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

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In the summer of 2020, the National Aeronautics and Space Administration (NASA) launched a spacecraft as part of the Mars 2020 mission. The rover on the spacecraft uses a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) to provide continuous electrical and thermal power for the mission. The MMRTG uses radioactive plutonium dioxide. NASA prepared a Supplemental Environmental Impact Statement (SEIS) for the mission in accordance with the National Environmental Policy Act. The SEIS provides information related to updates to the potential environmental impacts associated with the Mars 2020 mission as outlined in the Final Environmental Impact Statement (FEIS) for the Mars 2020 Mission issued in 2014 and associated Record of Decision (ROD) issued in January 2015. The Nuclear Risk Assessment (NRA) 2019 Update includes new and updated Mars 2020 mission information since the publication of the 2014 FEIS and the updates to the Launch Approval Process with the issuance of Presidential Memorandum on Launch of Spacecraft Containing Space Nuclear Systems, National Security Presidential Memorandum 20 (NSPM-20). The NRA 2019 Update addresses the responses of the MMRTG to potential accident and abort conditions during the launch opportunity for the Mars 2020 mission and the associated consequences. This information provides the technical basis for the radiological risks discussed in the SEIS. This paper provides a summary of the methods and results used in the NRA 2019 Update.

I. INTRODUCTION

In the summer of 2020, the National Aeronautics and Space Administration (NASA) launched a spacecraft as part of the Mars 2020 mission. The rover on the spacecraft uses a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) to provide continuous electrical and thermal power for the mission. The MMRTG uses radioactive plutonium dioxide. NASA prepared a Supplemental Environmental Impact Statement (SEIS) for the mission in accordance with the National Environmental Policy Act (NEPA). The SEIS provides information related to updates to the potential environmental impacts associated with the Mars 2020 mission as outlined in the Final Environmental Impact Statement[1] (FEIS) for the Mars 2020 Mission issued in 2014 and associated Record of Decision (ROD) issued in January 2015.

The environmental analysis presented in the 2014 FEIS was based on the United States Department of Energy's (DOE's) Nuclear Risk Assessment (NRA) for the Mars 2020 Mission Environmental Impact Statement[2] (2014 NRA). The 2014 NRA was based on the best available information on mission-specific parameters and expendable launch vehicle estimates that NASA provided to DOE in 2013. Since publication of the 2014 FEIS and issuance of the ROD in 2015, NASA had actively advanced the mission. Investments were made that constitute irrevocable commitment of funds, resources, and decisions, including the Mars 2020 rover, payload design, power system fueling, Mars landing site selection, selection of the launch vehicle, and selection of the launch period. The *Nuclear Risk Assessment 2019 Update for the Mars 2020 Mission Environmental Impact Statement*[3] (2019 NRA) included the new and updated Mars 2020 mission information since the publication of the 2014 FEIS and the updates to the Launch Approval Process with the issuance of *Presidential Memorandum on Launch of Spacecraft Containing Space Nuclear Systems, National Security Presidential Memorandum-20*[4] (NSPM-20). The 2019 NRA addresses the responses of the MMRTG to potential accident and abort conditions during the launch opportunity for the Mars 2020 mission and the associated consequences[3]. This provides the technical basis for the radiological risks discussed in the SEIS. This paper provides a summary of the methods and results used in the 2019 NRA.

The Mars 2020 mission spacecraft was launched from Cape Canaveral Air Force Station (CCAFS), Space Launch Complex (SLC) 41. The launch vehicle (LV) for the Mars 2020 mission was an Atlas V 541, which consists of a Common Core Booster (CCB), four solid rocket boosters (SRBs), and one Centaur III with a 5.4-m diameter payload fairing. NASA had narrowed the launch period to an approximate 20-day launch period opening in July 2020 and closing in August 2020, with the actual launch at 7:50 am EDT, on Thursday July 30, 2020. The analyses for the 2019 NRA sampled weather data from

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several recent years for the months of July and August to span the range of possible launch conditions[3].

The Mars 2020 rover uses one MMRTG to provide continuous power. The MMRTG contains eight General Purpose Heat Source (GPHS) modules. The MMRTG used for the Mars 2020 rover contains ~4.8 kg of plutonium dioxide (PuO2) in ceramic form, with an inventory of ~59,000 curies (Ci), due primarily to plutonium-238 (Pu-238), an alpha-emitting radioisotope with a half-life of 87.7 years. The MMRTG was provided by the U.S. Department of Energy (DOE). Due to the radioactive nature of this material and the potential for accidents resulting in its release to the environment, safety is an inherent consideration in all steps from mission design through launch.

The DOE is responsible for quantifying the risks of its nuclear hardware subjected to the effects of potential launch accidents. The purpose of the 2019 NRA is to provide this information in support of the SEIS for the mission[3], with the SEIS being prepared by NASA in accordance with requirements under the NEPA. In 2019, the Launch Approval Process was updated with the issuance of NSPM-20[4]. The results in the 2019 NRA are shown in a format for comparisons with previous analyses and a format to support NSPM-20.

The SEIS-supporting assessment presented herein is based in part on 1) spacecraft descriptions, accident environments, and LV information provided by NASA[1], 2) information regarding accident probabilities provided by NASA[5] and 3) information available from the LV manufacturers' User's Guides[6]. Most of this information has been updated since 2013. The results shown in the 2019 NRA are derived from those presented in the Mars 2020 mission Final Safety Analysis Report (FSAR), which utilized the above updated information[3].

II. ACCIDENT SCENARIOS AND CONSEQUENCES

The 2019 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 (the portion of the release that becomes airborne) and their probabilities, and 3) the radiological consequences and mission risks associated with such releases[3]. The radioactive material inventory of interest, for a single MMRTG, is about 59,000 Ci of primarily Pu-238[3]. The activity includes minor contributions from other related plutonium and actinide radionuclides in the fuel. The methodology used in developing the accident probabilities, source terms and consequences is detailed in the 2019 NRA[3].

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.
- 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.

II.A. MMRTG Response to Accident Environment

The response of the MMRTG and its components 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 source term for the range of accident scenarios and environments that could potentially occur during the mission. The protection provided by the aeroshell module, its graphitic components and the iridium clad encapsulating the PuO_2 fuel, minimizes the potential for release in accident environments. Potential responses of the MMRTG and its components in accident environments 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 spacecraft on steel or concrete can lead to a release. For impacting configurations that include more of the launch vehicle, 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 source terms through melting of the iridium clad and partial vaporization of the PuO_2.

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

II.B. Radiological Consequences

Source terms and their respective probabilities were determined by Monte Carlo simulations using 100,000 trials or more for each of the various accident scenarios. The subsequent radiological consequences due to the potential PuO_2 releases were calculated. In the consequence simulations, 100 percent of the source term was assumed to be airborne, which may be conservative since much of the source term would be trapped by the graphite materials and other debris. Furthermore, simulations show that particles larger than 100 microns would fall to the ground rapidly (generally within a few meters).

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

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

The maximum individual dose is the mean (for historical meteorological conditions) maximum (for location) dose delivered to a single individual for a given accident, considering the probability distribution over all release conditions. Collective dose is the sum of the radiation dose received by all individuals exposed to radiation from a given source term in units of "person-rem." Internal doses are determined using age and particle-size dependent dose coefficients based on Federal Guidance Report No. 13 (FGR 13) models[7].

Health effects are estimated on a cancer site-specific basis, as recommended by ICRP for non-uniform exposures such as those from Pu-238, which is primarily an inhalation hazard. Health effects are calculated per exposure pathway using risk coefficients based on the biokinetic and dosimetric models in FGR-13[7]. Contributions to health effects for each cancer site are summed over all exposure pathways for an individual. To estimate the number of health effects for a certain cancer type, individual health effects for each cancer type are multiplied by the number of individuals potentially receiving that cancer.

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

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

The results for land area contaminated are reported in terms of the area contaminated at or above a level of 0.2 $\mu Ci/m^2$ (a reference contamination level considered in the risk analyses of previous missions and a former Environmental Protection Agency (EPA) screening level used to determine the need for further action, such as monitoring or cleanup)[8,9].

The potential for crop contamination is based on the Derived Intervention Limit (DIL), as defined by the Food and Drug Administration (FDA)[10]. An average DIL of 2.5 Bq/kg (edible portion of the crop) is assumed. The DIL is converted to a cropland deposition threshold by considering the annual average uptake factor of deposited radionuclides and annual crop yields (kilogram of edible food per square meter of land). The number of square kilometers of cropland that exceeds this value for each crop type is determined from atmospheric transport calculations, cropland location maps, and the average fraction of each crop type within 100 km of the launch site, in Southern Africa or the around the world.

The uncertainty in the risk values is a function of the uncertainty in the probability of an accident occurring, the uncertainty in the probability of a release given an accident, and uncertainty in the probability of a consequence greater than a specified level given a release. An analysis to estimate uncertainties in accident probabilities, source terms, radiological consequences, and mission risks was performed as part of the Mars 2020 analysis. The Mars 2020 analysis shows that the uncertainties in the overall mission consequence risks are dominated by uncertainties in the launch accident probabilities[3].

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

Table I. Overall mission exceedance probabilities for maximum individual dose levels in the NSPM-20 safety guidelines.

Maximum Individual Dose Level	Safety Guideline	Mean Exceedance Probability
25 mrem	1.0E-02	3.0E-04
5 rem	1.0E-04	1.3E-05
25 rem	1.0E-05	1.0E-06

Incorporating all the sources of uncertainty discussed above in the analyses, produces the lower and upper 90% uncertainty intervals about the exceedance probabilities of the maximum individual dose levels in the NSPM-20 safety guidelines, which are shown in Table II. As seen in Table II, the lower and upper 90% uncertainty intervals are all lower than the safety guidelines as well.

Table II. Overall mission uncertainty intervals for maximum individual dose levels in the NSPM-20 safety guidelines.

Maximum Individual Dose Level	Safety Guideline	Lower 90% Uncertainty Interval	Upper 90% Uncertainty Interval
25 mrem	1.0E-02	1.3E-04	7.6E-04
5 rem	1.0E-04	4.7E-06	4.8E-05
25 rem	1.0E-05	2.6E-07	3.7E-06

III. COMPARISON WITH 2014 NRA

For the Mars 2020 mission, multiple mission parameters and launch vehicle changes occurred since 2013. These changes include more details regarding the design of the rover and scientific payload (including instrumentation), the selection of the Mars landing site, the selection of the launch vehicle and refinement of the launch period. Changes to the modeling approach for the 2019 NRA were made based on the technical reviews of previous missions, the ongoing review of the Mars 2020 mission analyses, and NASA and DOE safety testing program data. The analysis incorporated updated analytical models and computer simulation input parameters, informed by best available knowledge.

Models and parameter input updates using the best available information for conducting the nuclear safety analysis for the source term modeling include: 1) solid propellant fragmentation and trajectory; 2) liquid and solid propellant fire environments; 3) plutonia release model; 4) potential debris impact area; 5) blast model information; and 6) module and iridium cladding response to impact forces. Updates for the atmospheric transport modeling include: 1) weather data; 2) propellant plume rise; and 3) particle tracking in plumes. Updates for the consequence modeling include: 1) age-specific and organ-specific dose coefficients; 2) health effects calculations using organ-specific risk coefficients for Pu-238 and exposure pathways; and 3) use of region-specific crop information.

III.A. Probabilities

A comparison of the accident probabilities from the 2014 NRA[2] and the 2019 NRA[3] are shown below in Table III. The accident probabilities have increased for accidents during Phase 0 and Phase 5. The accident probabilities have decreased for accidents during Phases 1, 2, 3, and 4. This results in a decrease in the probability of an accident of about 50% for the overall mission for the 2019 NRA relative to the probabilities used in the

2014 NRA. These changes in accident probabilities are a result of launch vehicle updates since 2013.

Table III. Comparison of accident probability between the 2014 NRA and 2019 NRA.

Mission Phase	2014 Accident Probability	2019 Accident Probability	Ratio (2019/ 2014)
0 (Prelaunch)	3.28E-05	1.04E-04	3.2
1 (Early Launch)	3.12E-03	1.71E-03	0.5
2 (Late Launch)	3.63E-03	2.52E-03	0.7
3 (Suborbital)	1.31E-02	6.82E-03	0.5
4 (Orbital)	4.66E-03	1.21E-03	0.3
5 (Long-Term)	1.00E-06	1.43E-04	143.0
Overall Mission[a]	2.46E-02	1.25E-02	0.5

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

A comparison of the total probability of release from the 2014 NRA[2] and the 2019 NRA[3] are shown below in Table IV. Comparing the 2014 and 2019 total probabilities of release shows that they have decreased for Phases 2, 3, and 4 and increased for Phases 0, 1, and 5. This results in an increase in the total probability of release for the overall mission by a factor of 2.7 for the 2019 NRA relative to the 2014 NRA. This increase is due to the updated source term modeling discussed above.

Table IV. Comparison of total probability of release between the 2014 NRA and 2019 NRA.

Mission Phase	2014 Total Probability of Release	2019 Total Probability of Release	Ratio (2019/ 2014)
0 (Prelaunch)	1.07E-05	6.26E-05	5.9
1 (Early Launch)	8.77E-05	8.98E-04	10.2
2 (Late Launch)	7.71E-06	2.57E-06	0.3
3 (Suborbital)	1.48E-05	7.33E-06	0.5
4 (Orbital)	2.61E-04	6.61E-05	0.3
5 (Long-Term)	9.43E-08	8.52E-06	90.3
Overall Mission[a]	3.83E-04	1.04E-03	2.7

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

III.B. Source Terms and Consequences

A comparison of the mean source term given a release between the 2014 NRA[2] and the 2019 NRA[3] is shown in Table V. The mean source term given a release has increased in all phases and increased by a factor of 63 for the overall mission for the 2019 NRA relative to the 2014 NRA. This increase is due to the updated source term modeling discussed above.

Table V. Comparison of source terms between the 2014 NRA and 2019 NRA.

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

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

A comparison of the overall mission mean consequence results given a release between the 2014 NRA[2] and the 2019 NRA[3] is given below Table VI. The overall mission mean consequence results given a release have increased for the 2019 NRA relative to the 2014 NRA for all the measures, except for cropland intervention area. In general, consequence measures increase as source terms increase, but the increase is not necessarily one to one. Potential consequences also depend on the particle size distribution of the source term and the surrounding thermal environments. The increases in consequence measures are less than the increase in the overall mission source term for the 2019 NRA (see factor of 63 in Table V) due to the updates to the atmospheric transport and consequence modeling discussed above.

Table VI. Comparison of consequence measures between the 2014 NRA and 2019 NRA.

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

a. Overall mission values weighted by total probability of release for each mission phase.
b. Land area contaminated above a screening level of 0.2 $\mu Ci/m^2$.
c. Cropland area contaminated above the DIL based on region-specific crops. For Phases 0, 1, and 2 a value of 7.3 $\mu Ci/m^2$ was used. For Phase 3 a value of 1.4 $\mu Ci/m^2$ was used. For Phases 4 and 5 a value of 1.8 $\mu Ci/m^2$ was used.

III.C. Risks

The change in risk for each of the consequence measures is equal to the change in the mean given a release and the change in the total probability of release. Recall from Table IV, that for the overall mission, the total probability of release increased by a factor of 2.7. A comparison of the risk results from the 2014 NRA[2] and the 2019 NRA[3] is shown in Table VII. The table shows that the risk of each consequence measure has increased since the 2014 NRA, except for cropland intervention, which stayed about the same. The 2014 NRA presented uncertainties as within a factor of 25 for the risk estimates[2]. The health effect risk, cropland intervention risk and maximum individual health effect risk are within the factor of 25. The maximum individual dose risk, collective dose risk and land contamination risk are above the factor of 25. The increases in risk arise from the culmination of the updates to the accident probabilities and the source term and consequence modeling updates described above.

Table VII. Comparison of consequence risks between the 2014 NRA and 2019 NRA.

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

a. Overall mission values weighted by total probability of release for each mission phase.
b. Land area contaminated above a screening level of 0.2 $\mu Ci/m^2$.
c. Cropland area contaminated above the DIL based on region-specific crops. For Phases 0, 1, and 2 a value of 7.3 $\mu Ci/m^2$ was used. For Phase 3 a value of 1.4 $\mu Ci/m^2$ was used. For Phases 4 and 5 a value of 1.8 $\mu Ci/m^2$ was used.

IV. CONCLUSIONS

In the summer of 2020, NASA launched a spacecraft as part of the Mars 2020 mission. The rover on the spacecraft uses a MMRTG to provide continuous electrical and thermal power for the mission. NASA prepared a Supplemental Environmental Impact Statement (SEIS) for the Mars 2020 mission in accordance with the National Environmental Policy Act (NEPA). The 2019 NRA addresses the responses of the MMRTG to potential accident and abort conditions during the launch opportunity for the Mars 2020 mission and the associated consequences[3]. This provides the technical basis for the radiological risks discussed in the SEIS.

Since publication of the 2014 FEIS and issuance of the ROD in 2015, NASA had actively advanced the mission. Investments were made that constitute irrevocable commitment of funds, resources, and decisions, including the Mars 2020 rover, payload design, power system fueling, Mars landing site selection, selection of the launch vehicle, and selection of the launch period. The 2019 NRA[3] included the new and updated Mars 2020 mission information since the publication of the 2014 FEIS and the updates to the Launch Approval Process with the issuance of NSPM-20[4].

The safety guidelines in NSPM-20 designate target probabilities for three dose levels to any member of the public. The three dose levels, 25 mrem, 5 rem, and 25 rem, have target probabilities of 0.01 (1 in 100), $1x10^{-4}$ (1 in 10,000) and $1x10^{-5}$ (1 in 100,000), respectively[4]. The calculated mean probabilities and the lower and upper 90% uncertainty intervals of exceeding the three dose levels for the overall Mars 2020 mission are all lower than the safety guidelines.

Incorporating all the mission updates and model and parameter changes, affected the results of the 2019 NRA. Comparisons of the results of the 2019 NRA with the 2014 NRA show a decrease (0.5 factor) in the overall mission probability of an accident, with an increase (2.7 factor) in the total probability of release. The overall mission source term increased by a factor of 63, while the various consequence measures changed by factors that ranged from 0.4 to 35.7. This led to an increase in the consequence risks for the 2019 NRA that ranged from factors of 1.0 to 97.5.

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