Summary of the Nuclear Risk Assessment for the Mars 2020 Mission Environmental Impact Statement

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Abstract. In the summer of 2020, the National Aeronautics and Space Administration (NASA) plans to launch a spacecraft as part of the Mars 2020 mission. One option for the rover on the proposed spacecraft uses a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) to provide continuous electrical and thermal power for the mission. NASA has prepared an Environmental Impact Statement (EIS) in accordance with the National Environmental Policy Act. The EIS includes information on the risks of mission accidents to the general public and on-site workers at the launch complex. The Nuclear Risk Assessment (NRA) addresses the responses of the MMRTG option to potential accident and abort conditions during the launch opportunity for the Mars 2020 mission and the associated consequences. This information provides the technical basis for the radiological risks of the MMRTG option for the EIS. This paper provides a summary of the methods and results used in the NRA.

Keywords: nuclear risk assessment, environmental impact statement, Mars 2020 mission.

INTRODUCTION

In the summer of 2020, the National Aeronautics and Space Administration (NASA) plans to launch a rover to the surface of Mars as part of the Mars 2020 mission. One option for the proposed rover includes the use of radioactive materials in a single Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) to provide continuous power for the mission. NASA prepared an Environmental Impact Statement (EIS) for the mission in accordance with the National Environmental Policy Act (NEPA). The EIS includes information on the risks of mission accidents to the general public and on-site workers at the launch complex. The Nuclear Risk Assessment (NRA) addresses the responses of the proposed MMRTG option to potential accident and abort conditions during the launch opportunity for the Mars 2020 mission and the associated consequences [1]. This information provides the technical basis for the radiological risks of the MMRTG option for the EIS. This paper provides a summary of the methods and results used in the NRA [1].

The purpose of the proposed Mars 2020 mission would be to conduct comprehensive science on the surface of Mars and demonstrate technological advancements in the exploration of Mars. Mars 2020 mission investigations would reflect several of the high-priority scientific investigations recommended to NASA by the planetary science community. The overall scientific goal would be to address the questions of habitability and the potential origin and evolution of life on Mars.

The Mars 2020 mission spacecraft would be launched from Cape Canaveral Air Force Station (CCAFS), Florida. NASA has not yet selected the launch vehicle for the mission. However, there are four candidate Launch Vehicles (LVs) being considered for the Mars 2020 mission based upon the stated launch opportunity, spacecraft mass and mission requirements: the Atlas V 541, the Atlas V 551, the Delta IV Heavy, and the Falcon Heavy. The Atlas V, the Delta IV, and the Falcon would be launched from CCAFS Space Launch Complex (SLC)-41, SLC-37, or SLC-40, respectively. The potential consequences of the Atlas V 541 are assumed to be enveloped by those of the Atlas V 551. The 551 has similar accident modes and uses an additional solid rocket motor compared with the 541. As of the writing of the NRA [1], for the Falcon Heavy LV, flight history, detailed design and in-flight performance data do not exist. Therefore, assumptions have been made regarding the vehicle design and number of successful flights prior to the Mars 2020 launch date. These assumptions reflect the expectation that the Falcon Heavy will achieve the degree of success and documented reliability prior to its use for missions carrying radioisotope power sources. Further, it is assumed that, to the first order, the Falcon Heavy accident modes and probabilities are equivalent to the Delta IV Heavy.

There would be one primary launch period of opportunity: July 7, 2020 to August 5, 2020 and one backup in August 2020. If the mission needs to be delayed to 2022, there is a launch opportunity within August and September of 2022. The analyses for the NRA sample weather data from several recent years for the months of July, August, and September in order to span the range of possible launch conditions [1]. In addition, since NASA has not selected the time of launch on a given day, the NRA assumes a daytime launch [1]. The planned mission trajectory would place the spacecraft in a heliocentric orbit prior to completion of the Stage 2 second burn. After separation from Stage 2, the spacecraft would be in a heliocentric interplanetary trajectory. If the spacecraft fails to intersect Mars, there is a very small but finite probability that it might return to Earth over the next several centuries.

The baseline Mars 2020 rover would use one MMRTG to provide continuous power. The MMRTG would contain eight General Purpose Heat Source (GPHS) modules. The MMRTG would contain 4.8 kg of plutonium dioxide (PuO_2) in ceramic form, with an estimated inventory of 60,000 curies (Ci), due primarily to plutonium-238 (Pu-238), an alpha-emitting radioisotope with a half-life of 87.7 years. The MMRTG would be provided by the U.S. Department of Energy (DOE). Due to the radioactive nature of this material and the potential for accidents resulting in its release to the environment, safety is an inherent consideration in all steps from mission design through launch.

DOE is responsible for quantifying the risks of its nuclear hardware subjected to the effects of potential launch accidents. The purpose of the NRA is to provide this information in support of the EIS for the mission, being prepared by NASA in accordance with requirements under the NEPA. There would also be a Presidential Nuclear Launch Approval Process for the mission subject to the requirements of Presidential Directive / National Security Council Memorandum Number 25 (PD/NSC-25), for which DOE would prepare a Final Safety Analysis Report (FSAR).

The EIS-supporting assessment presented herein is based in part on 1) spacecraft descriptions, accident environments, and LV information provided by NASA [2], 2) information regarding accident probabilities provided by NASA [3] and 3) information available from the LV manufacturers' User's Guides [4,5,6,7]. A composite approach has been taken in reporting the results in the NRA for accident probabilities, airborne portion of potential releases of PuO_2 in case of an accident (source terms), radiological consequences, and mission risks [1]. In the composite approach, the results for the Atlas V 541, the Atlas V 551, the Delta IV Heavy, and the Falcon Heavy would be combined in a probability-weighted manner with equal weight being given to each launch vehicle (25% each). Since the detailed calculations for the Atlas V 551 are being used to represent the Atlas V 541, and since the detailed calculations for the Delta IV Heavy are being used to represent the Falcon Heavy, the net result is that the Atlas V 551 calculations and the Delta IV Heavy calculations will be weighted 50% each. This approach reflects the state of knowledge at this early planning stage in the mission with respect to the candidate LVs being considered for the Mars 2020 mission. Differences in results among the various candidate LVs are not considered significant, given the uncertainties in the estimates being made in the nuclear risk assessment.

ACCIDENT PROBABILITIES AND SOURCE TERMS

The NRA considers: 1) potential accidents associated with the launch, and their probabilities and accident environments; 2) the response of the radioisotope hardware to accident environments with respect to source terms (that portion of the release that becomes airborne) and their probabilities, and 3) the radiological consequences and mission risks associated with such releases. The radioactive material inventory of interest, for a single MMRTG, is about 60,000 Ci of primarily Pu-238 [1]. The activity includes minor contributions from other related plutonium and actinide radionuclides in the fuel. This section addresses the potential accidents and hardware response; the next section addresses potential consequences and risks. The methodology used in developing the accident probabilities and source terms is detailed in the NRA [1].

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

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

The information on accidents and their probabilities has been based on information presented in [3].

MMRTG Response to Accident Environments

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

- Prior safety testing of the General Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG) and its components.
- Modeling of the response of the MMRTG and its components to accident environments using a continuum mechanics code.
- A comparison of the MMRTG with the GPHS-RTG in terms of structural features and accident environment responses.
- The types of LV 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 aeroshell module, its graphitic components and the iridium clad encapsulating the PuO_2 fuel, minimizes the potential for release in accident environments. Potential responses of the MMRTG and its components in accident environments are summarized as follows:

- <u>Explosion Overpressure and Fragments</u>: Liquid propellant explosions from LV destruct and resulting fragments are estimated to result in some MMRTG damage but no fuel release.
- <u>Impact</u>: Fracturing of the GPHS module and its graphitic components under mechanical impact conditions provide energy-absorbing protection to the iridium clad. Most impacts of an intact MMRTG or GPHS modules on steel or concrete near the launch pad could result in zero or small releases of PuO_2, depending on the impact velocity. Similarly, should Suborbital or Orbital Reentry accident conditions lead to GPHS modules impacting hard rock following reentry, a small release could occur. Grounds impact of an intact Space Vehicle (SV) for an early launch accident is expected, since the SV back shell and heat shield prevents the LV breakup during a destruct event. The combined effect of the SV hitting the ground and the MMRTG subsequently being hit by the SV components above it occasionally results in a fuel release, depending on the impact velocity and orientation. Larger intact configurations could result in higher releases for certain orientations in which launch vehicle and/or SV components impact directly onto the MMRTG.
- <u>Thermal</u>: Exposure of released PuO_2 to a liquid propellant fireball environment would be of short duration (nominally 20 s or less). Minor vaporization of exposed particulate would occur depending on the timing of the ground impact release and the fireball development. The fireball temperature would decrease in temperature to nominally 2,177 ^{o}C in less than 1 s (below which PuO_2 vaporization is negligible), and continue dropping as the fireball expands. For the Atlas V 551, exposure of released PuO_2 fuel to the higher-temperature (up to 2827 ^{o}C), longer burning (up to 250 s) solid-propellant from the Solid Rocket

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

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

The response of the MMRTG to accident environments can be summarized as follows:

- Most launch accidents in Phases 0 and 1 would lead to one of several types of ground impact configurations. Ground impacts of the SV on steel or concrete can occasionally lead to a release. For larger impacting configurations, larger fuel releases are expected. Exposure to a liquid propellant fireball could lead to some vaporization of released PuO_2 depending on the relative timing of the impact release and the fireball development. Subsequent exposure of MMRTG hardware and PuO_2 to burning solid propellant could result in considerably larger releases through melting of the iridium clad and partial vaporization of the PuO_2.
- Nearly all Phase 2 accidents lead to impact of debris in the Atlantic Ocean with no releases. There could be some small in-air releases from blast-driven in-air fragment impacts.
- Phase 3 accidents lead to suborbital reentry and usually ground impact of the intact SV and MMRTG. Some small releases are likely due to impact of the MMRTG by SV hardware. There would be a hydrazine fire and a potential minor vaporization from it. There would be no solid propellant fires or releases due to them.
- Phase 4 and 5 accidents lead to orbital and long-term reentry heating and ground impact environments. The GPHS modules are designed to survive reentry; however, any ground impact on hard rock could result in small releases of PuO_2.

Source Terms and Probabilities

A summary of the composite accident and source term probabilities by mission phase, along with mean and 99th percentile source terms, are presented in Table 1 for the MMRTG. These results were determined by a Monte Carlo simulation using 150,000 trials or more for each of the various accident scenarios and launch vehicle options. In these simulations, 100 percent of released material with a physical diameter less than 100 microns was assumed to be airborne, which may be conservative since much of the released fuel would be trapped by the graphitics and other debris. Simulations show that particles larger than 100 microns would fall to the ground within a few meters of the source.

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

The 99th percentile release is obtained by sorting the trials by the total amount released. Then the release amount for which 1% of the trials are greater is defined as the 99th percentile. The 99th percentile source term is the value predicted to be exceeded with a probability of 0.01 (1 in 100), either given an accident, or given a release. In this context, the 99th percentile release value reflects the potential for larger radionuclide releases at lower probabilities.

Most accidents do not result in a release; hence the 99th percentile release given an accident is lower than the 99th percentile release given a release. For some launch phases, the probability of a release is so low that the 99th percentile release is zero, given an accident.

Table 1. Source Term Summary for the MMRTG[a,b,c]

Mission Phase	Accident Probability	Conditional Probability of Release	Total Probability of Release	Source Term (Ci)			
				Mean Given an Accident	Mean Given a Release	99th Percentile Accident	99th Percentile Release
0 (Prelaunch)	3.28E-05	3.27E-01	1.07E-05	9.20E-02	2.82E-01	4.75E-02	6.68E+00
1 (Early Launch)	3.12E-03	2.81E-02	8.77E-05	1.66E+00	5.90E+01	1.64E+01	6.33E+02
2 (Late Launch)	3.63E-03	2.12E-03	7.71E-06	3.40E-05	1.60E-02	-	2.31E-01
3 (Suborbital)	1.31E-02	1.13E-03	1.48E-05	4.70E-02	4.16E+01	-	9.29E+02
4 (Orbital)	4.66E-03	5.62E-02	2.61E-04	2.96E-02	5.27E-01	6.51E-01	6.15E+00
5 (Long-Term)	1.00E-06	9.43E-02	9.43E-08	7.29E-02	7.73E-01	1.48E+00	7.82E+00
Overall Mission	2.46E-02	1.56E-02	3.83E-04	2.42E-01	1.55E+01	9.49E-03	3.41E+02

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

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

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

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

- Phase 0 (Prelaunch): During the Prelaunch period, prior to ignition of the Stage 1 liquid rocket engine, on-pad accidents could result in a release at a total probability of 1.07×10^{-5} (1 in 93,000). The mean source term given an accident is estimated to be 0.09 Ci, the mean source term given a release is estimated to be 0.28 Ci, the 99th percentile given an accident is estimated to be 0.048 Ci, while the 99th percentile source term given a release is estimated to be 6.7 Ci.
- Phase 1 (Early Launch): During Phase 1 from ignition to t_x s, after which there would be no potential for land impacts in the launch area, the total probability of release is 8.8×10^{-5} (1 in 11,000). The mean source term given an accident is estimated to be 1.7 Ci, the mean source term given a release is estimated to be 59 Ci, the 99th percentile given an accident is estimated to be 16 Ci, while the 99th percentile source term given a release is estimated to be 630 Ci.
- Phase 2 (Late Launch): In Phase 2 all accidents lead to impact of debris in the Atlantic Ocean. However, there are some very small releases in air from blast-generated debris. The total probability of release is 7.7×10^{-6} (1 in 130,000). The mean source term given an accident is estimated to be 0.000034 Ci, the mean source term given a release is estimated to be 0.016 Ci, the 99th percentile given an accident is estimated to be 0 Ci, while the 99th percentile source term given a release is estimated to be 0.23 Ci.
- Phase 3 (Suborbital Reentry): Accidents during Phase 3 include suborbital reentries. Prior to the attainment of Earth park orbit, these conditions could lead to prompt suborbital reentry within minutes. This could result in impacts of the intact SV entry vehicle and MMRTG along the vehicle flight path over the Atlantic Ocean and southern Africa. Additional suborbital land impacts are possible after crossing over Africa, depending on the launch vehicle selected and its nominal mission timeline. Should the SV impact land, releases are possible. The total probability of release in Phase 3 is estimated to be 1.5×10^{-5} (or 1 in 67,000). The mean source term given an accident is estimated to be 0.047 Ci, the mean source term given a release is estimated to be 42 Ci, the 99th percentile given an accident is estimated to be 0 Ci, while the 99th percentile source term given a release is estimated to be 930 Ci.
- Phases 4 (Orbital Reentry): Accidents which occur after attaining park orbit could result in orbital decay reentries from minutes to years after the accident, affecting Earth surfaces between approximately 29° North Latitude and 29° South Latitude. The SV and MMRTG would break apart during reentry, releasing the GPHS modules. The modules would survive reentry, but could release fuel if they impact hard rock. The total probability of release is estimated to be 2.6×10^{-4} (or 1 in 3,800). The mean source term given an accident is estimated to be 0.030 Ci, the mean source term given a release is estimated to be 0.53 Ci, the 99th percentile given an accident is estimated to be 0.65 Ci, while the 99th percentile source term is estimated to be 6.2 Ci.

- Phase 5 (Long-Term Orbital Reentry): There is a set of reentry accidents which occur after attaining Earth escape. This could result in return to Earth from a heliocentric orbit many years after the accident if the spacecraft misses Mars, affecting Earth surfaces at any latitude. The reentry velocity would be larger than in Phase 4 and the heating environment would be more severe. The total probability of release is estimated to be 9.4×10^{-8} (or 1 in 11,000,000). The mean source term given an accident is estimated to be 0.073 Ci, the mean source term given a release is estimated to be 0.77 Ci, the 99^{th} percentile given an accident is estimated to be 1.48 Ci, while the 99^{th} percentile source term is estimated to be 7.8 Ci.

RADIOLOGICAL CONSEQUENCES, MISSION RISKS AND UNCERTAINTIES

The radiological consequences and mission risks due to the potential PuO_2 releases presented above are presented below. Uncertainties in the reported results are also discussed. The methodology used in developing estimates for the radiological consequences and mission risks is presented in the NRA [1].

Radiological Consequences

The radiological consequences resulting from the given accident scenarios have been calculated in terms of: 1) maximum individual dose, 2) collective dose, 3) health effects, and 4) land area contaminated at or above specified levels. The radiological consequences are based on atmospheric transport and settling simulations. Biological effects models, based on methods prescribed by the National Council on Radiation Protection and Measurements (NCRP) and the International Commission on Radiological Protection (ICRP), have been applied in past missions to predict the number of incremental latent cancer fatalities over 50 years (health effects) induced following a fuel release accident and assuming no mitigation measures. This present analysis uses scaling laws (consequences per Ci of fuel released) developed from more detailed calculations.

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

The maximum individual dose is the mean (for historical meteorological conditions) maximum (for location) dose delivered to a single individual for a given accident, considering the probability distribution over all release conditions. Collective dose is the sum of the radiation dose received by all individuals exposed to radiation from a given release in units of "person-rem." Internal doses are determined using particle-size dependent dose conversion factors based on ICRP-66/67 [8,9] and ICRP-60 [10].

The health effects represent incremental cancer fatalities over 50 years induced by releases, determined using a health effect estimator of 6×10^{-4} fatalities per person-rem for the general population based on recommendations by the Interagency Steering Committee on Radiation Standards (ISCORS) [11]. This is an update to the previous values of the ICRP-60 estimators of 5×10^{-4} fatalities per person-rem for the general population and 4×10^{-4} for workers [10]. The health effects estimators are based on a linear, no-threshold model relating health effects and effective dose. This means that health effects scale linearly as the dose decreases down to zero, rather than assuming a threshold dose below which there would be no health effects. To estimate the total health effects within the population, the probability of incurring a health effect is estimated for each individual in the exposed population, given a release, and then the probabilities are summed over that population.

Potential environmental contamination criteria for assessing contaminated land areas are 1) areas exceeding given screening activity concentration levels (0.1 and 0.2 $\mu Ci/m^2$), and 2) dose-rate related criteria (15, 25, and 100 mrem/yr) considered by the U.S. Environmental Protection Agency (EPA), the Nuclear Regulatory Commission (NRC), and DOE in evaluating the need for land cleanup following radioactive contamination [12]. The results for land area contaminated are reported in terms of the area contaminated at or above a level 0.2 $\mu Ci/m^2$, a reference contamination level considered in the risk analyses of previous missions. The area of land contaminated above the

EPA lifetime-risk criterion, associated with an average annual dose rate criterion of 15 mrem/yr, could be higher or lower than the land area contaminated above the 0.2 $\mu Ci/m^2$ level in the first year following the release, depending on the particle size distribution of the release and the time-dependent resuspension factor (the ratio of the airborne concentration to the ground concentration). The resuspension contribution to dose assumes that no mitigation measures are taken. Following the first year, areas contaminated above the 15 mrem/yr criterion would be expected to decrease to values comparable to that associated with the 0.2 $\mu Ci/m^2$ level as the resuspension factor decreases in time.

The potential for crop contamination is based on the Derived Intervention Limit (DIL), as defined by the Food and Drug Administration (FDA) [13]. An average DIL of 2.5 Bq/kg (edible portion of the crop) is assumed. The DIL is converted to a cropland deposition threshold by considering the annual average uptake factor of deposited radionuclides and annual crop yields (kilogram of edible food per square meter of land). The number of square kilometers of cropland that exceeds this value for each crop type is determined from atmospheric transport calculations, cropland location maps, and the average fraction of each crop type in the Kennedy Space Center vicinity or the state of Florida, depending on the extent of the plume.

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

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

Table 2. Mean Radiological Consequence Summary for the MMRTG[a,b,c]

Mission Phase	Accident Probability	Release Probability	Maximum Individual Dose (rem)		Collective Dose (person-rem)		Health Effects		Land Contamination (km^2)		Cropland Intervention (km^2)	
			Given an Accident	Given a Release	Given an Accident	Given a Release	Given an Accident	Given a Release	Given an Accident	Given a Release	Given an Accident	Given a Release
0 (Prelaunch)	3.28E-05	1.07E-05	9.42E-05	2.88E-04	7.50E-01	2.29E+00	4.50E-04	1.38E-03	1.15E-02	3.52E-02	2.02E-04	6.17E-04
1 (Early Launch)	3.12E-03	8.77E-05	1.70E-03	6.04E-02	1.35E+01	4.81E+02	8.12E-03	2.89E-01	2.07E-01	7.37E+00	3.64E-03	1.29E-01
2 (Late Launch)	3.63E-03	7.71E-06	3.48E-08	1.64E-05	2.77E-04	1.30E-01	1.66E-07	7.84E-05	4.24E-06	2.00E-03	7.45E-08	3.51E-05
3 (Suborbital)	1.31E-02	1.48E-05	4.81E-05	4.26E-02	3.83E-01	3.39E+02	2.30E-04	2.04E-01	5.88E-03	5.20E+00	1.03E-04	9.12E-02
4 (Orbital)	4.66E-03	2.61E-04	3.03E-05	5.39E-04	2.41E-01	4.30E+00	1.45E-04	2.58E-03	3.70E-03	6.59E-02	6.49E-05	1.16E-03
5 (Long-Term)	1.00E-06	9.43E-08	7.46E-05	7.91E-04	5.94E-01	6.30E+00	3.57E-04	3.78E-03	9.10E-03	9.66E-02	1.60E-04	1.69E-03
Overall Mission	2.46E-02	3.83E-04	2.47E-04	1.59E-02	1.97E+00	1.26E+02	1.18E-03	7.59E-02	3.02E-02	1.94E+00	5.30E-04	3.40E-02

a. The table presents composite results for the LVs under consideration, determined by taking the probability-weighted value of each set of results.
b. Land area contaminated above a screening level of 0.2 μCi/m^2.
c. Overall mission values weighted by total probability of release for each mission phase.

Table 3. 99th Percentile Radiological Consequence Summary for the MMRTG[a,b,c]

Mission Phase	Probability of 99th Percentile	Release Probability	Maximum Individual Dose (rem)		Collective Dose (person-rem)		Health Effects		Land Contamination (km^2)		Cropland Intervention (km^2)	
			Given an Accident	Given a Release	Given an Accident	Given a Release	Given an Accident	Given a Release	Given an Accident	Given a Release	Given an Accident	Given a Release
0 (Prelaunch)	3.28E-07	1.07E-07	4.86E-05	6.83E-03	3.87E-01	5.44E+01	2.32E-04	3.27E-02	5.93E-03	8.34E-01	1.04E-04	1.46E-02
1 (Early Launch)	3.12E-05	8.77E-07	1.67E-02	6.48E-01	1.33E+02	5.16E+03	8.01E-02	3.10E+00	2.04E+00	7.91E+01	3.59E-02	1.39E+00
2 (Late Launch)	3.63E-05	7.71E-08	-	2.36E-04	-	1.88E+00	-	1.13E-03	-	2.88E-02	-	5.05E-04
3 (Suborbital)	1.31E-04	1.48E-07	-	9.51E-01	-	7.57E+03	-	4.55E+00	-	1.16E+02	-	2.04E+00
4 (Orbital)	4.66E-05	2.61E-06	6.66E-04	6.30E-03	5.30E+00	5.01E+01	3.19E-03	3.01E-02	8.13E-02	7.69E-01	1.43E-03	1.35E-02
5 (Long-Term)	1.00E-08	9.43E-10	1.51E-03	8.01E-03	1.20E+01	6.37E+01	7.23E-03	3.83E-02	1.85E-01	9.77E-01	3.24E-03	1.72E-02
Overall Mission	2.46E-04	3.83E-06	9.71E-06	3.49E-01	7.73E-02	2.78E+03	4.65E-05	1.67E+00	1.19E-03	4.26E+01	2.08E-05	7.48E-01

a. The table presents composite results for the LVs under consideration, determined by taking the probability-weighted value of each set of results.
b. Land area contaminated above a screening level of 0.2 μCi/m^2.
c. Overall mission values weighted by total probability of release for each mission phase.

Mission Risks

A summary of the mission risks is presented in Table 4. For the purpose of the NRA [1], risk is defined as the expectation of health effects in a statistical sense (i.e., the product of total probability times the health effects resulting from a release, and then summed over all conditions leading to a release). The risk is determined for each mission phase and the overall mission. Since the health effects resulting from a release equals the sum of the probability of a health effect for each individual in the exposed population, risk can also be interpreted as the total probability of one health effect given the mission (for risk much less than one). All of the Phases 0 and 1 releases are within a few km of the launch pad. Nearly all of the Phase 3 releases are within southern Africa. All of the Phase 4 releases are between 29^o N and 29^o S latitude. Phase 5 releases can occur anywhere on the globe where there is land. The mission risk for the MMRTG configuration is 2.9x10^{-5}.

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

Mission Phase	Accident Probability	Mean Health Effects, Given an Accident	Mission Risks
0 (Prelaunch)	3.28E-05	4.50E-04	1.48E-08
1 (Early Launch)	3.12E-03	8.12E-03	2.53E-05
2 (Late Launch)	3.63E-03	1.66E-07	6.04E-10
3 (Suborbital)	1.31E-02	2.30E-04	3.02E-06
4 (Orbital)	4.66E-03	1.45E-04	6.75E-07
5 (Long-Term)	1.00E-06	3.57E-04	3.57E-10
Overall Mission	2.46E-02	1.18E-03	2.90E-05

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

For the Mars 2020 configuration with an MMRTG, Phase 1 accidents contribute 87 percent of the risk. Another descriptor used in characterizing risk is the maximum individual risk, presented in Table 5. The maximum individual risk is defined in the NRA [1] to be the risk to the person receiving the maximum individual dose in a given mission phase.

Table 5. Maximum Individual Risk for the MMRTG[a]

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

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

Uncertainties

An analysis to estimate uncertainties in probabilities, source terms, radiological consequences, and mission risks has not been performed as part of the NRA [1]. Such an analysis will be performed in the FSAR. Based on experience with uncertainty analyses in the risk assessment of past missions (e.g., the Cassini, Mars Exploration Rover 2003, Pluto New Horizons, and Mars Science Laboratory), the uncertainty in the mission risk for the Mars 2020 mission can be estimated. Those analyses have shown that the uncertainty in the mission risk is dominated by uncertainties in the launch accident probability and the overall probability is about a factor of 25 higher or lower than the median for the 5th and 95th percentiles. For the MMRTG option, treating the best estimate of the Mars 2020 mission risk of 2.9x10^{-5} as the median of the uncertainty probability distribution (i.e., it is equally probable that the mission risk could be higher or lower than this value), the mission risk at the 5th and 95th percentile confidence levels are estimated to be 1.2x10^{-6} and 7.3x10^{-4}, respectively.

CONCLUSION

In the summer of 2020, NASA plans to launch a rover to the surface of Mars as part of the Mars 2020 mission. One option for the proposed rover includes the use of radioactive materials in a single MMRTG to provide continuous power for the mission. NASA has prepared an EIS for the mission in accordance with the NEPA. The EIS includes information on the risks of mission accidents to the general public and on-site workers at the launch complex. The NRA addresses the responses of the proposed MMRTG option to potential accident and abort conditions during the launch opportunity for the Mars 2020 mission and the associated consequences [1]. This information provides the technical basis for the radiological risks of both options for the EIS.

All of the Phases 0 and 1 releases are within a few km of the launch pad. Nearly all of the Phase 3 releases are within southern Africa. All of the Phase 4 releases are between 29^{o} N and 29^{o} S latitude. Phase 5 releases can occur anywhere on the globe where there is land. For the Mars 2020 configuration with an MMRTG, Phase 1 accidents contribute 87 percent of the risk. The mission risk for the MMRTG configuration is 2.9×10^{-5}, and the 5th and 95th percentile confidence levels are estimated to be 1.2×10^{-6} and 7.3×10^{-4}, respectively.

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