# 4. ENVIRONMENTAL CONSEQUENCES

This chapter of the Mars 2020 mission Draft Environmental Impact Statement (DEIS) presents information on the potential environmental impacts of launching the proposed mission. The evaluations presented in this DEIS; based on representative configurations of Atlas V, Delta IV, and Falcon Heavy launch vehicles; were completed prior to NASA's selection of the launch vehicle for the Mars 2020 mission. NASA considers these evaluations to adequately bound the potential environmental consequences of the alternatives described in this DEIS. If new and or significant information becomes available, NASA would evaluate the need for additional environmental analysis and documentation.

The potential environmental impacts of launching the proposed Mars 2020 mission are expected to be similar in nature to those evaluated in the *Mars Science Laboratory Mission Final Environmental Impact Statement* (MSL FEIS) (NASA 2006). The proposed Mars 2020 mission would be launched on a similar medium to large expendable launch vehicle, resulting in similar normal launch and launch accident non-radiological impacts. The Mars 2020 spacecraft for the proposed action would be essentially identical to the MSL spacecraft and have a similar Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) as a power source. Therefore, it is expected that the radiological impacts of accidents would also be similar to those evaluated in the MSL EIS. Mars 2020 mission-specific nuclear risk analyses have been performed by the Department of Energy (DOE) for both the MMRTG-powered alternative and the solar power augmented with Light-Weight Radioisotope Heater Unit (LWRHU) alternative. These analyses evaluated the impacts of launch accidents using representative configurations of the Atlas V and Delta IV launch vehicles proposed for the Mars 2020 mission and the results are reported in the *Nuclear Risk Assessment for the Mars 2020 Mission Environmental Impact Statement* (SNL 2014).

The MMRTG hardware has already been manufactured and assembled by industry under contract to DOE; those flight units are in bonded storage at the contractor facility. Testing and fueling of the MMRTGs would be done by DOE at existing facilities. The plutonium dioxide would be formed into pellets suitable for use in an MMRTG or LWRHU at DOE's Los Alamos National Laboratory (LANL) in New Mexico. The pellets would be encapsulated in an iridium cladding at LANL. The encapsulated pellets would then be shipped to Idaho National Laboratory (INL) in Idaho for final MMRTG assembly and testing. The LWRHUs have already been manufactured; final assembly of the LWRHUs occurred at LANL. DOE would then transport the MMRTG or LWRHUs to the appropriate launch site. The impacts of these activities have been addressed in existing DOE environmental documentation (DOE 1993, 2000, 2002b, 2008, 2013).

DOE's process for preparing an MMRTG for the proposed Mars 2020 mission would be very similar to the process they used in preparing nearly identical MMRTGs for the MSL and Pluto New Horizons missions. The environmental impacts of preparing an MMRTG by the DOE for the Mars 2020 mission have already been evaluated in existing DOE NEPA documents. The plutonium that would be used for an MMRTG for the Mars 2020 mission was previously purchased from Russia and is in secure storage vaults at DOE facilities. As stated y the terms of the purchase agreement with Russia, plutonium can only be used for peaceful space exploration missions. The stockpiled plutonium would be fabricated into fueled clads at the Los Alamos National Laboratory (LANL). (The potential impacts of that process are described in the LANL Site-Wide EIS (DOE 2008).) The fuel clads would then be securely shipped to the Idaho National Laboratory (INL) for integration into MMRTG assemblies. The potential impacts of that process have been described in the LANL Site-Wide EIS and other specific DOE NEPA documents addressing portions of the MRTG fabrication process (DOE 2002b, 2008). The DOE found that the principal environmental impacts — shipping the plutonium in various forms, fabricating the plutonium into fueled clads, then fabricating the clads into an MMRTG, and shipping to CCAFS—are the generation of solid radioactive wastes and potential external radiation exposure to DOE facility radiation workers. Radioactive wastes would be generated at LANL and INL. Most of the radioactive wastes would be in the form of plutonium-contaminated solid wastes called transuranic (TRU) wastes. Production of an MMRTG for a potential Mars 2020 mission would temporarily increase radioactive wastes generated annually by LANL and INL and routinely shipped for ultimate deep geologic disposal at the DOE Waste Isolation Pilot Plant facility in New Mexico. The generation, handling, transportation, and disposal of these wastes have been described and impacts evaluated in multiple DOE NEPA documents (DOE 1993, 2000, 2002b, 2008, 2013). Since the production of an MMRTG for the proposed Mars 2020 mission would use similar steps, processes, and facilities as that followed for recent space missions, no new environmental impacts would be expected.

The discussion of the environmental impacts associated with Alternatives 1, 2, and 3 are separated into four categories of impacts:

- Environmental impacts associated with preparation for launch,
- Environmental impacts associated with a normal (successful) launch,
- Non-radiological impacts associated with launch accidents, and
- Radiological impacts associated with launch accidents.

The impacts associated with the first two categories would occur with every launch. The impacts from the second two would be seen only if there were to be a failure of the launch vehicle that results in an accident either with or without the release of radioactive material. For the three alternatives, the environmental impacts associated with preparation for a launch, a normal launch, and the non-radiological impacts of a launch accident would be the same for that launch system with or without radiological materials on a rover. These impacts are discussed in Section 4.1 for the Proposed Action, Alternative 1, Section 4.2, Environmental Impacts of Alternative 2, and Section 4.3, Environmental Impacts of Alternative 3.

## 4.1 ENVIRONMENTAL IMPACTS OF THE PROPOSED ACTION (ALTERNATIVE 1)

Under Alternative 1, NASA proposes to continue preparations for and to implement the Mars 2020 mission. The proposed Mars 2020 mission would include an autonomous rover that would perform science operations on the surface of Mars. One MMRTG would provide the necessary electric power to operate the Mars 2020 rover and its science instruments. The Mars 2020 spacecraft would be launched on an Atlas V, a

Delta IV Heavy, or a Falcon Heavy launch vehicle (see Section 2.1.5) from SLC-41, SLC-37, or LC-39A, respectively, at CCAFS/KSC.

Sections 4.1.1 and 4.1.2 present the environmental impacts of preparing for launch and the environmental impacts resulting from a normal launch event, respectively. These impacts were addressed in the MSL EIS (NASA 2006), the *Final Environmental Assessment for Launch of NASA Routine Payloads on Expendable Launch Vehicles* (Routine Payload EA) (NASA 2011), the PEIS MEP (NASA 2005a), *Environmental Assessment for Falcon 9 and Falcon 9 Heavy Launch Vehicle Programs from Space Launch Complex 4 East Vandenberg Air Force Base California* (USAF 2011), and the *Final Supplemental Environmental Assessment to the November 2007 Environmental Assessment for the Operation and Launch of the Falcon 1 and Falcon 9 Space Vehicles At Cape Canaveral Air Force Station Florida (SpaceX 2013b)*. The USAF has assessed environmental impacts of Atlas V and Delta IV launches through 2020 based upon an annual average launch rate of 10 launches and 11 launches, respectively, from CCAFS (USAF 2000). Launch of the Mars 2020 mission would be included in and not increase this previously approved launch rate. Launch of a Falcon Heavy was addressed in the Routine Payload EA (NASA 2011) and the environmental impacts are expected to be similar to that of an Atlas V or Delta IV launch vehicle.

The potential non-radiological environmental impacts of a launch accident are discussed in Section 4.1.3. Section 4.1.4 addresses radiological impacts, which may result from a launch accident.

### 4.1.1 Environmental Consequences of Preparing for Launch

Launch processing activities for the Mars 2020 mission would be subject to Federal, state, and local environmental laws and regulations; and USAF and NASA regulations and requirements (see Section 4.9). All CCAFS/KSC launch sites have established plans to implement these regulations, including hazardous materials management plans and hazardous waste disposal plans. Responsibilities and procedures for management of hazardous materials and hazardous wastes (HM/HW) are clearly defined in those operating plans. Processing facilities must prepare and retain a written contingency plan and emergency procedures for responding to emergencies involving hazardous materials. In addition, all proposed processing facilities and launch sites have active pollution prevention programs to reduce the use of hazardous materials and generation of hazardous waste.

Spacecraft and launch vehicle processing at CCAFS or KSC would involve a number of industrial activities that include the use of hazardous materials, and would generate hazardous wastes, other solid and liquid wastes, and air emissions. Such hazardous materials would include but not be limited to acetone, chromate conversions coating, denatured alcohol, epoxy, flux, inks, lacquer, paints, propellants, oils, solvents, primers, sealants, and other process chemicals.

NASA or its contractors would acquire the required hazardous materials for the Mars 2020 mission use and would properly dispose of any generated hazardous wastes. If the Mars 2020 spacecraft uses an MSL heritage cooling system, it would contain about 5 liters (1.3 gallons) of trichlorofluoromethane (also known as Freon-11), a Class I ODS, as the coolant circulated in stainless steel tubing for spacecraft thermal control. Freon-11 would be loaded into the spacecraft via a closely monitored, closed-loop system that would minimize the possibility of a significant portion of the substance escaping to open atmosphere.

CCAFS, KSC, NASA, and NASA Launch Service (NLS) contractors must adhere to established programs for pollution and spill prevention. Airborne emissions from liquid propellant loading and off-loading of spacecraft and launch vehicles are closely monitored using vapor detectors. Systems for loading hypergolic fuels (fuels which ignite spontaneously when mixed with an oxidizer) also use air emission controls (USAF 1998). Liquid hypergolic fuels make up the largest proportion of hazardous materials used in processing spacecraft and these propellants are extremely hazardous and toxic. However, they are transported and controlled by the facility propellant contractor and are not stored at the processing facilities. Each facility that is permitted to process hypergolic propellant transfers is configured to manage hypergolic propellants and waste products in accordance with Federal, state, and local regulations (NASA 2011).

Some spacecraft and launch vehicle integration personnel would be exposed to very low doses of radiation (substantially below regulatory limits) during pre-launch testing and integration of the MMRTG to the Mars 2020 spacecraft. Integration and launch processing activities involving ionizing and non-ionizing radiation at KSC and CCAFS are subject to extensive review and authorization of all activities by the local radiation protection authority prior to initiation of any operation. Such operations are actively monitored by launch site radiation safety personnel to ensure adherence to approved operating and emergency procedures and to maintain operational personnel exposures at levels that are as low as reasonably achievable (USAF 1999, NASA 2001).

The hazardous materials used to process spacecraft and launch vehicles could potentially generate hazardous waste. Liquid and solid waste would be generated almost exclusively from fuel and oxidizer transfer operations. Processing of launch vehicles would increase hazardous waste production at CCAFS/KSC launch sites by very small percentages. The spacecraft and launch vehicle contractors would be responsible for identifying, containing, labeling, and accumulating the hazardous wastes in accordance with all applicable Federal, state, and local regulations. All hazardous wastes generated from spacecraft and launch vehicle processing would be transported, treated, stored, and disposed of by the responsible base contractor (NASA 2011).

Due to extensive HM/HW management programs and established safety programs, processing the spacecraft and the launch vehicle for the Mars 2020 mission is not expected to cause adverse environmental impacts.

DOE's preparation of an MMRTG for the proposed Mars 2020 mission would be very similar to their process in preparing the nearly identical MMRTG for the MSL mission. The environmental impacts of preparing an MMRTG by the DOE for the Mars 2020 mission have already been evaluated in existing DOE NEPA documents (DOE 1993, 2000, 2002, 2002b, 2008, 2013).

### 4.1.2 Environmental Impacts of a Normal Launch

Environmental impacts of a normal launch of the Mars 2020 mission on an expendable launch vehicle would be associated with airborne exhaust emissions from propellant combustion, hazardous materials usage, hazardous waste generation, and wastewater generation.

#### 4.1.2.1. Land Use

The proposed processing and launch of spacecraft would not include any new construction or modification of facilities or roadways that would potentially impact land resources. Processing activities would take place within closed structures, and precautions would be taken to prevent spills and control hazardous materials in accordance with facility operating plans. Spills of liquid propellants would be controlled through catchment systems and holding tanks in the processing facilities and would not impact surrounding soils or land use resources (NASA 2011).

Processing and launch of the Mars 2020 mission on either an Atlas V, Delta IV, or Falcon Heavy would be consistent with the designated land uses of CCAFS and KSC; and no impacts to land use resources are anticipated (USAF 2001, NASA 2002b, NASA 2005a, NASA 2006, NASA 2011).

#### 4.1.2.2. Air Quality

Inadvertent releases of toxic air contaminants are possible as a result of improper handling of hazardous materials during payload processing, transportation, and launch. During payload processing and transportation, the largest releases would result from the spillage of the entire quantity of liquid propellants. CCAFS and KSC have safety procedures in place to ensure that these events are unlikely to occur and all spills must be managed in accordance with existing Spill Prevention, Control, and Countermeasures (SPCC) plans. Liquid propellants would be stored in tanks near the launch pad and within cement containment basins designed to retain 110 percent of the storage tank volume. Propellant spills from the launch vehicle would be channeled into sealed concrete catchment basins and disposed of according to appropriate Federal and state regulations. Propellant loading operations would be postponed if Range Safety models predict that a potential propellant spill would result in a toxic hazard to the public or unprotected personnel (NASA 2011).

ODSs may be used in fully self-contained spacecraft cooling systems. Any ODS use would be accomplished in accordance with Federal, state, and local laws regulating ODS use, reuse, storage, and disposal. Release of materials other than propulsion system exhaust would be limited to inert gases. Preparation of rocket vehicles would not result in a release of ODSs into the atmosphere (NASA 2011).

Rocket launches can cause short-term impacts on local air quality from routine launch vehicle exhaust emissions. After ignition of the first stage and the first few seconds of liftoff through launch vehicle ascent, the exhaust emissions would form a buoyant cloud at the launch pad. This high-temperature cloud would rise quickly and stabilize at an altitude of several hundred meters near the launch area. The cloud would then dissipate through mixing with the atmosphere. The exhaust products would be distributed along the launch vehicle's trajectory as the vehicle moves through the atmosphere. Airborne emissions from a normal launch of the Mars 2020 mission at CCAFS/KSC would not be expected to result in adverse impacts to the public (USAF 1998, USAF 2000, NASA 2005a, NASA 2006, NASA 2011). The nearest residential areas to SLC-37, LC-39A, or SLC-41 are about 10 to 20 kilometers (km) (6 to 12 miles) in the cities of Merritt Island to the southwest, Cape Canaveral and Cocoa Beach to the south, and Titusville to the west.

First-stage liquid propellant engines that use rocket propellant-1 (RP-1) and liquid oxygen (LOx), such as the Atlas V and Falcon Heavy, would primarily produce carbon monoxide (CO), carbon dioxide ($CO_2$), and water vapor as combustion products. First-stage liquid propellant engines that use liquid hydrogen ($LH_2$) and LOx, such as the Delta IV, would produce water vapor. Solid propellant, consisting of ammonium perchlorate, aluminum powder, and hydroxyl-terminated polybutadiene (HTPB) binder in the solid rocket boosters (SRBs) of the Atlas V, would primarily produce aluminum oxide ($Al_2O_3$) particulates, CO, hydrogen chloride (HCl), and nitrogen ($N_2$). Under the high temperatures of the SRB's exhaust, the CO would be quickly oxidized to $CO_2$, and the $N_2$ may react with ambient oxygen to form nitrogen oxides ($NO_X$). Most of these emissions would be removed from the atmosphere over a period of less than one week, yielding no long-term accumulation of these products (USAF 1998).

No short- or long-term air quality impacts are expected as a result of the handling and usage of liquid propellants and ODSs during a normal launch. Previous analyses have shown that emissions from a normal launch of an Atlas V with SRBs would not create short- or long-term adverse impacts to air quality in the region (USAF 2000, NASA 2005a, NASA 2011). The same result would be expected from the launch of a Delta IV Heavy or Falcon Heavy rocket. Section 4.1.2.14 discusses local as well as global ozone impacts.

#### 4.1.2.3. Noise

Noise impacts may be considered substantial if (1) the proposed action substantially increases the ambient noise level for adjoining areas, and (2) the increased ambient noise affects the use of the adjoining areas. NASA, the FAA, and USAF carefully consider the potential impacts from noise, (including sonic boom) on workers and the public as well as environmental resources including endangered species, marine mammals, historic structures, or any other protected property (NASA 2011).

The processing of the proposed spacecraft would not produce any substantial amount of noise outside of the processing facilities. The facilities employed for spacecraft processing, however, may generate moderate amounts of industrial noise due to operating machinery, generators, public address systems, and similar typical industrial systems. All such systems are subject to occupational safety and health regulations, and hearing protection would be utilized if and when required. The standard for noise, such as from generators, is based on the Noise Control Act of 1972 (P.L. 92-574), as amended. State and local standards serve as a guide if these are at least as stringent as Federal standards (NASA 2011).

Noise impacts associated with launches occur due to sound from the launch pad from ignition through lift-off. Increased noise levels would occur for only a short period (typically less than two minutes) during the vehicle's early ascent, and diminish rapidly as the vehicle gains altitude and moves downrange offshore (USAF 1998).

Non-essential workers would not be present in the launch area during the Mars 2020 liftoff, and those essential workers remaining in the area would be exposed to noise levels anticipated to be below Occupational Safety and Health Administration (OSHA) regulations for unprotected workers (140 A-weighted decibels (dBA) maximum and 115 dBA over a 15-minute average). While some area residents may be momentarily annoyed by noise during the Mars 2020 launch, such noise would be transient and would not be expected to exceed the EPA maximum 24-hour average exposure level of 70 dBA[12] for the general public and would therefore present no health hazard (NASA 2005a).

Sonic booms would be generated by the normal launch of the Mars 2020 mission, but would occur offshore over the Atlantic Ocean and no adverse impact to human populations would be expected. Ships and other vessels in the area would be warned in advance of the launch event and would not be adversely affected (USAF 1998).

Florida scrub jays and southeastern beach mice occur in the vicinity of launch facilities at CCAFS and KSC. A small potential exists that individuals of these species would be directly impacted by noise from launch operations. Previous environmental analyses concluded that impacts on these species are expected to be minimal. The behavior of scrub jays observed after Delta, Atlas, and Titan launches has been normal, indicating no noise-related effects (Schmalzer 1998, NASA 2011).

Sonic booms created by launches from CCAFS/KSC would occur over the open Atlantic Ocean. Typically, marine species in the ocean's surface waters are present in low densities (although spring and fall migration will see periodic groups of migrating whales that follow the coastline), and the sonic boom footprint lies over 48 km (30 mi) from CCAFS/KSC. Therefore, sonic booms from launches are not expected to adversely affect the survival of any marine species (USAF 1998, NASA 2011).

#### 4.1.2.4. Geology and Soils

For the Atlas V with SRBs, the Mars 2020 launch would result in deposition of solid rocket exhaust products, consisting primarily of $Al_2O_3$ particulates and HCl, onto soils.

During a Delta II launch on November 4, 1995, pH in the surrounding air was monitored to detect any changes caused by HCl vapors or deposition. Test strips were placed at the perimeter of the launch pad and launch conditions were calm, which would yield maximum HCl deposition. No pH changes were observed on any test strips, and there was no evidence of acid deposition. The lack of pH changes associated with the small

[12] For comparison, a typical household vacuum cleaner generates about 70 dBA at a distance of 3 m (10 ft); the sound level in a quiet bedroom at night is about 30 dBA (USAF 1998).

ground cloud indicates that even with exposure to the concentrated cloud, acid deposition would be minimal (USAF 1996b, NASA 2011).

Soils typically contain a substantial amount of organic matter, which results in a natural buffering capacity that would potentially counteract the effects of any HCl they receive. The soils of the barrier islands in this region are alkaline with high buffering capacity (Schmalzer 1998). For example, despite additions of substantial amounts of acidic deposition from 43 launches over a 10-year period, the affected soils at CCAFS showed no decrease in buffering capacity. The HCl content of the exhaust plume from SRBs would not be expected to adversely affect soils around launch sites at any of the proposed launch sites. In addition, aluminum oxide would not affect the soils because it would be deposited as a stable compound. Therefore, no measurable direct or indirect, short- or long-term effects on soil chemistry would be expected as a result of launch activities (USAF 1998, NASA 2011).

#### 4.1.2.5. Water Quality

Impacts on water resources may be considered significant if processing or launch activities interfere with surface water drainage, exceed the capacity of regional water supply systems, or result in degradation of surface water or groundwater quality such that existing water uses would be impaired.

Processing activities would take place within existing structures and precautions would be taken to prevent and control spills of hazardous materials. Large spills of spacecraft liquid propellant would be controlled through catchment systems in the processing facilities. All chemicals used for processing would be managed to prevent contamination of surface waters and groundwater.

Large quantities of water are used during launch of an Atlas V, a Delta IV, or a Falcon Heavy for cooling, acoustic damping, post-launch wash-down, fire suppression, and potable uses. The city of Cocoa, which pumps water from the Floridan aquifer, is contracted to supply water to CCAFS and KSC, and has sufficient capacity to supply sources to meet usage demands for launch of the Mars 2020 mission. Water used at the launch complex during launch would be collected and treated, if necessary, prior to being released to the CCAFS/KSC industrial wastewater treatment plant. At KSC, well water is also used for some industrial purposes, including service to the LOx storage tanks at LC-39A (KSC 2013).No short- or long-term environmental impacts from contaminated wastewater are expected as a result of normal launch operations.

Short-term acidification of surface water could result from contact with the launch exhaust cloud and through HCl fallout from the exhaust cloud. Wet deposition of HCl may also occur during simultaneous rainfall. Impacts on surface waters would be restricted to the area immediately adjacent to the launch pad. No substantial impacts on surface waters of nearby oceans, lagoons, or large inland water bodies should occur due to their buffering capacity. A short-term decrease in pH could occur in small streams and canals near the launch pad. Since there would only be a temporary decrease in pH, aluminum oxide deposition should not contribute to increased aluminum solubility in area surface waters (Schmalzer 1998, NASA 2011). A normal launch would have no substantial long-term impacts on the local water quality.

Under normal flight conditions, vehicle stages that do not reach orbit have trajectories that result in ocean impact. Stages that reach initial orbit would eventually reenter the atmosphere as a result of orbital decay. Corrosion of stage hardware would contribute various metal ions to the water column. Due to the slow rate of corrosion in the deep-ocean environment and the large quantity of water available for dilution, toxic concentrations of metals are not likely to occur.

The relatively small amounts of propellant left in the vehicle stages that impact the ocean could release solid and liquid propellants into the water column; however this release would be slow, with potentially toxic concentrations occurring only in the immediate vicinity of the propellant. Insoluble fractions of RP-1 propellant would float to the surface and spread rapidly to form a localized surface film that would evaporate. Hydrazine fuels are soluble and would also disperse rapidly. Because of the small amount of residual propellants present, and the large volume of water available for dilution, no long-term adverse impacts to hydrology or surface water quality would be expected from a normal launch of the Mars 2020 mission (USAF 1998, NASA 2005a, NASA 2011).

#### 4.1.2.6. Offshore Environment

Offshore environments at CCAFS/KSC would receive jettisoned launch vehicle sections in pre-approved drop zones (see Section 4.1.2.11). Small amounts of residual propellants associated with these launch vehicle sections would be released to the surrounding water. Metal parts would eventually corrode, but toxic concentrations of the metals would be unlikely because of the slow rate of the corrosion process and the large volume of ocean water available for dilution (USAF 1998, NASA 2005a). In this regard, there would be no short- or long-term effects of jettisoned launch vehicle sections on offshore environments.

#### 4.1.2.7. Biological Resources

Impacts to biological resources may be considered significant if processing and launch activities could materially impact a threatened or endangered species or critical habitat, substantially diminish habitat for a plant or animal species, substantially diminish a regionally or locally important plant or animal species, interfere substantially with wildlife movement or reproductive behavior, and/or result in a substantial infusion of exotic plant or animal species.

Launch vehicle processing would occur in existing facilities and payloads would be transported on existing roadways. Adjacent habitats would not be disturbed. Exterior lighting at all facilities used for spacecraft processing at CCAFS/KSC would comply with established lighting policy for minimizing disorienting effects on sea turtle hatchlings.

Biological resources may be impacted due to launch activities in terms of the following categories: (1) exhaust emissions directly at the launch pad that remain and are deposited in the area, (2) near-field impacts from the exhaust cloud (generally within 500 m (1,640 ft)) but sometimes up to 1 km (0.62 mi) from the pad, and (3) impacts from far-field deposition of the buoyant portion of the launch cloud (more than a few km from the launch pad).

The near-field impacts from an exhaust cloud depend primarily on the amount of sound-suppression water (its evaporation lowers the temperature and the altitude of the exhaust cloud) and on the time the launch vehicle remains near the launch pad during ascent. The observations of near-field impacts from previous launches have been well documented based on years of launching the space shuttle and expendable launch vehicles. For launch of the space shuttle, observations have included destruction of sensitive plant species followed by re-growth during the same growing season and 2 to 3 days drop in pH (a measure of acidity/alkalinity) in nearby waters (down to 1 m (3.3 ft) which have resulted in fish kills in nearby shallow surface waters. This was followed by a return to normal pH levels. There was also a possibility of death of fauna, including burrowing animals, in the path of the exhaust cloud. These near-field impacts from exhaust clouds were observed at distances up to a few hundred meters from the launch pad, well within launch site boundaries, and did not reach human populations offsite (NASA 2007, NASA 2011).

Minor brush fires are infrequent byproducts of launches and are usually contained and limited to vegetation within the launch complexes. HCl deposition could be created by rain falling through the SRB exhaust cloud. Wet deposition of HCl on leaves has been observed to persist on leaf surfaces for considerable periods; no mortality of these plants and no changes in plant community composition or structure have been observed in the far field related to launch effects (NASA 2007).

The U.S. Fish and Wildlife Service (USFWS) and the National Marine Fisheries Service (NMFS) have previously reviewed NEPA documentation for the Atlas and Delta launch vehicles at CCAFS/KSC and have specified required launch restrictions and other impact mitigation measures. Any additional permits, permit modifications, and/or mitigation measures based on selection of the Falcon Heavy rocket will be obtained/addressed by CCAFS/KSC prior to implementation of the proposed action.

Unlike the experience with space shuttle launches, exhaust plumes from solid and liquid propellants produced by expendable launch vehicles such as the Delta and Atlas launch vehicles have not produced substantial acidification and have not resulted in recorded fish kills to date. Without substantial acidification of surface waters, any aluminum oxide deposited in surface waters would remain insoluble and nontoxic to the biota. No animal mortality has been observed at CCAFS/KSC that could be attributed to Delta and Atlas launches (Schmalzer 1998, NASA 2011)

In summary, biological resources are not expected to be adversely affected by the Mars 2020 launch except for short-term effects on fauna and flora in the immediate vicinity of the launch complex. Impacts to vegetation from other launch vehicles have been observed up to about 800 meters (2,625 feet) from the launch pads. Acidic deposition from solid propellant exhaust products and high temperatures from the exhaust cloud could damage or kill biota within the immediate vicinity of the launch pad; however, long-term population effects on terrestrial biota would not be expected. Jettisoned launch vehicle sections that land in the ocean would be subject to corrosion and release of residual propellant. However, it is unlikely that these vehicle sections would have an adverse impact on marine species (USAF 1996a, NASA 2005a, NASA 2006, NASA 2011).

During the launch, wildlife in the vicinity of the launch site would be temporarily disturbed due to noise, generally amounting to a startle effect. Because launches are infrequent events, no long-term impacts would be anticipated on wildlife and marine species from noise from the Mars 2020 launch (NASA 2005a).

No adverse impacts on threatened or endangered species would be expected from a normal launch. Observations of conditions at launch facilities provided evidence that the extent of impacts from similar launches have been minimal to threatened/endangered species located near the launch complex (USAF 2000). Launch of the Mars 2020 mission would not interfere with CCAFS/KSC management of Florida scrub jay habitat. CCAFS/KSC have a light management plan that addresses mitigation of impacts to nesting sea turtles during nighttime launches and the plan would be implemented should the Mars 2020 launch occur at night (USAF 2001).

#### 4.1.2.8. Socioeconomics and Children's Environmental Health and Safety

Launch of the proposed Mars 2020 mission from CCAFS/KSC would be part of the normal complement of launches. Thus, a single launch would result in negligible impacts to socioeconomic factors such as demography, employment, transportation, and public or emergency services.

The only location where children are concentrated in the vicinity of the proposed launch areas is at the KSC Child Development Center, which is more than 9.6 km (6.0 mi) from any of the launch sites. Children at the Center may be exposed to increased noise levels during launches. However, noise levels are expected to be greatly diminished at that distance from the launch pad. Estimates of sound levels that the KSC Child Development Center would experience during a launch event with either of the potential Mars 2020 launch vehicles would be comparable to that previously evaluated for an Ares 1 or Ares V launch, which were estimated to result in the rise of daycare center exterior sound levels to 80 or 90 dBA. The interior sound levels at this time may differ from 10 to 15 dBA less than the exterior. The duration of these increased sound levels, both interior and exterior, would be less than 30 seconds (NASA 2007c). These sound levels would be shorter in duration and lower in frequency than experienced during the use of gas-powered mowers maintaining the grounds at the KSC Child Development Center. Therefore, the proposed action would not pose disproportionately high or adverse short- or long-term impacts to children's environmental health or safety (NASA 2013a).

#### 4.1.2.9. Cultural/Historic/Archaeological Resources

Impacts on cultural resources could be considered substantial if the proposed action results in disturbance or loss of values or data that qualify a site for listing in the National Register of Historic Places (NRHP); substantial disturbance or loss of data from newly discovered properties or features prior to their recordation, evaluation and possible treatment; or substantial changes to the natural environment or access to it such that the practice of traditional culture or religious activities would be lost.

The proposed action would use existing facilities for payload processing, existing roadways for payload transportation, and existing launch facilities. No new facilities are proposed and no new construction or modifications to existing facilities would be required for the proposed action. There would be no effect on buildings, structures, objects, districts, or sites such as LC-39A that are listed or eligible for listing in the NRHP. New facilities or modifications to existing facilities required to support near-term Falcon Heavy operations at KSC/CCAFS are expected to be in place with multiple Falcon Heavy launches occurring prior to the proposed Mars 2020 mission. In addition, there is a programmatic agreement between KSC, the Advisory Council on Historic Places and the Florida State Historic Preservation Officer regarding management of historic properties at KSC (NASA 2005a, 2010, 2011). No short- or long-term impacts would occur to cultural, historic, or archeological resources as a result of a normal launch.

#### 4.1.2.10. Hazardous Materials and Hazardous Waste

Hazardous materials and solid wastes are controlled in accordance with federal and state regulations. CCAFS and KSC have established procedures to implement these regulations. All hazardous material releases must be reported to the Florida Department of Environmental Protection (FDEP). All hazardous waste must be properly containerized, stored, labeled, manifested, shipped, and disposed of in full regulatory compliance. Any hazardous materials remaining after completion of processing would be properly stored for future use or disposal in accordance with applicable regulations.

The processing of a launch vehicle at a launch site requires the use of hazardous materials and results in the production of hazardous wastes. Impacts due to use of large quantities of hazardous materials and creation of large quantities of hazardous waste could be significant; however, through the use of established hazardous material management and pollution prevention procedures the amounts would be minimized to the greatest extent possible. Hazardous materials and hazardous waste impacts from launch and launch vehicle processing are therefore considered minimal (KSC 2013).

With the proper procedures and safeguards in place, it is not expected that soil, water or groundwater impacts would be caused by operations associated with handling hazardous materials or the production and handling of hazardous waste during a normal launch phase. In this regard, no short- or long-term impacts are expected.

#### 4.1.2.11. Health and Safety

At CCAFS/KSC, procedures would be in place for the Mars 2020 mission launch operations, and would include considerations for a normal launch, launch-related accidents, fire protection, alarm, fire suppression, flight termination, and explosive safety (USAF 1998, USAF 2000). Using procedures established for existing launch systems, risks to installation personnel and the general public would be minimized to acceptable levels during both a normal and aborted launch in accordance with the most current USAF's *Range Safety User Requirements Manual* (USAF 2004).

Regardless of the launch vehicle selected, Range Safety at CCAFS/KSC would use models to predict launch hazards to the public and to launch site personnel prior to the launch. The most substantial potential health hazard during a normal Mars 2020 launch would be exposure to HCl emitted from the Atlas V SRBs if the Atlas V is selected as the launch vehicle. These models calculate the risk of injury resulting from toxic exhaust gases from normal launches and from potentially toxic concentrations due to a failed launch. The launch would be postponed if the predicted collective public risk of injury from exposure to toxic exhaust gases exceeds acceptable limits (USAF 2004). This approach takes into account the exhaust plume's concentration, direction, and dwell time; and emergency preparedness procedures (USAF 2000).

CCAFS/KSC Range Safety would monitor launch surveillance areas to ensure that risks to people, aircraft, and surface vessels are within acceptable limits. For the Mars 2020 mission, a launch trajectory would be created and modified to ensure safety on the ground and at sea, and control areas and airspace would be closed to the public as required. The underlying areas at risk from falling debris or jettisoned stages would be cleared until all launch operations are completed. The SRB casings of the Atlas V would land closest to shore, in pre-approved drop zones centered at distances of approximately 230 km (143 mi) from shore. The strap-on common booster cores (CBCs) of the Delta IV and the boosters of the Falcon Heavy would land in pre-approved drop zones farther from shore. Finally, the payload fairing sections and the first stage would land much farther from shore, also in pre-approved drop zones (USAF 2000). These distances would be highly dependent on the specific Mars 2020 launch vehicle, its launch trajectory characteristics, and other factors such as wind effects.

The USAF would disseminate a Notice to Aviators through the Federal Aviation Administration (FAA); and air traffic in a FAA-designated area around the launch corridor would be controlled. Radar surveillance for intruding aircraft within a 50 nautical mile (93 km, 58 miles) radius of the launch site would be conducted beginning 30 minutes prior to the scheduled launch and continue until the launch is complete. The USAF also would ensure that a Notice to Mariners within a predetermined impact debris corridor is disseminated 10 working days prior to launch. The U.S. Coast Guard would transmit marine radio broadcast warnings to inform vessels of the effective closure time of the sea impact debris corridor. Warning signs would be posted in various Port Canaveral areas for vessels leaving port (USAF 1998). In addition, Patrick Air Force Base would maintain a website and toll-free telephone number with launch hazard area information for mariners and restricted airspace information for pilots.

#### 4.1.2.12. Environmental Justice

Launch of the proposed Mars 2020 mission would not be anticipated to result in disproportionately high and adverse impacts to low income or minority populations. Further details are presented in Appendix C.

#### 4.1.2.13. Aesthetics

Because the launch sites at CCAFS/KSC considered for the proposed action are existing sites and are located in industrialized areas, the visual sensitivity is low. Therefore, the proposed action is not expected to have short- or long-term impacts related to aesthetics.

#### 4.1.2.14. Global Environment

While not regulated, rocket engine combustion is known to produce gases and particles that reduce stratospheric ozone concentrations locally and globally (WMO 2006, NASA 2011). A large fraction of these emissions, $CO_2$ for example, are chemically inert and do not affect ozone levels directly. Other emissions, such as HCl and $H_2O$, are not highly reactive, but have an impact on ozone globally since they participate in chemical reactions that help determine the concentrations of ozone-destroying gases known as radicals.

Table 4-1 presents the emissions from propulsion systems of the type utilized by launch vehicles that could most affect stratospheric ozone, grouped according to oxidizer and fuel combination: solid propellant using ammonium perchlorate and aluminum, LOx and liquid hydrogen, and LOx and kerosene. Table 4-1 does not account for all emissions, only those most relevant to ozone chemistry. For example, all of the systems emit $CO_2$, but $CO_2$ does not play a direct role in ozone chemistry in the stratosphere.

**Table 4-1. Launch Vehicle Emissions**

| Propellant | Launch Vehicles | Emissions |
|---|---|---|
| LOx/$H_2$ | Delta IV | $H_2O$ ($NO_x$, $HO_x$) |
| LOx/RP-1 (kerosene) | Atlas series, Falcon series | $H_2O$ ($NO_x$, $HO_x$), soot (carbon), $H_2SO_4$ |
| Solid | Atlas series with SRBs | $H_2O$, HCl, $Cl_x$, $NO_x$, ($HO_x$), $Al_2O_3$ |

**Note:** $Al_2O_3$, soot, and sulfate particles less than 5 microns. Parenthesis denotes compounds that have not yet been measured but are expected to be present.
**Key:** $Al_2O_3$=Alumina; Clx=Chlorine, includes: Cl, $Cl_2$, and ClO; $H_2$=Hydrogen; $H_2O$=Water; HCl=Hydrogen Chloride; HOx=Hydrogen Oxides, includes: OH=hydroxide ion, $H_2O$; $H_2SO_4$=Hydrogen Sulfate; LOx=Liquid oxygen; NOx=Nitrogen Oxides, includes: NO, $NO_2$, $NO_3$; RP-1=Rocket Propellant.

The relative emission rate (mass of emitted compound per mass of propellant consumed) has not been accurately determined for all of the compounds listed in Table 4-1. Rocket engine combustion computer models have been used to estimate the emission rates for some compounds (NASA 2011).

Direct measurements using high-altitude aircraft have validated the model predictions in some cases (Ross 2000, Ch. Voigt et.al. 2013). The combustion models have not yet been used to estimate the rates for some important compounds, although theoretical considerations suggest they should be present in the exhaust in small quantities.

The impact of rocket emissions is separated into an immediate local response following each launch and a long-term global response that reflects the steady, cumulative influence of all launches. Fast chemical reactions between reactive plume gases, particles, and the surrounding air cause the local response. This can result in 100 percent ozone loss within the plume (Ross 2000, Murray, et.al. 2013). This phase can last for several days until the reactive exhaust gases have been largely deactivated, and the plume has substantially dispersed. The ozone loss in this phase, while dramatic, does not likely contribute significantly to the global impact (Danilin 2001), at least for SRB emissions and additional data collected by NASA indicate local ozone levels tended to recover to ambient levels after a number of hours (NASA 2011, Murray et al. 2013).

The global response is driven by the accumulation of all gas and particulate emissions over a long period of time after the exhaust has been mixed throughout the stratosphere. An approximate steady state is achieved as exhaust from newer launches replaces the exhaust from older launches, which is removed from the stratosphere by the global atmospheric circulation, a process that takes about 3 years. The emitted compounds add to the natural reservoirs of reactive gases and particle populations that control ozone amounts (NASA 2011).

Of the three propellant combinations that would be utilized by the proposed launch vehicles and listed in Table 4-1, only SRB emissions have been studied in depth. The local and global impact of chlorine emitted by SRBs has been extensively measured and modeled and is relatively well understood (i.e., WMO 1991, 2006). SRBs release reactive chlorine gases directly in the stratosphere and in this case, the quantities are small in comparison with other tropospheric sources. Stratospheric accumulation of chlorine and alumina exhaust from current launch activities leads to small (less than 0.1 percent) global column ozone decreases and data support this conclusion (WMO 2006, NASA 2011).

The global atmospheric models that have been successfully applied to SRB emissions have not been applied to liquid emissions. The few findings that have been published highlight the reactive gas and soot emissions of kerosene-fueled engines and associated potential for ozone impacts (Newman 2001; Ross 2000). Because of the scant data and lack of modeling tools, it is not possible to estimate the impact of liquid propellant systems with the same degree of confidence as has been done for solid propellant systems. Further research is required before the stratospheric impacts of $LOx/LH_2$ and LOx/RP-1 (kerosene) combustion emissions can be quantified (NASA 2011).

Among the proposed launch vehicles, the Atlas V 551 emits the greatest amount of SRB exhaust into the stratosphere. It has been estimated that the ozone loss per Atlas V 551 launch is 0.077 percent (USAF 2000). The present state of the stratosphere is characterized by global ozone loss of about 4 percent, caused by past use of chlorofluorocarbons (CFCs) and other controlled materials (NASA 2011). The launch of any of the proposed launch vehicles is not expected to significantly increase ozone loss.

As a result of launch of the Delta or Falcon rockets, black carbon "soot" would be emitted directly in the stratosphere above 20 km (12 mi). These black carbon or soot particles can have a greater impact on climate change than rocket emissions of $CO_2$. Black carbon is known to be the second most important compound driving climate change. In modeling studies, utilizing the Whole Atmosphere Community Climate Model, researchers have shown these soot particles may accumulate into a thin cloud at an altitude of about 40 km (25 mi), which remains relatively localized in latitude and altitude (Ross, et al. 2010). The model suggests that if this layer reached high enough concentrations, the Earth's surface and atmospheric temperatures could be altered. The globally integrated effect of these changes is, as for carbon dioxide, to increase the amount of solar energy absorbed by the Earth's atmosphere. Research on the potential climate change impacts of black carbon from rockets is in a very early stage and projections of impacts are being refined (NASA 2013a).

Mitigation and/or minimization of this potential impact are being addressed in the aerospace industry by advancing propulsion system designs and innovative fuel mixtures that burn cleaner and reduce soot formation (NASA 2013a). At present, impacts from black carbon "soot" emitted as a result of the launch of one Atlas or Falcon series vehicle are considered minor

Concerning long-term effects, launch of the proposed Mars 2020 mission on the Atlas V, Delta IV, or Falcon Heavy would not be expected to make substantial contributions to the amounts of ozone-depleting chemicals or greenhouse gases in the atmosphere. Some short-term ozone depletion affects would occur within the exhaust plume of the launch vehicle, but the depletion trail would be largely temporary and dissipate within a few hours of the vehicle's passage. Greenhouse gases, principally $CO_2$ (from the Atlas V and Falcon Heavy), would be emitted during launch, but the amount would be negligible. The Falcon Heavy is estimated to produce up to 976,000 kg (2,151,000 lb) of $CO_2$ per launch (USAF2011). This is on the order of one hundred-thousandths ($10^{-5}$) of a percent compared to the net greenhouse gases emitted by the United States in 2011 of approximately $5.8x10^{12}$ kg ($1.3x10^{13}$ lb) measured as carbon dioxide equivalent (EPA 2013).

In conclusion, the amount of greenhouse gases emitted by the launch vehicle for the Mars 2020 mission would therefore be anticipated to negligibly contribute to ozone depletion and global climate change (NASA 2005a).

#### 4.1.2.15. Orbital and Reentry Debris

During the launch sequence of either the Atlas V, the Delta IV, or the Falcon Heavy for the Mars 2020 mission (see Figures 2-12, 2-14, and 2-16 respectively), the SRB casings of the Atlas V, the strap-on CBCs of the Delta IV, or the boosters of the Falcon Heavy; the first stage, and the PLF would be jettisoned and fall into the Atlantic Ocean in predetermined drop zones (see Section 4.1.2.11) well before reaching Earth's orbit. Shortly after separating from the first stage, the second stage engine would be ignited, accelerating the second stage and the attached spacecraft to low Earth orbit. After a brief coast period, the second stage engine would be reignited, accelerating to Earth escape velocity. After propellant depletion, the second stage would be separated from the Mars 2020 spacecraft, and the second stage would continue separately into interplanetary space. Therefore, a normal launch of the Mars 2020 mission would not contribute to orbital or reentry debris.

### 4.1.3 Non-radiological Environmental Impacts of Potential Accidents

The potential non-radiological environmental impacts associated with expendable vehicle launch accidents have been discussed in previous USAF environmental documentation (USAF 1998, USAF 2000), and are summarized here and augmented with new information where applicable. A variety of accidents could occur during preparations for launch and during launch. Only two types of non-radiological accidents would have potential environmental consequences: a liquid propellant spill occurring after the start of propellant loading operations and a launch accident. A launch accident that leads to loss of the Mars 2020 mission is estimated to occur with a probability of about 25 times out of 1,000 (SNL 2014). All launch accidents would have non-radiological impacts.

The potential consequences of these accidents are presented below.

#### 4.1.3.1. Liquid Propellant Spills

A typical Atlas V uses about 284,089 kg (626,309 lb) of RP-1 and LOx for the first stage, and about 20,830 kg (45,922 lb) of $LH_2$ and LOx, with less than 91 kg (201 lb) of hydrazine for the Centaur second stage (USAF 2000, ILS 2001). A typical Delta IV Heavy uses about 606,300 kg (1,336,663 lb) of $LH_2$ and LOx for the first stage, about 27,200 kg (60,000 lb) of $LH_2$ and LOx for the second stage, with about 154 kg (340 lb) of hydrazine for the second stage (ULA 2013, Freeman 2006). The proposed Falcon Heavy would be expected to use about 784,000 kg (1,730,000 lb) of RP-1 and LOx for the first stage, and about 49,000 kg (108,000 lb) of $LH_2$ and LOx for the second stage (NASA 2011).

The Mars 2020 spacecraft would use about 460 kg (1014 lb) of hydrazine. The first stage and second stage fueling operations for both vehicles are performed in accordance with CCAFS/KSC propellant loading protocols. Standard procedures such as use of closed loop systems are practiced, which would minimize worker exposure and the potential for fuel releases.

Accidental leaks or spills of RP-1, LOx, $LH_2$, and hydrazine could occur during propellant loading and unloading activities. Range safety requirements specify that plans and procedures be in place to protect the workforce and the public during fueling operations (USAF 2004). Spill containment would be in place prior to any propellant transfer to capture any potential release. Hydrazine transfer would involve a relatively small amount of liquid through a relatively small transfer system, so any leakage would be held to an absolute minimum. It is expected that, because of the limited quantities involved, there would be no impact to the public.

Spill kits located in the work area would be used if a release were detected during RP-1 loading. Personnel would be present in the immediate area to handle any release. Workers would be required to wear personal protective equipment while loading RP-1 and hydrazine, and all unprotected workers would be removed from the area prior to loading. The operator would remotely close applicable valves to minimize any release and safe the system.

If a spill or release is detected during LOx and $LH_2$ loading at the launch pad, the operator would remotely close the applicable valves to minimize the amount of liquid released, and safe the system. Water deluge would be used if heat were detected in the area of concern. Deluge water would be collected and treated, if necessary, prior to being released to the CCAFS/KSC wastewater treatment plant.

#### 4.1.3.2. Launch Failures and Suborbital, Orbital and Reentry Debris

***Air Quality***

The USAF has modeled postulated accidents at CCAFS involving combustion of typical launch vehicle propellants (USAF 2000). Representative meteorological conditions were used in the analyses to model movement of the exhaust cloud. Release and combustion of both liquid and solid propellants were assumed to be involved. For the modeled accidents, the principal constituents resulting from burning propellant were CO, $Al_2O_3$ particulates, and HCl; but also included $H_2$, $H_2O$, and $CO_2$. Although $Al_2O_3$ particulates would be deposited from the explosion cloud as it was carried downwind, little wet deposition of HCl would be expected unless rain falls through the cloud of combustion products. The estimated concentrations of combustion products resulting from these postulated accidents were found to be well within applicable Federal, state, and USAF standards. Based on these analyses, emissions resulting from an accident during the Mars 2020 mission launch would not be expected to exceed any of the applicable environmental standards, and would not adversely create short- or long-term impacts on air quality in the region.

***Geology and Soils***

Launch accidents could result in impacts on near-field soils due to contamination from rocket propellant. In the unlikely occurrence of a launch accident, any spilled propellant would be collected and disposed of by a certified disposal/remediation contractor in accordance with the facility Spill Prevention, Control, and Countermeasures (SPCC) plan. Contaminated soils would be removed and treated as hazardous waste in accordance with Federal, state, and local regulations. Short-term impacts to soils may result but would be minimal due to soil buffering capacities. No long-term adverse impacts to geology or soils at CCAFS/KSC would be expected from the Mars 2020 launch (USAF 1998, NASA 2005a, NASA 2006, NASA 2011)

***Water Quality***

Unburned pieces of solid propellant with high concentration of ammonium perchlorate could fall on land or into nearby bodies of water. Trace amounts of solid propellant could disassociate into ammonium ion and perchlorate ion. At low to moderate concentrations, the ammonium ion is a plant nutrient and could stimulate plant growth for short periods of time. At higher concentrations, the ammonium ion is toxic to aquatic life and could cause short-term mortalities of aquatic animals within the immediate vicinity of the launch vehicle impact.

Perchlorate could leach into surrounding water, but it would take about one-half year for 90 percent of the perchlorate to leach out in fresh water and about one year for 90 percent to leach out in salt water. At these rates, the perchlorate would be diluted as it mixes with the surrounding water. Therefore, no substantial impacts to water quality and biota in those areas would be expected as the solid propellant dissolves slowly. Pieces of unburned solid propellant falling on land would be collected and disposed of as hazardous waste. Similarly, large pieces falling in fresh water areas would be collected and properly disposed of, minimizing the potential for perchlorate contamination (DOD 2003).

Launch vehicle debris from a liquid propellant fueled rocket is considered a negligible hazard because virtually all hazardous materials are consumed in the destruct action or dispersed in the air, and only structural debris could potentially fall into the water. As with solid propellant, liquid propellant fuel also introduces ammonium perchlorate oxidizer into the water by leaching over a period of time. Studies have shown that the rate of perchlorate extraction is a function of water temperature and salinity, with the highest rates observed at the highest temperature and lowest salinity (USAF 2005).

The low toxicity of this compound together with the slow release into the water does not present a known substantial health hazard to marine life (TRW 2002).

***Biological Resources***

Birds, reptiles, and small mammals would be most at risk from impacts due to a launch accident. Potential fires could result in temporary loss of habitat and mortality for species that do not leave the area. An accident on the launch pad would frighten nearby sensitive animal species that use the Indian and Banana Rivers (such as birds in rookeries and neo-tropical birds). Threatened and endangered species, such as manatees, sea turtles, and other aquatic species, would not be expected to be adversely affected by a launch accident. Launch pad accidents resulting in full stack intact impact could result in impacts on local water bodies due to contamination from rocket propellant. In the unlikely occurrence of a launch accident, spilled propellant could enter water bodies close to the launch pad and could cause contamination primarily from hydrazine, monomethyl hydrazine (MMH), nitrogen tetroxide (NTO), and SRB propellant. Powdered aluminum from the SRB propellant would rapidly oxidize to aluminum oxide, which is non-toxic at the pH that prevails in surface waters surrounding all proposed launch sites (NASA 2011).

In the event of a launch accident, hydrazine fuel tanks may impact water. Hydrazine fuels are soluble and would disperse rapidly. Because of the small amount of hydrazine present (even in the event of a full spacecraft fuel tank impacting water), short-term impacts on the near-shore environments may result, but long-term impacts would not be significant due to the buffering capacity of large water bodies (NASA 2008). Debris from launch failures has the potential to adversely affect managed fish species and their habitats in the vicinity of the launch site. Ammonium perchlorate in solid propellant contains chemicals that, in high concentrations, have the potential to result in adverse impacts to the marine environment. As noted above, however, perchlorate would leach out slowly and be diluted to low concentrations in the surrounding water, posing little impact to the marine environment (DOD 2003). The USAF has consulted with the National Marine Fisheries Service on essential fish habitat regarding launches from CCAFS (USAF 2000) of vehicles using SRBs. Launch of the Mars 2020 mission from CCAFS would be covered under this consultation.

Residual RP-1 fuel is weakly soluble, would spread over the surface of the water, and should evaporate within a few hours, resulting in only a short-term impact to aquatic biota.

The environmental impact of objects falling into the ocean would depend on the physical properties of the materials (e.g., size, composition, quantity, and solubility) and the marine environment of the impact region. Based on past analyses of other space components, it is expected that the environmental impact of reentering orbital debris would be negligible (NASA 2005b; USAF 1998). There is a remote possibility that surviving pieces of debris could impact marine life or vessels on or near the ocean surface. Once the pieces travel a few feet below the ocean surface, their velocity would be slowed to the point that the potential for direct impact on sea life would be low (NASA 2008, NASA 2011).

***Health and Safety***

A launch vehicle accident either on or near the launch pad within a few seconds of lift-off presents the greatest potential for impact to human health, principally to workers. For the proposed Mars 2020 mission, the primary potential health hazard during a launch accident would be from the HCl emitted from burning solid propellant from the SRBs. Range Safety at CCAFS/KSC uses models to predict launch hazards to the public and to personnel prior to every launch. These models calculate the risk of injury resulting from toxic gases, debris, and blast overpressure from potential launch failures. Launches are postponed if the predicted collective public risk of injury exceeds acceptable limits, which are applied separately for the risk of injury from exposure to toxic gases, debris, and blast overpressure (USAF 2004). This approach takes into account the probability of a catastrophic failure, the resultant plume's toxic concentration, direction, and dwell time, and emergency preparedness procedures (USAF 2000).

Range Safety requirements mandate destruct systems on liquid propellant tanks and SRBs (see Section 2.1.6.4). In the event of destruct system activation, the propellant tanks and SRB casings would be ruptured and the entire launch vehicle would be destroyed. A catastrophic launch failure would involve burning solid propellant and the ignition of liquid propellant. The potential short-term effects of an accident would include a localized fireball, falling debris from explosion of the vehicle, release of unburned propellants and propellant combustion products, on-pad or very low altitude explosions, death or damage to nearby biota, and brush fires near the launch pad.

Beginning two hours before launch, a Brevard County Emergency Management Center representative would be present at a CCAFS launch console with direct audio and video communications links to the Center. The USAF also has a direct emergency phone line to the Florida State Emergency Response Center.

For suborbital, orbital. and reentry debris, standard safety review processes require that NASA missions comply with the re-entry requirements of the NASA Standard 8719.14, Process for Limiting Orbital Debris. This NASA Standard (i.e., Requirement 4.7.1) limits the risk of human casualty from re-entry debris to 1 in 10,000 and requires that missions be designed to assure that, in both controlled and uncontrolled entries, domestic and foreign landmasses are avoided.

NASA studied the potential risks associated with reentry and Earth impact of spacecraft propellant tanks, specifically in regard to a late launch failure to insert a spacecraft into a typical parking orbit for later deep space trajectory injection. The study relied primarily on existing data and analyses supplemented by a detailed assessment of the potential impacts of a suborbital accident from the Eastern Range (CCAFS) involving approximately 400 kg (882 lb) of hydrazine reaching land. This case was determined to represent a wide range of potential accidents involving hydrazine propellants (NASA 2011).

The study of a postulated release of approximately 400 kg of residual hydrazine as a result of a suborbital accident for a launch from the Eastern Range indicates there is less than 1 chance in 10,000 (including the probability of the launch accident and ground impact) of harming any individual based on the 1-hour interim Acute Exposure Guideline Level-2 (AEGL-2) value of 13 ppm (17 mg/m3) established by the EPA for hydrazine [http://www.epa.gov/oppt/aegl/index.htm]. In fact, a larger release of hydrazine (i.e., a factor of 2 to 3 higher) or approximately 1,200 kg under the same circumstances would still pose less than 1 chance in 10,000 of harming any individual, including the probability of the launch accident and ground impact (NASA 2011). Specifically, for the MSL spacecraft, an analysis showed that under certain launch accident conditions, there was a small probability the spacecraft with a full propellant load (475 kg) could reenter prior to achieving orbit and impact land in southern Africa or Madagascar. The probability of such an accident occurring and leading to a land impact was determined to be on the order of 1 in 20,000. The overall risk of an individual injury resulting from the land impact of a spacecraft and exposure to hydrazine was determined to be less than 1 in 100,000 (NASA 2010b).

In accident scenarios occurring after achievement of the parking orbit, analysis for the MSL spacecraft determined it could reenter from orbit and potentially impact land anywhere between 36° north and south of the equator. Under these conditions, only a small portion (i.e., less than about 5%) of the full propellant load could reach the ground if the tanks did not burst due to reentry heating effects and release their contents into the atmosphere. The overall probability of this type of accident occurring was determined to be less than 1 in 200. In this type of accident, it is extremely unlikely that there would be any residual hydrazine remaining inside the propellant tanks at the point of ground impact (NASA 2010b).

Because of the increasing number of objects in space and their potential for reentry, NASA adopted guidelines and assessment procedures to reduce the number of non-operational spacecraft and spent rocket upper stages orbiting the Earth. NASA's launch Project Managers must employ design and operation practices that limit the generation of orbital debris, consistent with mission requirements and cost effectiveness.

NPR 8715.6A, *NASA Procedural Requirements for Limiting Orbital Debris*, requires that each program or project conduct a formal assessment for the potential to generate orbital debris and to analyze the impacts of space structure reentry. NASA also has a technical standard (NASA-STD 8719.14) and corresponding handbook (NASA-NHBK 8719.14) to provide specific guidelines and methods to limit orbital debris generation.

To mitigate potential safety and environmental impacts from orbital debris generation and space structure reentry, all NASA orbital missions originating from the proposed launch facilities would comply with the processes outlined in NPR8715.6A and NASA-

STD 8719.14, both of which establish requirements for (1) limiting the generation of orbital debris, (2) assessing the risk of collision with existing space debris, (3) assessing the potential of space structures to impact the surface of the Earth, and (4) assessing and limiting the risk associated with the end of mission of a space object. These requirements apply to both full spacecraft and jettisoned components, including launch vehicle orbital stages.

For accidents involving suborbital debris, parts of the exploded vehicle would fall back to Earth. Except for on-pad or near-pad accidents, most of the fragments would fall into the Atlantic Ocean, where the metal parts would eventually corrode. Toxic concentrations of metals would be unlikely because of slow corrosion rates and the large volume of ocean water available for dilution (USAF 1996, NASA 2011).

### 4.1.4 Environmental Impacts of Potential Accidents Involving Radioactive Material

NASA and the U.S. Department of Energy (DOE) have assessed the potential environmental impacts of launch accidents involving release of plutonium dioxide ($PuO_2$). The analysis results indicate that the most likely outcome of implementing the proposed Mars 2020 mission is a successful launch of the spacecraft toward Mars. If, however, a launch accident were to occur, the most probable outcome is an accident without a release of the $PuO_2$. Specifically:

- There is a 97.5% chance of a successful launch.
- There is a 2.5% chance of a launch accident.
- There is a 1 in 2,600 chance of a launch accident that would release plutonium dioxide.
    - There is a 1 in 11,000 chance of a launch accident that would result in a release of plutonium dioxide in the launch area.
    - There is a 1 in 3,500 chance of a launch accident that would result in a release of plutonium dioxide outside the launch area.
- No radiological fatalities would be expected to occur as a result of any accident.
- The average maximum dose to any member of the public from an accident with a release would be equal to about 3 months of exposure to natural background radiation for a person living in the United States.

The launch success probability is estimated for a composite launch vehicle to successfully complete all pre-launch operations, first stage flight, second stage flight, and conclude with successful insertion of the spacecraft into the proper Earth escape trajectory toward Mars. The composite launch vehicle accident probabilities were derived by combining the estimated accident probabilities for the Atlas V and Delta IV launch vehicles from the Mars 2020 Representative Databook (NASA 2013). As such, these estimated probabilities do not reflect the reliability of any single launch vehicle.

The consequences and their probabilities are based upon these launch vehicle accident probabilities and estimated release probabilities in DOE's *Nuclear Risk Assessment for the Mars 2020 Mission Environmental Impact Statement* (SNL 2014).

This section summarizes the results from the DOE's nuclear risk assessment (SNL 2014).

NASA, DOE, and its contractors have conducted several safety assessments of launching and operating spacecraft using RTGs (e.g., the Galileo mission in 1989, the Ulysses mission in 1990, the Cassini mission in 1997, the New Horizons mission in 2005, and the Mars Science Laboratory mission in 2011). In developing the nuclear risk assessment for this DEIS, NASA and DOE have drawn from an extensive experience base that involves:

- testing and analysis of the General Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG) and its components (e.g., fueled iridium clads and GPHS modules) (see Section 2.1.3) under simulated launch accident environments;
- evaluating the probability of launch-related accidents based on evaluations of system designs and launch histories, including extensive studies of the January 1997 Delta II accident at CCAFS, and of launch vehicle designs; and
- estimating the outcomes of the response of an RTG and its components to the launch accident environments.

The information and results presented in the DOE risk assessment and summarized in this DEIS are the result of the evolution of the risk assessments performed for previous missions which included nuclear materials (e.g., Cassini, the Mars Exploration Rovers (MERs), New Horizons, and Mars Science Laboratory).

#### 4.1.4.1. Risk Assessment Methodology

The nuclear risk assessment for the Mars 2020 mission considers (1) potential accidents associated with the launch and their probabilities and resulting environments; (2) the response of the MMRTG to such accident environments in terms of varying amounts of radioactive material that are released and become airborne (source terms) and the release probabilities; and (3) the radiological consequences and risks associated with such a release. The risk assessment was based on an MMRTG typical radioactive material inventory of approximately 60,000 curies (Ci) of plutonium (Pu) 238 (an alpha-emitter with a 87.7 year half-life) in the form of plutonium dioxide. The activity includes minor contributions from other related plutonium and actinide radionuclides (see Table 2-3).

As discussed in Chapter 2, previous missions (MER and MSL, for example) have carried instruments that included up to two curies of radioactive source material. While the Science Definition Team for the Mars 2020 Mission identified the types of instruments that would be needed to meet the goals of the mission (Mars 2020 SDT 2013), it did not specify the instrumentation that would be included on the rover. NASA is currently in the process of selecting the instrumentation package for the Mars 2020 mission. The selection criteria do not preclude instrumentation with small quantity radioactive sources. Therefore, in addition to the plutonium in the MMRTG, the Mars 2020 rover could carry small quantities of radioactive sources. DOE's risk analysis does address small quantity source terms. Previous analyses have shown that of the radioisotopes that might be used on the science instruments for the Mars 2020 mission, the most risk significant isotope would be curium-244 (Cm-244). This isotope has previously been used on the MERs as well as on the MSL Curiosity rover. Since the selection of science instruments, and any associated radioisotopes, is pending and is independent of the power source for the rover (MMRTG, solar, or solar and LWRHUs) the results of the small source term risk analysis are presented separately from those for the MMRTG. These results should provide some perspective on the relative risks associated with the MMRTG and any small quantity radioactive sources that could be used in the Mars 2020 mission.

A composite approach has been taken in reporting the results in the DOE risk assessment for this DEIS for accident probabilities, potential releases of $PuO_2$ in case of an accident (with that portion of the release becoming airborne called source terms), radiological consequences, and mission risks. In the composite approach, the results for the representative Atlas V 551 and Delta IV Heavy launch vehicles were combined in a probability-weighted manner. DOE's risk assessment was developed during the time when the candidate launch vehicles being considered by NASA for the Mars 2020 mission were the Atlas V 541 and 551, the Delta IV Heavy, and the Falcon Heavy. Data for the Atlas V 551 was used to represent both Atlas V launch vehicles; Delta IV Heavy data was used to represent both the Delta IV Heavy and the Falcon Heavy. The primary difference between the Atlas V 551 and the Atlas V 541 is one additional solid rocket booster on the Atlas V 551. Therefore, the consequences associated with launch accidents for the Atlas V 541 would be enveloped by those for the Atlas V 551 launch accidents. While many details regarding the Falcon Heavy design are not presently available, both the Delta IV Heavy and Falcon Heavy are large boost capacity liquid fueled launch vehicles. Both consist of a liquid propellant fueled first stage core with two nearly identical boosters and a second stage powered by a single liquid fueled engine. Differences in the launch vehicles in terms of design, accident probabilities, and accident environments have been taken into account in developing composite results.

The basic steps in the risk assessment methodology are presented in Figure 4-1. The nuclear risk assessment for the Mars 2020 mission DEIS began with the identification of initial launch vehicle system failures and the subsequent chain of accident events that could ultimately lead to accident environments that could threaten the MMRTG. These launch vehicle system failures were based on Atlas V 551 and Delta IV Heavy system reliabilities and estimated failure probabilities developed by NASA (NASA 2012, 2013).

Some intermediate accident events (such as fragments from a propellant tank explosion) and final accident configurations (such as the MMRTG impacting the ground near burning solid propellant) have the potential to create accident environments that could damage the MMRTG and result in the release of $PuO_2$. Based on analyses performed for earlier missions that carried radioisotope devices[13], DOE identified the specific accident events that could potentially threaten the MMRTG. Eight accident events were identified for consideration for the Mars 2020 mission DEIS:

[13] RTGs and radioisotope heater units (which contain about 2.7 grams (0.1 ounce) of $PuO_2$, and generate 1 watt of heat for passive thermal control). Radioisotope heater units are not planned for the Proposed Action (Alternative 1).

(1) Liquid propellant explosions;

(2) Solid propellant explosions;

(3) Liquid propellant fires;

(4) Solid propellant fires;

(5) Fragments;

(6) Ground impacts;

(7) Debris impact; and

(8) Reentry conditions (i.e., aerodynamic loads and aerodynamic heating).

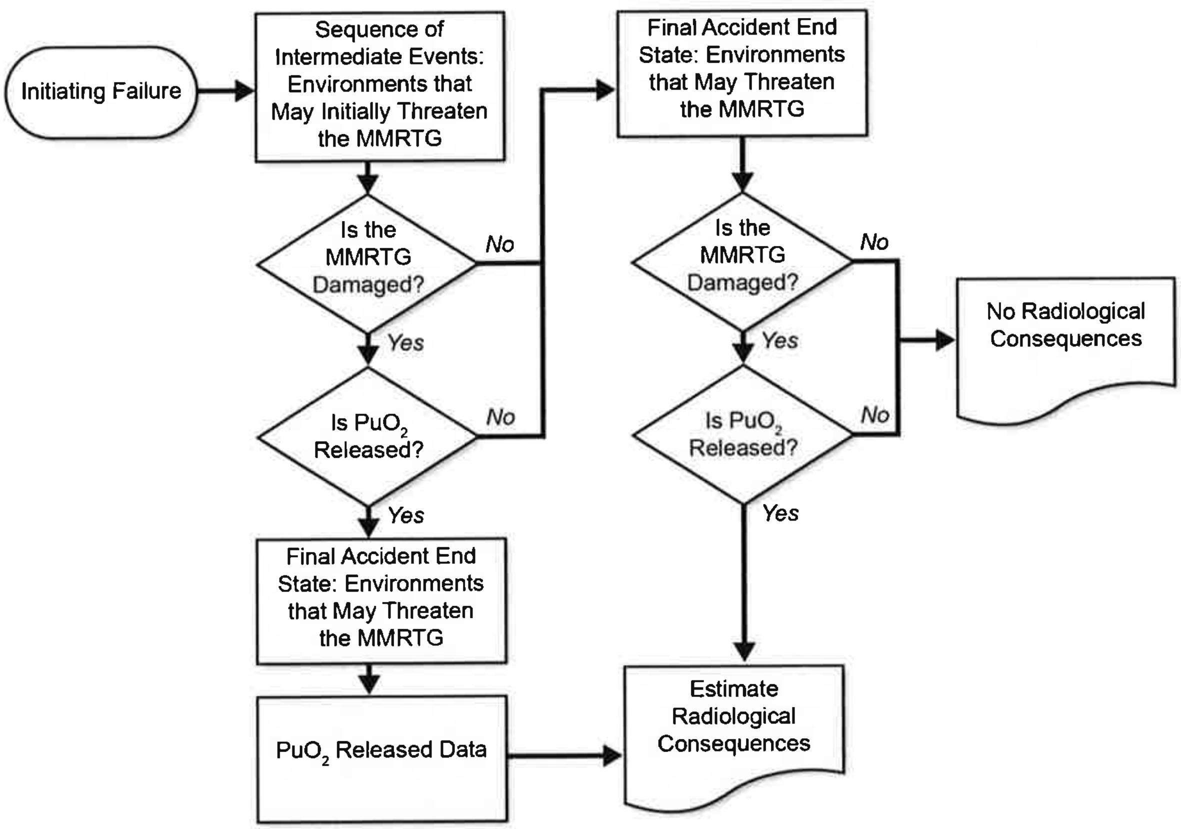


**Figure 4-1. The Radiological Risk Assessment Methodology**

A given accident could involve one or more of these environment characteristics. The severity of the environments would vary from accident to accident. NASA has conducted a number of experiments to improve understanding of accident environments. The ongoing Solid Propellant Fire Tests and the Star 37 Motor Drop Tests are two most recent experiments for this purpose.

DOE determined the response of the MMRTG and GPHS modules to these accident environments and estimated the amount of radioactive material that could potentially be released. Results of DOE's testing and analyses program for previous configurations of RTGs were used to determine if a release of radioactive material from the MMRTG could potentially occur. The release fractions (the fraction of the $PuO_2$ that would be released to the environment) were determined by considering five accident environments: explosive overpressure, fragment impact, mechanical impact, thermal environments (liquid propellant fires and explosions and solid propellant fires), and reentry conditions. The source term (that portion of $PuO_2$ released from the MMRTG that becomes airborne and can be transported downwind) for the MMRTG are based on the results of DOE safety testing and computer modeling.

DOE's testing program examined the response of the MMRTG and GPHS modules to accident environments. The testing program has improved DOE's understanding of the response of the MMRTG and GPHS modules to reentry, impact, and solid propellant fire conditions. DOE incorporated design modifications to address issues identified in testing or changes in mission architecture. In particular, the GPHS modules have been updated over time with design improvements for increased reentry survivability, impact, and fire protection since its original design for the GPHS-RTG.

A better understanding of the response of the MMRTG to accident environments has also allowed DOE to reduce conservatisms in the computer models used to simulate their response to accident environments. Combined with improving computing capabilities (both in machine capability and computer model refinements that result in higher fidelity models), the computer models are better and more precisely able to predict the response of the MMRTG to accident environments.

The consequences of postulated releases were estimated by determining the consequences associated with each of the two surrogate launch vehicles (the Atlas V 551 and the Delta IV Heavy) as they would be used for the Mars 2020 mission. Parameters considered in the consequence analysis include: 2020 population estimates, plume configuration, launch complex location, historical meteorology during the July to September launch period, particle size distributions derived from the response of the MMRTG to accident environments, and key environmental factors such as solid propellant amount and geometry. Consequence values for population dose, maximum exposed individual dose, population health effects[14], and land contamination were estimated at both mean and $99^{th}$ percentile values.

### 4.1.4.2. Launch Accidents and Accident Probabilities

For the purpose of this risk assessment, the Mar 2020 mission was divided into six mission phases on the basis of mission elapsed time, the time in seconds relative to launch, reflecting principal launch events. The key events in defining the mission

[14] Additional latent cancer fatalities due to a radioactive release (i.e., the number of cancer fatalities resulting from this release that are in addition to those cancer fatalities which the general population would normally experience from other causes).

phases are: the start of the first stage main engines which occurs shortly before liftoff, liftoff[15], the time at which the there is no longer a possibility that debris from an accident would impact in the vicinity of the launch area, the time at which any debris from an accident would be subject to suborbital reentry heating, and the time orbit is achieved. These events occur at different mission elapsed times for the Atlas V and Delta IV vehicles.

- Phase 0—Pre-Launch: from the installation of the MMRTG to just prior to the start of the first stage main engine
- Phase 1—Early Launch: from the start of the first stage main engines to just prior to the time after which there would be no potential for debris or an intact vehicle configuration to impact land in the launch area, and water impact would occur
- Phase 2—Late Launch: from the end of Phase 1 to when the launch vehicle reaches an altitude of about 30 km (100,000 ft), an altitude above which reentry heating could occur
- Phase 3—Suborbital Reentry: from an altitude of about 30 km (100,000 ft) to the first engine cutoff of the second stage and the Command Destruct System (CDS) is disabled
- Phase 4—Orbit Reentry: from the first engine cutoff of the second stage to separation of the spacecraft from the second stage
- Phase 5—Long-term Reentry: from spacecraft separation to no chance of spacecraft reentry.

The methodology used to calculate the Atlas V and Delta IV probabilities utilized flight histories of comparable United States and Russian launch vehicles flown since 1988. This flight history consists of earlier versions of Atlas and Titan launch vehicles manufactured by the Lockheed Martin Corporation, Delta launch vehicles manufactured by The Boeing Company, and other launch vehicles. This is done to provide some assurance to the estimate that all past applicable and partially applicable flight failure experiences are considered in the reliability estimate of the launch vehicle for the Mars 2020 mission. The analytical approach for the overall mission launch reliability is considered by NASA to be generally representative of the available launch vehicles for this mission, including the Falcon Heavy, and is based upon the most recent best available information at the time of the analysis. NASA continues to evaluate the reliability of the candidate launch vehicles (NASA 2013).

Accidents and their associated probabilities were developed in terms of initiating failures, defined as the first system-level indication of an anomaly that could lead to a launch abort (i.e., safe hold or termination of the launch countdown), catastrophic accident, or mission failure. An example of an initiating failure would be a trajectory control malfunction resulting in the launch vehicle deviating from its planned trajectory. An initiating failure is the beginning of a sequence of intermediate events that lead to a

[15] The main engine undergoes an automatic health check beginning at first-stage main engine start. Should a malfunction be detected before liftoff, the engine would be shut down and the launch would be aborted.

range of possible end states, including accident configurations involving the MMRTG and various launch vehicle stages[16] and the Mars 2020 spacecraft. For example, activation of the Flight Termination System (FTS) following a trajectory control malfunction could lead to the MMRTG impacting the ground. Associated with the accident configuration end states are the environments that could damage the MMRTG and result in the release of $PuO_2$.

Pre-Launch ($T < 0$ seconds) initiating failures include tank failures, MMRTG cooling system failures, and inadvertent FTS activation. Pre-Launch initiating failures generally involve conditions that can be mitigated by existing systems or procedures, leading to mission abort rather than accidents that threaten the MMRTG.

The Launch and Post Launch ($T \geq 0$seconds) initiating failures include:

- Ground Support Equipment failure during liftoff
- Trajectory and attitude control malfunctions
- Propellant tank failures
- Catastrophic main engine failures affecting either the Stage 1 or Stage 2 engines
- SRB case failure (in the Atlas V 551)
- Structural failure
- Inadvertent FTS activation or payload fairing (PLF) separation
- Staging failure.

The post launch (Phase 1 and 2) accident end states that can result from the initiating failures are determined to a large degree by the FTS actions (see Section 2.1.6.4) that occur or do not occur during the accident progression following the initiating failure. Important FTS considerations affecting the end states are:

- Automatic Destruct System (ADS). The ADS destroys the Stages 1 and 2 liquid propellant tanks and the SRBs (on the Atlas V 551). The ADS is safed (automatically deactivated) prior to Stage 1 / 2 separation.
- Command Destruct System (CDS): The CDS is activated by the Mission Flight Control Officer (MFCO) and destroys the launch vehicle in the same manner as the ADS. The MFCO would likely issue a CDS in case of a trajectory or attitude control malfunction, where the launch vehicle deviation from the planned trajectory violates specific range safety criteria for continuation of a safe launch. Should the MFCO response time needed for a CDS be insufficient, ground impact of the entire vehicle (termed full-stack intact impact, or FSII) could result. The CDS is safed at the end of the first Stage 2 burn.

The initiating failures therefore lead to one or more of the following accident end states, denoting conditions of first threat to the MMRTG:

[16] For brevity in the following discussion, the first and second stages of the Mars 2020 launch vehicle and the Mars 2020 spacecraft, are sometimes referred to as Stages 1 and 2, and SV respectively.

- On-Pad Explosion, occurring as a result of accidents occurring during Pre-Launch or very near the pad just prior to actual liftoff and 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 spacecraft (SC) to an FTS would depend on the launch vehicle and the accident environment conditions
- Full Stack Intact Impact (FSII), in which the entire launch vehicle stack impacts the ground
- Stage 2/ Space Vehicle (SV) Impact, in which Stage 2/SV impacts the ground
- SV Intact Impact (SVII), in which the intact SV impacts the ground
- Sub-orbital reentry
- Orbital reentry, referring to reentry after decay from orbit. Other types of reentry are possible (e.g., prompt), but at a much lower probability.
- Long-term reentry, referring to Earth reentry of the spacecraft after a spacecraft maneuver failure enroute to Mars. These type accidents may not occur for tens to hundreds of years after launch.

The composite accident end state probabilities for the composite launch vehicle are presented in Table 4-2.

For this DEIS, the initiating probabilities and total probabilities of an accident with a release of PuO2 are grouped into categories that allow for a descriptive characterization of the likelihood of each accident. The categories and their associated probability ranges are:

- unlikely: 10-2 to 10-4 (1 in 100 to 1 in 10 thousand)
- very unlikely: 10-4 to 10-6 (1 in 10 thousand to 1 in 1 million)
- extremely unlikely: less than 10-6 (less than 1 in 1 million).

Some of these types of launch accidents occurred during the early development of launch vehicles in the United States; subsequently, changes were made to both vehicle design practices and range safety systems to prevent future occurrences. These accidents, in general, require multiple failures of both launch vehicle and range safety systems. Probability differences of a factor of a few percent would not represent statistically significant differences and are well within uncertainty bounds. The discussion of the probabilities by broad frequency categories is more appropriate.

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## Table 4-2. Alternative 1 Accident End State Probabilities

| Ground Impact Configuration[(a)] | Phase 0 | Phase 1 | Phase 2 | Phase 3 | Phase 4 | Phase 5 | Total Probability |
|---|---|---|---|---|---|---|---|
| On-Pad Explosion | $3.0 \times 10^{-5}$ | $9.8 \times 10^{-5}$ | - | - | - | - | $1.3 \times 10^{-4}$ |
| FSII | - | $2.2 \times 10^{-5}$ | - | - | - | - | $2.2 \times 10^{-5}$ |
| Stage 2/SV | - | $4.8 \times 10^{-5}$ | - | - | - | - | $4.8 \times 10^{-5}$ |
| SVII | $2.8 \times 10^{-6}$ | $6.3 \times 10^{-7}$ | - | - | - | - | $3.4 \times 10^{-6}$ |
| Low Altitude FTS | - | $2.9 \times 10^{-3}$ | - | - | - | - | $2.9 \times 10^{-3}$ |
| High Altitude FTS | - | - | $3.6 \times 10^{-3}$ | - | - | - | $3.6 \times 10^{-3}$ |
| Sub-Orbital Reentry | - | - | - | $1.3 \times 10^{-2}$ | - | - | $1.3 \times 10^{-2}$ |
| Orbital Reentry | - | - | - | - | $4.7 \times 10^{-3}$ | - | $4.7 \times 10^{-3}$ |
| Long-term Reentry | - | - | - | - | - | $1.0 \times 10^{-6}$ | $1.0 \times 10^{-6}$ |
| **Total** | **$3.3 \times 10^{-5}$** | **$3.1 \times 10^{-3}$** | **$3.6 \times 10^{-3}$** | **$1.3 \times 10^{-2}$** | **$4.7 \times 10^{-3}$** | **$1.0 \times 10^{-6}$** | **$2.5 \times 10^{-2}$** |

Source: SNL 2014

(a) The table presents a composite of the accident end state probabilities for the Atlas V 551and the Delta IV Heavy, determined by taking the probability-weighted value of the two sets of results, treating the conditional probability of having a given launch vehicle as 0.5.

Some of these types of launch accidents occurred during the early development of launch vehicles in the United States; subsequently, changes were made to both vehicle design practices and range safety systems to prevent future occurrences. These accidents, in general, require multiple failures of both launch vehicle and range safety systems. Probability differences of a factor of a few percent would not represent statistically significant differences and are well within uncertainty bounds. The discussion of the probabilities by broad frequency categories is more appropriate.

The potential accident environments include blast (explosion overpressure), fragments, thermal energy (burning liquid propellant and/or solid propellant), reentry conditions (aerodynamic loads and heating), and surface impact. 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 its timing (relative to launch). There are two representative launch vehicles for the Nuclear Risk Assessment that bound the set of LV that could be selected for the proposed Mars 2020 mission: the Atlas V 551 and the Delta IV Heavy. DOE's nuclear risk assessment for this DEIS uses a composite average of the two sets of accident probabilities in performing the nuclear risk assessment for the Mars 2020 mission, as presented in Table 4-2. This approach reflects the state of knowledge at this early stage in the mission with respect to the launch vehicle to be used on the Mars 2020 mission. Preliminary analyses indicate that the differences between the two representative launch vehicles are not expected to be significant, given the uncertainties in estimates made as part of the overall nuclear risk assessment. At the same time, differences in accident environments for the two representative launch vehicles are taken into account in developing composite source terms for use in the analysis.

#### 4.1.4.3. MMRTG Response to Accident Environments

The nature and severity of the accident environments and the design features of the MMRTG and its components determine the response of the MMRTG and its components to the accident environments. These responses are then characterized in terms of the probability of release and the source terms.

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

- prior safety testing of the GPHS-RTG and its components (including the GPHS module),
- modeling of the response of the MMRTG and its components (including the GPHS module) to accident environments, and
- the types of launch vehicle accidents and their environments.

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 GPHS module, its graphite components, and the iridium clad encapsulating the $PuO_2$ reduces the potential for release in accident environments. Potential responses of the MMRTG and its components in accident environments are summarized below (SNL 2014).

- **Explosion Overpressure and Fragments:** Liquid propellant explosions and resulting fragments are expected to damage the MMRTG, but not result in any release of plutonium dioxide.

- **Impact:** The GPHS module and its graphitic components are expected to fracture under mechanical impact conditions. This provides some energy absorbing protection to the fueled clad. Under most accident conditions this results in little or no release of plutonium dioxide from the GPHS modules.
    - Most impacts of an intact MMRTG or GPHS modules on steel or concrete near the launch pad could result in little or no release of $PuO_2$, depending on the impact velocity.
    - Suborbital or Orbital Reentry accidents lead to GPHS modules impacting rock following reentry; a small release could occur.
    - The SV is expected to stay intact until impact due to the protection of the SV back shell and heat shield in any ground impact. 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:** The response of the $PuO_2$ to the thermal environment is highly dependent upon the intensity of that environment. Exposure to liquid propellant and solid propellant fires results in very different source terms.

 - 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 $PuO_2$ particles would occur depending on the timing of the ground impact release and the fireball development. Vaporization of $PuO_2$ is negligible below about 2,177°C (3,951°F) and the fireball temperature would decrease below this temperature in less than 1 second, and continue dropping as the fireball expands.
 - For the Atlas V 551, exposure of released $PuO_2$ fuel to the higher-temperature (up to 2,827°C (5,121°F)), longer burning (up to 250 seconds) 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 more exposed $PuO_2$ and additional partial vaporization. The GPHS 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:** Impacts resulting from reentry of the MMRTG are dependent upon when and from where reentry occurs.
 - Most suborbital reentries are predicted to result in intact impact of the SV due to the presence of the SV aeroshell for Mars entry. Releases in these cases are similar in nature to those from SV impact near the launch pad.
 - Reentry from circular orbital decay or long-term reentry is predicted to cause breakup of the SV and the MMRTG with subsequent release of the GPHS modules. (This breakup of the MMRTG and release of the GPHS modules is intentional and designed to limit the release of $PuO_2$ in this type of accident.) 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 if the impact is on rock or a similar hard surface. No release is expected from a water impact or soil impact.

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, or free 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 the 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 components and $PuO_2$ to burning solid propellant could result in increased releases through partial vaporization of the $PuO_2$.

Nearly all Phase 2 accidents lead to impact of debris in the Atlantic Ocean with no releases. However, there are some very small releases in air from blast-generated debris.

Phase 3 accidents could lead to sub-orbital reentry heating and ground impact of the intact SV and MMRTG. The GPHS modules are designed to survive reentry, however, any subsequent ground impact of the MMRTG on hard surfaces (e.g., rock) could result in small releases of $PuO_2$. Additionally, there is a possibility that the Mars 2020 entry vehicle aeroshell might provide some reentry protection such that the SV or portions of it, including the rover/MMRTG or the MMRTG, could survive reentry and result in SV components impacting the MMRTG. This could also occasionally result in small releases of $PuO_2$.

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 $PuO_2$.

#### 4.1.4.4. Accident Probabilities and Source Terms

In the nuclear risk assessment, DOE evaluated each of the identified end states and estimated the accident environments to which the MMRTG would likely be exposed. From that information, conditional probabilities that a release would occur and estimated source terms were developed based on the known response of GPHS modules to various accident environments.

The probability of a launch accident involving any release of $PuO_2$ is very small, approximately 1 in 2,600. The most severe accident environments would occur during launch area accidents that might expose the MMRTG to mechanical impacts, explosion overpressures and fragments, and fire environments from burning liquid and solid propellants.

A summary of the accident and source term probabilities by mission phase, along with mean and 99$^{th}$ percentile source terms, is presented in Table 4-3. For the purpose of this DEIS, "source term" is defined as the quantity of radioisotope that is released from the fueled clads in the GPHS modules and becomes airborne. Consequences associated with the material released in an accident are driven by the portion of the release that can become airborne and be transported away from the impact site. Not all of the material released from the fueled clads is expected to become airborne; the amount that does is dependent upon the accident conditions. Several factors contribute to a reduction in the released material to the source term. Some of the release could become trapped in debris or slag at the MMRTG impact site. Plutonium dioxide could be retained inside the graphite components of the GPHS module, and some could be shielded from any fire environments by the graphite components and other debris, including sand. In addition, the size of the plutonium dioxide particles affects the likelihood of the plutonium dioxide becoming airborne, the larger the particles the less likely they are to become airborne.

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## Table 4-3. Summary of Accident Probabilities and MMRTG Source Terms

| Mission Phase [(a)] | Accident Probability | Source Term, Ci (given an accident) | | Conditional Probability of Release [(b)] | Total Probability of a Release | Source Term [(c)], Ci (given a release) | |
|---|---|---|---|---|---|---|---|
| | | Mean | 99th Percentile | | | Mean | 99th Percentile |
| 0: Pre-Launch | Very Unlikely ($3.3x10^{-5}$) | 0.092 | 0.048 | 0.33 | Very Unlikely ($1.1x10^{-5}$) | 0.28 | 6.7 |
| 1: Early Launch | | | | | | | |
| On-Pad Explosion | Very Unlikely ($9.8x10^{-5}$) | 2.0 | 0.035 | 0.085 | Very Unlikely ($8.3x10^{-6}$) | 23 | 40 |
| FSII | Very Unlikely ($2.2x10^{-5}$) | 15 | 340 | 0.14 | Very Unlikely ($3.2x10^{-6}$) | 110 | 1,800 |
| Stage 2/SV | Very Unlikely ($4.8x10^{-5}$) | 2.8 | 55 | 0.036 | Very Unlikely ($1.8x10^{-6}$) | 77 | 910 |
| SVII | Extremely Unlikely ($6.3x10^{-7}$) | 2.7 | 40 | 0.054 | Extremely Unlikely ($3.4x10^{-8}$) | 50 | 580 |
| Low Altitude FTS | Unlikely ($2.9x10^{-3}$) | 1.5 | 16 | 0.025 | Very Unlikely ($7.5x10^{-5}$) | 61 | 620 |
| Overall Phase 1 | Unlikely ($3.1x10^{-3}$) | 1.7 | 16 | 0.028 | Very Unlikely ($8.8x10^{-5}$) | 59 | 630 |
| 2: Late Launch | Unlikely ($3.6x10^{-3}$) | $3.4x10^{-5}$ | - | 0.0021 | Very Unlikely ($7.7x10^{-6}$) | 0.016 | 0.23 |
| 3: Suborbital | $1.3x10^{-2}$ | 0.047 | - | 0.0013 | Very Unlikely ($1.5x10^{-5}$) | 42 | 930 |
| 4: Orbital | Unlikely ($4.7x10^{-3}$) | 0.030 | 0.65 | 0.056 | Unlikely ($2.6X10^{-4}$) | 0.53 | 6.2 |
| 5: Long-term Reentry | Very Unlikely ($1.0x10^{-6}$) | 0.073 | 1.5 | 0.094 | Extremely Unlikely ($9.4x10^{-8}$) | 0.77 | 7.8 |
| **Overall Mission [(d)]** | **$2.5x10^{-2}$** | **0.24** | **0.0095** | **0.016** | **Unlikely ($3.8x10^{-4}$)** | **16** | **340** |

Source: SNL 2014

(a) The table presents a composite of the results for the Atlas V 551 and the Delta IV Heavy, determined by taking the probability-weighted value of the two sets of results, treating the conditional probability of having a given launch vehicle as 0.5.
(b) The conditional probability of a release of $PuO_2$ given that an accident has occurred.
(c) Total source terms given. The source term is that portion of the release which becomes airborne would represent the amounts of $PuO_2$ released that are no more than 100 microns (100 micrometers) in diameter. Particles larger than this do not generally become airborne and would remain in the vicinity of the accident.
(d) Overall mission values are weighted by the total probability of release for each mission phase.

**Notes:** Differences in multiplications and summations are due to rounding of results as reported in SNL 2014. Probability categories, i.e., unlikely, very unlikely, defined by NASA.

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As noted in Table 4-3, particles larger than 100 micrometers (µm) are expected to remain in the vicinity of the MMRTG impact site. The 99$^{th}$ percentile source term is the value predicted to be exceeded with a probability of 0.01 (1 in 100), given a release in an accident. (This percentile is derived from a statistical analysis to model the progression of the accident. In this analysis, DOE has used a computer code that performs multiple trials, typically 150,000, in which the probabilities of the parameters that affect the size of the source term are varied according to their probability distributions. The 99$^{th}$ percentile is therefore the value exceeded in 1 percent of these trials.) In this context, the 99$^{th}$ percentile value reflects the potential for higher radionuclide releases at lower probabilities. The 99$^{th}$ percentile releases are one to approximately 24 times the mean estimates reported in this DEIS, but at probabilities of a factor of 100 times lower than the mean probabilities.

- **Phase 0 (Pre-Launch):** During the pre-launch period, and prior to ignition of the Stage 1 liquid rocket engine, most initiating failures result in a mission abort. Those failures that result in on-pad accidents and a release have a total probability of $1.1 \times 10^{-5}$ (1 in 93,000). The mean source term, given that an accident with a release has occurred, is estimated to be 0.28 Ci.
- **Phase 1 (Early Launch):** During Phase 1, during which land impacts, including near the launch complex, are possible, the accidents resulting in a release have a total probability estimated to be $8.8 \times 10^{-5}$ (or 1 in 11,000). The mean source term, given that an accident with a release has occurred, is estimated to be 59 Ci.

  Most initiating failures occurring in Phase 1 would lead to activation of the FTS. The elements of the FTS are highly redundant and reliable. As a result, the expected outcome of a Phase 1 accident is ground impact of the spacecraft or portions thereof, including possibly the rover with attached MMRTG, the MMRTG alone, or free GPHS modules. In this case, mechanical damage and, for an Atlas V 551 accident, potential exposure to burning solid propellant could occur. The probability for this impact configuration with a release is estimated to be $7.5 \times 10^{-5}$ (or 1 in 13,000), with an estimated mean source term, given an accident with a release has occurred, is estimated to be 61 Ci).

  A much less likely outcome of a Phase 1 accident involves failure of some or all of the FTS elements to perform properly. This could lead to ground impact of the spacecraft (with the MMRTG inside) still attached to other launch vehicle stages (Stages 1 and 2, or Stage 2). Since this would require multiple failures of safety systems, such ground impact configurations leading to a release are very unlikely, estimated probability of $5.0 \times 10^{-6}$ (1 in 200,000). However, because the MMRTG could impact the ground within the spacecraft at higher velocities and with additional mass above the spacecraft due to the attached Stage(s), the potential for more severe mechanical damage is higher than with the expected accident conditions associated with normal activation of the FTS. For impact configurations leading to the largest estimated releases, such as the Intact Stage 2/SV and the FSII, slightly larger estimated mean source terms given an accident with a release, of 77 Ci and 110 Ci, respectively could occur.

- **Phase 2 (Late Launch):** All accidents that could occur in Phase 2 would lead to impact of debris in the Atlantic Ocean. Most such accidents result in no release of $PuO_2$. However, in some cases, small quantities of $PuO_2$ can be released. It is possible that blast and fragment impacts could result in some at altitude releases. The total probability of a release is very unlikely — $7.7x10^{-6}$ (one in 130,000). The estimated mean source term, given an accident with a release would be 0.016 Ci.
- **Phase 3 (Suborbital):** Accidents during Phase 3 include sub-orbital reentries. Prior to the attainment of Earth parking orbit, these conditions could lead to prompt sub-orbital reentry within minutes. Following spacecraft breakup during reentry, this could result in impacts of individual GPHS modules along the vehicle flight path over the Atlantic Ocean and southern Africa. Additional sub-orbital land impacts are possible after crossing over Africa, depending on the launch vehicle and its mission timeline. Should the GPHS modules impact hard surfaces (e.g., rock), small releases are possible at ground level. There is a possibility that the SV or portions thereof, including the rover/MMRTG or the MMRTG would survive sub-orbital reentry. The total probability of release in Phase 3 is estimated to be $1.5x10^{-5}$ (or 1 in 67,000). The mean source term given that a release has occurred is estimated to be 42 Ci.
- **Phase 4 (Orbital):** Accidents which occur after attaining parking 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. Post-reentry impact releases would be similar to those in Phase 3. The total probability of a release is estimated to be $2.6x10^{-4}$ (or 1 in 3,800). The mean source term given that a release has occurred is estimated to be 0.53 Ci.
- **Phase 5 (Long-Term Reentry):** The potential exists for an inadvertent long-term (hundreds to thousands of years) reentry should the SC be left in an Earth crossing orbit. Based on considerations of long-term inadvertent reentry for other missions, the probability of such an occurrence is estimated to be less than $1x10^{-6}$. Post-reentry impact releases would be similar to those in Phase 3. The total probability of a release is estimated to be $9.4x10^{-8}$ (or 1 in 11,000,000). The mean source term given that a release has occurred is estimated to be 0.77 Ci.

#### 4.1.4.5. Radiological Consequences

The radiological consequences (assuming no post-accident mitigation) of a given accident that results in a radiological release have been calculated in terms of maximum individual dose, collective dose, health effects, and land area contaminated at or above specified levels. The radiological consequences have been determined from atmospheric transport and dispersion simulations incorporating both launch-site specific and worldwide meteorological and population data. Biological effects models, based on methods prescribed by the Interagency Steering Committee on Radiation Standards (ISCORS), were applied to predict the number of health effects following a launch accident that results in a release of $PuO_2$. The analysis assumes that no mitigation measures (e.g., sheltering, evacuation, and decontamination) are taken to reduce the health impacts. Additional information on the behavior of plutonium in the environment (environmental transport and health impact mechanisms) can be found in Appendix B.

The maximum individual dose is the mean maximum dose delivered to a single individual for a given accident. 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-60 (ICRP 1979) and ICRP-66/67 (ICRP 1993, ICRP 1994). The exposure pathways considered include direct inhalation, inhalation of re-suspended material, ingestion (e.g., vegetables, fruit, and seafood), and external exposure. Due to the insoluble nature of $PuO_2$, other secondary exposure pathways (e.g., meat and milk) would be far less important, and their contributions to dose would be negligible. The collective dose is used to estimate the health effects impacts of launch accidents.

The health effects represent incremental cancer fatalities induced by releases, determined using the ISCORS estimates of $6 \times 10^{-4}$ fatalities per person-rem for the general population (DOE 2002). The health effects estimators are based on a linear, non-threshold model relating health effects and effective dose. This means that health effects decrease as the dose decreases down to zero, rather than assuming a threshold dose below which there would be no health effects. The probability of incurring a health effect is estimated for each individual in the exposed population and then the probabilities summed over the population; an estimate of the total health effects in the population results.

Table 4-4 presents a summary of DOE's risk assessment of radiological consequences given an accident with a release for each of the mission phases. The radiological consequences were estimated by mission phase in terms of both the mean and $99^{th}$ percentile values. The $99^{th}$ percentile radiological consequence is the value predicted to be exceeded 1 percent of the time for an accident with a release.

The radiological consequences summarized in Table 4-4 are proportional to the source terms listed in Table 4-3. Key results for the mean estimates are summarized below; the corresponding $99^{th}$ percentile estimates can be found in Table 4-4.

Should the mission be delayed, the proposed Mars 2020 mission would be launched during the next available launch opportunity in August through September 2022. Since this launch period is in a similar season as the 2020 launch period, the projected radiological impacts associated with releases from the MMRTG (Alternative 1) would be similar to those associated with the 2020 launch, with only a small increase in population impacts due to population growth. Thus, within the overall uncertainties, the radiological impacts associated with a 2022 launch would be the same as those for the proposed 2020 launch. This similarity in impacts for a 2020 and a 2022 mission launch applies to the impacts associated with releases from LWRHUs (Alternative 3) and science instrument sources (Alternative 1, 2, and 3).

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## Table 4-4. Summary of Estimated MMRTG Accident Radiological Consequences

| Mission Phase [a] | Total Probability of Release | Maximum Individual Dose, rem | | Health Effects [b] | | Land Contamination [c] $km^2$ | |
|---|---|---|---|---|---|---|---|
| | | Mean | 99th Percentile | Mean | 99th Percentile | Mean | 99th Percentile |
| 0: Pre-Launch | Very Unlikely ($1.1x10^{-5}$) | 0.00029 | 0.0068 | 0.0014 | 0.033 | 0.035 | 0.83 |
| Early Launch | | | | | | | |
| On-Pad Explosion | Very Unlikely ($8.3x10^{-6}$) | 0.024 | 0.040 | 0.11 | 0.19 | 2.9 | 4.9 |
| FSII | Very Unlikely ($3.2x10^{-6}$) | 0.11 | 1.9 | 0.52 | 8.9 | 13 | 230 |
| Stage2/SV | Very Unlikely ($1.8x10^{-6}$) | 0.079 | 0.93 | 0.38 | 4.5 | 9.7 | 110 |
| SVII | Extremely Unlikely ($3.4x10^{-8}$) | 0.051 | 0.59 | 0.25 | 2.9 | 6.3 | 73 |
| Low Altitude FTS | Very Unlikely ($7.5x10^{-5}$) | 0.062 | 0.63 | 0.30 | 3.0 | 7.6 | 77 |
| 1: Overall Phase 1 | Very Unlikely ($8.8x10^{-5}$) | 0.060 | 0.65 | 0.29 | 3.1 | 7.4 | 79 |
| 2: Late Launch | Very Unlikely ($7.7x10^{-6}$) | $1.6x10^{-5}$ | 0.0002 | $7.8x10^{-5}$ | 0.0011 | 0.0020 | 0.029 |
| 3: Suborbital | Very Unlikely ($1.5x10^{-5}$) | 0.043 | 0.95 | 0.20 | 4.6 | 5.2 | 120 |
| 4: Orbital | Unlikely ($2.6X10^{-4}$) | 0.0005 | 0.0063 | 0.0026 | 0.030 | 0.066 | 0.77 |
| 5: Long-term Reentry | Extremely Unlikely ($9.4x10^{-8}$) | 0.0008 | 0.0080 | 0.0038 | 0.038 | 0.097 | 0.98 |
| **Overall Mission [d]** | **Unlikely ($3.8x10^{-4}$)** | **0.016** | **0.35** | **0.076** | **1.7** | **1.9** | **43** |

Source: SNL 2014

(a) The table presents a composite of the results for the Atlas V 551 and the Delta IV Heavy, determined by taking the probability-weighted value of the two sets of results, treating the conditional probability of having a given launch vehicle as 0.5.
(b) Based on ISCOR health effects recommendation of $6x10^{-4}$ health effects per person-rem for the general population.
(c) Land area contaminated above 0.2 μCi/$m^2$; 1 $km^2$ = 0.386 $mi^2$.
(d) Overall mission values weighted by total probability of release for each mission phase.

**Notes:** Differences in multiplications and summations are due to rounding of results as reported in SNL 2014. Probability categories, *i.e.*, unlikely, very unlikely, defined by NASA.

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- **Phase 0 (Pre-Launch):** The initiating failures that result in Phase 0 accident configurations are very unlikely, having very low probabilities of occurrence. Most problems that arise during Phase 0 can be successfully mitigated by safety systems and procedures leading to safe hold or termination of the launch countdown.

  In the very unlikely possibility (probability of $1.1 \times 10^{-5}$ or a 1 in 91,000 chance) that an accident were to occur during Phase 0, however, there is a potential for measurable releases and contamination. The probability of the MMRTG being close to large pieces of burning solid propellant would be higher in Phase 0 accidents than in other phases. For this very unlikely accident with a release, the mean maximum dose to an individual is estimated to be approximately 0.00029 rem (0.29 millirem), less than 0.1 percent of the dose an individual might receive annually from natural background radiation[17].

  Assuming no mitigation actions, such as sheltering and exclusion of people from contaminated land areas, the radiation doses to the potentially exposed population are predicted to result in 0.0014 mean health effects among the potentially exposed population.

  For Phase 0 accidents with a release, the mean area contaminated above 0.2 microcuries per square meter ($\mu Ci/m^2$) (see Section 4.1.4.7) is estimated to be about 0.035 square kilometers ($km^2$) (about 0.014 square miles ($mi^2$)). Detectable levels below 0.2 $\mu Ci/m^2$ would be expected over a larger area.

- **Phase 1 (Early Launch):** Phase 1 consequences consist of contributions from two types of accident scenarios. Most initiating failures occurring in Phase 1 would lead to activation of the FTS. The elements of the FTS are highly redundant and very reliable. As a result, the expected outcome of a Phase 1 accident is that the SV and MMRTG or its components could fall free to the ground and would be subject to mechanical damage and potential exposure to burning solid propellant resulting in a release of material. For this very unlikely impact configuration, with a probability estimated to be $7.5 \times 10^{-5}$ (or 1 in 13,000), the mean maximum individual dose is estimated to be 0.062 rem (62 millirem), equivalent to about 20 percent of the dose an individual might receive annually from natural background radiation.

  Assuming no mitigation action, such as sheltering, the radiation dose to the potentially exposed population is predicted to result in 0.30 mean health effects among the potentially exposed population over the long term.

  The risk assessment indicates that about 7.6 $km^2$ (about 2.9 $mi^2$) could be contaminated above 0.2 $\mu Ci/m^2$.

[17] An average of about 0.31 rem per year for an individual in the United States from natural sources. Man-made sources add an additional 0.060 to 0.31 rem. The dominant man-made contribution is from medical radiological diagnosis and therapy. See Section 3.2.6 for further information.

A less likely outcome of a Phase 1 accident involves failure of some or all of the FTS elements to perform properly. This could lead to ground impact of the spacecraft (with the MMRTG inside) still attached to other launch vehicle stages (Stages 1 and 2, or Stage 2). Since this would require multiple failures of safety systems, such ground impact configurations leading to a release are very unlikely, estimated probability of 5.0 $\times 10^{-6}$ (1 in 200,000). However, because the MMRTG could impact the ground within the spacecraft at high speed, the potential for more severe mechanical damage and exposure to burning liquid and, possibly, solid propellant, could result in higher source terms.

In the more severe impact configurations leading to the largest estimated releases, such as the FSII, mean exposures as high as about 0.11 rem (110 millirem) to the maximum exposed individual might occur. This dose is about a third of the dose an individual might receive annually from natural background radiation. Assuming no mitigation action, such as sheltering, radiation doses to the potentially exposed population are predicted to result in an estimated 0.52 mean health effects. An estimated area of nearly 13 $km^2$ (about 5.0 $mi^2$) might be contaminated above 0.2 $\mu Ci/m^2$. Detectable levels below 0.2 $\mu Ci/m^2$ would be expected over a larger area.

- **Phase 2 (Late Launch):** The total probability of a release in Phase 2, categorized as very unlikely, is estimated to be $7.7 \times 10^{-6}$ (or 1 in 130,000). Accidents in this phase result in smaller releases and impacts than in any other phase. The mean maximum individual dose is estimated to be $1.6 \times 10^{-5}$ rem (0.016 millirem), a very small fraction of the dose an individual might receive annually from natural background radiation.

  Assuming no mitigation action, such as sheltering, the radiation dose to the potentially exposed population is predicted to result in $7.8 \times 10^{-5}$ mean health effects among the potentially exposed population over the long term.

  The risk assessment indicates that about 0.002 $km^2$ (about 0.0008 $mi^2$) could be contaminated above 0.2 $\mu Ci/m^2$.

- **Phases 3 (Suborbital):** The total probability of a release in Phase 3, categorized as very unlikely, is estimated to be $1.5 \times 10^{-5}$ (or 1 in 68,000). Mean consequences are estimated to be 0.043 rem (43 millirem) for maximum individual dose,0.20 health effects among the potentially exposed population , and 5.2 $km^2$ (about 2.0 $mi^2$) could be contaminated above 0.2 $\mu Ci/m^2$.

- **Phase 4 (Orbital):** The total probability of a release in Phase 4, categorized as very unlikely, is estimated to be $2.6 \times 10^{-4}$ (or 1 in 3,800). Mean consequences are estimated to be 0.0005 rem (0.5 millirem) for the maximum individual dose, 0.0026 health effects among the potentially exposed population, and 0.066 $km^2$ (about 0.025 $mi^2$) could be contaminated above 0.2 $\mu Ci/m^2$.

- **Phase 5 (Long-term Reentry):** The total probability of a release in Phase 5, categorized as extremely unlikely, is estimated to be $9.4 \times 10^{-8}$ (or 1 in 11,000,000). Mean consequences are estimated to be 0.0008 rem (0.8 millirem) for the maximum individual dose, 0.0038 health effects among the potentially exposed population, and 0.097 $km^2$ (about 0.037 $mi^2$) could be contaminated above 0.2 $\mu Ci/m^2$.

#### 4.1.4.6. Discussion of the Results

***Maximum Individual Doses***

The maximum individual dose is the maximum dose delivered to a single individual for each accident. During Phase 1, the predicted mean radiation dose to the maximally exposed individual ranges from about 0.024 rem (24 millirem) for the on-pad explosion launch area accident up to about 0.11 rem (110 millirem) for a very unlikely FSII in combination with burning solid propellant. No near-term radiological effects would be expected from any of these exposures. The dose to the maximally exposed individual for the FSII is the largest single maximally exposed individual dose for any phase. Each exposure would increase the statistical likelihood of a health effect. It should be noted that the prediction of doses to the maximally exposed individual is subject to large variations and uncertainties in the locations of individuals, meteorological conditions, periods of exposure, and dispersion modeling.

***Population Exposures***

Impacts to downwind populations that might be exposed to releases following an accident are estimated by first calculating the collective dose to that population. This is simply the sum of the radiation dose received by all individuals exposed to radiation from a given release. These collective doses are assumed to result in the potential for health effects among the potentially exposed population following an accident. The health effects induced by releases are calculated using the methods described above in Section 4.1.4.5. The consequences discussed below have been estimated considering impacts to both the local population and the global population. Because of a variety of factors, principally involving meteorological conditions at the time of launch and the amount and particle size distribution of any $PuO_2$ released, not all persons in the affected regions would be exposed to a release.

Prior to launch, most problems that could potentially lead to an accident would be mitigated by safety systems and procedures that would lead to safe hold or termination of the launch countdown. After launch, most significant problems would lead to activation of the FTS, which would result in the destruction of all of the vehicle stages. This would lead to the spacecraft or portions thereof, including possibly the rover with attached MMRTG, the MMRTG alone, or free GPHS modules, falling to the ground, where it could be subject to ground impact mechanical damage and potential exposure to burning solid propellant. The probability for this scenario with a release is $7.5 \times 10^{-5}$ (or 1 in 13,000). Assuming no mitigation actions, such as sheltering and exclusion of people from contaminated land areas, the radiation dose to the potentially exposed population is predicted to result in less than one additional health effect over the long term. The mean estimate for this release scenario is 0.30 health effects.

Even for the very and extremely unlikely launch area accidents, mean releases are not significantly higher than for the most probable accident and release. Assuming no mitigation actions (e.g., sheltering), estimated mean health effects range from a low of less than 0.11 to a high of 0.52. As with the maximum individual dose the largest population dose is associated with a phase 1 release. In the event of a launch area accident, it is unlikely that any given racial, ethnic, or socioeconomic group of the population would bear a disproportionate share of the consequences.

### *Impacts of Radiological Releases on the Environment*

The environmental impacts of the postulated accidents include the potential for $PuO_2$ to be released to the environment, resulting in land and surface water contamination. The health and environmental impacts associated with plutonium-238 in the environment were addressed extensively in the EISs for previous NASA missions that used RTGs, including the Galileo, Ulysses, Cassini, New Horizons and Mars Science Laboratory missions (NASA 1989, NASA 1990, NASA 1995, NASA 1997, NASA 2005, NASA 2006). Each of these documents identified the potential for launch area accidents contaminating land areas. These EISs referenced evaluations of the potential impacts of $PuO_2$ releases on natural vegetation, wetlands, agricultural land, urban areas, inland water, the ocean, and other global areas. Based on these previous analyses, the potential impacts of plutonium releases from the launch area accidents on the environment are discussed in Appendix B.

The affected environment, described in Section 3 of this DEIS, includes the regional area near CCAFS and the global area. Launch area accidents (Phases 0 and 1) would initially release material into the regional area, defined in this DEIS to be within 100 km (62 mi) of the launch pad. Since some of the accidents result in the release of very fine particles (less than a micron in diameter), a portion of such releases could be transported beyond 100 km (62 mi) and become well mixed in the troposphere, and thus affecting the global environment. Releases during Phase 3 could involve reentering GPHS modules that could impact the ground in southern Africa. Releases during Phase 4 could affect the environment anywhere between 29° north and 29° south latitude. Releases during phase 5 could nominally affect the environment anywhere on Earth, but only when the spacecraft impacts land.

Potential environmental contamination was evaluated in terms of areas exceeding various screening levels (0.1 and 0.2 $\mu Ci/m^2$), and dose-rate related criteria (15, 25, and 100 millirem per year) considered by the U.S. Environmental Protection Agency (EPA), the Nuclear Regulatory Commission, and DOE in evaluating the need for land cleanup following radioactive contamination.

The risk assessment for this DEIS uses the 0.2 $\mu Ci/m^2$ screening level (a screening level used in prior NASA environmental documentation (e.g., NASA 1989, NASA 1997, NASA 2002b, NASA 2005) as an indicator of the extent of land area contaminated due to a release of $PuO_2$ from a potential launch accident. The results are summarized in Table 4-4. 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 potential for resuspension. The resuspension contribution to dose assumes that no mitigation measures are taken.

DOE's risk assessment indicates that for the most likely type of launch area accidents with a release, (that is the intentional destruction of all the vehicle stages) would result in about 7.6 $km^2$ (about 2.9 $mi^2$) being contaminated above 0.2 µCi/$m^2$. The risk assessment also indicates that in at least one very unlikely ground impact configuration, FSII with a total estimated probability of 3.2 x$10^{-6}$ (one in 310,000), a mean area of 13 $km^2$ (about 5.0 $mi^2$) could be contaminated above 0.2 µCi/$m^2$. Detectable levels below 0.2 µCi/$m^2$ would be expected over an even larger area.

Land areas contaminated at levels above 0.2 µCi/$m^2$ would potentially need further action, such as monitoring or cleanup. Costs associated with cleanup efforts, as well as continued monitoring activities, could vary widely depending upon the characteristics of the contaminated area. These costs do not include costs of government oversight, management or administration nor litigation costs. Indirect costs could double the cost per unit area. Potential cost estimating factors for decontamination (cleanup) of various land types are summarized in Table 4-5. These cost factors address a wide variety of possible actions, including land acquisition, waste disposal, site restoration, and final surveys of remediated sites.

**Table 4-5. Potential Land Decontamination Cost Factors**

| Land Type | Cost Factor in 2013 Dollars | |
|---|---|---|
| | Cost per $km^2$ | Cost per $mi^2$ |
| Farmlands | $110 million | $285 million |
| Rangeland | $108 million | $280 million |
| Forests | $196 million | $507 million |
| Mixed-Use Urban Areas[a] | $600 million | $1.6 billion |

a. Mixed use urban area applicable to a U.S. city of approximately 100,000 population. Costs are not applicable to downtown business districts, heavy industrial areas, or high-rise apartment buildings.

Source: Adapted from Chanin et al. 1996

In addition to the potential direct costs of radiological surveys, monitoring, and potential cleanup following an accident, there are potential secondary societal costs associated with the decontamination and mitigation activities with the very unlikely, potentially higher consequence launch area accidents. Those costs could include, but may not be limited to:

- temporary or longer term relocation of residents;
- temporary or longer term loss of employment;
- destruction or quarantine of agricultural products, including citrus crops;
- land use restrictions (which could affect real estate values, tourism and recreational activities);
- restriction or bans on commercial fishing; and
- public health effects and medical care.

As indicated in Table 4-5, costs for farmland decontamination have been identified. In addition to the costs of decontamination, there is the potential that the contamination of crops would require additional mitigation measures. These actions could be required to prevent contaminated foodstuffs from being consumed by the public. In the case of plutonium dioxide contamination, the preventive measures could include the collection and disposal of contaminated crops. The Food and Drug Administration has established Derived Intervention Levels (DILs) (FDA 1998) designed to limit the dose to an individual from consuming contaminated foodstuff. These DILs identify recommended levels of contamination above which individuals consuming the contaminated foodstuff would receive an unacceptable dose. The DIL varies depending upon the receptor (the individual consuming the foodstuff) primarily based upon the age of the individual. In the case of plutonium-238, the limiting DIL (that is, the lowest allowable concentration) of 2.5 Bq/kg [18] (FDA 1998) is the DIL for infants.

As a part of the Nuclear Risk Assessment, DOE performed an analysis to determine the extent of cropland that could be contaminated to levels in excess of this DIL. The analysis used the same accident and meteorological data used in the NRA to address the release and dispersal of plutonium dioxide in the event of an accident, i.e., the same accident conditions, release quantities, and weather data. In addition, the analysis considered the following items:

- The acreage of land used as farmland (and the fraction of land used for each crop type (leafy vegetables, fruit, pasture, etc.),
- The types of crops grown in Florida and in the KSC area,
- The quantities of each crop type grown, and
- The fraction of plutonium dioxide deposited on cropland that would be deposited on or absorbed by each crop type.

The results of this analysis indicated that for all phases and for all accidents, the area contaminated above the DIL is consistently more than 50 times lower than (less than 2 percent) the area contaminated at or above the 0.2 $\mu Ci/m^2$ level that are shown in Table 4-4. For example, in assessing the Phase 1 accident with Low Altitude FTS, DOE calculated that the DIL value of 2.5 Bq/kg would be exceeded in an area of 0.13 $km^2$ (0.05 $mi^2$ or about 32 acres). This is the mean value for the cropland area where some mitigation measures could be required to limit the public health impact from the consumption of food contaminated by a release from this accident. The $99^{th}$ percentile area would be 1.35 $km^2$ (0.52 $mi^2$ or 330 acres). These values are less than 2% of the calculated land contamination area using the 0.2 $\mu Ci/m^2$ criteria (See Table 4-4) (SNL 2014).

The Price-Anderson Act of 1957, as amended (42 U.S.C. 2210), governs liability and compensation in the event of a nuclear incident arising out of the activities of the DOE. The Price-Anderson Act is incorporated into the Atomic Energy Act of 1954, as amended (42 U.S.C. 2011 et seq.). A "nuclear incident" is defined under the Atomic Energy Act as "any occurrence, including an extraordinary nuclear occurrence, within the United States causing, within or outside the United States, bodily injury, sickness,

[18] A Becquerel (Bq) is one disintegration per second. One curie is equal to 37,000 million Bq. The land contamination criteria of 0.2 microcuries/$m^2$ is equivalent to 7.4 Bq/$m^2$.

disease, or death, or loss of or damage to property, or loss of use of property, arising out of or resulting from the radioactive, toxic, explosive, other hazardous properties of source, special nuclear or byproduct material..." (42 U.S.C. 2014 (q)). In the case of the Mars 2020 mission, DOE retains title to the MMRTG. The MMRTG would, therefore, be subject to Price-Anderson Act provisions. In the unlikely event that an accident were to occur resulting in release of $PuO_2$, affected property owners would be eligible for reimbursement for loss of property due to contamination.

#### 4.1.4.7. Mission Risks

A summary of the mission risks is presented in Table 4-6. For the purpose of this DEIS, risk is defined as the expectation of health effects in a statistical sense (i.e., the product of total probability times the mean health effects resulting from a release, and then summed over all conditions leading to a release). The risk of health effects in the potentially exposed populations 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. The overall radiological risk for the Mars 2020 mission is estimated to be $2.6 \times 10^{-5}$. Thus, the total probability of one health effect for the Proposed Action (Alternative 1) is about 1 in 39,000.

**Table 4-6. Summary of MMRTG Health Effect Mission Risks**

| Mission Phase [a] | Accident Probability | Conditional Probability of a Release | Total Probability of a Release | Mean Health Effects (given a release) | Mission Risks |
|---|---|---|---|---|---|
| 0: Pre-Launch | $3.3 \times 10^{-5}$ | 0.33 | Very Unlikely ($1.1 \times 10^{-5}$) | 0.0014 | $1.5 \times 10^{-8}$ |
| 1: Early Launch | $3.1 \times 10^{-3}$ | 0.028 | Very Unlikely ($8.8 \times 10^{-5}$) | 0.29 | $2.5 \times 10^{-5}$ |
| 2: Late Launch | $3.6 \times 10^{-3}$ | 0.0021 | Very Unlikely ($7.7 \times 10^{-6}$) | $7.8 \times 10^{-5}$ | $6.0 \times 10^{-10}$ |
| 3: Suborbital | $1.3 \times 10^{-2}$ | 0.0013 | Very Unlikely ($1.5 \times 10^{-5}$) | 0.20 | $3.0 \times 10^{-6}$ |
| 4: Orbital | $4.7 \times 10^{-3}$ | 0.056 | Unlikely ($2.6 \times 10^{-4}$) | 0.0026 | $6.8 \times 10^{-7}$ |
| 5: Long-term Reentry | $1.0 \times 10^{-6}$ | 0.094 | Extremely Unlikely ($9.4 \times 10^{-8}$) | 0.0038 | $3.6 \times 10^{-10}$ |
| **Overall Mission** | **$2.5 \times 10^{-2}$** | **0.016** | **Unlikely ($3.8 \times 10^{-4}$)** | **0.076** | **$2.9 \times 10^{-5}$** |

Source: SNL 2014

(a) The table presents a composite of the results for the Atlas V 551 and the Delta IV Heavy, determined by taking the probability-weighted value of the two sets of results, treating the conditional probability of having a given launch vehicle as 0.5. Accident probabilities are the average of individual values for the two vehicles. Based on the current state of knowledge, the specific accident probabilities for the accident conditions for each vehicle are expected to be similar.

Differences in multiplications and summations are due to rounding of results as reported in SNL 2014.

Probability categories (i.e., unlikely, very unlikely) as defined by NASA.

The risk contribution from Phase 1 accidents, $2.5 \times 10^{-5}$ (or a probability of about 1 in 40,000 that a health effect will occur), represents 87 percent of the radiological risk for the Mars 2020 mission. The primary contributors to the Phase 1 risk in order of significance are (1) Low Altitude FTS, (2) FSII, and (3) On-Pad Explosion. Phase 3 contributes 10 percent of the overall mission risk, due primarily to releases from GPHS modules impacting hard surfaces (e.g., rock) following suborbital reentry and possibly other impact configurations up to and including the spacecraft.

The contributions to risk within 100 km (62 mi) of the launch site and in the global area are summarized in Table 4-7. The launch area risk is about 57 percent of the overall mission risk, while the risk to global areas is 43 percent. The launch area risks are due entirely from accidents during Phases 0 and 1, with Phase 1 being the primary contributor. The global risks are due to accidents in all mission phases, with Phase 1 being the primary contributor due to the atmospheric transport of small particles beyond 100 km from the launch site.

**Table 4-7. MMRTG Health Effect Mission Risk Contributions by Affected Region**

| Mission Phase [a] | Mission Risks | | |
|---|---|---|---|
| | Launch Area [b] | Global [c] | Total |
| 0: Pre-Launch | $8.9x10^{-9}$ | $5.9x10^{-9}$ | $1.5x10^{-8}$ |
| 1: Early Launch | $1.7x10^{-5}$ | $8.9x10^{-6}$ | $2.5x10^{-5}$ |
| 2: Late Launch | — | $6.0x10^{-10}$ | $6.0x10^{-10}$ |
| 3: Suborbital | — | $3.0x10^{-6}$ | $3.0x10^{-6}$ |
| 4: Orbital | — | $6.8x10^{-7}$ | $6.8x10^{-7}$ |
| 5: Long-term Reentry | — | $3.6x10^{-10}$ | $3.6x10^{-10}$ |
| **Overall Mission** | **$1.7x10^{-5}$** | **$1.3x10^{-5}$** | $2.9x10^{-5}$ |

Source: SNL 2014

(a) The table presents a composite of the results for the Atlas V 551 and the Delta IV Heavy, determined by taking the probability-weighted value of the two sets of results, treating the conditional probability of having a given launch vehicle as 0.5.

(b) Phases 0 and 1: within 100 km (62 mi) of the launch site.

(c) Phase 3: southern Africa; Phase 4: land impacts between 29° north and 29° south latitude.

**Note:** Differences in summations may be due to rounding

### *Individual Risks (Maximum Exposed Individual)*

Individual risk can be interpreted as the probability of a particular individual in the exposed population incurring a fatal cancer. For an accident near the launch site, not everyone within the regional area would be expected to receive a dose as a result of the accident. Due to meteorological conditions prevailing at the time of launch, only a portion of the total regional population is estimated to receive some measurable radiological exposure should an accident occur.

Even those individuals within the exposed population, such as those very close to the launch area that might receive the highest exposures, would face very small risks. The risk to the maximally exposed individual within the launch-area and global populations (Table 4-8) is estimated to be less than 1 in 300 million for the Mars 2020 mission. Most people in the potentially exposed population would have much lower risks.

**Table 4-8. MMRTG Maximum Individual Risk**

| Mission Phase [(a)] | Release Probability | Maximum Individual Dose, (rem) | Maximum Individual Risk [(b), (c)] |
|---|---|---|---|
| 0: Pre-Launch | Very Unlikely ($1.1\times10^{-5}$) | 0.00029 | $1.9\times10^{-12}$ |
| 1: Early Launch | Very Unlikely ($8.8\times10^{-5}$) | 0.060 | $3.2\times10^{-9}$ |
| 2: Late Launch | Very Unlikely ($7.7\times10^{-6}$) | $1.6\times10^{-5}$ | $7.6\times10^{-14}$ |
| 3: Suborbital | Very Unlikely ($1.5\times10^{-5}$) | 0.043 | $3.8 \times10^{-10}$ |
| 4: Orbital | Unlikely ($2.6\text{X}10^{-4}$) | 0.0005 | $8.5 \times10^{-11}$ |
| 5: Long-term Reentry | Extremely Unlikely ($9.4\times10^{-8}$) | 0.0008 | $4.5 \times10^{-14}$ |

Source: SNL 2014

(a) A composite of the results for the Atlas V 551 and the Delta IV Heavy, determined by taking the probability-weighted value of the two sets of results, treating the conditional probability of having a given launch vehicle as 0.5.

(b) Determined as the product of total probability of release, maximum individual dose (mean value) and a health effects estimator of $6\times10^{-4}$ latent cancer fatalities per rem.

(c) The individuals associated with the maximum individual risk in Phase 0 and 1 are assumed to be the same individual, so the two risks are additive. The individuals associated with the maximum individual risk in Phases 3, 4, and 5 would not be the same individual due to different global regions potentially affected.

Probability categories (i.e., unlikely, very unlikely) as defined by NASA.

The individual risk estimates are small compared to other risks. For example, Table 4-9 presents information on annual individual fatality risks to residents of the United States due to various types of hazards. This data indicates that in 2010 the average individual risk of accidental death in the United States was about 1 in 2,600 per year, while the average individual risk of death due to any disease, including cancer, was about 1 in 140.

#### 4.1.4.8. Uncertainty

An uncertainty analysis to estimate uncertainties in probabilities, source terms, radiological consequences, and mission risks has not been performed as part of this report. Based on experience with uncertainty analyses in the risk assessment of previous missions (e.g., for the Cassini, Mars Exploration Rover, New Horizons, and Mars Science Laboratory missions), the uncertainty in the estimated mission risk for the Mars 2020 mission can be approximated. The FSAR analysis for those missions indicate that the uncertainty is dominated by the uncertainty associated with the launch vehicle accident probabilities. The $5^{th}$ and $95^{th}$ percentile accident probabilities are about a factor of 25 lower and higher, respectively, than the accident median probabilities. The Mars 2020 mission risk estimate of $2.9\times10^{-5}$ (or a probability of about 1 in 34,000 that a health effect would occur) can be treated 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 risks at the $5^{th}$ and $95^{th}$ percent confidence levels are then estimated to be $1.2\times10^{-6}$ (or a probability of about 1 in 860,000 that a health effect will occur) and $7.3\times10^{-4}$ (or a probability of about 1 in 1,400 that a health effect will occur), respectively.

**Table 4-9. Calculated Individual Risk and Probability of Fatality by Various Causes in the United States in 2010**

| Accident Type | Number of Fatalities | Approximate Individual Risk Per Year | Probability |
|---|---|---|---|
| **Extremely Unlikely** | | | |
| Lightning | 29 | $9.39 \times 10^{-8}$ | 1 in 11 million |
| Tornadoes | 45 | $1.46 \times 10^{-7}$ | 1 in 6.9 million |
| Flood | 103 | $3.33 \times 10^{-7}$ | 1 in 3 million |
| Extreme Heat or Cold | 172 | $5.57 \times 10^{-7}$ | 1 in 1.8 million |
| **Very Unlikely** | | | |
| Legal Intervention | 412 | $1.33 \times 10^{-6}$ | 1 in 750,000 |
| All Weather | 490 | $1.59 \times 10^{-6}$ | 1 in 630,000 |
| Accidental Discharge of Firearms | 606 | $1.96 \times 10^{-6}$ | 1 in 510,000 |
| Water, Air and Space Transport Accidents (includes unspecified transport accidents) | 1,600 | $5.18 \times 10^{-6}$ | 1 in 190,000 |
| Accidental Exposure to Smoke, Fires and Flames | 2,782 | $9.01 \times 10^{-6}$ | 1 in 110,000 |
| Accidental Drowning and Submersion | 3,782 | $1.22 \times 10^{-5}$ | 1 in 82,000 |
| All Fatal Injuries at Work | 4,690 | $1.52 \times 10^{-5}$ | 1 in 66,000 |
| Assault (Homicide) | 16,259 | $5.27 \times 10^{-5}$ | 1 in 19,000 |
| Alcohol-induced deaths | 25,692 | $8.32 \times 10^{-5}$ | 1 in 12,000 |
| Falls | 26,009 | $8.42 \times 10^{-5}$ | 1 in 12,000 |
| Accidental Poisoning and Exposure to Noxious Substances | 33,041 | $1.07 \times 10^{-4}$ | 1 in 9,300 |
| Motor Vehicle | 35,332 | $1.14 \times 10^{-4}$ | 1 in 8,700 |
| Suicide | 38,364 | $1.24 \times 10^{-4}$ | 1 in 8,000 |
| Drug-induced deaths | 40,393 | $1.31 \times 10^{-4}$ | 1 in 7,600 |
| All Accidents | 120,859 | $3.91 \times 10^{-4}$ | 1 in 2,600 |
| **Unlikely** | | | |
| All Diseases | 2,254,585 | $7.30 \times 10^{-3}$ | 1 in 140 |
| **All Causes** | **2,468,435** | $\mathbf{7.99 \times 10^{-3}}$ | **1 in 125** |

**Sources:** USBC 2013b, BLS 2013, NOAA 2013, HHS 2013.

**Note:** The census population of the United States for the year 2010 was 308,745,538.

### 4.1.5 Radiological Impacts Due to Accidents Releasing Science Instrumentation Source Terms

The Mars 2020 mission may include instrumentation that requires the use of small quantities of radioactive material. While the specific suite of instrumentation has not been identified, instruments incorporating small sources have been used in past missions. The DOE performed a risk assessment using a representative instrument and source term, and information in previous risk assessments that addressed these types of sources. Since the instrument package for the Mars 2020 mission should be independent of the power source—MMRTG, solar, or solar augmented with LWRHUs—this analysis is applicable to all alternatives being considered.

#### 4.1.5.1. Response to Accident Environments and Accident Probabilities and Source Terms

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 an Alpha-Particle X-Ray Backscatter Spectrometer (APXS) is mounted close to a 3-micron-thick foil so that its alpha particles can probe the rocks on Mars. The MER EIS (NASA 2002b) presents estimated probabilities of release in an accident. These numbers are reproduced for the APXS Cm-244 and only the phase roll-ups are given. The mean release, given a release, is also obtained from the MER EIS (NASA 2002b). However, a launch accident is not always severe enough to cause a release. This results in a conditional probability of release less than one. Detailed analyses to obtain the 99th percentiles were not conducted.

The risks from other source terms from instruments considered for analysis in the DOE NRA (the Co-57 in the Mossbauer spectrometer and the tritium in the Dynamic Albedo of Neutrons (DAN) instrument), 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. The risks associated with these possible source terms were not analyzed. Thus, the reported source terms, consequences, and risks are for the Cm-244 in the APXS, and these are expected to approximate the source terms and consequences for all the science instruments.

The probability of a launch accident involving any release of radioactive material from the science instruments is approximately 1 in 87. Because the science instrument radioisotope must be relatively unprotected to perform its function, both the probability of release and the quantity of material released is only slightly affected by the accident environments. The source term values in all phases vary by at most a factor of about 6.

A summary of the accident and source term probabilities by mission phase, along with mean source terms, are presented in Table 4-10.

- **Phase 0 (Pre-Launch):** During the Pre-launch period prior to ignition of the Stage 1 liquid rocket engine, on-pad accidents could result in a release at a total probability of $1.8\times10^{-6}$ (one 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.

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## Table 4-10. Summary of Science Instrumentation Radioisotope Accident Probabilities and Source Terms

| Mission Phase [(a)] | *Accident Probability* | Conditional Probability of Release [(b)] | Total Probability of a Release | Mean Source Term Given an Accident | Mean Source Term Given a Release |
|---|---|---|---|---|---|
| 0: Pre-Launch | Very Unlikely ($3.3x10^{-6}$) | 0.56 | Very Unlikely ($1.8x10^{-6}$) | 0.018 | 0.033 |
| 1: Early Launch | Unlikely $3.1x10^{-3}$ | 0.19 | Unlikely ($6.0x10^{-4}$) | 0.0021 | 0.011 |
| 2: Late Launch | Unlikely $3.6x10^{-3}$ | 0.032 | Unlikely ($1.2x10^{-4}$) | 0.00097 | 0.030 |
| 3: Suborbital | $1.3x10^{-2}$ | 0.50 | Unlikely ($6.6x10^{-3}$) | 0.015 | 0.030 |
| 4: Orbital | Unlikely ($4.7x10^{-3}$) | 0.90 | Unlikely ($4.2X10^{-3}$) | 0.027 | 0.030 |
| 5: Long-term Reentry | Very Unlikely ($1.0x10^{-6}$) | 1.00 | Very Unlikely ($1.0x10^{-6}$) | 0.060 | 0.060 |
| **Overall Mission [(c)]** | **$2.5x10^{-2}$** | **0.47** | **$1.2x10^{-2}$** | **0.013** | **0.028** |

Source: SNL 2014

(a) The table presents a composite of the results for the Atlas V 551 and the Delta IV Heavy, determined by taking the probability-weighted value of the two sets of results, treating the conditional probability of having a given launch vehicle as 0.5.
(b) The conditional probability of a release of Cm-244 given that an accident has occurred.
(c) Overall mission values weighted by total probability of release for each mission phase.
**Notes:** Differences in multiplications and summations are due to rounding of results as reported in SNL 2014.
Probability categories (i.e., unlikely, very unlikely) as defined by NASA.

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- **Phase 1 (Early Launch):** During Phase 1, during which there is the potential for land impacts in the launch area, the total probability of release is $6.0 \times 10^{-4}$ (one in 1,700). The mean source term given an accident with 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 into the air from blast-generated debris. The total probability of release is $1.2 \times 10^{-4}$ (one in 8,300). The mean source term given an accident with a release is estimated to be 0.030 Ci.
- **Phase 3 (Suborbital):** 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 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 $6.6 \times 10^{-3}$ (or 1 in 150). The mean source term given an accident with a release is estimated to be 0.030 Ci.
- **Phase 4 (Orbital):** Accidents that may 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 would break apart during reentry, releasing the LWRHUs before impact. The total probability of release is estimated to be $4.2 \times 10^{-3}$ (or 1 in 240). The mean source term given an accident with a release is estimated to be 0.030 Ci.
- **Phase 5 (Long-term Reentry):** The potential exists for an inadvertent long-term (hundreds to thousands of years) reentry should the SC be left in an Earth crossing orbit. Based on considerations of long-term inadvertent reentry for other missions, the probability of such an occurrence is estimated to be less than $1 \times 10^{-6}$, 1 in 1,000,000. The mean source term given an accident with a release is estimated to be 0.060 Ci.

The specific probability values presented in this DEIS are estimates and will likely differ from those that might ultimately be developed in the more detailed FSAR that would be prepared by DOE if the Proposed Action (Alternative 1) is selected. Some probabilities would likely increase while others may decrease. However, NASA expects the overall probability of an accidental release of radioactive material would not vary substantially from the values presented in this DEIS.

#### 4.1.5.2. Radiological Consequences

The radiological consequences of a given accident that results in a radiological release have been calculated in terms of maximum individual dose, collective dose, health effects, and land area contaminated at or above specified levels. The analysis of the radiological consequences associated with the science instrument small source term CM-244, was performed using the same techniques as previously described for the analysis of the consequences associated with the release of plutonium dioxide. Key results for the mean estimates are summarized below and in Table 4-11.

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**Table 4-11. Summary of Science Instrumentation Radioisotope Estimated Radiological Consequences**

| Mission Phase [a] | Total Probability of Release | Mean Maximum Individual Dose, rem | Mean Health Effects [b] | Mean Land Contamination [c] $km^2$ |
|---|---|---|---|---|
| 0: Pre-Launch | Very Unlikely ($1.8x10^{-6}$) | $3.4x10^{-5}$ | 0.00016 | 0.0041 |
| 1: Early Launch | Unlikely ($6.0x10^{-4}$) | $1.1x10^{-5}$ | $5.3x10^{-5}$ | 0.0014 |
| 2: Late Launch | Unlikely ($1.2x10^{-4}$) | $3.1x10^{-5}$ | 0.00015 | 0.0038 |
| 3: Suborbital | Unlikely ($6.6x10^{-3}$) | $3.1x10^{-5}$ | 0.00015 | 0.0038 |
| 4: Orbital | Unlikely ($4.2X10^{-3}$) | $3.1x10^{-5}$ | 0.00015 | 0.0038 |
| 5: Long-Term Reentry | Very Unlikely ($1.0x10^{-6}$) | $6.1x10^{-5}$ | 0.00029 | 0.0075 |
| **Overall Mission [d]** | **$1.2x10^{-2}$** | **$3.0x10^{-5}$** | **0.00014** | **$3.6x10^{-3}$** |

Source: SNL 2014

(a) The table presents a composite of the results for the Atlas V 551 and the Delta IV Heavy, determined by taking the probability-weighted value of the two sets of results and treating the conditional probability of having a given launch vehicle as 0.5. All values are for an accident with a release.

(b) Based on ISCORS health effects recommendation of $6x10^{-4}$ health effects per person-rem for the general population.

(c) Land area contaminated above 0.2 $\mu Ci/m^2$; 1 $km^2$ = 0.386 $mi^2$.

(d) Overall mission values weighted by total probability of release for each mission phase.

**Notes:** Differences in multiplications and summations are due to rounding of results as reported in SNL 2014.

Probability categories (i.e., unlikely, very unlikely) as defined by NASA.

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The consequences associated with the instrumentation source term are very similar for all launch phases. In general, the range of consequences varies by less than an order of magnitude (less than a factor of 10). The largest impacts are associated with Phase 5, the long-term reentry phase. For this phase, the maximum individual dose is $6.1\times10^{-5}$ rem, the collective population dose results in 0.00029 health effects; land contamination above the 0.2 µCi/m$^2$ level would be 0.0075 km$^2$ ($2.9\times10^{-3}$ mi$^2$, 1.9 acres).

4.1.5.3. Discussion of the Results

***Maximum Individual Doses***

The maximum individual dose is the maximum dose delivered to a single individual for each accident. During all phases, the predicted mean radiation dose to the maximally exposed individual ranges from about $1.1\times10^{-5}$ rem (0.011 millirem) up to about $6.1\times10^{-5}$ rem (0.061 millirem). The largest maximum individual dose is about two percent of the dose from natural background radiation. No short-term radiological effects would be expected from any of these exposures.

***Population Exposures***

The population exposure is the dose delivered to all affected individuals for each accident. During all phases, the predicted mean population dose are sufficiently small that no short-term radiological effects (the largest estimate of the number of latent cancer fatalities is 0.00029) would be expected from any of these exposures.

In the event of a launch area accident, it is unlikely that any given racial, ethnic, or socioeconomic group of the population would bear a disproportionate share of the consequences.

***Impacts of Radiological Releases on the Environment***

The affected environment, described in Section 3 of this DEIS, includes the regional area near CCAFS and the global area. Launch area accidents (Phases 0 and 1) would initially release material into the regional area, defined in this DEIS to be within 100 km (62 mi) of the launch pad. Since some of the accidents result in the release of very fine particles (less than a micron in diameter), a portion of such releases could be transported beyond 100 km (62 mi) and become well mixed in the troposphere, and thus affecting the global environment. Releases during Phase 3 could involve reentering material that could impact the ground in southern Africa. Releases during Phase 4 could affect the environment anywhere between 29° north latitude and 29° south latitude.

DOE's risk assessment indicates that, for all phases, an area of between $1.4\times10^{-3}$ km$^2$ ($5.4\times10^{-4}$ mi$^2$, 0.35 acres) to 0.0075 km$^2$ (0.0029 mi$^2$, 1.9 acres) could be contaminated above 0.2 µCi/m$^2$.

4.1.5.4. Mission Risks

A summary of the mission risks is presented in Table 4-12. For the purpose of this DEIS, risk is defined as the expectation of health effects in a statistical sense (i.e., the product of total probability times the mean health effects resulting from a release and then summed over all conditions leading to a release). The risk of health effects in the potentially exposed populations 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. The overall radiological risk from the instrument small source radioisotopes for the Mars 2020 mission is estimated to be $1.6 \times 10^{-6}$. Thus, the total probability of one health effect for the Proposed Action (Alternative 1) resulting from the use of Cm-244 in a science instrument is about 1 in 690,000.

**Table 4-12. Summary of Instrumentation Radioisotope Health Effect Mission Risks**

| Mission Phase [(a)] | Accident Probability | Conditional Probability of a Release | Total Probability of a Release | Mean Health Effects (given an release) | Mission Risks |
|---|---|---|---|---|---|
| 0: Pre-Launch | Very Unlikely ($3.3 \times 10^{-6}$) | 0.56 | Very Unlikely ($1.8 \times 10^{-6}$) | 0.00016 | $3.0 \times 10^{-10}$ |
| 1: Early Launch | Unlikely $3.1 \times 10^{-3}$ | 0.19 | Unlikely ($6.0 \times 10^{-4}$) | $5.3 \times 10^{-5}$ | $3.2 \times 10^{-8}$ |
| 2: Late Launch | Unlikely $3.6 \times 10^{-3}$ | 0.032 | Unlikely ($1.2 \times 10^{-4}$) | 0.00015 | $1.7 \times 10^{-8}$ |
| 3: Suborbital | $1.3 \times 10^{-2}$ | 0.50 | Unlikely ($6.6 \times 10^{-3}$) | 0.00015 | $9.6 \times 10^{-7}$ |
| 4: Orbital | Unlikely ($4.7 \times 10^{-3}$) | 0.90 | Unlikely ($4.2 \mathrm{X} 10^{-3}$) | 0.00015 | $6.1 \times 10^{-7}$ |
| 5: Long-Term Reentry | Very Unlikely ($1.0 \times 10^{-6}$) | 1.00 | Very Unlikely ($1.0 \times 10^{-6}$) | 0.00029 | $2.9 \times 10^{-10}$ |
| **Overall Mission** | **$2.5 \times 10^{-2}$** | **0.47** | **$1.2 \times 10^{-2}$** | **0.00014** | **$1.6 \times 10^{-6}$** |

Source: SNL 2014

(a) A composite of the results for the Atlas V 551 and the Delta IV Heavy, determined by taking the probability-weighted value of the two sets of results, treating the conditional probability of having a given launch vehicle as 0.5. Accident probabilities are the average of individual values for the two vehicles. Based on the current state of knowledge, the specific accident probabilities for the accident conditions for each vehicle are expected to be similar.

**Notes:** Differences in multiplications and summations are due to rounding of results as reported in SNL 2014.
Probability categories (i.e., unlikely, very unlikely) as defined by NASA.

The risk contribution from Phase 3 accidents represents 59 percent of the radiological risk for the Mars 2020 mission. Phase 4 contributes 38 percent of the overall mission risk.

The global risks are due to accidents in all mission phases and, because Phases 3 and 4 are the dominant risk contributing phases, most of the risk is to the global area—over 98 percent. The contribution to risk within 100 km (62 mi) of the launch site is about 1.4 percent. The launch area risks are due entirely from accidents during Phases 0 and 1.

### *Individual Risks (Maximum Exposed Individual)*

Individual risk can be interpreted as the probability of an individual in the exposed population incurring a fatal cancer. For an accident near the launch site, not everyone within the regional area would be expected to receive a dose as a result of the accident. Due to meteorological conditions prevailing at the time of launch, only a portion of the total regional population is estimated to receive some measurable radiological exposure should an accident occur.

Even those individuals within the exposed population that receive the maximum individual dose would face very small risks. The risk to the maximally exposed individual within the launch area and global populations from the release of the instrumentation radioisotopes is estimated to be exceedingly small for the Mars 2020 mission (Table 4-13).

**Table 4-13. Instrumentation Radioisotope Maximum Individual Risk**

| Mission Phase [(a)] | Release Probability | Maximum Individual Dose, (rem) | Maximum Individual Risk [(b), (c)] |
|---|---|---|---|
| 0: Pre-Launch | Very Unlikely ($1.8x10^{-6}$) | $3.4x10^{-5}$ | $3.7x10^{-14}$ |
| 1: Early Launch | Unlikely ($6.0x10^{-4}$) | $1.1x10^{-5}$ | $4.0x10^{-12}$ |
| 2: Late Launch | Unlikely ($1.2x10^{-4}$) | $3.1x10^{-5}$ | $2.2x10^{-12}$ |
| 3: Suborbital | Unlikely ($6.6x10^{-3}$) | $3.1x10^{-5}$ | $1.2x10^{-10}$ |
| 4: Orbital | Unlikely ($4.2X10^{-3}$) | $3.1x10^{-5}$ | $7.7x10^{-11}$ |
| 5: Long-Term Reentry | Very Unlikely ($1.0x10^{-6}$) | $6.1x10^{-5}$ | $3.7x10^{-14}$ |

Source: SNL 2014

(a) A composite of the results for the Atlas V 551 and the Delta IV Heavy, determined by taking the probability-weighted value of the two sets of results, treating the conditional probability of having a given launch vehicle as 0.5.

(b) Determined as the product of total probability of release, maximum individual dose (mean value), and a health effects estimator of $6x10^{-4}$ latent cancer fatalities per rem.

(c ) The individuals associated with the maximum individual risk in Phase 0 and 1 are assumed to be the same individual, so the two risks are additive. The individuals associated with the maximum individual risk in Phases 3, 4, and 5 would not be the same individual due to different global regions potentially affected.

**Note:** Probability categories (i.e., unlikely, very unlikely) as defined by NASA.

### 4.1.6 Radiological Contingency Response Planning

Prior to launch of the Mars 2020 mission, a comprehensive set of plans would be developed by NASA to ensure that any launch accident could be met with a well-developed and tested response. NASA's plans would be developed in accordance with the National Response Framework (NRF) (DHS 2013) and the NRF Nuclear/ Radiological Incident Annex (DHS 2008) with the combined efforts of the U.S. Department of Homeland Security (DHS), DHS's Federal Emergency Management Agency, DOE, the U.S. Department of Defense (DoD), the U.S. Department of State (DOS), the U.S. Environmental Protection Agency (EPA), the state of Florida, Brevard County, and local organizations. These organizations and other Federal agencies, as appropriate, could be involved in response to a radiological emergency. The radiological contingency planning and implementation for a Mars 2020 mission would be expected to be similar to the process used for the 2011 MSL mission launch (Scott 2012).

The radiological emergency response plan would be exercised prior to launch to verify that the response interfaces, command channels, and field response-organizations would be prepared to respond in the unlikely event of a launch accident. NASA would be the Coordinating Agency, and in the event of a declaration of an Incident of National Significance, would work with the DHS to coordinate the entire Federal response for launch accidents occurring within United States jurisdiction. Should a release of radioactive material occur in the launch area, the state of Florida, Brevard County, and local governments would determine an appropriate course of action for any regional areas (such as sheltering in place, evacuation, exclusion of people from contaminated land areas, or no action required) and would have full access to the coordinated Federal response. For accidents outside United States jurisdiction defined as Incidents of National Significance, NASA and DHS would assist the DOS in coordinating the United States' response via diplomatic channels and in deploying Federal resources as requested.

To manage the radiological contingency response, NASA would establish a radiological emergency response capability that would include a radiological assessment and command center, as well as field monitoring assets deployed prior to launch. The assessment and command center would be the focal point for NASA and DHS coordination efforts. This center would also be used to coordinate the initial Federal response to a radiological contingency until the Mars 2020 spacecraft has left Earth orbit. Pre-deployed assets to support a response to a potential launch accident would include representation from NASA, DHS, DOE, DoD, DOS, EPA, USAF, the National Oceanic and Atmospheric Administration (NOAA), the state of Florida, and Brevard County.

If impact of the Mars 2020 spacecraft occurs in the ocean following an accident, NASA would coordinate with the DHS, the U.S. Coast Guard, the U.S. Navy, and DOE to initiate security measures and assess the feasibility of search and retrieval operations. Efforts to recover the MMRTG or its components would be based on technical feasibility and consideration of any potential health hazards presented to recovery personnel and potential environmental impacts.

## 4.2 ENVIRONMENTAL IMPACTS OF ALTERNATIVE 2

With Alternative 2, NASA would discontinue preparations for the Proposed Action (Alternative 1) and implement an alternative Mars 2020 mission. The alternative Mars 2020 mission would include an autonomous rover that would perform science operations on the surface of Mars. Instead of an MMRTG, a solar array would provide the necessary electric power to operate the Mars 2020 rover and its science instruments.

The non-radiological impacts for this alternative would be identical to those described for Alternative 1 and are addressed in Sections 4.2.1 through 4.2.3.

### 4.2.1 Environmental Consequences of Preparing for Launch

With Alternative 2, the potential environmental consequences of preparing for launch would be the same as those described in Section 4.1.1 for the Proposed Action, with the exception that some spacecraft and launch vehicle integration personnel would not be exposed to radiation from the MMRTG during pre-launch testing and integration, since a radioisotope power system, the MMRTG, would not be used as the source of electrical power for the Alternative 2 Mars 2020 rover.

### 4.2.2 Environmental Impacts of a Normal Launch

With Alternative 2, the primary environmental impacts of a normal launch of the Mars 2020 mission would be the same as those described in Section 4.1.2 for the Proposed Action (Alternative 1).

### 4.2.3 Non Radiological Environmental Impacts of Potential Accidents

With Alternative 2, the environmental non-radiological impacts of potential accidents would be the same as those described in Section 4.1.3 for the Proposed Action (Alternative 1).

### 4.2.4 Radiological Environmental Impacts of Potential Accidents

If the rover should be equipped with science instrumentation that incorporates small radioisotope sources, the radiological risks from the release of these materials during an accident would be identical to those presented in Section 4.1.5. These risks are applicable to any rover that is equipped with this instrumentation, regardless of whether the power supply is an MMRTG, a solar array, or a solar array augmented with LWRHUs.

## 4.3 ENVIRONMENTAL IMPACTS OF ALTERNATIVE 3

In Alternative 3, NASA would discontinue preparations for the Proposed Action (Alternative 1) and implement an alternative Mars 2020 mission. The alternative Mars 2020 mission would include an autonomous rover that would perform science operations on the surface of Mars. A solar array would provide the necessary electric power to operate the Mars 2020 rover and its science instruments. In addition, the power from the solar array would be augmented by up to 71 LWRHUs. These LWRHUs would be used to provide thermal power to maintain the internal temperature of the rover within the required limits to ensure equipment and instrumentation survivability.

The non-radiological impacts for this alternative would be identical to those identified for the Proposed Action (Alternative 1) and are addressed in Sections 4.3.1 through 4.3.3. Environmental impacts of potential accidents involving radiological material for the rover powered by a solar array augmented with LWRHUs are addressed in Section 4.3.4 and Section 4.1.5. The impacts discussed in Section 4.3.4 are those associated with the release of $PuO_2$ from the LWRHUs during an accident. If the rover should be equipped with science instrumentation that incorporates small radioisotope sources, the radiological risks from the release of these materials during an accident would be identical to those presented in Section 4.1.5. These risks would be applicable to any rover that is equipped with this instrumentation, regardless of whether the power supply is an MMRTG, a solar array, or a solar array augmented with LWRHUs.

### 4.3.1 Environmental Consequences of Preparing for Launch

With Alternative 3, the potential environmental consequences of preparing for launch would be the same as those described in Section 4.1.1 for the Proposed Action, with the exception that some spacecraft and launch vehicle integration personnel would not be exposed to radiation from the MMRTG during pre-launch testing and integration, since a radioisotope power system, the MMRTG, would not be used as the source of electrical power for the Alternative 3 Mars 2020 rover.

### 4.3.2 Environmental Impacts of a Normal Launch

With Alternative 3, the primary environmental impacts of a normal launch of the Mars 2020 mission would be the same as those described in Section 4.1.2 for the Proposed Action (Alternative 1).

### 4.3.3 Non-radiological Environmental Impacts of Potential Accidents

With Alternative 3, the environmental non-radiological impacts of potential accidents would be the same as those described in Section 4.1.3 for the Proposed Action.

### 4.3.4 Radiological Environmental Impacts of Potential Accidents Involving Plutonium

NASA and the U.S. Department of Energy (DOE) have assessed the potential environmental impacts of launch accidents involving release of $PuO_2$. The likelihood that a malfunction or system failure would lead to launch accident is essentially the same for this alternative (a solar-powered rover with LWRHUs) as for Alternative 1 (an MMRTG powered rover).The analysis results indicate that the most likely outcome of implementing this alternative version of the Mars 2020 mission is a successful launch of the spacecraft toward Mars. If, however, a launch accident were to occur, the most probable outcome is an accident without a release of the $PuO_2$. Specifically:

- There is a 97.5% chance of a successful launch.
- There is a 2.5% chance of a launch accident.
- There is a 1 in 15,000 chance of a launch accident that would release plutonium dioxide.
    - There is a 1 in 16,000 chance of a launch accident that would result in a release of plutonium dioxide in the launch area.
    - There is a 1 in 420,000 chance of a launch accident that would result in a release of plutonium dioxide outside the launch area.
- No radiological fatalities would be expected to occur as a result of any accident.
- The average maximum dose to any member of the public would be equal to about 5 days of exposure to natural background radiation for a person living in the United States.

This section summarizes the results from the DOE's nuclear risk assessment (SNL 2014) for the solar-powered rover with LWRHUs.

#### 4.3.4.1. Risk Assessment Methodology

The nuclear risk assessment for this alternative for the Mars 2020 mission was performed using the same methodology as that used for Alternative 1. The discussion of the methodology is contained in Section 4.1.4.1. The DOE risk analysis was performed assuming that 80 LWRHUs could be used on the Mars 2020 rover. This is slightly more than the 71 LWRHUs that NASA anticipates could be used on the rover. The DOE analysis conservatively assumed more LWRHUs to address the possibility that design requirements could change requiring more thermal power to maintain the proper environment for rover equipment and instrumentation.

Safety testing and response analyses of the LWRHU to accident environments indicate that the protection provided by graphitic components 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 and/or cladding 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 bare clad.

#### 4.3.4.2. Launch Accidents and Accident Probabilities

Launch accidents and their associated probabilities were identified and developed using the methodology described in Section 4.1.4.2. As in the analysis for Alternative 1, the analysis considered two representative launch vehicles (the Atlas V 551 and the Delta IV Heavy) in developing the composite analysis results. The same six mission phases were identified for the analysis.

- Phase 0 - Pre-Launch,
- Phase 1 - Early Launch,
- Phase 2 - Late Launch,
- Phase 3 - Suborbital Reentry,
- Phase 4 - Orbit Reentry, and
- Phase 5 – Long-term Reentry.

The composite accident end-state probabilities for the launch vehicle are presented in Table 4-14. The only difference between these accident probabilities and those developed for Alternative 1 (Table 4-2) is in Phase 0. Because there is no MMRTG in this alternative, the accidents associated with loss of MMRTG cooling during Phase 0 are not applicable to this alternative. Therefore, the Phase 0 accident probability for the Mars 2020 mission using solar power augmented with LWRHUs is smaller ($3.3x10^{-6}$ instead of $3.3x10^{-5}$) than for the Mars 2020 MMRTG alternative.

**Table 4-14. Alternative 3: Accident End-state Probabilities**

| Ground Impact Configuration | Phase 0 | Phase 1 | Phase 2 | Phase 3 | Phase 4 | Phase 5 | Total Probability |
|---|---|---|---|---|---|---|---|
| On-Pad Explosion | $4.8 \times 10^{-7}$ | $9.8 \times 10^{-5}$ | - | - | - | - | $1.2 \times 10^{-4}$ |
| FSII | - | $2.2 \times 10^{-5}$ | - | - | - | - | $2.2 \times 10^{-5}$ |
| Stage 2/SV | - | $4.8 \times 10^{-5}$ | - | - | - | - | $4.8 \times 10^{-5}$ |
| SVII | $2.8 \times 10^{-6}$ | $6.3 \times 10^{-7}$ | - | - | - | - | $3.4 \times 10^{-6}$ |
| Low Altitude FTS | - | $2.9 \times 10^{-3}$ | - | - | - | - | $2.9 \times 10^{-3}$ |
| High Altitude FTS | - | - | $3.6 \times 10^{-3}$ | - | - | - | $3.6 \times 10^{-3}$ |
| Sub-Orbital Reentry | - | - | - | $1.3 \times 10^{-2}$ | - | - | $1.3 \times 10^{-2}$ |
| Orbital Reentry | - | - | - | - | $4.7 \times 10^{-3}$ | - | $4.7 \times 10^{-3}$ |
| Long Term | - | - | - | - | - | $1.0 \times 10^{-6}$ | $1.0 \times 10^{-6}$ |
| **Total** | **$3.3 \times 10^{-6}$** | **$3.1 \times 10^{-3}$** | **$3.6 \times 10^{-3}$** | **$1.3 \times 10^{-2}$** | **$4.7 \times 10^{-3}$** | **$1.0 \times 10^{-6}$** | **$2.5 \times 10^{-2}$** |

Source: SNL 2014

Note: This is a composite of the accident end state probabilities for the Atlas V 551 and the Delta IV Heavy, determined by taking the probability-weighted value of the two sets of results, treating the conditional probability of having a given launch vehicle as 0.5.

For this DEIS, the initiating probabilities and total probabilities of an accident with a release of PuO2 are grouped into categories that allow for a descriptive characterization of the likelihood of each accident. The categories and their associated probability ranges are:

- unlikely: 10-2 to 10-4 (1 in 100 to 1 in 10 thousand);
- very unlikely: 10-4 to 10-6 (1 in 10 thousand to 1 in 1 million); and
- extremely unlikely: less than 10-6 (less than 1 in 1 million).

The potential accident environments associated with accidents include blast (explosion overpressure), fragments, thermal energy (burning liquid propellant and/or solid propellant), reentry conditions (aerodynamic loads and heating), and surface impact. 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 its timing (relative to launch) of occurrence.

#### 4.3.4.3. LWRHU Response to Accident Environments

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.

#### 4.3.4.4. Accident Probabilities and Source Terms

In the nuclear risk assessment, DOE evaluated each of the identified end states and estimated the accident environments to which the LWRHUs would likely be exposed. From that information, conditional probabilities that a release would occur and estimated source terms were developed based on the known response of LWRHUs to various accident conditions.

As discussed earlier, the probability of a launch accident involving any release of $PuO_2$ is very small, approximately 1 in 15,000. The most severe accident environments would occur during launch area accidents that might expose the LWRHUs to mechanical impacts, explosion overpressures and fragments, and fire environments from burning liquid and solid propellants.

A summary of the accident and source term probabilities by mission phase, along with mean and 99$^{th}$ percentile source terms, is presented in Table 4-15. For the purpose of this DEIS, "source term" is defined as that portion of the release that becomes airborne and could be transported downwind.

The 99$^{th}$ percentile 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 99$^{th}$ percentile value reflects the potential for higher radionuclide releases at lower probabilities. The 99$^{th}$ percentile releases are up to 36 times the mean estimates reported in this DEIS, but at probabilities of a factor of 100 lower than the mean probabilities. Essential features of the results are summarized below.

- **Phase 0 (Pre-Launch):** During the pre-launch period, prior to ignition of the Stage 1 liquid rocket engine, most initiating failures result in a mission abort. Those failures that result in on-pad accidents could result in a release at a total probability of $3.1 \times 10^{-7}$ (1 in 3,200,000). The mean source term, given that an accident with a release has occurred, is estimated to be 3.0 Ci.
- **Phase 1 (Early Launch):** During Phase 1, during which land impacts, including near the launch complex, are likely, the accidents resulting in a release have a total probability estimate of $6.2 \times 10^{-5}$ (or 1 in 16,000). The mean source term, given an accident with a release has occurred, is estimated to be 4.1 Ci.

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## Table 4-15. Alternative 3: Summary of Accident Probabilities and LWRHU Source Terms

| Mission Phase [(a)] | Accident Probability | Source Term, Ci (given an accident) | | Conditional Probability of Release [(b)] | Total Probability of a Release | Source Term [(c)], Ci (given a release) | |
|---|---|---|---|---|---|---|---|
| | | Mean | $99^{th}$ Percentile | | | Mean | $99^{th}$ Percentile |
| 0: Pre-Launch | Very Unlikely ($3.3x10^{-6}$) | 0.28 | 5.0 | 0.093 | Extremely Unlikely ($3.1x10^{-7}$) | 3.0 | 21 |
| 1: Early Launch | | | | | | | |
| On-Pad Explosion | Very Unlikely ($9.8x10^{-5}$) | 0.16 | 2.7 | 0.12 | Very Unlikely ($1.2x10^{-5}$) | 1.3 | 3.2 |
| FSII | Very Unlikely ($2.2x10^{-5}$) | 8.1 | 270 | 0.13 | Very Unlikely ($3.0x10^{-6}$) | 60 | 380 |
| Stage 2/SV | Very Unlikely ($4.8x10^{-5}$) | 0.020 | 0.84 | 0.017 | Extremely Unlikely ($8.0x10^{-7}$) | 1.2 | 5.1 |
| SVII | Extremely Unlikely ($6.3x10^{-7}$) | 0.062 | 2.0 | 0.047 | Extremely Unlikely ($2.9x10^{-8}$) | 1.3 | 4.3 |
| Low Altitude FTS | Unlikely ($2.9x10^{-3}$) | 0.020 | 0.67 | 0.016 | Very Unlikely ($4.6x10^{-5}$) | 1.3 | 6.1 |
| Overall Phase 1 | Unlikely ($3.1x10^{-3}$) | 0.082 | 0.89 | 0.020 | Very Unlikely ($6.2x10^{-5}$) | 4.1 | 76 |
| 2: Late Launch | $3.6x10^{-3}$ | - | - | – | – | - | - |
| 3: Suborbital | $1.3x10^{-2}$ | 0.00022 | - | 0.00018 | Very Unlikely ($2.4x10^{-6}$) | 1.2 | 4.6 |
| 4: Orbital | Unlikely ($4.7x10^{-3}$) | - | - | - | - | - | - |
| 5: Long-term Reentry | Very Unlikely ($1.0x10^{-6}$) | - | - | - | - | - | - |
| **Overall Mission [(d)]** | **$2.5x10^{-2}$** | **0.011** | **-** | **0.0026** | **Very Unlikely ($6.5x10^{-5}$)** | **4.0** | **73** |

Source: SNL 2014

(a) A composite of the results for the Atlas V 551 and the Delta IV Heavy, determined by taking the probability-weighted value of the two sets of results, treating the conditional probability of having a given launch vehicle as 0.5.

(b) The conditional probability of a release of PuO2 given that an accident has occurred.

(c ) Total source terms given. The source term is that portion of the release which becomes airborne would represent the amounts of $PuO_2$ released that are no more than 100 microns (100 micrometers) in diameter. Particles larger than this do not generally become airborne and would remain in the vicinity of the accident.

(d) Overall mission values are weighted by the total probability of release for each mission phase.

**Notes:** Differences in multiplications and summations are due to rounding of results as reported in SNL 2014.

Probability categories (i.e., unlikely, very unlikely) as defined by NASA.

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Most initiating failures occurring in Phase 1 would lead to activation of the FTS. The elements of the FTS are highly redundant and reliable. As a result, the expected outcome of a Phase 1 accident is ground impact of the spacecraft or portions thereof, including possibly the rover with LWRHUs. In this case, mechanical damage and, for an Atlas V 551 accident, potential exposure to burning solid propellant could occur. The probability for this impact configuration with a release is estimated to be $4.6 \times 10^{-5}$ (or 1 in 22,000), with an estimated mean source term, given an accident with a release has occurred, is estimated to be 1.3 Ci).

A much less likely outcome of a Phase 1 accident involves failure of some or all of the FTS elements to perform properly. This could lead to ground impact of the spacecraft (with the LWRHUs inside) still attached to other launch vehicle stages (Stages 1 and 2, or Stage 2). Since this would require multiple failures of safety systems, such ground impact configurations leading to a release are very unlikely. However, because the LWRHUs could impact the ground within the spacecraft at higher velocities and with additional mass above the spacecraft due to the attached Stage(s), the potential for more severe mechanical damage is higher than with the expected accident conditions associated with normal activation of the FTS.

In the impact configurations leading to the largest estimated releases, such as the FSII, slightly larger estimated mean source terms, given an accident with a release, of 60 Ci. Both of these events would fall in the very unlikely range.

- **Phase 2 (Late Launch):** All accidents that could occur in Phase 2 lead to impact of debris in the Atlantic Ocean with no release of $PuO_2$.
- **Phase 3 (Suborbital):** 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 $2.4 \times 10^{-6}$ (or 1 in 420,000). The mean source term, given an accident with a release, is estimated to be 1.2 Ci.
- **Phase 4 (Orbital):** Accidents which occur after attaining parking 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. As previously stated, the LWRHU is designed to survive reentry environments and surface impacts. No releases are expected from accidents in this phase.
- **Phase 5 (Long-term Reentry):** The potential exists for an inadvertent long-term (hundreds to thousands of years) reentry should the SV be left in an Earth crossing orbit. Based on considerations of long-term inadvertent reentry for other missions, the probability of such an occurrence is estimated to be less than $1 \times 10^{-6}$. As previously stated, the LWRHU is designed to survive reentry

environments and surface impacts. No releases are expected from accidents in this phase.

The specific probability values presented in this DEIS are estimates and will likely differ from those that might ultimately be developed in the more detailed FSAR that would be prepared by DOE if this Alternative is selected. Some probabilities would likely increase while others may decrease. However, NASA expects the overall probability of an accidental release of radioactive material would not vary substantially from the values presented in this DEIS.

#### 4.3.4.5. Radiological Consequences

The radiological consequences of a given accident that results in a radiological release have been calculated in terms of maximum individual dose, collective dose, health effects, and land area contaminated at or above specified levels. The radiological consequences have been determined from atmospheric transport and dispersion simulations incorporating both launch-site specific and worldwide meteorological and population data. Biological effects models, based on methods prescribed by the ISCORS, were applied to predict the number of health effects following a launch accident that results in a release of $PuO_2$. The analysis assumes that no mitigation measures (e.g., sheltering, evacuation, and decontamination) are taken to reduce the health impacts. Additional information on the behavior of plutonium in the environment (environmental transport and health impact mechanisms) can be found in Appendix B.

The maximum individual dose is the mean maximum 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-60 (ICRP 1979) and ICRP-66/67 (ICRP 1993, ICRP 1994). The exposure pathways considered include direct inhalation, inhalation of re-suspended material, ingestion (e.g., vegetables, fruit, and seafood), and external exposure. Due to the insoluble nature of $PuO_2$, other secondary exposure pathways (e.g., meat and milk) would be far less important, and their contributions to dose would be negligible.

The health effects represent incremental cancer fatalities induced by releases, as determined by using the ISCORS estimates of $6 \times 10^{-4}$ fatalities per person-rem for the general population (DOE 2002). 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 the probabilities summed over the population, an estimate of the total health effects in the population results.

Table 4-16 presents a summary of DOE's risk assessment of radiological consequences for each of the mission phases. The radiological consequences were estimated by mission phase in terms of both the mean and $99^{th}$ percentile values. The $99^{th}$ percentile radiological consequence is the value predicted to be exceeded 1 percent of the time for an accident with a release. In this context, the $99^{th}$ percentile value reflects the potential for higher radiological consequences to the exposed population at lower probabilities. The $99^{th}$ percentile consequences are one to less than 42 times the mean estimates reported in this DEIS, but at probabilities of a factor of 100 lower than the mean probabilities.

The radiological consequences summarized in Table 4-16 are proportional to the source terms listed in Table 4-15, except that the scaling factors vary with the type and nature of the release. Key factors include the particle size distribution of the release, release height, and energy of the release. The higher dose numbers are associated with very small particles that might be released if the $PuO_2$ were exposed to solid propellant fires. The radiological dose per curie released is about ten times higher with the $PuO_2$ exposed to solid propellant fires. Key results for the mean estimates are summarized below; the corresponding $99^{th}$ percentile estimates can be found in Table 4-16.

- **Phase 0 (Pre-Launch):** The initiating failures that result in Phase 0 accident configurations are extremely unlikely, having very low probabilities of occurrence. The overall mean probability of a release is $3.1 \times 10^{-7}$ (or 1 in 3,200,000) during Phase 0. Most problems that arise during Phase 0 can be successfully mitigated by safety systems and procedures leading to safe hold or termination of the launch countdown.

- If an accident were to occur during Phase 0, however, there is a potential for measurable releases and contamination. The probability of the LWRHUs being close to large pieces of burning solid propellant would be higher in Phase 0 accidents than in other phases. The mean maximum dose to an individual is estimated to be approximately 0.003 rem (3 millirem), about one percent of the dose an individual might receive annually from natural background radiation[19].
- Assuming no mitigation actions, such as sheltering and exclusion of people from contaminated land areas, the radiation doses to the potentially exposed population are predicted to result in 0.015 mean health effects among the potentially exposed population.
- For Phase 0 accidents with a release, the mean area contaminated above 0.2 microcuries per square meter ($\mu Ci/m^2$) (see Section 4.1.4.7) is estimated to be about 0.37 $km^2$ (about 0.14 $mi^2$). Detectable levels below 0.2 $\mu Ci/m^2$ would be expected over a larger area.

[19] An average of about 0.31 rem per year for an individual in the United States from natural sources. Man-made sources add an additional 0.060 to 0.31 rem. The dominant man-made contribution is from medical radiological diagnosis and therapy. See Section 3.2.6 for further information.

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## Table 4-16. Summary of LWRHU Estimated Radiological Consequences

| Mission Phase [a] | Total Probability of Release | Maximum Individual Dose, rem | | Health Effects [b] | | Land Contamination [c] $km^2$ | |
|---|---|---|---|---|---|---|---|
| | | Mean | 99th Percentile | Mean | 99th Percentile | Mean | 99th Percentile [f]4.0 |
| 0: Pre-Launch | Extremely Unlikely ($3.1 \times 10^{-7}$) | 0.0030 | 0.022 | 0.015 | 0.10 | 0.37 | 2.6 |
| Early Launch | | | | | | | |
| On-Pad Explosion | Very Unlikely ($1.2 \times 10^{-5}$) | 0.0013 | 0.0032 | 0.0063 | 0.016 | 0.16 | 0.39 |
| FSII | Very Unlikely ($3.0 \times 10^{-6}$) | 0.062 | 0.38 | 0.30 | 1.8 | 7.5 | 47 |
| Stage2/SV | Extremely Unlikely ($8.0 \times 10^{-7}$) | 0.0013 | 0.0052 | 0.0060 | 0.025 | 0.15 | 0.64 |
| SVII | Extremely Unlikely ($2.9 \times 10^{-8}$) | 0.0014 | 0.0044 | 0.0066 | 0.021 | 0.17 | 0.54 |
| Low Altitude FTS | Very Unlikely ($4.6 \times 10^{-5}$) | 0.0013 | 0.0062 | 0.0061 | 0.030 | 0.16 | 0.76 |
| 1: Overall Phase 1 | Very Unlikely ($6.2 \times 10^{-5}$) | 0.0042 | 0.078 | 0.020 | 0.37 | 0.51 | 9.5 |
| 2: Late Launch | — | — | — | — | — | — | — |
| 3: Suborbital | Very Unlikely ($2.4 \times 10^{-6}$) | 0.0013 | 0.0047 | 0.0060 | 0.022 | 0.15 | 0.57 |
| 4: Orbital | — | — | — | — | — | — | — |
| 5: Long-term Reentry | — | — | — | — | — | — | — |
| **Overall Mission [d]** | **Very Unlikely ($6.5 \times 10^{-5}$)** | **0.0041** | **0.075** | **0.020** | **0.36** | **0.50** | **9.1** |

Source: SNL 2014

(a) A composite of the results for the Atlas V 551 and the Delta IV Heavy, determined by taking the probability-weighted value of the two sets of results, treating the conditional probability of having a given launch vehicle as 0.5.
(b) Based on ISCOR health effects recommendation of $6 \times 10^{-4}$ health effects per person-rem for the general population.
(c ) Land area contaminated above 0.2 µCi/m2; 1 km2 = 0.386 mi2.
(d) Overall mission values weighted by total probability of release for each mission phase.
**Notes:** Differences in multiplications and summations are due to rounding of results as reported in SNL 2014. Probability categories (i.e., unlikely, very unlikely) as defined by NASA.

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- **Phase 1 (Early Launch):** The Phase 1 consequences consist of contributions from two types of accident scenarios. Most initiating failures occurring in Phase 1 would lead to activation of the FTS. The elements of the FTS are highly redundant and very reliable. As a result, the expected outcome of a Phase 1 accident is that the SV and LWRHUs or its components could fall free to the ground and would be subject to mechanical damage and potential exposure to burning solid propellant. The probability for this very unlikely impact configuration with a release is $4.6 \times 10^{-5}$ (or 1 in 22,000). The mean maximum individual dose is estimated to be 0.0013 rem (1.3 millirem), less one percent of the dose an individual might receive annually from natural background radiation.

  Assuming no mitigation action, such as sheltering, the radiation dose to the potentially exposed population is predicted to result in 0.0062 mean health effects among the potentially exposed population over the long term.

  The risk assessment indicates that about 0.16 $km^2$ (about 0.062 $mi^2$) could be contaminated above 0.2 $\mu Ci/m^2$.

  A less likely outcome of a Phase 1 accident involves failure of some or all of the FTS elements to perform properly. This could lead to ground impact of the spacecraft (with the LWRHUs inside) still attached to other launch vehicle stages (Stages 1 and 2, or Stage 2). Since this would require multiple failures of safety systems, such ground impact configurations leading to a release are very unlikely. However, because the LWRHUs could impact the ground within the spacecraft at high speed, the potential for more severe mechanical damage and exposure to burning liquid and, possibly, solid propellant, could result in higher source terms.

  The more severe impact configurations, such as the FSII, would result in larger estimated mean releases. In the highest consequence case, identified in Table 4-16, mean exposures as high as about 0.062 rem (62 millirem) to the maximum exposed individual might occur with a total probability of $3.0 \times 10^{-6}$ or 1 in 330,000. Assuming no mitigation action, such as sheltering, radiation doses to the potentially exposed population are predicted to result in an estimated 0.30 mean health effects. An estimated area of 7.5 $km^2$ (about 2.9 $mi^2$) might be contaminated above 0.2 $\mu Ci/m^2$. Detectable levels below 0.2 $\mu Ci/m^2$ would be expected over a larger area.

- **Phase 2 (Late Launch):** No radiological consequences would be expected from an accident that could occur during Phase 2 since any accident during this mission phase would lead to impact of debris in the Atlantic Ocean with no release of $PuO_2$ from the LWRHUs.

- **Phases 3 (Suborbital):** The total probability of a release in Phase 3, categorized as very unlikely, is estimated to be $2.4 \times 10^{-6}$ (or 1 in 420,000). Mean consequences are estimated to be 0.0013 rem (1.3 millirem) for maximum individual dose, and a collective dose that results in 0.0060 health effects among the potentially exposed population. An estimated area of 0.15 $km^2$ (about 0.058 $mi^2$) might be contaminated above 0.2 $\mu Ci/m^2$.

- **Phase 4 (Orbital):** There are no radioactive releases during this phase and, therefore, no radiological consequences.
- **Phase 5 (Long-term Reentry):** There are no radioactive releases during this phase and, therefore, no radiological consequences.

4.3.4.6. Discussion of the Results

***Maximum Individual Doses***

The maximum individual dose is the maximum dose delivered to a single individual for each accident. During Phase 1, the predicted mean radiation dose to the maximally exposed individual ranges from about 0.0013 rem (1.3 millirem) for the on-pad explosion launch area accident up to about 0.062 rem (62 millirem) for a very unlikely FSII in combination with burning solid propellant. This maximum individual dose is the largest for any phase. No short-term radiological effects would be expected from any of these exposures. Each exposure would increase the statistical likelihood of a health effect. It should be noted that the prediction of doses to the maximally exposed individual is subject to large variations and uncertainties in the locations of individuals, meteorological conditions, periods of exposure, and dispersion modeling.

***Population Exposures***

Impacts to downwind populations that might be exposed to releases following an accident are estimated by first calculating the collective dose to that population. This is simply the sum of the radiation dose received by all individuals exposed to radiation from a given release. These collective doses are assumed to result in the potential for health effects among the potentially exposed population following an accident. The health effects induced by releases are calculated using the methods described above in Section 4.1.4.5. The consequences discussed below have been estimated considering impacts to both the local population and the global population. Because of a variety of factors, principally involving meteorological conditions at the time of launch and the amount and particle size distribution of any $PuO_2$ released, not all persons in the affected regions would be exposed to a release.

Prior to launch, most problems that could potentially lead to an accident would be mitigated by safety systems and procedures that would lead to safe hold or termination of the launch countdown. After launch, most significant problems would lead to activation of the FTS, which would result in the destruction of all of the vehicle stages. This would lead to the spacecraft or portions thereof, including possibly the rover with LWRHUs, falling to the ground, where it could be subject to ground impact mechanical damage and potential exposure to burning solid propellant. The probability for this scenario with a release is $4.6x10^{-5}$ (or 1 in 22,000). Assuming no mitigation actions, such as sheltering and exclusion of people from contaminated land areas, the radiation dose to the potentially exposed population is predicted to result in less than one additional health effect over the long term. The mean estimate for this release scenario is 0.0062 health effects.

Even for the very and extremely unlikely launch area accidents, mean releases are not significantly higher than for the most probable accident and release. Assuming no mitigation actions, such as sheltering, estimated health effects range from a low of less than 0.0063 to a high of 0.30. As with the maximum individual dose, the largest population dose is associated with a Phase 1 FSII release.

In the event of a launch area accident, it is unlikely that any given racial, ethnic, or socioeconomic group of the population would bear a disproportionate share of the consequences.

### *Impacts of Radiological Releases on the Environment*

The environmental impacts of the postulated accidents include the potential for $PuO_2$ to be released to the environment, resulting in land and surface water contamination. The affected environment, described in Section 3 of this DEIS, includes the regional area near CCAFS and the global area. Launch area accidents (Phases 0 and 1) would initially release material into the regional area, as defined in this DEIS, to be within 100 km (62 mi) of the launch pad. Since some of the accidents result in the release of very fine particles (less than a micron in diameter), a portion of such releases could be transported beyond 100 km (62 mi) and become well mixed in the troposphere, and thus affect the global environment. Releases during Phase 3 could involve reentering LWRHUs that could impact the ground in southern Africa. Releases during Phase 4 could affect the environment anywhere between 29° north and 29° south latitude.

The risk assessment for this DEIS uses the 0.2 $\mu Ci/m^2$ screening level (a screening level used in prior NASA environmental documentation (e.g., NASA 1989, NASA 1997, NASA 2002b, NASA 2005)) as an indicator of the extent of land area contaminated due to a release of $PuO_2$ from a potential launch accident. The results are summarized in Table 4-16.

DOE's risk assessment indicates that for the most likely type of launch area accidents with a release, the intentional destruction of all the vehicle stages would result in about 0.16 $km^2$ (about 0.062 $mi^2$) being contaminated above 0.2 $\mu Ci/m^2$. The risk assessment also indicates that in at least one very unlikely ground impact configuration—FSII with a total probability of release of $3.0 \times 10^{-6}$ (or 1 in 330,000)—a mean area of 7.5 $km^2$ (about 2.9 $mi^2$) could be contaminated above 0.2 $\mu Ci/m^2$. Detectable levels below 0.2 $\mu Ci/m^2$ would be expected over an even larger area.

Land areas contaminated at levels above 0.2 $\mu Ci/m^2$ would potentially need further action, such as monitoring or cleanup. Costs associated with these efforts, as well as continued monitoring activities, could vary widely depending upon the characteristics of the contaminated area. Potential cost estimating factors for decontamination of various land types are summarized in Table 4-5. These cost factors address a wide variety of possible actions, including land acquisition, waste disposal, site restoration, and final surveys of remediated sites.

As indicated in Table 4-5 costs for farmland decontamination have been identified. In addition to the costs of decontamination, there is the potential that the contamination of crops would require additional mitigation measures. Actions could be required to prevent contaminated foodstuffs from being consumed by the public. As discussed in Section 4.1.4.6, DOE performed an assessment of the areas that might be contaminated to the point that the FDA suggested DIL might be exceeded and mitigation measures may be required.

The results of this analysis indicated that for all phases and for all accidents, the area contaminated above the DIL is consistently more than 50 times lower than (less than 2 percent) the area contaminated at or above the 0.2 $\mu Ci/m^2$ level that are shown in Table 4-16. For example, in assessing the Phase 1 accident with Low Altitude FTS, DOE calculated that the DIL value of 2.5 Bq/kg would be exceeded in an area of 0.0028 $km^2$ (0.0011 $mi^2$ or about 0.69 acres). This is the mean value for the cropland area where some mitigation measures could be required to limit the public health impact from the consumption of food contaminated by a release from this accident. The $99^{th}$ percentile area would be 0.013 $km^2$ (0.0050 $mi^2$ or 3.2 acres). These values are less than 2% of the calculated land contamination area using the 0.2 $\mu Ci/m^2$ criteria (Table 4-16) (SNL 2014).

The Price-Anderson Act of 1957, as an amendment to the Atomic Energy Act of 1954 (42 U.S.C. 2210), governs liability and compensation in the event of a nuclear incident arising out of the activities of the DOE. A "nuclear incident" is defined under the Atomic Energy Act as “any occurrence, including an extraordinary nuclear occurrence, within the United States causing, within or outside the United States, bodily injury, sickness, disease, or death, or loss of or damage to property, or loss of use of property, arising out of or resulting from the radioactive, toxic, explosive, other hazardous properties of source, special nuclear or byproduct material..." (42 U.S.C. 2014 (q)). In the case of the Mars 2020 mission, DOE retains title to the LWRHUs. The LWRHUs would, therefore, be subject to Price-Anderson Act provisions. In the unlikely event that an accident were to occur resulting in release of $PuO_2$, affected property owners would be eligible for reimbursement for loss of property due to contamination.

In addition to the potential direct costs of radiological surveys, monitoring, and potential cleanup following an accident, there are potential secondary societal costs associated with the decontamination and mitigation activities with the very unlikely, potentially higher consequence launch area accidents. Those costs could include, but may not be limited to:

- temporary or longer term relocation of residents;
- temporary or longer term loss of employment;
- destruction or quarantine of agricultural products, including citrus crops;
- land use restrictions (which could affect real estate values, tourism, and recreational activities);
- restriction or bans on commercial fishing; and
- public health effects and medical care.

#### 4.3.4.7. Mission Risks

A summary of the mission risks is presented in Table 4-17. For the purpose of this DEIS, risk is defined as the expectation of health effects in a statistical sense (i.e., the product of total probability times the mean health effects resulting from a release, and then summed over all conditions leading to a release). The risk of health effects in the potentially exposed populations is determined for each mission phase and the overall mission.

**Table 4-17. Summary of LWRHU Health Effect Mission Risks**

| Mission Phase [(a)] | Accident Probability | Conditional Probability of a Release | Total Probability of a Release | Mean Health Effects (given a release) | Mission Risks |
|---|---|---|---|---|---|
| 0: Pre-Launch | $3.3\times10^{-6}$ | 0.093 | Extremely Unlikely ($3.1\times10^{-7}$) | 0.015 | $4.4\times10^{-9}$ |
| 1: Early Launch | $3.1\times10^{-3}$ | 0.020 | Very Unlikely ($6.2\times10^{-5}$) | 0.020 | $1.3\times10^{-6}$ |
| 2: Late Launch | $3.6\times10^{-2}$ | – | – | — | — |
| 3: Suborbital | $1.3\times10^{-2}$ | 0.00018 | Very Unlikely ($2.4\times10^{-6}$) | 0.0060 | $1.4\times10^{-8}$ |
| 4: Orbital | $4.7\times10^{-3}$ | - | - | - | - |
| 5: Long-term Reentry | $1.0\times10^{-6}$ | - | - | - | - |
| **Overall Mission** | **$2.5\times10^{-2}$** | **0.0026** | **Very Unlikely ($6.5\times10^{-5}$)** | **0.020** | **$1.3\times10^{-6}$** |

Source: SNL 2014

(a) A composite of the results for the Atlas V 551 and the Delta IV Heavy, determined by taking the probability-weighted value of the two sets of results, treating the conditional probability of having a given launch vehicle as 0.5. Accident probabilities are the average of individual values for the two vehicles. Based on the current state of knowledge, the specific accident probabilities for the accident conditions for each vehicle are expected to be similar.

Differences in multiplications and summations are due to rounding of results as reported in SNL 2014.

Probability categories (i.e., unlikely, very unlikely) as defined by NASA.

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. The overall radiological risk for the solar powered rover with LWRHUs Mars 2020 mission is estimated to be $1.3\times10^{-6}$. Thus, the total probability of one health effect for the Alternative 3 (with LWRHUs) is about 1 in 790,000.

The risk contribution from Phase 1 accidents, $1.3\times10^{-6}$ (or a probability of about 1 in 800,000 that a health effect will occur), represents nearly all of the radiological risk for the Mars 2020 mission. The primary contributors to the Phase 1 risk in order of significance are (1) FSII, (2) Low Altitude FTS, and (3) On-Pad Explosion.

The contributions to risk within 100 km (62 mi) of the launch site and in the global area are summarized in Table 4-18. The launch area risk is about 64 percent of the overall mission risk, while the risk to global areas is 36 percent. The launch area risks are due entirely from accidents during Phases 0 and 1, with Phase 1 being the primary contributor. The global risks are due to accidents in all mission phases, with Phase 1 being the primary contributor due to the atmospheric transport of small particles beyond 100 km from the launch site.

**Table 4-18. LWRHU Health Effect Mission Risk Contributions by Affected Region**

| Mission Phase [a] | Mission Risks | | |
|---|---|---|---|
| | Launch Area [b] | Global [c] | Total |
| 0: Pre-Launch | $2.7 \times 10^{-9}$ | $1.8 \times 10^{-9}$ | $4.4 \times 10^{-9}$ |
| 1: Early Launch | $8.1 \times 10^{-7}$ | $4.4 \times 10^{-7}$ | $1.3 \times 10^{-6}$ |
| 2: Late Launch | — | — | — |
| 3: Suborbital | — | $1.4 \times 10^{-8}$ | $1.4 \times 10^{-8}$ |
| 4: Orbital | — | — | - |
| 5: Long-term Reentry | — | — | - |
| **Overall Mission** | **$8.2 \times 10^{-7}$** | **$4.6 \times 10^{-7}$** | **$1.3 \times 10^{-6}$** |

Source: SNL 2014

(a) A composite of the results for the Atlas V 551 and the Delta IV Heavy, determined by taking the probability-weighted value of the two sets of results, treating the conditional probability of having a given launch vehicle as 0.5

(b) Phases 0 and 1: within 100 km (62 mi) of the launch site.

(c ) Phase 3: southern Africa; Phase 4: land impacts between 29° north and 29° south latitude.

**Note:** Differences in summations may be due to rounding

### *Individual Risks*

Individual risk can be interpreted as the probability of an individual in the exposed population incurring a fatal cancer. For an accident near the launch site, not everyone within the regional area would be expected to receive a dose as a result of the accident. Due to meteorological conditions prevailing at the time of launch, only a portion of the total regional population is estimated to receive some measurable radiological exposure should an accident occur.

Even those individuals within the exposed population, such as those very close to the launch area that might receive the highest exposures, would face very small risks. The risk to the maximally exposed individual within the launch area and global populations (Table 4-19) is estimated to be much less than 1 in 10,000,000 for Alternative 3 (with LWRHUs) of the Mars 2020 mission. Most people in the potentially exposed population would have much lower risks.

The individual risk estimates are small compared to other risks. For example, Table 4-9 presents information on annual individual fatality risks to residents of the United States due to various types of hazards. This data indicates that in 2010 the average individual risk of accidental death in the United States was about 1 in 2,600 per year, while the average individual risk of death due to any disease, including cancer, was about 1 in 140.

**Table 4-19. LWRHU Maximum Individual Risk**

| Mission Phase [a] | Release Probability | Maximum Individual Dose, (rem) | Maximum Individual Risk [b], [c] |
|---|---|---|---|
| 0: Pre-Launch | Extremely Unlikely ($3.1x10^{-7}$) | 0.0030 | $5.6x10^{-13}$ |
| 1: Early Launch | Very Unlikely ($6.2x10^{-5}$) | 0.0042 | $1.6x10^{-10}$ |
| 2: Late Launch | – | — | — |
| 3: Suborbital | Very Unlikely ($2.4x10^{-6}$) | 0.0013 | $1.8x10^{-12}$ |
| 4: Orbital | - | — | — |
| 5: Long-term Reentry | - | — | — |

Source: SNL 2014

(a) A composite of the results for the Atlas V 551 and the Delta IV Heavy, determined by taking the probability-weighted value of the two sets of results, treating the conditional probability of having a given launch vehicle as 0.5.

(b) Determined as the product of total probability of release, maximum individual dose (mean value) and a health effects estimator of $6x10^{-4}$ latent cancer fatalities per rem.

(c ) The individuals associated with the maximum individual risk in Phase 0 and 1 are assumed to be the same individual, so the two risks are additive. The individuals associated with the maximum individual risk in Phases 3, 4, and 5 would not be the same individual due to different global regions potentially affected.

**Note:** Probability categories, i.e., unlikely, very unlikely, defined by NASA.

#### 4.3.4.8. Uncertainty

An uncertainty analysis to estimate uncertainties in probabilities, source terms, radiological consequences, and mission risks has not been performed as part of this report. Based on experience with uncertainty analyses in the preliminary risk assessment of previous missions (e.g., for the Cassini, Mars Exploration Rover, New Horizons, and Mars Science Laboratory missions), the uncertainty in the estimated mission risk for the Mars 2020 mission can be approximated. The FSAR analysis for those missions indicate that the uncertainty is dominated by the uncertainty associated with the launch vehicle accident probabilities. The $5^{th}$ and $95^{th}$ percentile accident probabilities are about a factor of 25 lower and higher, respectively, than the accident median probabilities. The mission risk estimate for Alternative 3 (with LWRHUs) of $1.3x10^{-6}$ (or a probability of about 1 in 790,000 that a health effect will occur) can be treated 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 risks at the $5^{th}$ and $95^{th}$ percent confidence levels are then estimated to be $5.1x10^{-8}$ (or a probability of about 1 in 19,000,000 that a health effect will occur) and $3.2x10^{-5}$ (or a probability of about 1 in 32,000 that a health effect will occur), respectively.

### 4.3.5 Radiological Contingency Response Planning

Radiological contingency response planning for any configuration of the Mars 2020 mission that contains plutonium (either an MMRTG or LWRHUs) would be similar, and has been described in Section 4.1.6.

## 4.4 ENVIRONMENTAL IMPACTS OF THE NO ACTION ALTERNATIVE

Under the No Action Alternative, preparations for the proposed Mars 2020 mission would be discontinued and the mission would not be implemented. Environmental impacts associated with preparation of the proposed Mars 2020 spacecraft and the processing of the launch vehicle would not occur. There would be no local or global launch-related environmental impacts.

As a result of the No Action Alternative, NASA could decide to utilize the 2020 launch opportunity to Mars for a different mission, which could address some of the objectives of the proposed Mars 2020 mission or could have completely different objectives. In either case, such a mission would be outside the scope of this DEIS and new environmental documentation would be prepared.

## 4.5 CUMULATIVE IMPACTS

NEPA analyses conducted under the NEPA and its implementing regulations (CEQ, 1992), must include the evaluation of direct, indirect, and cumulative environmental impacts associated with a proposed action (40 CFR 1508.7). A cumulative impact is the "...impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions..." (32 CFR 651).

The potential cumulative impacts associated with use of the launch vehicles and facilities addressed within this DEIS have been assessed using currently available information. Implementing either the Proposed Action (Alternative 1), Alternative 2, or Alternative 3 (i.e., launch of the Mars 2020 mission) would not increase the number of either Atlas V or Delta IV launches beyond the scope of previously approved programs for CCAFS (USAF 1998, USAF 2000).

Various components of the spacecraft and launch vehicle for the proposed Mars 2020 mission would be manufactured at different sites in the United States, with final integration of the components occurring at KSC and CCAFS. Each of these sites would be required to follow applicable Federal, state, and local regulations governing these areas such as air pollution, noise ordinances, wastewater disposal, pollution prevention, disposal of hazardous waste, and worker safety and health (see Section 4.9). Spacecraft and launch vehicle manufacturing are specialized activities with only a very limited number of units manufactured each year. While such activities could generate air pollutants, noise, and hazardous waste, any quantities would be small compared to major industrial activities and subject to the appropriate Federal, state, and local environmental laws and regulations pertinent to the individual manufacturing facilities.

The MMRTG hardware has already been manufactured and assembled by industry under contract to DOE; those flight units are in bonded storage at the contractor facility. Testing and fueling of the MMRTGs would be done by DOE at existing facilities. The plutonium needed to fuel the MMRTG is currently in storage at a DOE facility. Production efforts would meet all current DOE safety and environmental requirements. The programmatic environmental impacts associated with MMRTG production were addressed by the DOE for the Mars 2020 mission in existing DOE NEPA documents (DOE 1993, 2000, 2002, 2002b, 2008, 2013).

The use of the facilities at KSC and CCAFS for processing the Mars 2020 spacecraft, launch vehicle components, and for launch of the mission would be consistent with existing land uses at each site. No new processing facilities for the Mars 2020 mission are expected at either KSC or CCAFS, and any impacts from the use of existing facilities are expected to be within the scope of previously approved programs (e.g., USAF 1998, USAF 2000, NASA 2002, NASA 2011). Implementing the Mars 2020 mission would unlikely add new jobs to the workforce at either site.

Launching the Mars 2020 spacecraft would principally contribute to exhaust emission impacts on and near SLC-37, LC-39A, or SLC-41 at CCAFS/KSC, depending on the launch vehicle. The USAF has monitored numerous launches from CCAFS (USAF 1998). Launch could result in scorched vegetation and partially or completely defoliated trees near the launch complex from flame and acidic deposition. Deposition could also impact nearby bodies of water, resulting in temporary elevation of acidity levels. While these impacts may persist with continued use of either launch complex, they are probably not irreversible. At KSC, NASA found that in affected areas near the Space Shuttle launch pads, vegetation reestablished itself after the launches stopped (Schmalzer, et al. 1998).

On a short-term basis, the Mars 2020 launch would contribute negligible amounts of ozone-depleting chemical compounds to the stratosphere. The USAF has estimated that the total contribution from large expendable launch vehicles with SRBs to the average annual depletion of ozone would be small (approximately 0.014 percent per year). By comparison, a 3 percent to 7 percent annual decrease in ozone at mid-latitudes occurs as a result of the current accumulation of all ozone-depleting substances in the stratosphere (USAF 2000). Moreover, the ozone depletion trail from a launch vehicle has been estimated to be largely temporary, and would be self-healing within a few hours of the vehicle's passage (AIAA 1991). Furthermore, because launches at CCAFS are always separated by at least a few days, combined impacts in the sense of holes in the ozone layer combining or reinforcing one another would not occur (USAF 2000).

Rocket launches result in the emission of greenhouse gases ($CO_2$, trace emissions of $NO_X$ emitted by the SRBs). The exhaust cloud would also contain CO, most of which, under the high temperatures of the SRB's exhaust, would quickly react with oxygen in the atmosphere to form $CO_2$. The principal source of carbon emissions that could be associated with spacecraft launches would be from NASA's energy use in support of the launches. The following annual greenhouse gas emissions were reported for 2011 in the U.S.: 5,612.9 million metric tons (mt) (6.187 billion tons) of $CO_2$ equivalent, 12.8 million mt (14.2 million tons) of $NO_X$, and 65.1 million mt (71.8 million tons) of CO (EPA 2013, EPA 2014).

Concerning cumulative ozone depletion impacts, while present day ozone loss caused by rocket emissions may be small, future ozone changes may not be; potential increases in rocket launch rates due to space tourism or by geoengineering measures in space should be considered. In addition, rocket-induced ozone loss might become more significant in the future when the anthropogenic stratospheric halogen loading decreases due to implementation of the Montreal Protocol (Murray et. al. 2013).

Since the Mars 2020 mission would not increase the previously analyzed launch rates, launch of the mission would not be anticipated to contribute further to the accumulation of greenhouse gases from expendable launch vehicles, there would not be any substantial increase in cumulative impacts for payload processing and launch. Therefore, the long-term, cumulative effects to the local and regional environment by the Proposed Action (Alternative 1), Alternative 2, or Alternative 3 would not be substantial (NASA 2011).Other activities on or near CCAFS that are not connected with the Mars 2020 mission that could occur during this timeframe include the proposed development and construction of the KSC Exploration Park (formerly the International Space Research Park (ISRP)) located on 160 hectares (400 acres) of KSC and the proposed development and construction of a commercial space launch facility, the Shiloh Launch Complex (FAA 2013b). NASA intends to expand the launch capability of the Shuttle Launch Complex (LC-39A and 39B) to include the ability to launch several vehicles including the Space Launch System and commercial launch vehicles. These and other potential construction activities at and in the vicinity of CCAFS could potentially contribute to increases in noise, particulates and dust, solid waste disposal, and the potential for involving wetlands and endangered species. An EIS for the ISRP has been prepared (NASA 2004). It is anticipated that, should NASA approve this project, phased construction would occur over the next 20 to 25 years. NASA has prepared an EIS for the expansion of SL 39A and B (NASA 2013). FAA is preparing an EIS for the Shiloh Launch Complex.

No cumulative impacts would occur under the No Action Alternative.

## 4.6 ENVIRONMENTAL EFFECTS THAT CANNOT BE AVOIDED

At lift-off and during ascent, the main engine and SRBs of the Atlas V would produce $Al_2O_3$, CO, HCl, and relatively smaller amounts of $CO_2$, $NO_X$, hydrogen, nitrogen, chlorine, and water. The main engines of the Delta IV would produce primarily water vapor and water. The exhaust cloud would be concentrated near the launch pad during the first moments of launch. Thereafter, the exhaust cloud would be transported downwind and upward, eventually dissipating to background concentrations.

Biota in the immediate vicinity of the Atlas V launch pad at SLC-41, the Delta IV launch pad at SLC-37, or the Falcon Heavy launch pad at LC-39A could be damaged or killed by the intense heat and HCl deposition (at SLC-41) from the exhaust cloud. No long-term adverse effects to biota would be anticipated. $Al_2O_3$ particulates from the Atlas V SRBs would also be deposited on soils and nearby surface waters at the launch site as the exhaust cloud travels downwind.

## 4.7 INCOMPLETE OR UNAVAILABLE INFORMATION

This DEIS has been developed before final preparations would be completed for the proposed Mars 2020 mission. The final mission and spacecraft designs would be subject to refinement and modification as the detailed mission planning and spacecraft design processes proceed. The results of this development process are not anticipated to substantively affect the environmental evaluations presented in this DEIS. However, should substantial change occur in the environmental impact analyses, NASA would evaluate the need for additional environmental analysis and documentation.

The launch vehicle to be used on the Mars 2020 mission has not been selected. Candidate vehicles include two versions of the Atlas V (the 541 and 551), the Delta IV Heavy, and the Falcon Heavy. The Falcon Heavy is under development and has not yet been flown. Some of the information presented in this DEIS regarding this launch vehicle is based upon the design and operation of the Falcon 9. In particular, launch vehicle preparation for the Falcon Heavy is based on preparation activities for the Falcon 9. The description of the launch complex assumed to be used for Falcon Heavy launches (LC-39A) is the description of the complex as it is now and does not include any modifications necessary to support Falcon Heavy launches.

The suite of science instruments to be used on the Mars 2020 rover have not been selected as of the preparation of this DEIS. It is possible that some of the instruments may use small quantities of radioisotopes for various functions (e.g., calibration). The risk assessment performed by the DOE addressed the possible use of this material through the use of a representative radioisotope and quantity in the NRA (SNL 2014).

The risk assessment for the Mars 2020 mission prepared by DOE evaluates postulated launch accidents that could potentially result in a release of $PuO_2$ from the MMRTG. DOE's risk assessment has made use of the techniques developed in risk analyses for previous NASA missions.

DOE's risk analysis makes use of the results of extensive testing for the response of plutonium dioxide to the environments associated with accident conditions. In addition, DOE has developed sophisticated computer models to predict the detailed sequences of events that might result in the release of plutonium dioxide to the environment under these accident conditions. These techniques represent state-of-the-art plutonium accident modeling. Several technical issues that could impact the results presented in this DEIS would undergo continuing evaluation as a part of a more detailed safety analysis should NASA proceed with the Proposed Action (Alternative 1) or the LWRHU-based Alternative 3. Issues that continue to be evaluated include:

- the solid propellant fire environment and its potential effect on the release of $PuO_2$ from the MMRTG; and
- the mechanical response of the MMRTG or LWRHUs for the mission-specific configuration of the Mars 2020 mission.

Recent solid fire propellant tests indicate that DOE's analysis is conservative, but the results of any future test programs could impact the modeling of the fire environment and its effects on the MMRTG. Therefore, this issue continues to be evaluated. The Mars 2020 mission, while using an MSL heritage design, would be expected to have some differences in the spacecraft and rover configurations. These differences could alter the conditional probabilities of MMRTG damage and $PuO_2$ release. As indicated below, a safety analysis (which would include another risk assessment) that incorporates more detailed configuration information will be performed for this mission.

Under Presidential Directive/National Security Council Memorandum 25, a separate nuclear launch safety review of the Mars 2020 mission would be conducted by NASA, DOE, DoD and EPA should NASA proceed with the Proposed Action (Alternative 1) or Alternative 3. As part of this process, DOE would prepare a Final Safety Analysis Report (FSAR) that would include a complete, detailed risk analysis. In preparing the FSAR, DOE would follow procedures and use techniques similar to those used in the risk analyses performed for earlier NASA missions using radioisotope devices. An Interagency Nuclear Safety Review Panel (INSRP) would be formed for the Mars 2020 mission, and would review this safety analysis. Should the FSAR present risk estimates that differ significantly from those presented in this DEIS, NASA would consider the new information, and determine the need for additional environmental analysis and documentation.

A detailed uncertainty analysis has not been performed as part of the risk assessment prepared for this DEIS. Based on uncertainty analyses performed for previous mission risk assessments (e.g., for the Cassini, Mars Exploration Rover, New Horizons, and Mars Science Laboratory missions), parameter and model uncertainties associated with estimating radiological consequences could result in risk estimates that vary from one to two orders of magnitude at the 5 percent and 95 percent confidence levels. The Mars 2020 FSAR would include the results of a formal uncertainty analysis based on the Mars 2020 risk analysis.

## 4.8 RELATIONSHIP BETWEEN SHORT-TERM USES OF THE HUMAN ENVIRONMENT AND THE MAINTENANCE AND ENHANCEMENT OF LONG-TERM PRODUCTIVITY

### 4.8.1 Short-Term Uses

Under Proposed Action (Alternative 1), Alternative 2, or Alternative 3, the Mars 2020 mission would be launched from CCAFS or KSC. The short-term affected environment would include the launch complex and surrounding areas. At CCAFS and KSC, short-term uses include commercial, NASA and USAF operations, urban communities, a fish and wildlife refuge, citrus groves, residential communities, and recreational areas. The proposed Mars 2020 mission would be conducted in accordance with past and ongoing NASA and USAF procedures for operations at CCAFS and KSC. Should an accident occur under the Proposed Action causing a radiological release, short-term uses of contaminated areas could be curtailed, pending mitigation.

### 4.8.2 Long-Term Productivity

No change to land use at CCAFS or KSC and the surrounding region is anticipated due to either the Proposed Action (Alternative 1), Alternative 2, or Alternative 3. The region would continue to support human habitation and activities; wildlife habitats; citrus groves; grazing and agricultural land; and cultural, historic, and archaeological areas. No long-term effects on these uses are anticipated because of any of these 3 alternatives. However, should an accident occur under the Proposed Action causing a radiological release, the long-term productivity of contaminated land areas could be impacted, pending mitigation.

The successful completion of the proposed Mars 2020 mission would benefit science and the United States space program, which is important to the economic stability of the area. In addition to the localized economic benefits from the proactive small and small disadvantaged business plan, implementing this mission has broader socioeconomic benefits. These include technology spin-offs, such as low-power digital receivers, to industry and other space missions, maintaining the unique capability of the United States to conduct complex planetary missions by a large number of scientists and engineers, and supporting the continued scientific development of graduate students in a number of universities and colleges. Furthermore, comprehensive formal and informal education programs would be conducted as education and public outreach efforts, and proactive small business plans would be available to provide opportunities for small businesses, small disadvantaged businesses, and woman-owned small businesses; and historically black colleges and universities. Data and images acquired by the Mars 2020 mission would be made available to the general public, schools, and other institutions via a broad variety of media, including the Internet. In short, the mission would maintain and foster the nation's human engineering and science expertize.

## 4.9 IRREVERSIBLE AND IRRETRIEVABLE COMMITMENT OF RESOURCES

An irretrievable resource commitment results when a spent resource cannot be replaced within a reasonable period of time. For the Proposed Action (Alternative 1), Alternative 2, and Alternative 3, quantities of various resources, including energy, fuels, and other materials, would be irreversibly and irretrievably committed. The use of these resources would be associated with the fabrication, launch, and operation of all elements of the proposed Mars 2020 mission.

### 4.9.1 Energy and Fuels

Fabrication of the Mars 2020 spacecraft and its launch vehicle would use electrical and fossil-fuel energy. This use constitutes an irretrievable commitment of resources but would not impose any significant energy impacts. The launch and operation of the spacecraft would consume solid and liquid propellant and related fluids. The solid propellant ingredients for the Atlas V SRBs would be ammonium perchlorate, aluminum powder, and HTPB binder. The liquid propellants would include RP-1 (for the Atlas V), hydrazine, $LH_2$, and LOx. Typical quantities that would be used are summarized in Section 2.1.5.

### 4.9.2 Other Materials

The total quantities of other materials used in the proposed Mars 2020 mission that would be irreversibly and irretrievable committed are relatively minor. Typically, these materials include steel, aluminum, titanium, iron, molybdenum, plastic, glass, graphite, nickel, chromium, lead, zinc, and copper. Small quantities of plutonium (for the MMRTG of the Proposed Action (Alternative 1) and even smaller quantity for the LWRHUs of Alternative 3) would be used. Less common materials may include small quantities of silver, mercury, gold, rhodium, gallium, germanium, hafnium, niobium, platinum, iridium, tantalum, and beryllium.

## 4.10 ENVIRONMENTAL COMPLIANCE AT CCAFS AND KSC

This section presents an overview of environmental laws, regulations, reviews and consultation requirements applicable to operations at CCAFS and KSC, and includes permits, licenses, and approvals. The information presented is summarized from the *Final Environmental Impact Statement for the Evolved Expendable Launch Vehicle Program* (USAF 1998), the *Final Supplemental Environmental Impact Statement for the Evolved Expendable Launch Vehicle Program* (USAF 2000), NASA's *Final Environmental Assessment for Launch of NASA Routine Payloads on Expendable Launch Vehicles,* (NASA 2011), and the KSC *Environmental Resources Document* (NASA 2010).

The referenced NEPA documents present the relevant discussions, analyses, potential environmental impacts, and applicable mitigation plans within each topic of concern. Launch services for the Mars 2020 mission would be provided by a commercial NLS contractor that would be required to adhere to facility permits and regulatory requirements. USAF requirements are cited for some of the environmental resource areas noted below as examples of the documentation the NLS contractor would need to implement. Launch of the Mars 2020 mission from CCAFS or KSC would follow all applicable environmental and health and safety regulatory requirements. No modifications to existing permits are anticipated for the Delta or Atlas launch vehicles. If the Falcon Heavy is selected as the launch vehicle, applicable permits will be obtained and/or existing permits will be modified accordingly.

### 4.10.1 Air Resources

Air permits are required for activities considered as stationary sources, such as launch support activities (e.g., vehicle preparation, assembly, propellant loading), having the potential to release threshold amounts of air pollutants but are not required for emissions from mobile sources such as launch vehicles during liftoff and ascent. Existing equipment and services would be used for preparation and launch of the selected launch vehicle.

CCAFS and KSC are classified as major sources because emissions are above major source thresholds. In this regard, CCAFS and KSC have both been issued Title V permits by the Florida Department of Environmental Protection (FDEP) and currently operate under their respective Title V permits. The NLS contractors are required to comply with all applicable Clean Air Act requirements for their launch service operations.

### 4.10.2 Water Resources

The Clean Water Act (CWA) of 1977, as amended (33 U.S.C. 1251 et seq.), provides regulatory guidelines for water quality.

Wastewater at CCAFS and KSC is discharged in accordance with its respective National Pollutant Discharge Elimination System (NPDES) permit conditions. Water used during launch would be discharged under the CCAFS/KSC NPDES permit issued by the Florida Department of Environmental Protection or generated wastewater would be tested and properly disposed of by a certified contractor.

### 4.10.3 Floodplains and Wetlands

Executive Order (EO) 11988, *Floodplain Management*, and EO 11990, *Protection of Wetlands*, would be followed. Most wetlands are considered waters of the U.S. and are under the jurisdiction of the CWA. A number of Federal agencies regulate and administer programs that can potentially affect wetlands and their likelihood for utilization including but not limited to the Army Corps of Engineers, Florida Department of Environmental Protection, U.S. Fish and Wildlife Service, Department of the Interior, and the Environmental Protection Agency.

No added impacts to floodplains and wetlands beyond those normally associated with typical launches would be anticipated. The proposed Mars 2020 launch would not be anticipated to add substantial impacts beyond those normally associated with a launch vehicle.

### 4.10.4 Hazardous Material Management

Hazardous materials are regulated under Federal laws such as the Comprehensive Environmental Response, Compensation, and Liability Act of 1980, as amended (42 U.S.C. 9601 et seq.); the Toxic Substances Control Act of 1986, as amended (15 U.S.C. 2601 et seq.); and the Hazardous Material Transportation Act of 1970, as amended (49 U.S.C. 1803 et seq.). In addition, Air Force Instruction (AFI) 32-7086, *Hazardous Material Management*, provides guidance for managing hazardous materials at all Air Force installations, including CCAFS.

As required by contract, all hazardous material would be procured and managed by the NSL contractor in accordance with all applicable Federal, state, and local requirements.

### 4.10.5 Hazardous Waste Management

The Resource Conservation and Recovery Act of 1976, as amended (42 U.S.C. 6901 et seq.), corresponding state law, and associated Federal and state regulations establish regulatory requirements for managing hazardous wastes. For example, Air Force Instruction AFI 32-7042, *Solid and Hazardous Waste Compliance*, and the 45th Space Wing Operations Plan 19-14, *Petroleum Products and Hazardous Waste Management Plan,* provide guidance on managing hazardous waste. Hazardous wastes must be collected, labeled appropriately, and stored in hazardous waste collection areas prior to disposal.

Hazardous wastes would be managed by the NLS contractor in accordance with all applicable Federal, state, and local requirements.

### 4.10.6 Pollution Prevention

The Pollution Prevention Act of 1990, as amended (42 U.S.C. 13101 et seq.), provides the regulatory framework for reducing pollution. For example, Department of Defense Directive 4210.15, *Hazardous Material Pollution Prevention*; USAF Policy Directive AFPD 32-70, *Environmental Quality*; and AFI 32-7080, *Pollution Prevention Program*, provide pollution prevention guidelines. NASA participates in a partnership with the military services called the Joint Group on Pollution Prevention to reduce or eliminate hazardous material or processes.

Pollution prevention guidelines are provided, for example, by the 45th Space Wing *Pollution Prevention Program Guide and Pollution Prevention Management Action Plan*.

### 4.10.7 Spill Prevention

Oil pollution prevention regulations in 40 CFR 112 require preparation and implementation of spill prevention, control, and countermeasures (SPCC) plans for all non-transportation-related facilities that store oil in excess of specific quantities [an aggregate aboveground container capacity greater than 1,320 gals (only containers greater than or equal to 55 gals are counted), or completely buried storage capacity greater than 42,000 gals] and that have discharged or could reasonably be expected to discharge oil into navigable waters of the U.S. or its adjoining shorelines. Since both CCAFS and KSC store more than 1,320 gals of oil above ground and, because a spill could reach a navigable U.S. waterway, the facilities are subject to the SPCC regulations (NASA 2010).

The NSL contractor would be responsible for prevention of spills or releases of hazardous material, and, in most cases, be responsible for cleanup of any released hazardous material in accordance with all applicable Federal, state, and local requirements. When a spill of a Federally-listed oil or petroleum occurs, the substance would be collected and removed for disposal by a certified contractor.

### 4.10.8 Biological Resources

Federal mandates for the conservation of biological resources include, but are not limited to, the Endangered Species Act of (ESA) 1973, as amended (16 U.S.C. 1531 et seq.); the Marine Mammal Protection Act of 1972, as amended (16 U.S.C. 1361 et seq.); and the Migratory Bird Treaty Act of 1918, as amended (16 U.S.C. 703 et seq.), Both CCAFS and KSC have ESA-listed (endangered or threatened) species. USAF and KSC consultations with the U.S. Fish and Wildlife Service and the National Marine Fisheries Service are in place or in process. Established standard practices (e.g., complying with the light management plan for nesting sea turtles and hatchlings) would be observed to minimize impacts to these resources.

Any consultation agreements would be modified, if necessary and as applicable, to address the Falcon Heavy launch vehicle if this vehicle is selected for launch of the Mars 2020 rover.

### 4.10.9 Coastal Zone Management

The regulatory framework for coastal zone management is provided by the Federal Coastal Zone Management Act of 1972, as amended (16 U.S.C. 1451 et seq.), which establishes a national policy to preserve, protect, develop, restore, and enhance the resources of the nation's coastal zone. CCAFS and KSC would follow the state of Florida's coastal zone management requirements. No added impacts beyond those normally associated with launches would be anticipated.

### 4.10.10 Cultural and Historic Resources

Directives of Section 106 of the National Historic Preservation Act of 1966, as amended (16 U.S.C. 470 et seq.), would be followed. The State Historic Preservation Officer and the Federal Advisory Council on Historic Preservation would be consulted if the USAF or KSC believe that the Mars 2020 mission might adversely affect cultural or historic resources, although no such adverse effects are anticipated at this time.

#### 4.10.11 Noise

Regulations and guidelines prescribed by the Noise Control Act of 1972, as amended (42 U.S.C. 4901 et seq.); the Occupational Safety and Health Administration; and the National Institute of Occupational Safety and Health would be followed at both CCAFS and KSC.

#### 4.10.12 Worker and Public Safety and Health

OSHA regulations would be followed to ensure worker and public safety and health from excessive noise, exposure to hazardous materials and hazardous wastes, and ingestion of toxic fumes from operations such as fueling. The 45th Space Wing at CCAFS has the responsibility to follow Range Safety guidelines as outlined in the *Range Safety User Requirements Manual* (USAF 2004). MMRTG handling at the launch site would be performed following applicable regulations as outlined in KHB 1860.1, *KSC Ionizing Radiation Protection Program* (NASA 2001) and in accordance with the DOE safety rules and regulations as summarized in a Mars 2020-specific Documented Safety Analysis that would be prepared by the DOE prior to activities in support of a Mars 2020 launch.

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