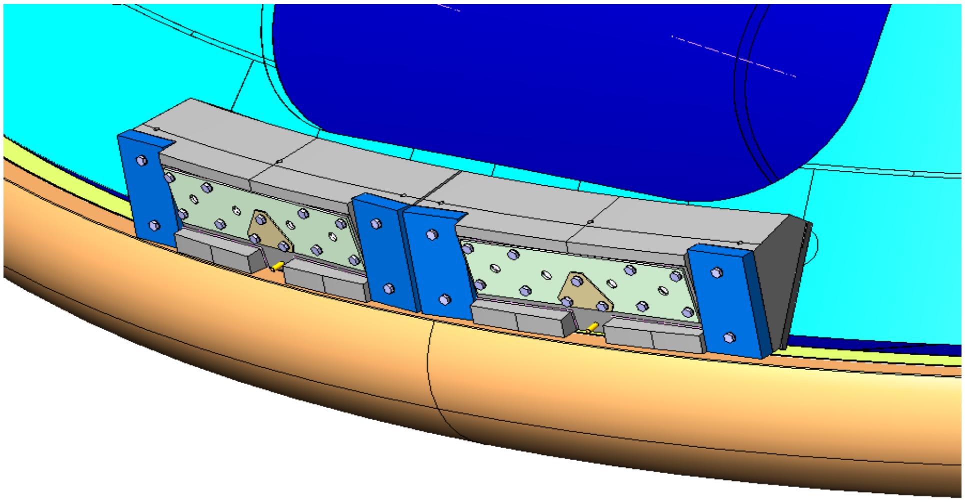


Figure 2-9. Schematic of Cruise Balance Mass

2.3.4. Rover

Like the MSL mission, the Mars 2020 entry, descent, and landing system employs a "Sky-Crane" concept whereby the rover will be lowered via a tether while the Descent Stage hovers above the Martian landing site. Prior to this actual touchdown maneuver, the system will deploy a mortar-launched parachute and then fire eight small liquid propellant rocket motors to further slow down and guide the Descent Stage. The rover will land with its wheels deployed. Figure 2-10 shows the deployed rover with the MMRTG at the far left.

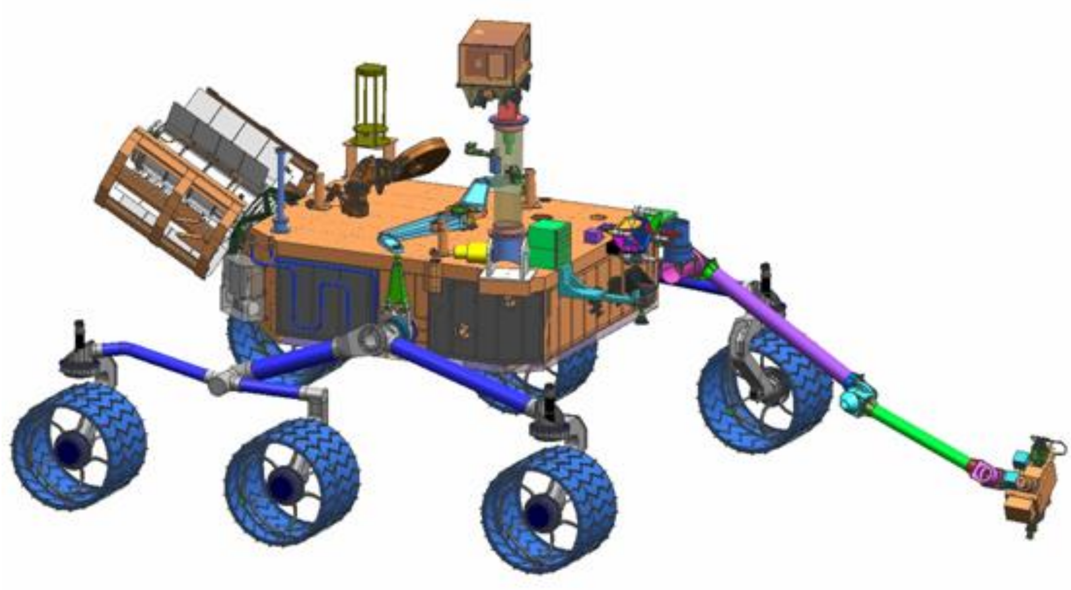


Figure 2-10. MSL Rover

The rover is made from an all-aluminum primary structure with machined panels. The warm electronics box portion (back) of the rover contains the avionics, and communication systems. The rover is designed to accommodate a payload module (front) that contains the science instruments and the robotic arm instruments. The rover has a remote sensing mast that provides an elevated platform for critical engineering and scientific assets such as navigation imaging cameras, science imaging, remote sensing instruments, and mast-mounted meteorology instruments. The rover would be about 2 m (6.6 ft) high from the ground to the top of the deployed remote sensing mast. The Mars 2020 rover will have different scientific instruments than the MSL rover due to differing mission goals.

2.3.5. Science Instrument Radioactive Sources

At this time the science instruments that would be on the Mars 2020 rover are not known. There might be small radioactive sources in some of the science instruments. For example, on the MSL rover Curiosity and the MER rovers, there are instruments that have small quantities of radioactive materials (small quantity sources) (References 2-5 through 2-7):

- Alpha-Particle X-Ray Backscatter Spectrometer (APXS): X-ray spectrometer for sample analysis, containing 0.060 Curies (Ci) of curium-244 (Cm-244) (MSL).
- Detection of Albedo Neutrons (DAN): Neutron Backscatter Spectrometer for subsurface hydrogen (water/ice) detection, containing 2 Ci of tritium (MSL).
- Miniaturized Mossbauer Spectrometer II (MIMOS-II): Mossbauer spectrometer (iron-bearing materials detection), containing 0.30 Ci of cobalt-57 (Co-57) (MER).

These instruments and the nuclear sources are not owned by nor provided by DOE. However, for completeness of the NRA they are listed here.

The amount of radioactive material contained in these small quantity sources are negligible compared to that contained in the MMRTG and LWRHUs. Their contributions to source terms and radiological consequences in postulated mission accidents are discussed later in this report. The same would be true of sources for the science instruments anticipated for the Mars 2020 rover.

2.3.6. Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)

The layout of the MMRTG is shown in Figure 2-11. This unit provides power for rover operations by converting heat from the radioactive decay of radioisotope fuel into electricity. The radioisotope fuel is PuO_2. The PuO_2 is in the form of small sintered ceramic pellets, each contained in an iridium clad and rugged aeroshell material (Fine Weave Pierced Fabric (FWPF)). There are 32 fuel pellets contained within the MMRTG.

The nominal thermal power of the combined isotopes of plutonium at launch would be 2000 W (The power from the other actinides is about 0.09 percent of the total.) This corresponds to about 62.5 W per pellet. The nominal total mass of oxide fuel is 4832 g, and the average fuel pellet weight is 151 g. The Pu-238 mass fraction in the fuel would be about 0.72. The total activity of the fuel at launch would be about 60,000 Ci. This translates to a specific activity level of the fuel at beginning of mission (BOM) of 12.4 Ci per gram of PuO_2. The specific activity level decreases with time, primarily from the decay of Pu-238, which has a half-life of 87.7 years.

The heat source in the MMRTG consists of eight Step 2 GPHS modules stacked along the axis of the cylinder. These are surrounded by 768 lead-telluride thermocouples. The temperature difference across the thermocouples mounted between the surface of the GPHS modules and the outer shell of the MMRTG enables the thermocouples to produce electricity. The MMRTG produces nominally 110 watts of electric power at launch.

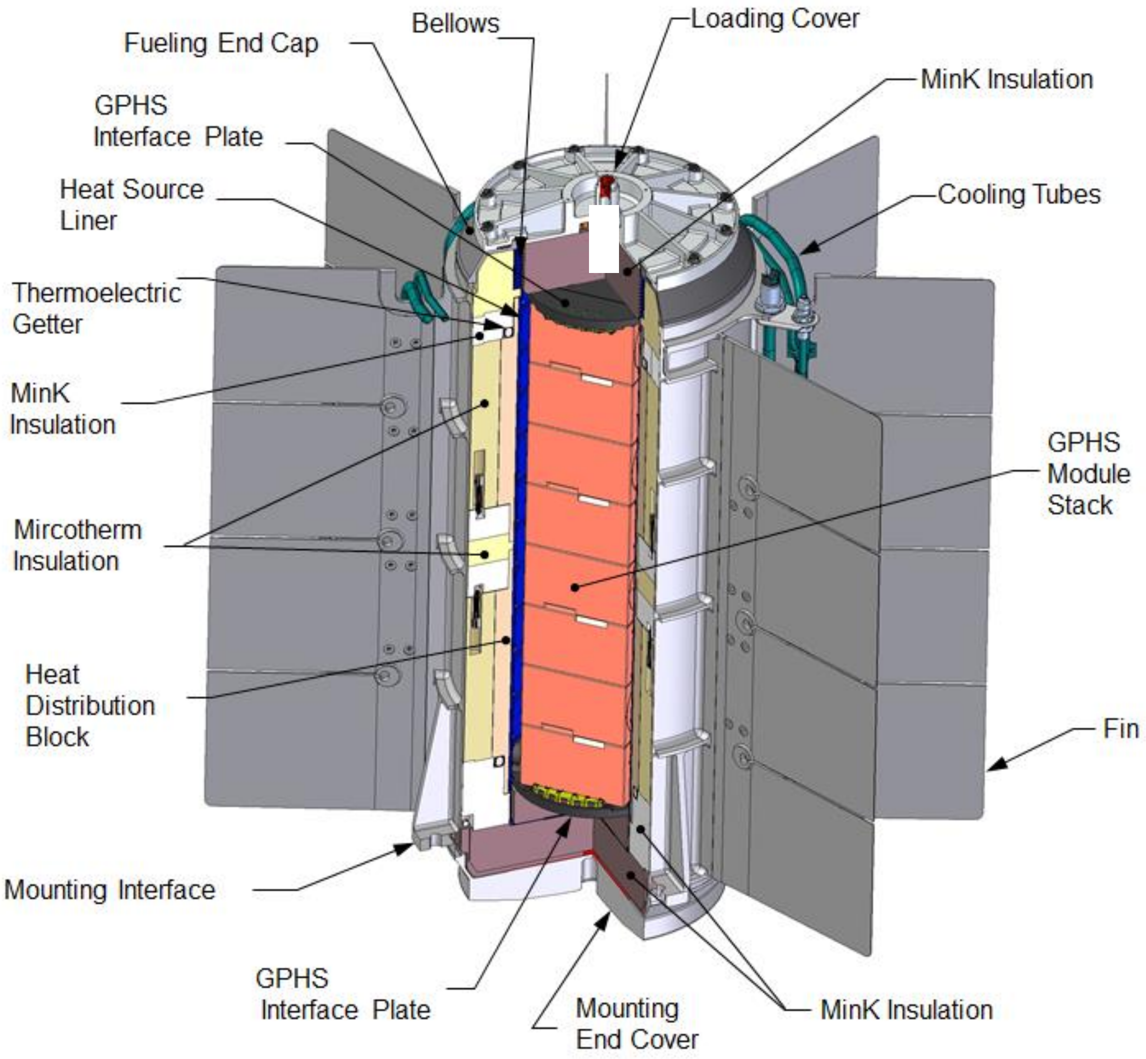


Figure 2-11. MMRTG

Each Step 2 GPHS module, as shown in Figure 2-12, contains two graphite impact shells (GISs). Each GIS contains two iridium encased fuel pellets, each of which contains about 151 g of PuO_2 fuel. The GISs and the aeroshells (the outer shells of the GPHS modules) are constructed from a three-dimensional (3-D) weave carbon-carbon material (FWPF). The aeroshell in the Step 2 GPHS is 5.08 mm (0.200 in) thicker in the direction along the stack than the Step 1 design used in the Pluto New Horizons (PNH) mission. It also retains the central web between the two GISs that was introduced with the Step 1 design, which provides improved reentry survival capability and impact protection. Typical radionuclide composition for a GPHS module is shown in Table 2-1.

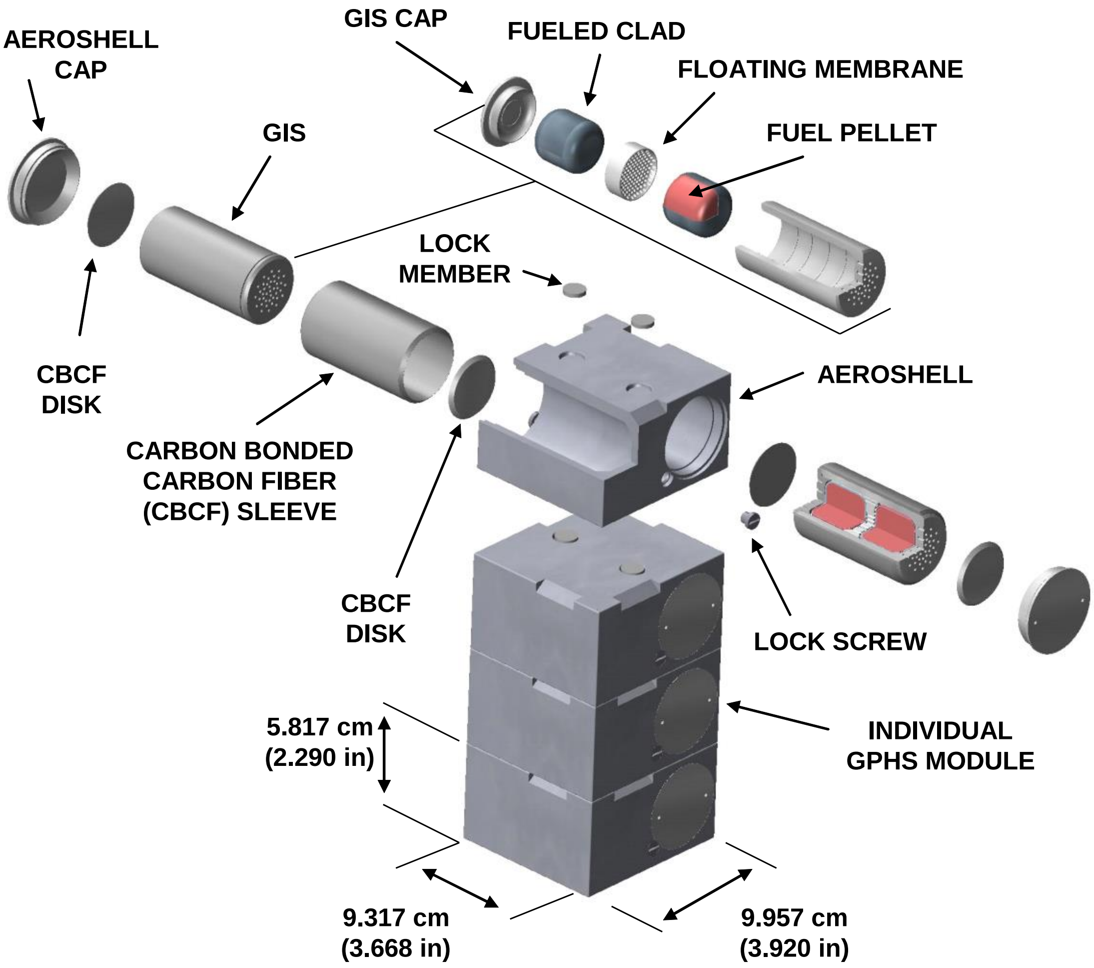


Figure 2-12. Step 2 General Purpose Heat Source Module

Table 2-1. Typical Radionuclide Composition for GPHS module

Fuel Component	Weight Percent	Half-Life (years)	Specific Activity (Ci/g)	Total Activity[a] (Ci)
Pu-236	6×10^{-8}	2.851	531.3	0.0002
Pu-238	72.33	87.7	17.12	7430
Pu-239	11.83	24,131	0.0620	2.200
Pu-240	1.70	6,569	0.2267	2.313
Pu-241	0.09	14.1	103.0	55.62
Pu-242	0.04	375,800	0.00393	0.0010
Total Pu	85.99			
Other Actinides	0.97	NA	NA	3
Impurities	1.14	NA	NA	NA
Oxygen	11.90	NA	NA	NA
Total Fuel	100.00	NA	NA	7492

[a] Based on 0.608 kg of fuel (151 g per fueled clad x 4 fueled clads per module).

The MMRTG operates at lower peak temperatures than the GPHS-RTG used in missions to Jupiter, Saturn and Pluto. The iridium clad on the PuO_2 pellets will be about 800^o C at launch of the MMRTG. For comparison, the clad temperature at launch for the GPHS-RTG was about 1090^o C. The ductility of iridium decreases as the temperature decreases. At the same time, the lower clad temperatures result in less grain growth (resulting in more grains per clad thickness), which in turn could improve impact response at the lower clad temperature. The effects of the lower temperatures and resulting ductility of the iridium are included in this risk assessment. The greater strength of the GPHS aeroshell resulting from the internal web and the thicker faces could compensate for the reduced ductility in the iridium. Advanced continuum mechanics modeling codes, along with benchmarking tests, were used in estimating the effect of these various changes. A summary of MMRTG properties is given in Table 2-2.

Table 2-2. MMRTG Properties

Characteristics	Quantity (Beginning of Mission)
Thermal Power	2000 W
Electrical Power Output	110 W
Output Voltage	28 V (nominal)
MMRTG Mass	43.6 kg w/o cooling tubes, 44.9 w cooling tubes
GPHS Module Mass	1.61 kg
Length	66.83 cm (26.31 in)
Diameter (Fin Tips)	64.24 cm (25.29 in)
Diameter (Housing)	26.59 cm (10.47 in)
Operating Life	14 yr
Components	**Quantity**
GPHS Modules	8
FWPF Aeroshells per GPHS Module	1
Graphite Impact Shells (GIS) per GPHS Module	2
Fueled Clads per GIS	2 (4 Clads per GPHS Module)
PuO_2 Fuel Pellets per Fueled Clad	1
Total GISs within the MMRTG	16
Total Fuel Pellets within the MMRTG	32

2.3.7. Light Weight Radioisotope Heater Units

As noted previously, the power alternative includes the use of up to 80 LWRHUs to provide heat to the spacecraft and rover. They are assumed to be internal to the rover chassis on a 20-cm by 20 cm plate, per NASA input. No credit was taken for any protection provided by the mounting structure. Each LWRHU (Figure 2-13 and Figure 2-14) provides about one thermal watt of heat derived from the radioactive decay of PuO_2 fuel, contained in a platinum-30 rhodium (Pt-30 Rh) alloy clad. The PuO_2 consists primarily of Pu-238 and has an isotopic composition very similar to that of the MMRTG fuel. The LWRHU design provides a high temperature capability by using a FWPF outer heat shield and a series of concentric pyrolytic graphite (PG) sleeves and end plugs to thermally insulate the clad. The LWRHUs are protected from ground or debris impact partially by the heat shield, but principally by the Pt-30 Rh clad. Each LWRHU will contain approximately 2.7 g of PuO_2 fuel, with an approximate activity of 33 Ci. The LWRHU is 2.6 cm in diameter and 3.2 cm long, with a total unit weight of about 40 g.

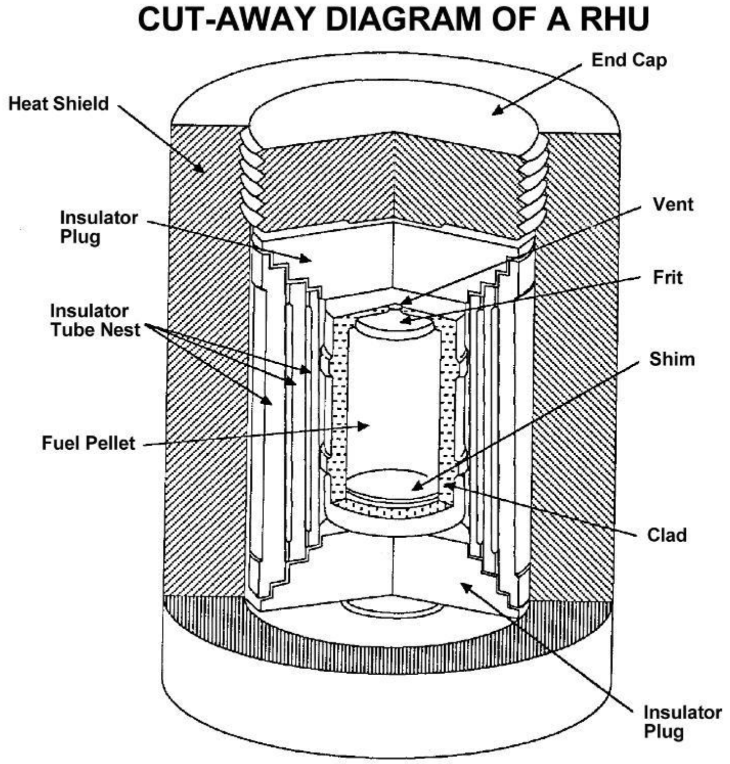


Figure 2-13. Light Weight Radioisotope Heater Unit Cutaway

Figure 2-14. Disassembled LWRHU

2.4. Launch Site Description

For each of the launch vehicles, the radioisotope hardware would be mounted on the spacecraft and launch vehicle several days before launch. The mission would be launched from the launch complex assigned to the respective launch vehicle. The Atlas V 551 (and 541) and Delta IV Heavy would be launched from CCAFS SLC-41 and SLC-37, respectively.

2.4.1. Atlas V Space Launch Complex 41

The Atlas V SLC-41, shown in Figure 2-15 (from Reference 2-1), is located in the northeastern section of CCAFS. Support facilities and equipment include the Vertical Integration Facility (VIF), the Mobile Launch Platform (MLP), the Payload Van (PVan) (not visible in the figure), and integrated Ground Support Equipment (GSE). The pad can launch any of the Atlas V vehicle configurations.

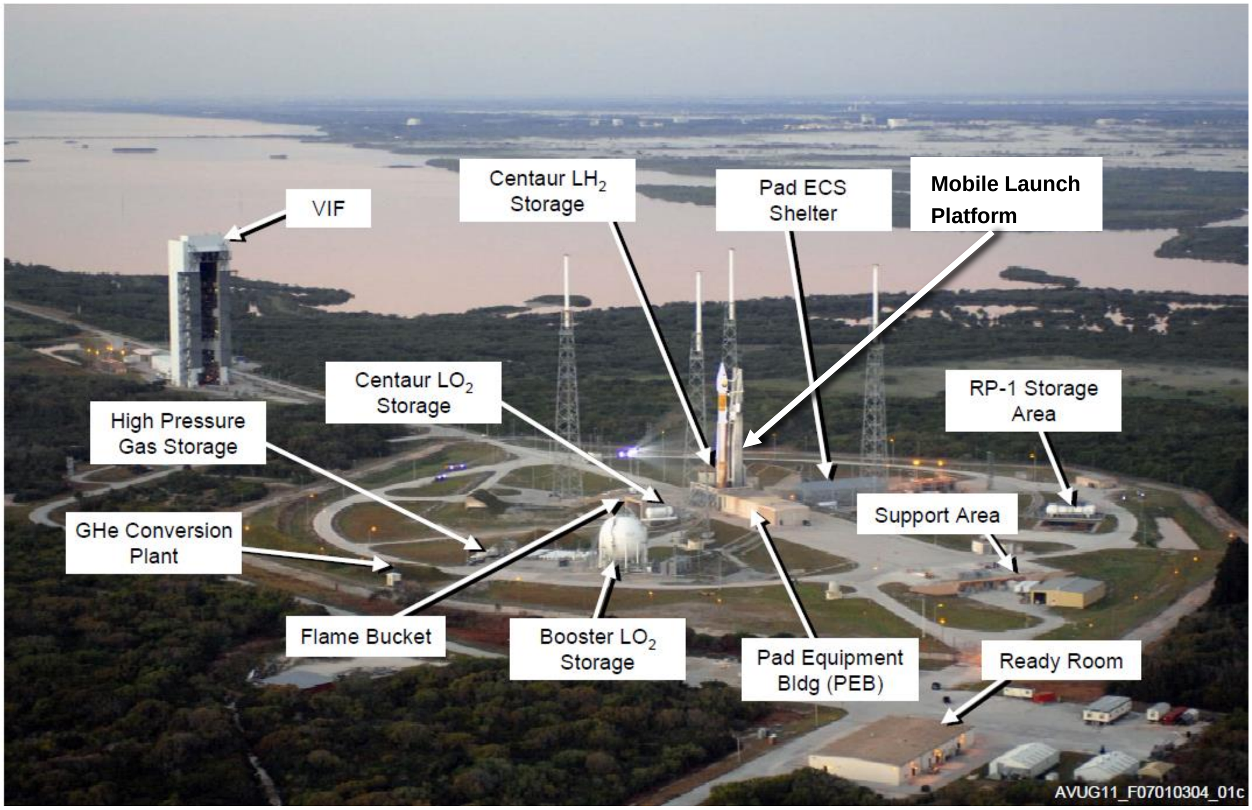


Figure 2-15. Atlas V Space Launch Complex 41

The VIF is a weather-enclosed steel structure with servicing provisions required for launch vehicle integration and checkout. Launch vehicle processing in the VIF includes stacking the CCB and Second Stage, installing the SRBs, performing launch vehicle subsystem checks and system verification, performing integrated system verification, final installations, and vehicle closeouts. No provisions for spacecraft propellant loading are available at the launch complex, either on-pad or in the VIF. If required, emergency spacecraft detanking on the launch complex would occur in the VIF. The Atlas V is fully integrated off-pad on the MLP in the VIF. On the day of launch, the Atlas V is transported from the VIF to the launch pad on the MLP, followed by LV propellant loading and launch countdown. All final spacecraft access activities, including removal of ordnance safe and arm devices, are made in the VIF. There are no provisions for spacecraft access at the pad. Rollback from the pad to the VIF can be accomplished in 6 hours if launch vehicle propellants have not been loaded, and within 18 hours if launch vehicle propellants must be detanked.

2.4.2. Delta IV Heavy Space Launch Complex 37

The CCAFS SLC-37, shown in Figure 2-16 (from Reference 2-3), is capable of launching the entire Delta IV family of vehicles and consists of one operational launch pad (SLC-37B), a site for a future launch pad (SLC-37A) and facilities (new and modified) that support pre-launch and launch operations. Additional facilities provide supporting functions for equipment and personnel.

SLC-37 is located in the northeastern section of CCAFS between the heritage Atlas complexes - SLC-36 and SLC-41. It consists of one launch pad (Pad B), a Mobile Service Tower (MST), a Fixed Umbilical Tower (FUT), a Common Support Building (CSB) (out of view to the left in the figure), a Support Equipment Building (SEB), a ready room, shops, and other facilities needed to prepare, service, and launch the Delta IV vehicles.

Figure 2-16. Space Launch Complex 37 Aerial View with Delta IV Heavy

2.5. Flight Safety System

The function of the Eastern Range Flight Safety organization is to ensure that hazards due to vehicle launches, including debris pieces resulting from a failure and/or subsequent destruct action, do not pose a significant danger to human life or property. During a vehicle launch, the MFCO monitors the vehicle flight to ensure that it does not fly-over geographic areas where it could present a hazard. The MFCO has the capability to destroy the vehicle should it malfunction, and particularly if it appears to be flying into an unacceptable area. A set of flight rules are defined several days before a mission to assist the MFCO in taking the appropriate action when required.

In order for the MFCO to perform his task, Impact Limit Lines (ILL) are defined prior to launch to map the appropriate geographic areas. Destruct lines are then defined to provide a margin of safety distance between the vehicle and the ILL, so that in the event of a destruct action the vehicle fragments will not fly beyond the ILL. During vehicle flight, if the vehicle trajectory indicates that the destruct lines will be violated, the MFCO can take appropriate action, including destruction of the vehicle, to terminate flight.

Range Safety System displays provide information to the MFCO during flight, including vehicle health and status, the pre-determined nominal flight limits, tracking data, and destruct lines. By means of the Range Safety Display in the Range Operations Control Center, the MFCO can monitor the vehicle's behavior and projected impact point and, in the event of a vehicle malfunction, evaluate real-time whether flight termination action is required.

2.6. Mission Profile Description

Representative mission timelines for the Atlas V 551 and Delta IV Heavy are presented in Table 2-3 (Reference 2-8), in terms of Mission Elapsed Time (MET).

The mission profile for the Atlas V begins during Pre-Launch, when final launch day activities include fueling the vehicle and performing the final countdown. Ignition of the Stage 1 CCB is followed by an engine health check. The MET = 0 s reference point is defined as the time at which the Stage 1 CCB completes the health check, and subsequently, the strap-on SRBs are ignited, and liftoff occurs. A pitch over maneuver begins just before tower clear. The Instantaneous Impact Point (IIP, vacuum) then clears land. At twice this time it is estimated that there is no potential for debris to impact land should an accident occur. At the end of the SRB burn, they are jettisoned. The PLF is then jettisoned followed by Stage 1 engine cutoff. The Stage 1 CCB burn ends, followed by Stage 1 / 2 separation. Just prior to Stage 1 / 2 separation, the ADS is disabled. Following Stage 1 / 2 separation, Stage 2 burn 1 starts. The Stage 2 burn 1 ends after achieving orbit, at which time the CDS is disabled. Just prior to achieving orbit, the IIP would cross Africa. After a coast period to realign Stage 2 and the payload, Stage 2 is restarted for burn 2. During the Stage 2 burn 2, a heliocentric Earth-escape velocity is achieved. This is followed by Stage 2 burn 2 cutoff, and then Stage 2 / spacecraft separation. At this point the spacecraft would be on an interplanetary trajectory to Mars.

The mission profile for the Delta IV Heavy begins during Pre-Launch with final launch day activities include fueling the vehicle and performing the final countdown. The mission sequence of events following the Pre-Launch events begins with initiating a sequence leading to ignition of the Stage 1 CBC and the two SCBCs following an engine health check. The MET = 0 s reference point is defined as the time at which the Stage 1 completes the health check, and subsequently liftoff occurs. Following tower clear and climb out, a pitch over maneuver begins and the IIP then clears land. After completion of the SCBC burn, the two SCBCs are jettisoned as the CBC continues to burn. The PLF is then jettisoned, followed at a later time by completion of the CBC burn, followed by Stage 1 / 2 separation. Just prior to Stage 1 / 2 separation, the ADS is disabled. Following Stage 1 / 2 separation, Stage 2 burn 1 begins and ends after achieving orbit, at which time the CDS is disabled. Prior to achieving orbit, the IIP would cross Africa. After a coast period to realign Stage 2 and the payload, Stage 2 is restarted for burn 2. During the Stage 2 burn 2, a heliocentric Earth escape velocity is achieved. This is followed by Stage 2 burn 2 cutoff, and then Stage 2 /spacecraft separation. At this point the spacecraft would be on an interplanetary trajectory to Mars.

Table 2-3. Representative Atlas V 551 and Delta IV Heavy Timelines

Event Description	**Atlas 551 MET** (s)	**Delta IV-H MET** (s)
Liquid Propellant Ignition	-2.7	-5.5
CCB Passes Health Check	0	
SRB Ignition	0. 8	
Liftoff	1.1	0
Tower Clear (~200 ft) (t1)	5.0	6.7
Start Pitch (t2)	4.1	13.0
Land Clear Instantaneous Impact Pt (t3)	18.0	38.7
No potential land impact (t3 x 2)	36.0	77.4
100,000 ft	86.9	129.3
Strap-On Engine Cutoff	92.3	238.4
Strap-On Engine Jettison	108.0 - 109.5	240.5
Payload Fairing Jettison	217.8	272.0
Stage 1 Engine Cutoff	275.5	336.2
Stage 1/2 Separation	281.5	342.2
Second Stage Engine Start 1	291.5	355.2
Landfall IIP trace for Western Africa	647.2	714.6
Land clear IIP trace for Eastern Africa	657.7	726.2
Last IIP point on Earth (IIP Vanish)	661.7	735.5
Second Stage Engine Cutoff 1	676.7	752.3
Second Stage Engine Start 2	2468.0	2900.8
Earth Escape Velocity Achieved	2910.0	3635.2
Second Stage Engine Cutoff 2	2936.3	3704.8
Stage 2/Spacecraft Separation	3165.3	4254.8

2.7. References

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2-2. United Launch Alliance, *Delta IV Launch Services User's Guide,* United Launch Alliance, Centennial, CO, September 2013.

2-3. National Aeronautics and Space Administration, *Final Environmental Impact Statement for the Mars Science Laboratory Mission, Volume 1, Executive Summary and Chapters 1 through 8*, Science Mission Directorate, NASA, Washington, DC, November 2006.

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2-5. R. Gellert, et al., "The Alpha-Particle-X-ray-Spectrometer (APXS) for the Mars Science Laboratory (MSL) Rover Mission," *40th Lunar and Planetary Science Conference*, March 23-27, 2009, The Woodlands, TX, paper 2364, 2009.

2-6. M. Busch and O. Aharonson, "Measuring subsurface water distribution using the Dynamic Albedo of Neutrons instrument on Mars Science Laboratory," *Nucl. Instr. and Methods in Phys. Res. A*, 592, pp 393-399, 2008.

2-7. G. Klingelhofer, "The Miniaturized Mössbauer Spectrometer Mimos II of the Athena Payload for the 2003 MER Missions," *Sixth International Conference on Mars*, July 20-25, 2003, Pasadena, CA, paper 3132, 2003.

2-8. ASCA, Incorporated, *Mars 2020 Launch Accident Probability Data for EIS Risk Assessment, Revision Draft*, AR 13-02, Prepared for National Aeronautics and Space Administration, Kennedy Space Center, September 2013.

3. ACCIDENT PROBABILITIES AND SOURCE TERMS

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 release that becomes airborne) and their probabilities, and 3) the radiological consequences and mission risks associated with such releases. The radioactive material inventory of interest, for a single MMRTG, is about 60,000 Ci of primarily Pu-238. The inventory for 80 LWRHUs is about 2640 Ci. 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 4.0 addresses potential consequences and risks. The methodology used in developing the accident probabilities and source terms 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 or LWRHUs 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, and water impact would occur.
- 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 Command Destruct System (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 or LWRHUs might first experience a potentially damaging environment. An example of an AOC would be an FTS action, such as a low altitude CDS or ADS 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:

- ADS or CADS: The ADS or CADS destructs the Stages 1 and 2 liquid-propellant tanks and the strap on boosters. The ADS or CADS is safed (disabled) prior to Stage 1 / 2 separation.
- CDS: The CDS is activated by the MFCO and destroys the launch vehicle in the same manner as an ADS. 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 safed at the end of Stage 2 burn 1.

Prelaunch AICs include crane drops, tank failures, and MMRTG loss of cooling. They primarily result in space vehicle (SV) impact, but some very low probability scenario results in 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 or LWRHUs. The $T \geq 0$ AICs include:

- GSE failure during liftoff
- Trajectory and attitude control malfunctions (ACMs)
- 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 or LWRHUs:

- On-Pad Explosion. 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.

- Low and High Altitude FTS. "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 SV to an FTS would depend on the launch vehicle, and the accident environment conditions.
- FSII. The entire launch vehicle stack impacts the ground intact.
- Stage 2/Space Vehicle Intact Impact (Stage 2/SVII). Stage 2/SV impacts the ground intact.
- SV Intact Impact (SVII). The SV impacts the ground intact.
- Suborbital reentry.
- 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.

The AOC probabilities on a composite basis (50% Atlas V 551 and 50% Delta IV Heavy) are presented in Table 3-1 (derived from material in Reference 3-1).

Table 3-1. Accident Probabilities for the MMRTG (Composite LV)

Mission Phase	Probability
0 (Prelaunch)	3.28E-05
1 (Early Launch)	
On-Pad Explosion	9.76E-05
FSII	2.24E-05
Stage 2/SV	4.83E-05
SVII	6.32E-07
Low Altitude FTS	2.95E-03
Overall Phase 1	3.12E-03
2 (Late Launch)	3.63E-03
3 (Suborbital)	1.31E-02
4 (Orbital)	4.66E-03
5 (Long-Term)	1.00E-06
Overall Mission	2.46E-02

The postulated accident environments associated with potential accidents include blast (explosion overpressure), MMRTG or LWRHU impact on a surface, fragment impact on the

MMRTG or LWRHU, 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 MET of occurrence.

For the LWRHUs, the AOC probability for Prelaunch is 3.30×10^{-6} since there is no loss of MMRTG coolant accident. All other probabilities are the same as for the MMRTG.

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 maximum 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:

- Prevent to the greatest extent possible, the release of fuel.
- Minimize the release and airborne dispersion of fuel, especially of biologically significant, small, respirable particles.
- Minimize contamination of the environment (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 (2400 ^{o}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 (2443 ^{o}C) and exhibits excellent impact response.
- 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 Module Graphitic Components: The GPHS outer aeroshell and GIS are composed of FWPF, a three-dimensional (3-D) 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 to 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 GIS, 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

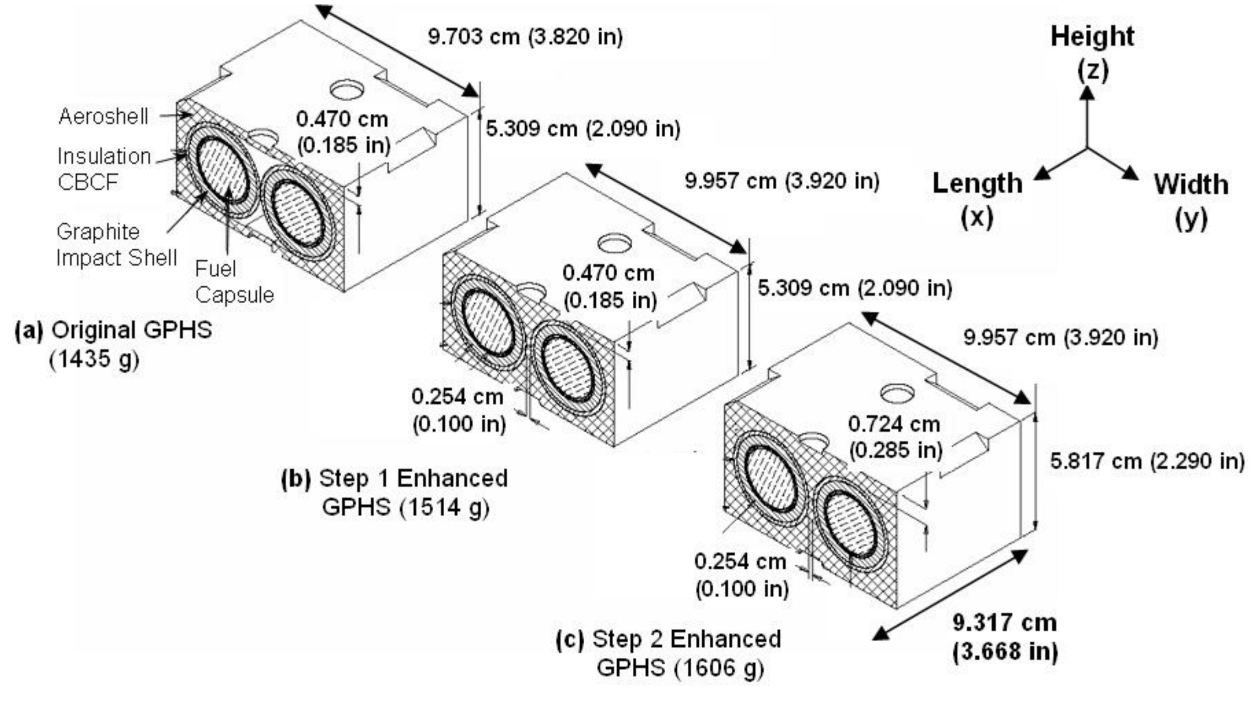

Figure 3-1. Progression of Changes from Step 0 to Step 2 GPHS Modules

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 release 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:

- Explosion Overpressure and Fragments: Liquid propellant explosions from LV destruct and resulting fragments are estimated to result in some MMRTG damage but no fuel release.
- Impact: 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 zero or small 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 small release could occur. Grounds impact of an intact SV for an early launch accident is expected, since the SV back shell and heat shield prevents the LV breakup during a destruct event. The combined effect of the SV hitting the ground and the MMRTG subsequently being hit by the SV components above it occasionally 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 releases for certain orientations in which launch vehicle and/or SV 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.

For the Atlas V 551, exposure of released PuO_2 fuel to the higher-temperature (up to 2827 ^{o}C), 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 in 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 SV due to the presence of the SV Mars aeroshell. Most of these impacts occur in water with no release. Land impact can result in releases that are similar in nature to those from impact near the launch pad, but without the presence of solid propellant fires. Releases 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 SV 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 (e.g., FSII, Stage 2/SV, SV, SV/MMRTG, MMRTG and GPHS modules). Ground impacts of the SV on steel or concrete can occasionally lead to a release. For larger impacting configurations, such as an FSII or Stage 2/SV intact impact, larger fuel releases 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 considerably larger releases 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 SV and MMRTG. Some small releases are likely due to impact of the MMRTG by SV hardware. There would be a hydrazine fire and very minor additional release from it. 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 small releases of PuO_2.

3.4. LWRHU Response to Accident Environments

This section summarizes the accident environment response analyses performed for the LWRHU. Safety testing and response analyses of the LWRHU to accident environments indicate that the protection provided by graphitic components (the aeroshell) and the platinum-30 rhodium (Pt-30Rh) clad encapsulating the PuO_2 fuel makes releases unlikely due to purely mechanical damage, including overpressures and fragments. The primary release mechanism is from impact by very heavy LV fragments. Another release mode is from exposure to high-temperature burning solid-propellant fuel, which could lead to clad melting and partial vaporization of the PuO_2. Should the aeroshell be damaged or stripped, a greater amount of fuel could be vaporized. If the aeroshell remains intact, any vaporized fuel release would be limited to that which permeates through the graphitic components of the aeroshell, which would be a very small fraction (about 1/1000) of that vaporized fuel associated with a clad.

Most launch accidents in Phases 0, 1, and 3 would lead to intact impact of various SV/launch vehicle configurations. The resulting impact could lead to mechanical damage of the LWRHU aeroshell, depending on the orientation at impact, and subsequent exposure to burning solid propellant. This in turn could potentially lead to PuO_2 releases from the fire. In addition, impact by large pieces of LV or SV debris could lead to some mechanical release of PuO_2.

Phase 2 results in water impact and no release. For Phases 4 and 5 of the mission, accidents could lead to reentry heating and ground impact environments. The LWRHU is designed to survive the reentry environments and subsequent surface impacts. No clad melt, eutectic formation with graphitics, or release is expected from impact following orbital or suborbital reentry.

3.5. Source Terms and Probabilities

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 for the MMRTG (baseline) and in Table 3-3 for 80 LWRHUs. These results were determined by a Monte Carlo simulation using 150,000 trials or more for each of the various accident scenarios and launch vehicle options. In these simulations, 100 percent of released material with a physical diameter less than 100 microns was assumed to be airborne, which may be conservative since much of the released fuel would be trapped by the graphitics and other debris. Simulations show that particles larger than 100 microns would fall to the ground within a few meters of the source.

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

The 99th percentile release is obtained by sorting the trials by the total amount released. Then the release amount for which 1% of the trials are greater is defined as the 99th percentile. 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 release value reflects the potential for larger radionuclide releases at lower probabilities. Most accidents do not result in a release; hence the 99th percentile release given an accident is lower than the 99th percentile release given a release. For some launch phases, the probability of a release is so low that the 99th percentile release is zero, given an accident.

Table 3-2. Source Term Summary for the MMRTG[a,b,c]

Mission Phase	Accident Probability	Conditional Probability of Release	Total Probability of Release	Source Term (Ci)			
				Mean Given an Accident	Mean Given a Release	99th Percentile Accident	99th Percentile Release
0 (Prelaunch)	3.28E-05	3.27E-01	1.07E-05	9.20E-02	2.82E-01	4.75E-02	6.68E+00
1 (Early Launch)							
On-Pad Explosion	9.79E-05	8.51E-02	8.30E-06	1.97E+00	2.31E+01	3.50E-02	3.95E+01
FSII	2.24E-05	1.43E-01	3.21E-06	1.51E+01	1.05E+02	3.35E+02	1.81E+03
Stage 2/SV	4.83E-05	3.61E-02	1.75E-06	2.79E+00	7.72E+01	5.49E+01	9.10E+02
SVII	6.32E-07	5.41E-02	3.42E-08	2.72E+00	5.03E+01	4.01E+01	5.82E+02
Low Altitude FTS	2.95E-03	2.52E-02	7.45E-05	1.53E+00	6.06E+01	1.58E+01	6.17E+02
Overall Phase 1	3.12E-03	2.81E-02	8.77E-05	1.66E+00	5.90E+01	1.64E+01	6.33E+02
2 (Late Launch)	3.63E-03	2.12E-03	7.71E-06	3.40E-05	1.60E-02	-	2.31E-01
3 (Suborbital)	1.31E-02	1.13E-03	1.48E-05	4.70E-02	4.16E+01	-	9.29E+02
4 (Orbital)	4.66E-03	5.62E-02	2.61E-04	2.96E-02	5.27E-01	6.51E-01	6.15E+00
5 (Long-Term)	1.00E-06	9.43E-02	9.43E-08	7.29E-02	7.73E-01	1.48E+00	7.82E+00
Overall Mission	2.46E-02	1.56E-02	3.83E-04	2.42E-01	1.55E+01	9.49E-03	3.41E+02

a. The table presents composite results for the LVs under consideration, determined by taking the probability-weighted value of each set of results.

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

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

Table 3-3. Source Term Summary for the LWRHUs[a,b,c]

Mission Phase	Accident Probability	Conditional Probability of Release	Total Probability of Release	Source Term (Ci)			
				Mean Given an Accident	Mean Given a Release	99th Percentile Accident	99th Percentile Release
0 (Prelaunch)	3.30E-06	9.29E-02	3.06E-07	2.75E-01	2.96E+00	5.03E+00	2.10E+01
1 (Early Launch)							
On-Pad Explosion	9.76E-05	1.23E-01	1.20E-05	1.59E-01	1.29E+00	2.67E+00	3.16E+00
FSII	2.24E-05	1.34E-01	3.00E-06	8.09E+00	6.03E+01	2.65E+02	3.75E+02
Stage 2/SV	4.83E-05	1.66E-02	8.00E-07	2.03E-02	1.22E+00	8.42E-01	5.10E+00
SVII	6.32E-07	4.65E-02	2.94E-08	6.22E-02	1.34E+00	1.96E+00	4.29E+00
Low Altitude FTS	2.95E-03	1.57E-02	4.62E-05	1.97E-02	1.26E+00	6.71E-01	6.08E+00
Overall Phase 1	3.12E-03	1.99E-02	6.21E-05	8.20E-02	4.12E+00	8.90E-01	7.61E+01
2 (Late Launch)	3.63E-03	-	-	-	-	-	-
3 (Suborbital)	1.31E-02	1.79E-04	2.35E-06	2.20E-04	1.23E+00	-	4.55E+00
4 (Orbital)	4.66E-03	-	-	-	-	-	-
5 (Long-Term)	1.00E-06	-	-	-	-	-	-
Overall Mission	2.45E-02	2.64E-03	6.48E-05	1.06E-02	4.01E+00	-	7.31E+01

a. The table presents composite results for the LVs under consideration, determined by taking the probability-weighted value of each set of results.

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

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

Unlike the MMRTG and the LWRHUs, the radioisotope sources in the science instruments are not designed to be contained in a launch accident. For example, the Cm-244 in the APXS is mounted close to a 30-micron thick foil so that its alpha particles can probe the rocks on Mars. The Mars Exploration Rover (MER) EIS (Reference 3-2) presents estimated probabilities of release, given an accident. These numbers are reproduced in Table 3-4 for the APXS Cm-244; only the phase roll-ups are given. The mean release, given a release, is also obtained from Reference 3-2. A launch accident is not always severe enough to cause a release. This results in a conditional probability of release less than one. The mean release given an accident is equal to the mean release given a release, times the conditional probability of release. Detailed analyses to obtain the 99th percentiles were not conducted.

The risks from the Co-57 in the Mossbauer spectrometer, and from the tritium in the DAN, are orders of magnitude lower than for the Cm-244 because of the much lower energy of the emitted gamma rays or beta particles, and the lower quality factor of the radiation (References 3-2 and 3-3). Hence they will not be analyzed further. The reported source terms and consequences are thus for the Cm-244 in the APXS, and these are expected to approximate the source terms and consequences for all of the science instruments.

Table 3-4. Source Term Summary for Generic Science Instrument Sources[a,b]

Mission Phase	Accident Probability	Conditional Probability of Release	Total Probability of Release	Source Term (Ci)	
				Mean Given an Accident	Mean Given a Release
0 (Prelaunch)	3.30E-06	5.56E-01	1.83E-06	1.83E-02	3.30E-02
1 (Early Launch)	3.12E-03	1.92E-01	5.99E-04	2.07E-03	1.08E-02
2 (Late Launch)	3.63E-03	3.22E-02	1.17E-04	9.66E-04	3.00E-02
3 (Suborbital)	1.31E-02	5.00E-01	6.58E-03	1.50E-02	3.00E-02
4 (Orbital)	4.66E-03	9.00E-01	4.19E-03	2.70E-02	3.00E-02
5 (Long-Term)	1.00E-06	1.00E+00	1.00E-06	6.00E-02	6.00E-02
Overall Mission	2.45E-02	4.68E-01	1.15E-02	1.29E-02	2.76E-02

a. The table presents composite results for the LVs under consideration, determined by taking the probability-weighted value of each set of results.

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

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 $1.07\text{x}10^{-5}$ (1 in 93,000). The mean source term given an accident is estimated to be 0.09 Ci, the mean source term given a release is estimated to be 0.28 Ci, the 99th percentile given an accident is estimated to be 0.048 Ci, while the 99th percentile source term given a release is estimated to be 6.7 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 $8.8\text{x}10^{-5}$ (1 in 11,000). The mean source term given an accident is estimated to be 1.7 Ci, the mean source term given a release is estimated to be 59 Ci, the 99th percentile given an accident is estimated to be 16 Ci, while the 99th percentile source term given a release is estimated to be 630 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 $7.7\text{x}10^{-6}$ (1 in 130,000). The mean source term given an accident is estimated to be 0.000034 Ci, the mean source term given a release is

estimated to be 0.016 Ci, the 99th percentile given an accident is estimated to be 0 Ci, while the 99th percentile source term given a release is estimated to be 0.23 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 SV entry vehicle 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 launch vehicle selected and its nominal mission timeline. Should the SV impact land, releases are possible. The total probability of release in Phase 3 is estimated to be 1.5×10^{-5} (or 1 in 67,000). The mean source term given an accident is estimated to be 0.047 Ci, the mean source term given a release is estimated to be 42 Ci, the 99th percentile given an accident is estimated to be 0 Ci, while the 99th percentile source term given a release is estimated to be 930 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 29° North Latitude and 29° South Latitude. The SV and MMRTG would break apart during reentry, releasing the GPHS modules. The modules would survive reentry but could release fuel if they impact rock. The total probability of release is estimated to be 2.6×10^{-4} (or 1 in 3,800). The mean source term given an accident is estimated to be 0.030 Ci, the mean source term given a release is estimated to be 0.53 Ci, the 99th percentile given an accident is estimated to be 0.65 Ci, while the 99th percentile source term is estimated to be 6.2 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 9.4×10^{-8} (or 1 in 11,000,000). The mean source term given an accident is estimated to be 0.073 Ci, the mean source term given a release is estimated to be 0.77 Ci, the 99th percentile given an accident is estimated to be 1.48 Ci, while the 99th percentile source term is estimated to be 7.8 Ci.

Essential features of the results for the 80 LWRHUs 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 3.1×10^{-7} (1 in 3,200,000). The mean source term given an accident is estimated to be 0.28 Ci, the mean source term given a release is estimated to be 3.0 Ci, the 99th percentile given an accident is estimated to be 5.0 Ci, while the 99th percentile source term is estimated to be 21 Ci.
- Phase 1 (Early Launch): During Phase 1 from Post Engine Health Check to t_x s, after which there would be no potential for land impacts in the launch area, the total probability of release is 6.2×10^{-5} (1 in 16,000). The mean source term given an accident is estimated to be 0.082 Ci, the mean source term given a release is estimated to be 4.1

Ci, the 99th percentile given an accident is estimated to be 0.89 Ci, while the 99th percentile source term is estimated to be 76 Ci.

- Phase 2 (Late Launch): In Phase 2 all accidents lead to impact of debris in the Atlantic Ocean with no releases.
- 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 SV entry vehicle and LWRHUs along the vehicle flight path over the Atlantic Ocean and Africa. Additional suborbital land impacts are possible after crossing over Africa, depending on the launch vehicle selected and its nominal mission timeline. Should the SV impact land, releases are possible. The total probability of release in Phase 3 is estimated to be 2.4×10^{-6} (or 1 in 420,000). The mean source term given an accident is estimated to be 0.00022 Ci, the mean source term given a release is estimated to be 1.2 Ci, the 99th percentile given an accident is estimated to be 0 Ci, while the 99th percentile source term is estimated to be 4.6 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 29^{o} North Latitude and 29^{o} South Latitude. The SV would break apart during reentry, releasing the LWRHUs before impact. No fuel would be released.
- Phase 5 (Long-Term 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 initiating failure 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 LWRHUs would be released during reentry and no fuel would be released.

Essential features of the results for the science instrument sources 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 1.8×10^{-6} (1 in 550,000). The mean source term given an accident is estimated to be 0.018 Ci and the mean source term given a release is estimated to be 0.033 Ci.
- Phase 1 (Early Launch): During Phase 1 from Post Engine Health Check to t_x s, after which there would be no potential for land impacts in the launch area, the total probability of release is 6.0×10^{-4} (1 in 1700). The mean source term given an accident is estimated to be 0.0021 Ci and the mean source term given a release is estimated to be 0.011 Ci.
- Phase 2 (Late Launch): In Phase 2 all accidents lead to impact of debris in the Atlantic Ocean. However, there are some releases in air from blast-generated debris. The total probability of release is 1.2×10^{-4} (1 in 8300). The mean source term given an accident is estimated to be 0.00097 Ci and the mean source term given a release is estimated to be 0.030 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 SV entry vehicle and LWRHUs along the vehicle flight path over the Atlantic Ocean and Africa. Additional suborbital land impacts are possible after crossing over Africa, depending on the launch vehicle selected and its nominal mission timeline. Should the SV impact land, releases are possible. The total probability of release in Phase 3 is estimated to be 6.6×10^{-3} (or 1 in 150). The mean source term given an accident is estimated to be 0.015 Ci and the mean source term given a release is estimated to be 0.030 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 29^{o} North Latitude and 29^{o} South Latitude. The SV would break apart during reentry, releasing the LWRHUs before impact. The total probability of release is estimated to be 4.2×10^{-3} (or 1 in 240). The mean source term given an accident is estimated to be 0.027 Ci, the mean source term given a release is estimated to be 0.030 Ci.
- Phase 5 (Long-Term 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 initiating failure 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 1.0×10^{-6} (or 1 in 1,000,000). The mean source term given an accident is estimated to be 0.060 Ci, the mean source term given a release is estimated to be 0.060 Ci.

3.6. References

3-1. ASCA, Incorporated, *Mars 2020 Launch Accident Probability Data for EIS Risk Assessment, Revision Draft*, AR 13-02, Prepared for National Aeronautics and Space Administration, Kennedy Space Center, September 2013.

3-2. National Aeronautics and Space Administration, *Final Environmental Impact Statement for the Mars Exploration Rover-2003 Project,* Office of Space Science, NASA, Washington, DC, December 2002.

3-3. C. M. Lederer, Hollander, J. M., and Perlman, I., *Table of Isotopes, Sixth Edition,* J. Wiley & Sons, Inc., New York, NY 1968.

4. RADIOLOGICAL CONSEQUENCES, MISSION RISKS AND UNCERTAINTIES

The radiological consequences and mission risks due to the potential PuO_2 releases presented in Section 3.0 are presented below in Sections 4.1 and 4.2, respectively. Uncertainties in the reported results are discussed in Section 4.3. 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 contaminated at or above specified levels. The radiological consequences are based on atmospheric transport and settling simulations. Biological effects models, based on methods prescribed by the National Council on Radiation Protection and Measurements (NCRP) and the International Commission on Radiological Protection (ICRP), have been applied in past missions 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. This present analysis uses scaling laws (consequences per Ci of fuel released) developed from more detailed calculations.

Multiple exposure pathways are considered in these types of analysis. One pathway is direct inhalation 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-yr 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 release in units of "person-rem." Internal doses are determined using particle-size dependent dose conversion factors based on ICRP-66/67 (References 4-1 and 4-2) and ICRP-60 (Reference 4-3).

The health effects represent incremental cancer fatalities over 50 years induced by releases, determined using a health effect estimator of $6x10^{-4}$ fatalities per person-rem for the general population based on recommendations by the Interagency Steering Committee on Radiation Standards (ISCORS) Reference 4-4. This is an update to the previous values of the ICRP-60 estimators of $5x10^{-4}$ fatalities per person-rem for the general population and $4x10^{-4}$ for workers (Reference 4-3). 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.

Potential environmental contamination criteria for assessing contaminated land areas are 1) areas exceeding given screening activity concentration levels (0.1 and 0.2 $\mu Ci/m^2$), and 2) dose-rate related criteria (15, 25, and 100 mrem/yr) considered by the U.S. Environmental Protection Agency (EPA), the Nuclear Regulatory Commission (NRC), and DOE in evaluating the need for land cleanup following radioactive contamination (Reference 4-5). The results for land area contaminated are reported in terms of the area contaminated at or above a level 0.2 $\mu Ci/m^2$ (the latter being a reference contamination level considered in the risk analyses of previous missions and a former EPA screening level used to determine the need for further action, such as monitoring or cleanup.). The area of land contaminated above the EPA lifetime-risk criterion, associated with an average annual dose rate criterion of 15 mrem/yr, could be higher or lower than the land area contaminated above the 0.2 $\mu Ci/m^2$ level in the first year following the release, depending on the particle size distribution of the release and the time-dependent resuspension factor (the ratio of the airborne concentration to the ground concentration). The resuspension contribution to dose assumes that no mitigation measures are taken. Following the first year, areas contaminated above the 15 mrem/yr criterion would be expected to decrease to values comparable to that associated with the 0.2 $\mu Ci/m^2$ level as the resuspension factor decreases in time.

The potential for crop contamination is based on the Derived Intervention Limit (DIL), as defined by the Food and Drug Administration (FDA) (Reference 4-6). 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 in the KSC area or the state of Florida, depending on the extent of the plume.

A summary of the radiological consequences by mission phase is presented in Table 4-1 through Table 4-4 in terms of the mean and 99th percentile values. Two mean values are displayed: one is based on the average of all release amounts when an accident occurs (including accidents with no release), the other is based on the average release amount 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 the value predicted to be exceeded 1 percent of the time. In this context, the 99th percentile value reflects the potential for higher radiological consequences to the exposed population at lower probabilities than would normally be expected from accidents involving a release to the environment. Again, two 99th percentile values are displayed: one is based on the 99th percentile of all release amounts when an accident occurs (including accidents with no release), the other is based on the 99th percentile release amount considering only non-zero releases. Most accidents do not result in a release; hence the 99th percentile consequence given an accident is lower than the mean consequence given a release. For some launch phases, the probability of a release is so low that the 99th percentile release is zero and the 99th percentile consequence is zero (given an accident).

Table 4-1. Mean Radiological Consequence Summary for the MMRTG[a,b,c]

Mission Phase	Accident Probability	Release Proba-bility	Maximum Individual Dose (rem)		Collective Dose (person-rem)		Health Effects		Land Contamination (km^2)		Cropland Intervention (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)	3.28E-05	1.07E-05	9.42E-05	2.88E-04	7.50E-01	2.29E+00	4.50E-04	1.38E-03	1.15E-02	3.52E-02	2.02E-04	6.17E-04
1 (Early Launch)												
On-Pad Explosion	9.76E-05	8.30E-06	2.01E-03	2.37E-02	1.60E+01	1.88E+02	9.63E-03	1.13E-01	2.46E-01	2.89E+00	4.31E-03	5.07E-02
FSII	2.24E-05	3.21E-06	1.54E-02	1.08E-01	1.23E+02	8.57E+02	7.38E-02	5.15E-01	1.88E+00	1.31E+01	3.31E-02	2.31E-01
Stage 2/SV	4.83E-05	1.75E-06	2.85E-03	7.90E-02	2.27E+01	6.29E+02	1.37E-02	3.78E-01	3.48E-01	9.65E+00	6.11E-03	1.69E-01
SVII	6.32E-07	3.42E-08	2.78E-03	5.14E-02	2.22E+01	4.09E+02	1.33E-02	2.46E-01	3.40E-01	6.28E+00	5.96E-03	1.10E-01
Low Altitude FTS	2.95E-03	7.45E-05	1.56E-03	6.20E-02	1.25E+01	4.93E+02	7.48E-03	2.96E-01	1.91E-01	7.57E+00	3.35E-03	1.33E-01
Overall Phase 1	3.12E-03	8.77E-05	1.70E-03	6.04E-02	1.35E+01	4.81E+02	8.12E-03	2.89E-01	2.07E-01	7.37E+00	3.64E-03	1.29E-01
2 (Late Launch)	3.63E-03	7.71E-06	3.48E-08	1.64E-05	2.77E-04	1.30E-01	1.66E-07	7.84E-05	4.24E-06	2.00E-03	7.45E-08	3.51E-05
3 (Suborbital)	1.31E-02	1.48E-05	4.81E-05	4.26E-02	3.83E-01	3.39E+02	2.30E-04	2.04E-01	5.88E-03	5.20E+00	1.03E-04	9.12E-02
4 (Orbital)	4.66E-03	2.61E-04	3.03E-05	5.39E-04	2.41E-01	4.30E+00	1.45E-04	2.58E-03	3.70E-03	6.59E-02	6.49E-05	1.16E-03
5 (Long-Term)	1.00E-06	9.43E-08	7.46E-05	7.91E-04	5.94E-01	6.30E+00	3.57E-04	3.78E-03	9.10E-03	9.66E-02	1.60E-04	1.69E-03
Overall Mission	2.46E-02	3.83E-04	2.47E-04	1.59E-02	1.97E+00	1.26E+02	1.18E-03	7.59E-02	3.02E-02	1.94E+00	5.30E-04	3.40E-02

a. The table presents composite results for the LVs under consideration, determined by taking the probability-weighted value of each set of results.

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

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

Table 4-2. 99th Percentile Radiological Consequence Summary for the MMRTG[a,b,c]

Mission Phase	Probability of 99th Percentile	Release Proba-bility	Maximum Individual Dose (rem)		Collective Dose (person-rem)		Health Effects		Land Contamination (km²)		Cropland Intervention (km²)	
			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)	3.28E-07	1.07E-07	4.86E-05	6.83E-03	3.87E-01	5.44E+01	2.32E-04	3.27E-02	5.93E-03	8.34E-01	1.04E-04	1.46E-02
1 (Early Launch)												
On-Pad Explosion	9.76E-07	8.30E-08	3.58E-05	4.04E-02	2.85E-01	3.22E+02	1.71E-04	1.93E-01	4.37E-03	4.93E+00	7.68E-05	8.65E-02
FSII	2.24E-07	3.21E-08	3.43E-01	1.86E+00	2.73E+03	1.48E+04	1.64E+00	8.88E+00	4.19E+01	2.27E+02	7.35E-01	3.98E+00
Stage 2/SV	4.83E-07	1.75E-08	5.62E-02	9.32E-01	4.48E+02	7.42E+03	2.69E-01	4.46E+00	6.86E+00	1.14E+02	1.20E-01	2.00E+00
SVII	6.32E-09	3.42E-10	4.10E-02	5.95E-01	3.27E+02	4.74E+03	1.96E-01	2.85E+00	5.01E+00	7.26E+01	8.79E-02	1.27E+00
Low Altitude FTS	2.95E-05	7.45E-07	1.62E-02	6.32E-01	1.29E+02	5.03E+03	7.74E-02	3.02E+00	1.98E+00	7.71E+01	3.47E-02	1.35E+00
Overall Phase 1	3.12E-05	8.77E-07	1.67E-02	6.48E-01	1.33E+02	5.16E+03	8.01E-02	3.10E+00	2.04E+00	7.91E+01	3.59E-02	1.39E+00
2 (Late Launch)	3.63E-05	7.71E-08	-	2.36E-04	-	1.88E+00	-	1.13E-03	-	2.88E-02	-	5.05E-04
3 (Suborbital)	1.31E-04	1.48E-07	-	9.51E-01	-	7.57E+03	-	4.55E+00	-	1.16E+02	-	2.04E+00
4 (Orbital)	4.66E-05	2.61E-06	6.66E-04	6.30E-03	5.30E+00	5.01E+01	3.19E-03	3.01E-02	8.13E-02	7.69E-01	1.43E-03	1.35E-02
5 (Long-Term)	1.00E-08	9.43E-10	1.51E-03	8.01E-03	1.20E+01	6.37E+01	7.23E-03	3.83E-02	1.85E-01	9.77E-01	3.24E-03	1.72E-02
Overall Mission	2.46E-04	3.83E-06	9.71E-06	3.49E-01	7.73E-02	2.78E+03	4.65E-05	1.67E+00	1.19E-03	4.26E+01	2.08E-05	7.48E-01

a. The table presents composite results for the LVs under consideration, determined by taking the probability-weighted value of each set of results.

b. Land area contaminated above a screening level of 0.2 µCi/m².

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

Table 4-3. Mean Radiological Consequence Summary for the LWRHUs[a,b,c]

Mission Phase	Accident Probability	Release Proba-bility	Maximum Individual Dose (rem)		Collective Dose (person-rem)		Health Effects		Land Contamination (km^2)		Cropland Intervention (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)	3.30E-06	3.06E-07	2.81E-04	3.03E-03	2.24E+00	2.41E+01	1.35E-03	1.45E-02	3.43E-02	3.70E-01	6.03E-04	6.49E-03
1 (Early Launch)												
On-Pad Explosion	9.76E-05	1.20E-05	1.63E-04	1.32E-03	1.30E+00	1.05E+01	7.81E-04	6.33E-03	1.99E-02	1.61E-01	3.50E-04	2.83E-03
FSII	2.24E-05	3.00E-06	8.28E-03	6.17E-02	6.59E+01	4.91E+02	3.96E-02	2.95E-01	1.01E+00	7.53E+00	1.77E-02	1.32E-01
Stage 2/SV	4.83E-05	8.00E-07	2.07E-05	1.25E-03	1.65E-01	9.97E+00	9.92E-05	5.99E-03	2.53E-03	1.53E-01	4.44E-05	2.68E-03
SVII	6.32E-07	2.94E-08	6.36E-05	1.37E-03	5.07E-01	1.09E+01	3.04E-04	6.55E-03	7.77E-03	1.67E-01	1.36E-04	2.93E-03
Low Altitude FTS	2.95E-03	4.62E-05	2.02E-05	1.29E-03	1.61E-01	1.02E+01	9.65E-05	6.15E-03	2.46E-03	1.57E-01	4.32E-05	2.76E-03
Overall Phase 1	3.12E-03	6.21E-05	8.39E-05	4.21E-03	6.68E-01	3.35E+01	4.01E-04	2.01E-02	1.02E-02	5.14E-01	1.80E-04	9.02E-03
2 (Late Launch)	3.63E-03	-	-	-	-	-	-	-	-	-	-	-
3 (Suborbital)	1.31E-02	2.35E-06	2.25E-07	1.26E-03	1.79E-03	1.00E+01	1.08E-06	6.02E-03	2.75E-05	1.54E-01	4.82E-07	2.70E-03
4 (Orbital)	4.66E-03	-	-	-	-	-	-	-	-	-	-	-
5 (Long-Term)	1.00E-06	-	-	-	-	-	-	-	-	-	-	-
Overall Mission	2.45E-02	6.48E-05	1.08E-05	4.10E-03	8.62E-02	3.26E+01	5.18E-05	1.96E-02	1.32E-03	5.00E-01	2.32E-05	8.78E-03

a. The table presents composite results for the LVs under consideration, determined by taking the probability-weighted value of each set of results.

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

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

Table 4-4. 99th Percentile Radiological Consequence Summary for the LWRHUs[a,b,c]

Mission Phase	Probability of 99th Percentile	Release Proba-bility	Maximum Individual Dose (rem)		Collective Dose (person-rem)		Health Effects		Land Contamination (km^2)		Cropland Intervention (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)	3.30E-08	3.06E-09	5.15E-03	2.15E-02	4.10E+01	1.71E+02	2.46E-02	1.03E-01	6.28E-01	2.62E+00	1.10E-02	4.60E-02
1 (Early Launch)												
On-Pad Explosion	9.76E-07	1.20E-07	2.73E-03	3.23E-03	2.17E+01	2.57E+01	1.31E-02	1.55E-02	3.33E-01	3.94E-01	5.85E-03	6.92E-03
FSII	2.24E-07	3.00E-08	2.72E-01	3.83E-01	2.16E+03	3.05E+03	1.30E+00	1.83E+00	3.31E+01	4.68E+01	5.82E-01	8.21E-01
Stage 2/SV	4.83E-07	8.00E-09	8.61E-04	5.22E-03	6.86E+00	4.16E+01	4.12E-03	2.50E-02	1.05E-01	6.37E-01	1.85E-03	1.12E-02
SVII	6.32E-09	2.94E-10	2.00E-03	4.39E-03	1.60E+01	3.50E+01	9.59E-03	2.10E-02	2.45E-01	5.36E-01	4.30E-03	9.41E-03
Low Altitude FTS	2.95E-05	4.62E-07	6.87E-04	6.22E-03	5.47E+00	4.95E+01	3.28E-03	2.98E-02	8.38E-02	7.60E-01	1.47E-03	1.33E-02
Overall Phase 1	3.12E-05	6.21E-07	9.10E-04	7.78E-02	7.25E+00	6.20E+02	4.35E-03	3.72E-01	1.11E-01	9.50E+00	1.95E-03	1.67E-01
2 (Late Launch)	3.63E-05	-	-	-	-	-	-	-	-	-	-	-
3 (Suborbital)	1.31E-04	2.35E-08	-	4.66E-03	-	3.71E+01	-	2.23E-02	-	5.69E-01	-	9.98E-03
4 (Orbital)	4.66E-05	-	-	-	-	-	-	-	-	-	-	-
5 (Long-Term)	1.00E-08	-	-	-	-	-	-	-	-	-	-	-
Overall Mission	2.45E-04	6.48E-07	-	7.48E-02	-	5.96E+02	-	3.58E-01	-	9.13E+00	-	1.60E-01

a. The table presents composite results for the LVs under consideration, determined by taking the probability-weighted value of each set of results.

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

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

Table 4-5. Mean Radiological Consequence Summary for Generic Science Instrument Sources[a,b,c]

Mission Phase	Accident Probability	Release Probability	Maximum Individual Dose (rem)		Collective Dose (person-rem)		Health Effects		Land Contamination (km^2)		Cropland Intervention (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)	3.30E-06	1.83E-06	1.88E-05	3.38E-05	1.49E-01	2.69E-01	8.98E-05	1.62E-04	2.29E-03	4.12E-03	4.02E-05	7.23E-05
1 (Early Launch)	3.12E-03	5.99E-04	2.12E-06	1.11E-05	1.69E-02	8.80E-02	1.01E-05	5.29E-05	2.59E-04	1.35E-03	4.55E-06	2.37E-05
2 (Late Launch)	3.63E-03	1.17E-04	9.89E-07	3.07E-05	7.87E-03	2.44E-01	4.73E-06	1.47E-04	1.21E-04	3.75E-03	2.12E-06	6.58E-05
3 (Suborbital)	1.31E-02	6.56E-03	1.53E-05	3.07E-05	1.22E-01	2.44E-01	7.34E-05	1.47E-04	1.87E-03	3.75E-03	3.29E-05	6.58E-05
4 (Orbital)	4.66E-03	4.19E-03	2.76E-05	3.07E-05	2.20E-01	2.44E-01	1.32E-04	1.47E-04	3.37E-03	3.75E-03	5.92E-05	6.58E-05
5 (Long-Term)	1.00E-06	1.00E-06	6.14E-05	6.14E-05	4.89E-01	4.89E-01	2.94E-04	2.94E-04	7.49E-03	7.49E-03	1.32E-04	1.32E-04
Overall Mission	2.45E-02	1.15E-02	1.39E-05	2.96E-05	1.10E-01	2.36E-01	6.64E-05	1.42E-04	1.69E-03	3.62E-03	2.97E-05	6.35E-05

a. The table presents composite results for the LVs under consideration, determined by taking the probability-weighted value of each set of results.

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

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

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4.2. Mission Risks

A summary of the mission risks is presented in Table 4-6, Table 4-7 and Table 4-8. For the purpose of this report, 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 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, risk can also be interpreted as the total probability of one health effect given the mission (for risk much less than one). All of the Phases 0 and 1 releases are within a few km of the launch pad. Nearly all of the Phase 3 releases are within Africa. All of the Phase 4 releases are between 29^{o} N and 29^{o} S latitude. Phase 5 releases can occur anywhere on the globe where there is land. The mission risk for the MMRTG configuration is $2.9\text{x}10^{-5}$. The mission risk for the 80-LWRHU configuration is $1.3\text{x}10^{-6}$. The mission risk for the science instruments is $1.6\text{x}10^{-6}$.

Table 4-6. Mission Risk Summary for the MMRTG[a]

Mission Phase	Accident Probability	Mean Health Effects, Given an Accident	Mission Risks
0 (Prelaunch)	3.28E-05	4.50E-04	1.48E-08
1 (Early Launch)			
On-Pad Explosion	9.76E-05	9.63E-03	9.39E-07
FSII	2.24E-05	7.38E-02	1.65E-06
Stage 2/SV	4.83E-05	1.37E-02	6.60E-07
SVII	6.32E-07	1.33E-02	8.41E-09
Low Altitude FTS	2.95E-03	7.48E-03	2.21E-05
Overall Phase 1	3.12E-03	8.12E-03	2.53E-05
2 (Late Launch)	3.63E-03	1.66E-07	6.04E-10
3 (Suborbital)	1.31E-02	2.30E-04	3.02E-06
4 (Orbital)	4.66E-03	1.45E-04	6.75E-07
5 (Long-Term)	1.00E-06	3.57E-04	3.57E-10
Overall Mission	2.46E-02	1.18E-03	2.90E-05

a. The table presents composite results for the LVs under consideration, determined by taking the probability-weighted value of each set of results.

Table 4-7. Mission Risk Summary for the LWRHUs[a]

Mission Phase	Accident Probability	Mean Health Effects, Given an Accident	Mission Risks
0 (Prelaunch)	3.30E-06	1.35E-03	4.43E-09
1 (Early Launch)			
On-Pad Explosion	9.76E-05	7.81E-04	7.62E-08
FSII	2.24E-05	3.96E-02	8.86E-07
Stage 2/SV	4.83E-05	9.92E-05	4.79E-09
SVII	6.32E-07	3.04E-04	1.92E-10
Low Altitude FTS	2.95E-03	9.65E-05	2.85E-07
Overall Phase 1	3.12E-03	4.01E-04	1.25E-06
2 (Late Launch)	3.63E-03	-	-
3 (Suborbital)	1.31E-02	1.08E-06	1.41E-08
4 (Orbital)	4.66E-03	-	-
5 (Long-Term)	1.00E-06	-	-
Overall Mission	2.45E-02	5.18E-05	1.27E-06

a. The table presents composite results for the LVs under consideration, determined by taking the probability-weighted value of each set of results.

Table 4-8. Mission Risk Summary for Generic Science Instrument Sources[a]

Mission Phase	Accident Probability	Mean Health Effects, Given an Accident	Mission Risks
0 (Prelaunch)	3.30E-06	8.98E-05	2.96E-10
1 (Early Launch)	3.12E-03	1.01E-05	3.17E-08
2 (Late Launch)	3.63E-03	4.73E-06	1.72E-08
3 (Suborbital)	1.31E-02	7.34E-05	9.64E-07
4 (Orbital)	4.66E-03	1.32E-04	6.15E-07
5 (Long-Term)	1.00E-06	2.94E-04	2.94E-10
Overall Mission	2.45E-02	6.64E-05	1.63E-06

a. The table presents composite results for the LVs under consideration, determined by taking the probability-weighted value of each set of results.

For the Mars 2020 configuration with an MMRTG, Phase 1 accidents contribute 87 percent of the risk. The primary AOC contributors to the Phase 1 risk in order of importance are 1) Low Altitude FTS and 2) FSII. For the Mars 2020 configuration with 80 LWRHUs, Phase 1 accidents contribute 99 percent of the risk. The primary AOC contributors to the Phase 1 risk in order of importance are 1) Low Altitude FTS, 2) FSII, and 3) On-Pad Explosion. For the Mars 2020 configuration with science instruments, Phase 3 accidents contribute 59 percent of the risk and Phase 4 accidents contribute 38 percent of the risk.

Risk contributions to the launch area (defined here as being within 100 km of the launch pad) and global areas are summarized in Table 4-9, Table 4-10 and Table 4-11 for configurations with an MMRTG, 80 LWRHUs and science instruments, respectively.

Table 4-9. Mission Risk Contributions by Affected Region for the MMRTG[a]

Mission Phase	Mission Risks		
	Launch Area	Global	Total
0 (Prelaunch)	8.94E-09	5.85E-09	1.48E-08
1 (Early Launch)	1.65E-05	8.88E-06	2.53E-05
2 (Late Launch)	-	6.04E-10	6.04E-10
3 (Suborbital)	-	3.02E-06	3.02E-06
4 (Orbital)	-	6.75E-07	6.75E-07
5 (Long-Term)	-	3.57E-10	3.57E-10
Overall Mission	1.65E-05	1.26E-05	2.90E-05

a. The table presents composite results for the LVs under consideration, determined by taking the probability-weighted value of each set of results.

Table 4-10. Mission Risk Contributions by Affected Region for the LWRHUs[a]

Mission Phase	Mission Risks		
	Launch Area	Global	Total
0 (Prelaunch)	2.68E-09	1.75E-09	4.43E-09
1 (Early Launch)	8.13E-07	4.39E-07	1.25E-06
2 (Late Launch)	-	-	-
3 (Suborbital)	-	1.41E-08	1.41E-08
4 (Orbital)	-	-	-
5 (Long-Term)	-	-	-
Overall Mission	8.15E-07	4.55E-07	1.27E-06

a. The table presents composite results for the LVs under consideration, determined by taking the probability-weighted value of each set of results.

Table 4-11. Mission Risk Contributions by Affected Region for Generic Science Instrument Sources[a]

Mission Phase	Mission Risks		
	Launch Area	Global	Total
0 (Prelaunch)	1.79E-10	1.17E-10	2.96E-10
1 (Early Launch)	2.06E-08	1.11E-08	3.17E-08
2 (Late Launch)	-	1.72E-08	1.72E-08
3 (Suborbital)	-	9.64E-07	9.64E-07
4 (Orbital)	-	6.15E-07	6.15E-07
5 (Long-Term)	-	2.94E-10	2.94E-10
Overall Mission	2.07E-08	1.61E-06	1.63E-06

a. The table presents composite results for the LVs under consideration, determined by taking the probability-weighted value of each set of results.

The launch area risk for the MMRTG is 57 percent of the overall mission risk, and the global area risk is 43 percent. The launch area risk for the LWRHU is 64 percent of the overall mission risk, and the global area risk is 36 percent. The launch area risk for the science instruments is 1 percent of the overall mission risk, and the global area risk is 99 percent. Launch area risks are due entirely from accidents during Phases 0 and 1, with Phase 1 being the primary contributor. Global risks are due to accidents in all mission phases, with Phase 1 being the primary contributor resulting from the atmospheric transport of small particles beyond 100 km from the launch pad.

Another descriptor used in characterizing risk is the maximum individual risk, presented in Table 4-12, Table 4-13 and Table 4-14. 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.

Table 4-12. Maximum Individual Risk for the MMRTG[a]

Mission Phase	Accident Probability	Mean Maximum Individual Dose, Given an Accident (rem)	Maximum Individual Risk
0 (Prelaunch)	3.28E-05	9.42E-05	1.86E-12
1 (Early Launch)	3.12E-03	1.70E-03	3.18E-09
2 (Late Launch)	3.63E-03	3.48E-08	7.59E-14
3 (Suborbital)	1.31E-02	4.81E-05	3.80E-10
4 (Orbital)	4.66E-03	3.03E-05	8.47E-11
5 (Long Term)	1.00E-06	7.46E-05	4.48E-14

a. The table presents composite results for the LVs under consideration, determined by taking the probability-weighted value of each set of results.

Table 4-13. Maximum Individual Risk for the LWRHUs[a]

Mission Phase	Accident Probability	Mean Maximum Individual Dose, Given an Accident (rem)	Maximum Individual Risk
0 (Prelaunch)	3.30E-06	2.81E-04	5.57E-13
1 (Early Launch)	3.12E-03	8.39E-05	1.57E-10
2 (Late Launch)	3.63E-03	-	-
3 (Suborbital)	1.31E-02	2.25E-07	1.77E-12
4 (Orbital)	4.66E-03	-	-
5 (Long Term)	1.00E-06	-	-

a. The table presents composite results for the LVs under consideration, determined by taking the probability-weighted value of each set of results.

Table 4-14. Maximum Individual Risk for Generic Science Instrument Sources[a]

Mission Phase	Accident Probability	Mean Maximum Individual Dose, Given an Accident (rem)	Maximum Individual Risk
0 (Prelaunch)	3.30E-06	1.88E-05	3.72E-14
1 (Early Launch)	3.12E-03	2.12E-06	3.98E-12
2 (Late Launch)	3.63E-03	9.89E-07	2.16E-12
3 (Suborbital)	1.31E-02	1.53E-05	1.21E-10
4 (Orbital)	4.66E-03	2.76E-05	7.73E-11
5 (Long Term)	1.00E-06	6.14E-05	3.69E-14

a. The table presents composite results for the LVs under consideration, determined by taking the probability-weighted value of each set of results.

4.3. Uncertainties

An analysis to estimate uncertainties in probabilities, source terms, radiological consequences, and mission risks has not been performed as part of this report. Such an analysis will be performed in the FSAR. Based on experience with uncertainty analyses in the risk assessment of past missions (e.g., the Cassini, Mars Exploration Rover 2003, Pluto New Horizons, and Mars Science Laboratory), the uncertainty in the mission risk for the Mars 2020 mission can be estimated. Those analyses have shown that the uncertainty in the mission risk is dominated by uncertainties in the launch accident probability and the overall probability is about a factor of 25 higher or lower than the median for the 5th and 95th percentiles. For the MMRTG option, treating the best estimate of the Mars 2020 mission risk of 2.9×10^{-5} as the median of the uncertainty probability distribution (i.e., it is equally probable that the mission risk could be higher or lower than this value), the mission risk at the 5th and 95th percentile confidence levels are estimated to be 1.2×10^{-6} and 7.3×10^{-4}, respectively. For the 80-LWRHU option, treating the best estimate of the Mars 2020 mission risk of 1.3×10^{-6} as the median of the uncertainty probability distribution, the 5th and 95th percentile levels for risk would be 5.2×10^{-8} and 3.3×10^{-5}, respectively. For the scientific instruments, treating the best estimate of the Mars 2020 mission risk of 1.6×10^{-6} as the median of the uncertainty probability distribution, the 5th and 95th percentile levels for risk would be 6.4×10^{-8} and 4.0×10^{-5}, respectively.

4.4. References

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APPENDIX A: RISK ASSESSMENT METHODOLOGY

A.1 Introduction

The NASA's 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. An alternative power source is a set of solar panels with up to 80 LWRHUs. Each MMRTG contains about 4.832 kg of PuO_2, or an estimated 60,000 Ci of radioactivity. Each LWRHU contains 2.7 g of PuO_2 with an inventory of nominally 33 Ci each, or 2,640 Ci total. The MMRTG and LWRHUs would be provided to NASA by the U.S. 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 EIS for the mission in accordance with requirements under the NEPA. This appendix describes the methodology used to assess the risk.

A.2 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 and LWRHUs 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.

The risk assessment for the EIS has been prepared in advance of the more detailed FSAR being prepared in accordance with DOE Directives and a formal launch approval process required by PD/NSC-25. The FSAR will be developed in a manner similar to that outlined in the steps above. Prior to the availability of the FSAR, information and results presented in this report have been developed based on: 1) consideration of the nuclear risk assessment performed for the Mars Science Laboratory (Reference A-1), and 2) additional Mars 2020 mission-specific analyses using statistical accident modeling.

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 2.0), 2) accidents, probabilities and source terms (Section 3.0), and 3) radiological consequences, mission risks and uncertainties (Section 4.0).

A.3 Developing Methodology

A.3.1 Mission Risk and Related Factors

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

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

where

R = Risk in terms of expectation of health effects.
P_{TOT} = Total probability of release
H = Health effects in terms of latent cancer fatalities over 50 years, given a release

(<u>Note</u>: Risk defined in this manner can also be interpreted as the total probability of one health effect. 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:

$$P_{TOT} = P_{ACC}\,P_{CON} \qquad \text{(A-2)}$$

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 health effects, H, can be expressed as:

$$H = Q_{ST}\, h \tag{A-3}$$

where

Q_{ST} = Mean source term, given a release (Ci)
h = Mean health effects per Ci of source term

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

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

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.

It is desirable to renormalize results on a per Ci inventory basis. This can be done by expressing the source term as:

$$Q_{ST} = Q_{INV}\, S_{FRA} \tag{A-5}$$

where

Q_{INV} = Total inventory of nuclear hardware, Ci.
S_{FRA} = Mean source term fraction, i.e., the ratio of the source term amount to the total inventory).

Using Equations A-4 and A-5, risk can now be expressed as:

$$R = \left(P_{ACC}\, Q_{INV}\right)\left(P_{CON}\, S_{FRA}\, h\right) \tag{A-6}$$

The key to using results from source term calculations is the determination of the second set of factors: $P_{CON} S_{FRA}\, h$. The product, $P_{CON} S_{FRA}\, h$, represents the risk per Ci of total inventory given the accident. Alternatively, the product represents the total probability of one health effect per Ci of total inventory given the accident.

A.3.2 Radiological Consequences and Related Factors

The above approach can be extended to arrive at each type of radiological consequence as described below. An important consideration is that most of the health effects or other consequences of interest are caused by fuel particles that are small enough to be become airborne and transported by the wind. For this analysis, this consists of PuO_2 particles 100 microns (0.1 mm) or smaller in physical diameter. Note that 100 microns physical diameter corresponds to about 310 microns aerodynamic equivalent diameter (AED) because of the high density of plutonium dioxide. PuO_2 particles this size fall at about 1.6 m/s. Detailed atmospheric transport calculations have shown that consequences scale fairly linearly with mass in this particle size range.

With these considerations, the mean health effects, H, may be calculated as

$$H = Q_{INV}\, S_{FRA}\, h \tag{A-7}$$

where

h = Mean health effects per Ci of of source term

The maximum individual dose, M (rem) is

$$M = Q_{INV}\, S_{FRA}\, m \tag{A-8}$$

where

m = Maximum individual dose per Ci of source term (rem)

The collective dose, C is

$$C = Q_{INV}\, S_{FRA}\, c \tag{A-9}$$

where

c = Collective dose per Ci of source term (person-rem)

The land area contaminated above a specified level is not strictly linear with the quantity released. Assuming that the variable is linear with the quantity release, however, does provide a first order estimate of the area contaminated. A more refined estimate requires that atmospheric transport and dispersion modeling be performed with a given source term value. The latter approach has not been taken in developing the results for this report. For this analysis, the land area contaminated above a specified level (0.2 $\mu Ci/m^2$), A_c (km^2), is calculated as

$$A_c = Q_{INV}\, S_{FRA}\, a_c \tag{A-10}$$

where

a_c = Land area contaminated above specified level (0.2 $\mu Ci/m^2$), per Ci of source term (km^2)

In a similar fashion, the total area of cropland which is above the DIL for each particular plot (and which may be scattered in small plots over a large area) is calculated as

$$A_I = Q_{INV}\, S_{FRA}\, a_I \tag{A-11}$$

where

a_I = Sum of all cropland areas above the intervention level for that crop, per Ci of source term (km^2)

The 99th percentile source term is also of interest. The 99th percentile release source term is the value predicted to be exceeded with a probability of 0.01 (1 in 100), given a release in an accident. In this context, the 99th percentile value reflects the potential for larger radionuclide releases at lower probabilities than would be expected from accidents involving a release. The 99th percentile accident source term is the value predicted to be exceeded with a probability of 0.01 (1 in 100), given an accident. The total probability of the 99th percentile source term, P_{99}, can be determined from sorting the results of numerous Monte Carlo calculations that are performed. The 99th percentile consequences are scaled from the 99th percentile source term values. The 99th percentile consequences are determined by using the 99th percentile source term values with the respective consequence factors described in the next section.

The radiological consequence factors used in the above equations have been developed by modeling the atmospheric transport and deposition of the particles in detail for some representative accident scenarios, applying the ICRP and ISCORS health effects models, and using the results to determine the consequence factors for that scenario. These factors were then applied to all similar accident scenarios.

A.4 Application of Methodology

This section describes the manner in which the methodology outlined in Section A.3 is applied in order to arrive at the results reported in Sections 3.0 and 4.0 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-6 affecting mission risk and the information presented in Sections 3.0 (Accident Probabilities and Source Terms) and 4.0 (Radiological Consequences and Mission Risks) of the main text:

- Accident Probability, P_{ACC}
- Conditional Probability of Release, P_{CON}
- Source Term Fraction, S_{FRA}
- Health Effects per Ci of source term, h

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 3.0 of the main text.

Conditional Probability of Release, P_{CON}, and Source Term Fraction, S_{FRA}: 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 and the LWRHU to various accident environments was estimated based on continuum mechanics code modeling for a range of conditions. The mean source term fraction, S_{FRA}, is the total source term amount divided by the total MMRTG or LWRHU inventory. The resulting source terms and probabilities are summarized in Section 3.0 of the main text.

Mean Health Effects per Ci of Source Term, h: The mean health effects per Ci, h , 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 releases, and 3) a blend of the first two types reflecting the modification of an initial mechanical impact release that is subsequently exposed to burning 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. Only the second distribution is used for the Delta IV Heavy since it has no solid propellant.
- 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 release. The location of the release (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 releases is based on a range of time- and spatially-dependent meteorological conditions representative of the period of launch opportunity.

- Population distribution: This distribution can be either for: 1) the launch site region or 2) worldwide, depending on the release location and subsequent atmospheric transport and dispersion characteristics of the release.
- Internal dose conversion factors: Particle-size dependent internal dose factors are based on those presented in ICRP-66 (Reference A-2). 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 release in units of "person-rem."
- Health effects estimator: The health effects represent incremental cancer fatalities over 50 years induced by releases, determined from the ISCORS estimator of $6x10^{-4}$ fatalities per person-rem for the general population (Reference A-3). 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. When 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, an estimate of the total health effects in the population results.

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

The methodology developed for use in this report made estimates of *h* for each combination of accident environment and mission phase described above under the discussion of conditional probability, P_{CON}, and source term fraction, S_{FRA}. Atmospheric transport and dispersion modeling has been performed to develop values of *h*, taking into account: 1) the location of the launch complex, 2) the vertical plume configuration associated with potential accidents, 3) meteorological conditions for the period of launch opportunity, 4) different particle size distributions, and 5) population growth to July 2020.

A set of approximate consequence scaling factors (*h, m, c,* and *a*) was developed by performing detailed atmospheric transport and health effects calculations for numerous source terms and weather conditions to obtain a set of consequences for each configuration, and then taking the mean consequence for this set and dividing by the mean source term radioactivity level (in Ci). Specifically, the scaling factors were generated by taking the consequence of interest (e.g. mean health effects) that result from all particle sizes and then dividing by the mean of the released amount (in Ci) that comes from particles less than 100 microns in physical diameter for that accident scenario. This approach was taken because it was determined that most of the dose, health effects, and even land contamination came from small particles, and that the total amounts of these consequences (from all particle sizes) scaled close to linearly with the released amount of particles less than 100 microns in physical diameter. The consequence factors so determined were found to be the same (within about a factor of 1.5) for all accident scenarios, and for the

MMRTG and the LWRHU. Thus a single set of these factors could be made that were applicable to all configurations. This set of factors is shown in Table A-1. They are based on the mean of the factors over all scenarios analyzed, plus one standard deviation (to ensure better inclusion of outliers). The atmospheric transport and dispersion modeling was used to determine the fraction of risk within 100 km of the launch pad.

Table A-1. Consequence Factors Affecting Mission Risk[a]

Maximum Individual Dose Factor: m (rem/Ci)	Col. Dose Factor c (person-rem/Ci)	Health Effects Factor h (HE/Ci)	Contaminated Land Factor a_c (km^2/Ci)	Cropland Intervention Factor a_I (km^2/Ci)
1.02E-03	8.15E+00	4.89E-03	1.25E-01	2.19E-03

a. Factors are in terms of Ci of source term, which is the released mass below 100 microns physical diameter (about 310 microns AED).

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