Technical Basis Related to the Posture of NASA's Office of Safety and Mission Assurance for the Launch of Radioactive Material Other than Space Nuclear Systems

Volume 1–Overview of Analysis and Results

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1. Introduction

1.1. Background

NASA has launched and reentered payloads[1] containing radioactive material for over 50 years. The isotopes, their quantity, and their form have varied significantly. The handling of this material prior to its integration into the spacecraft at the launch Center (and after its return to Earth after flight, if applicable) falls under the purview of the Office of the Chief Health and Medical Officer's (OCHMO) activities related to the oversight of ionizing radiation and the general NASA institutional safety activities. The requirements for OCHMO's Program are contained in NASA Procedural Requirements (NPR) 1800.1, Chapter 4, "Environmental Health," (NASA, 2009) and the launch Center's Radiation Safety Officer carries out these activities. Once the radioactive material is integrated into the spacecraft at the launch Center, it falls under the purview of the Office of Safety and Mission Assurance's (OSMA) Nuclear Flight Safety Program and the associated nuclear launch authorization or concurrence process. The requirements for these activities are currently in NPR 8715.26, "Nuclear Flight Safety" (NASA, 2022).

Historically, OSMA concurrence was required for any launch or reentry involving radioactive material. However, OSMA recently revisited this posture due to changes in the Federal policy in this area, and the significant accrued experience. In a January 15, 2021 memorandum entitled, "Categorical Relief for Launches and Reentries Involving an A2 Mission Multiple Less Than 0.001" (NASA, 2021), OSMA documented a rationale for excluding the smallest quantities of radioactive material from warranting OSMA concurrence. OSMA anchored the basis associated with that initial step, in part, on a planned subsequent effort to assess the issue more quantitatively. The current report represents that more quantitative study. More specifically, this document addresses the potential risks and other considerations associated with launching small quantities of radioactive material (below the level requiring the Federally-mandated process in National Security Presidential Memorandum- (NSPM-) 20, "Presidential Memorandum on Launch of Spacecraft Containing Space Nuclear Systems" (USG, 2019) to provide the technical basis for when such activities require OSMA concurrence versus notification, as it relates to nuclear flight safety. Other NASA and Federal requirements (e.g., OCHMO's ionizing radiation protection requirements for Center activities, crew safety requirements, National Environmental Policy Act (NEPA) requirements, NASA mishap and contingency planning requirements) are unaffected by the findings of this document.

1.2. Approach and Acknowledgements

This study is documented in two volumes. This volume, Volume 1, contains an overview of the analysis and results at a level-of-detail accessible to most readers and suitable for public release. Volume 2 provides significantly more detail about the analysis and results, and in so doing, describes details of spaceflight activities that contain sensitive information. For this reason, Volume 2 will not be made publicly available.

The basic approach in this study is to rely on order-of-magnitude (parametric) quantitative assessments, and to involve as many affected stakeholders as practical. The study includes many of the same considerations and investigations as a probabilistic risk assessment (PRA) would since one of the needs is to characterize potential risk. However, the study is not an actual PRA in terms of its detailed approach, its scope, or its level of fidelity, nor does it strive to meet any particular standard for conducting PRAs. This study does not form a precedent of any kind for conducting the safety analyses pertinent to space nuclear systems. Rather, it leverages the useful features of contemporary risk assessment methodologies (and particularly those of event tree analysis) in order to develop an analysis that marries the strengths of

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[1] This activity encompasses any radioactive material on an integrated launch vehicle, sounding rocket, or scientific balloon.

deterministic and probabilistic analyses, while maintaining a level-of-effort for this study in keeping with the previously demonstrated low potential radiological risk of these types of spaceflight activities.

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2. Historical Information

2.1. Federal launch authorization evolution

The history of Federal launch authorization policy and practice has been summarized in numerous articles and reports, and this history is only briefly recapped here for the purpose of basic reader familiarity. In 1961, National Security Action Memorandum (NSAM) 50 (USG, 1961) expressed concern that the President wasn't sufficiently plugged in to upcoming activities involving the use of Systems for Nuclear Auxiliary Power (SNAP) nuclear power systems on Transit satellites. Soon thereafter, in 1963, NSAM 235 (USG, 1963) established a policy for involvement in scientific or technological experiments with possible large-scale adverse environmental effects, but only mentioned nuclear in the context of atmospheric nuclear tests. That same year, the Department of Defense (DoD) and the Atomic Energy Commission (AEC) worked out a more formalized interagency review approach and formally included NASA in those activities for the first time. The previous approvals were based on reviews that were more compartmentalized amongst the participating agencies. This activity ultimately led to issuance of a Report to the Administrator of NASA in 1965, entitled, "A Recommended Approach to "Interagency Nuclear Safety Review of Aerospace Nuclear Systems" (USG, 1965a). This report laid the groundwork for an interagency NASA-DOD-AEC nuclear safety review termed the "Interagency Safety Review Panel." Also in 1965, the Johnson Administration revised NSAM 50 to: (i) establish the President as the approval authority for the launch of nuclear power devices; (ii) articulate that the basis for approval would consider the probability of mission success, health and safety factors, and international political considerations, and would be based on recommendations from the cognizant departments or agencies; and (iii) assign the Executive Secretary of the National Aeronautics and Space Council (NASC) as the entity that would request Presidential approval (USG, 1965b).

By the 1968 Systems for Nuclear Auxiliary (SNAP)-27/Apollo Lunar Surface Experiments Package (ALSEP) review, a structure of NASA, DoD, and AEC Coordinators, supported by five working groups comprised of Federal employees and contractors was established. This general structure persisted through the Mars 2020 Mission review, which that interagency review team completed in 2019. Later writings about the late 1960s activities (e.g., Kerr, 1982) cite concerns over classified information handling as a main reason that an ad hoc interagency panel was employed rather than a standing committee. This review body was later changed to the Interagency Safety Evaluation Panel (by 1973), and after that to the Interagency Nuclear Safety Review Panel (INSRP) by 1975.

In 1970 the NASC issued "National Safety and Review Approvals Procedures for Minor Radioactive Source in Space Operations" (USG, 1970), with the key effect of separating out treatment for minor radioactive sources not requiring Presidential approval, while retaining a Federally mandated tracking and reporting process. In 1977, Presidential Directive/National Security Council Memo No. 25 (PD/NSC-25) rescinded prior memoranda and established a basic process for the same types of experiments, including a specific process (in Paragraph 9) for launching space nuclear systems (USG, 1977). It created a threshold delineating those major sources that required Presidential approval versus those minor sources that did not. That threshold was based on the amount of radioactivity and the radiotoxicity grouping defined in the 1970 NASC report. This remained the Federal policy for the next 18 years.

In 1995, the Clinton Administration issued an "Official Use Only" revision to PD/NSC-25 (USG, 1995) which replaced the paragraph related to launches of space nuclear systems. Its effect relative to launches of minor sources of radioactive material was to establish thresholds whereby launches containing greater than 0.1 percent of the A2 value listed in the 1990 version of International Atomic Energy Agency (IAEA) Specific Safety Requirements (SSR) No. 6 (IAEA, 1990) were reportable to the Office of Science and Technology Policy (OSTP) on a quarterly basis, while launches containing greater than 1,000 times the A2 value required the interagency review process and Presidential approval. The Clinton

Administration revised PD/NSC-25 again the following year (USG, 1996), but only to remove a clause that stated that the INSRP reported to OSTP. That policy remained in effect for the next 23 years. It is worth noting that the A2 value (and the underlying IAEA Q-system) were employed as a matter of convenience. They are more applicable for launch of small radioactive sources, since those sources have little to no designed protection, but both the A1 and A2 values are derived using assumptions related to land, sea, and air transport (rather than spaceflight).

In 2019, the Trump Administration issued National Security Presidential Memorandum No. 20 (NSPM-20), "Presidential Memorandum on Launch of Spacecraft Containing Space Nuclear Systems" (USG, 2019). It completely overhauled the Federal launch policy in many important ways, most all of which were focused on the process for launching space nuclear systems. For the current discussion, a key side effect was that the policy removed the reporting requirement for the launch of small radioactive sources (i.e., it eliminated the quarterly reporting requirement tied to launches containing greater than 0.1 percent of the A2 value). This change, in combination with the many changes to the approval process of space nuclear systems, signaled a clear desire to risk-inform the Federal launch process, which was viewed by many to be overly invasive.

A separate important aspect of NSPM-20 was the establishment of Safety Guidelines. Within the construct of NSPM-20, these Safety Guidelines create a piece-wise linear relationship of dose and exceedance probability that provides a measure of "How Safe is Safe Enough?" NSPM-20 does not specifically direct this Safety Guideline to be used for the launch of small radioactive sources not subject to NSPM-20. Nevertheless, these Safety Guidelines do provide a useful landmark. Small radioactive sources are not subject to NSPM-20 because they are expected to be of lower risk, and so they should routinely fall well below the NSPM-20 Safety Guidelines.

2.2. Overview of NASA's historical launch contexts

Volume 2 of this report makes use of the last 25 years of NASA Nuclear Flight Safety authorizations to inform the conditions considered in the new analysis, and details are provided herein. Only a high-level summary is provided here, to familiarize the reader with the broad range of conditions relevant to the current study. As shown in Table 1, on average there are approximately four to five flights per year involving small radioactive sources, spanning a large range of radioisotopes, A2 mission multiples, launch Centers, and launch vehicles. Given the focus of this study, this table does not consider the space nuclear systems launched during this time period.

Table 1—Nuclear Flight History Variability Synopsis for Small Radioactive Sources

Item	**Approx. Count for Flights Involving Radioactive Material (1996-2021)**
No. of flights	~120
No. of different radioisotopes flown	~25
Radioisotope forms	Sealed source, coatings on lenses, metal foil within ionization chambers, etc.
A2 mission multiple	$<1\cdot10^{-8}$ to ~0.1
No. of different launch Centers/sites used	~15
No. of different launch or reentry vehicles used	~20
Types of vehicles used	Re-usable (Shuttle), Expendable Launch Vehicles, in-air launch platforms, sounding rockets, scientific balloons, re-entering spacecraft

There were exceedingly few incidents recorded involving these flights, with a key exception being the several small radioactive sources aboard STS-107 (Columbia) at the time of its total loss in 2003.

Note that it is not uncommon for small radioactive sources to be part of a spacecraft that is deliberately de-orbited for burnup in the upper atmosphere. Unlike space nuclear systems, these small radioactive sources do not have engineered safety features, and so they readily incinerate along with the rest of the spacecraft in these situations.

2.3. Relevant information related to terrestrial regulation

Regarding terrestrial regulation of smaller quantities of radioactive material, there are two primary regulators of interest: the U.S. Nuclear Regulatory Commission (NRC) and the Pipeline and Hazardous Materials Safety Administration (PHMSA). In this context, the U.S. NRC relates to both the Federal regulator and the many activities that occur under the jurisdiction of U.S. NRC Agreement States. Note that NASA also does work extensively with the Department of Energy (DOE), which is a terrestrial nuclear authority under the Atomic Energy Act. However, the nuclear-related cooperation with the DOE is predominantly related to space nuclear systems, which aren't within the scope of this report.

The U.S. NRC regulates civilian use of nuclear material (except in instances where DOE authorization applies–see 10 Code of Federal Regulations (CFR) 70.11). It does so in partnership with the Environmental Protection Agency (EPA), the Food and Drug Administration, and State Governments. Within the U.S. NRC's regulations, 10 CFR 20 addresses standards for radiation protection, 10 CFR 30 addresses domestic licensing of byproduct material[2], and 10 CFR 71 addresses packaging and transportation. The U.S. NRC does not license non-terrestrial uses of nuclear technology, and so the launch of any radioactive material terrestrially covered by U.S. NRC license involves removing that material from its NRC license and transferring it to the responsibility of either the Federal Aviation Administration (FAA) [for a commercial launch] or the sponsoring Agency (for a Government-sponsored launch), per NSPM-20. Some aspects of this reciprocity are acknowledged in NUREG-1556, Volume 19, Revision 1, Section 2.10.

PHMSA, a part of the Department of Transportation (DOT), is responsible for regulating and ensuring the safe and secure movement of hazardous materials to industry and consumers by all terrestrial modes of transportation (land, sea, and air), including pipelines. Shipment of radioactive material is addressed in 49 CFR 172 Subpart B, as a Class 7 hazardous material, and requirements are addressed throughout 49 CFR 172. These regulations do not consider radioactive material intended for use in space any differently than all other radioactive material. PHMSA and U.S. NRC authorities related to handling of radioactive material often adjoin.

Not all radioactive material is subject to licensing and oversight. For instance, 10 CFR 30.14 outlines some instances where byproduct material is exempt from various U.S. NRC regulations. Meanwhile, 10 CFR 30.15 lists specific instances where possession and use of devices containing radioactive material isn't subject to licensing if the quantity of material falls below specified limits (e.g., timepieces, static eliminator devices, marine compasses, electron tubes, etc.). However, even here, the manufacturing of

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[2] Amongst other radionuclides, this category includes any material that has been made radioactive through the use of a particle accelerator or any discrete source of radium-226 used for a commercial, medical, or research activity. In addition, the NRC, in consultation with the EPA, DOE, Department of Homeland Security and others, can designate as byproduct material any source of naturally-occurring radioactive material, other than source material, that it determines would pose a threat to public health and safety or the common defense and security of the United States. Practically speaking, most (but not all) small quantities of radioactive material that NASA uses fall in to the category of byproduct material.

such devices or the modification of such devices for research is still subject to licensing. Other sub-parts of Part 30 similarly provide exemptions for other contexts and 10 CFR 30.70 through 30.72 provide lists of radionuclide-specific concentrations to be used in determining these exemption, where cited. The bottom line is that some radioactive material is not subject to licensing requirements, but this situation is very case-specific.

Also note that contractual limits can also be relevant. For example, Federal Acquisition Regulation Clause 23.602 states that: "The contracting officer shall insert the clause at 52.223-7, Notice of Radioactive Materials, in solicitations and contracts for supplies which are, or which contain- (a) radioactive material requiring specific licensing under regulations issued pursuant to the Atomic Energy Act of 1954; or (b) radioactive material not requiring specific licensing in which the specific activity is greater than 0.002 microcuries per gram or the activity per item equals or exceeds 0.01 microcuries. Such supplies include, but are not limited to, aircraft, ammunition, missiles, vehicles, electronic tubes, instrument panel gauges, compasses and identification markers."

For NASA's nuclear flight safety program, any radioactive material that is being tracked from a terrestrial perspective due to being subject to, or potentially subject to, US NRC, Agreement State, or PHMSA regulations, or NASA contractual obligations, is of interest and requires nuclear flight safety consideration prior to launch or return. The question becomes one of when that consideration should solely amount to notifying NASA HQ versus when it should require NASA HQ's concurrence or authorization prior to launch or return.

2.4. High-level summary of the DoD and FAA situation

The prior section described, in general terms, the aspects of terrestrial nuclear regulation that apply to NASA's use of smaller quantities of radioactive material. This section touches briefly on launch and return authorization authorities that sometimes adjoin with or supplant NASA's launch and return authorization authority.

In the context of this discussion, DoD's relevance is as the operator of the Eastern Range (Space Launch Detla 45) and Western Range (Space Launch Delta 30), and as the facility owner for some launch sites used by NASA missions. In these capacities, the Range Commander is an additional launch or return authority. The governing requirements document is DAFMAN-91-110, Nuclear Safety Review and Launch Approval for Space or Missile Use of Radioactive Material, which in turn invokes other relevant documents such as Air Force Manual (AFMAN) 48-148, Ionizing Radiation Protection, and AFMAN 40-201, Radioactive Materials (RAM) Management. The Department of the Air Force's requirements in this area closely align with those of NASA (i.e., there is nearly reciprocity between the two organizations relative to nuclear flight safety).

The FAA, a part of the DOT, licenses commercial space transportation including launch and reetnry and the operation of non-federal launch sites (spaceports). FAA recently published a new risk-informed and performance based Rule, 14 CFR 450 covering commercial launch and reentry licensing more generally, which addresses new activities (some legacy activities remain under 14 CFR 417 until its sunset period expires). 14 CFR 450 addresses radioactive material in 450.43(i)(1)(v) and 450.43(i)(2)(iv) for payload reviews, 450.45(e)(6) for safety review and approval, and 450.185(a)(1)(v) for ground hazard analysis. NASA and the FAA have yet to harmonize their processes for nuclear flight safety, but both general and mission-specific coordination does typically occur.

2.5. Summary of A2 and the IAEA Q-system

As mentioned previously, NASA (and Federal) Nuclear Flight Safety policy leverage the use of the IAEA A2 multiple as a means of normalizing the material-at-risk hazard across radionuclides. The A2 multiple is based on a methodology termed the "Q-system" that is intended for land, sea, and air transport, but which nevertheless provides a convenient first-in for assessing the potential risk of a launch or return.

The approach taken for defining A2 values involves radionuclide-specific calculations that factor in assumptions about the exposure conditions and then use the results of those calculations to assign a normalization value to each radionuclide. The basic intent is to determine the quantity of that radionuclide that when present in a damaged "Type A" package would result in an effective or committed dose to a person in the vicinity of the package of 50 mSv (5 rem). Associated doses of 0.5 Sv (50 rem) to an individual organ or 0.15 Sv (15 rem) to the lens of the eye are also used. The time and distance of the receptor are assumed to be 1 meter for 30 minutes. Five dose pathways are considered: external photons, external beta, inhalation, contamination, and submersion in noble gases. The assessment of each exposure pathway has its own set of modeling assumptions.

From this analysis, both an A1 and A2 value are assigned. The A1 value is intended for use with special form material (material that is indisperisble even if the packaging is lost), whereas the A2 value is intended for use with other-than special form material. A2 is the value generally applicable to the radioactive material of interest in this study. The list of A2 values are available in the aforementioned IAEA SSR-6, with the current revision being the 2018 revision (IAEA, 2018). NASA Procedural Requirements (NPR) 8715.26 Appendix D includes a simple example of using the A2 values to calculate the A2 mission multiple for a launch or return.

2.6. Synopsis of relevant prior spaceflight analyses

There are exceedingly few past analyses of the consequences or risks posed by small radioactive sources in space launch or return. Most assessments for NASA and DoD activities are done on a case-by-case basis, and terrestrial nuclear authorities typically only perform assessments in support of missions that will fly space nuclear systems. In some cases, missions have included both a space nuclear system (almost always a Pu-238-based radioisotope power system) and small sources, and in a subset of these, the small sources were included in the nuclear safety analyses and the nuclear safety review. Even there, these assessments are typically mission-specific in considering the launch site, launch vehicle, radioisotope, etc., while also using very general (and intended to be conservative) assumptions about the accident source term. Also, most such studies are non-public.

A review of past studies leads to some basic orientation-level information, as follows:

- The packaging of radioactive material for spaceflight typically does not aim to protect the source from energetic accident environments, and the release of the radioactive material in such environments is expected to range from substantial to complete, though the respirable source term will only be a fraction of the total release.
- Due to the difference in protective features, smaller radioactive sources actually pose a much (orders-of-magnitude) higher per-Curie hazard than radioisotope power systems, which is then offset by the significantly (by many orders-of-magnitude) lower quantity of radioactivity in these smaller radioactive sources.
- At the "extreme" (meaning a source that is on the upper end of the spectrum of small sources traditionally flown with no protection, compared to a small radioisotope power system with robust protection), small quantities of radioactive material with little protection against release

can have consequences and risks comparable to those associated with the larger amounts of radioactive material contained in radioisotope heater units (RHUs).

3. Overview of the Newly Performed Analyses

3.1. Overview of the Process

The overall process followed is depicted in Figure 1. This process includes using scenario-based analysis and scenario-independent analysis (also referred to as variability analysis in this study) to arrive at a broad set of results that can be presented both as probabilistically weighted consequences and radiological exposure exceedance probabilities. The steps are described in the following sections.

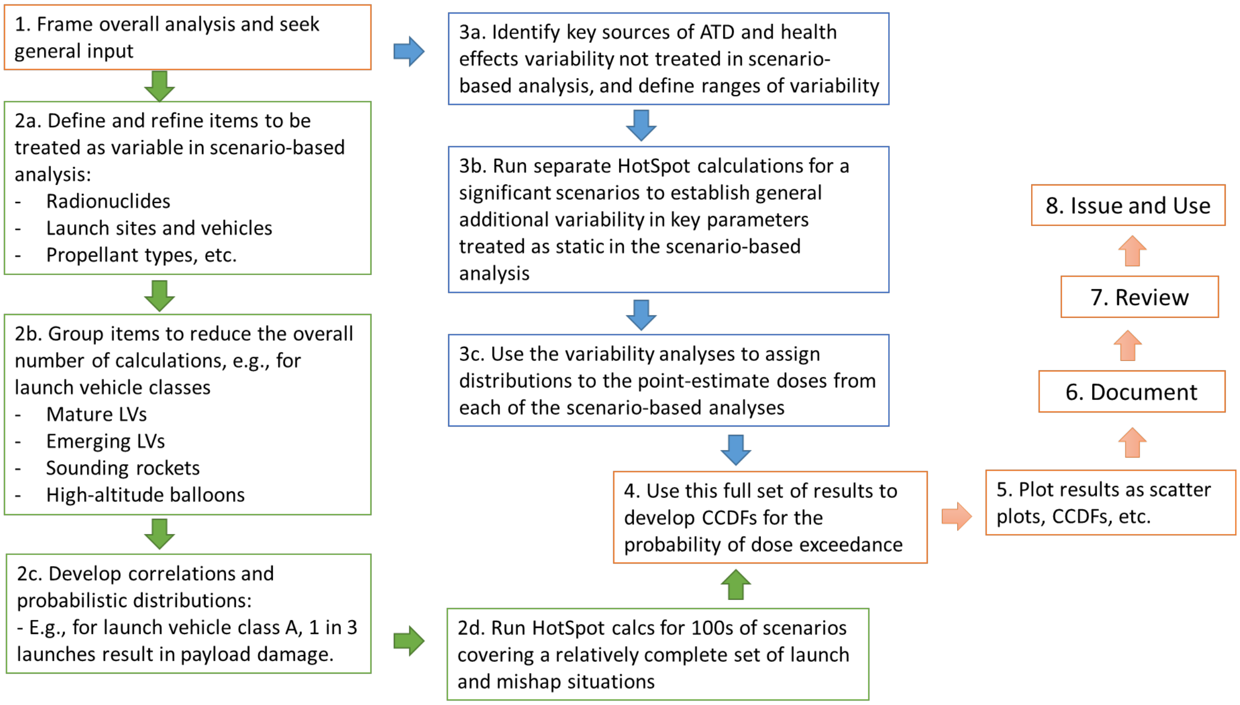

Figure 1—Overview of the Process Used to Conduct New Analysis
[Orange denotes over-arching steps; green denotes scenario-based analysis; blue denotes scenario-independent (a.k.a., variability) analysis] [ATD = atmospheric transport and dispersion; CCDF = complementary cumulative distribution function]

3.2. Step 1—Frame overall analysis

For the analytical approach, a specific launch context is described in terms of the radionuclide being flown. These material-at-risk and launch contexts are not probabilistic, they are boundary conditions for the downstream analysis, and each has a probability of 1 (i.e., they are initial conditions). These specified conditions included:

- a specified radioisotope representative of a group of isotopes that pose a similar hazard, chosen based on radiotoxicity grouping and a review of actual sources flown;
- a generic launch site typical of the vehicle in question;
- a vehicle, in this case being either a scientific balloon, a sounding rocket, or a large launch vehicle;
- the propellant type indicative of the vehicle in question.

Table 2 to Table 5 show the choices made for these four sets of conditions. The analyses performed are not intended to be highly-representative of any individual launch vehicle or launch site. They are deliberately performed in a quasi-generic setting in order to support the end-use of the results of this study (i.e., a blanket determination covering all potential vehicles and launch sites). The details of how the authors arrived at these assumptions are described in detail in Volume 2.

Table 2—Radionuclide Grouping and Representative Selection

Group Designation	**Radionuclides**	**Scientific Balloon**	**Sounding Rocket**	**Launch Vehicle**
Group A	Am-241, Cm-244, Gd-148, Ra-226	Cm-244	Cm-244	Am-241
Group B	Co-60, Cs-137, Eu-152, Eu-155, Fe-59, Na-22, Sr-90, Th-232	Not analyzed	Not analyzed	Not analyzed
Group C	Ba-133, C-14, Ca-45, Cd-109, In-114m, U(depleted)	Cd-109	Not analyzed	Cd-109
Group D	Co-57, H-3, Ni-63	Not analyzed	H-3[1]	H-3[1]
Group E	Ca-41, Fe-55	Not analyzed	Not analyzed	Fe-55

[1] In the implementation of this radionuclide in the HotSpot calculations, HotSpot's default treatment is used, which assumes 100% tritium oxide (HTO) and that two-thirds of the CEDE is due to inhalation and one-third is due to absorption through the intact skin (ICRP 30, Part 1, 1978, page 65).

Table 3—Launch Sites Retained for Further Study

Vehicle Category	**Corresponding Launch Sites Retained for Study**
Scientific Balloons	Analysis is not site specific, but most launches have historically occurred at Fort Sumner, New Mexico
Sounding Rockets	Analysis is not site specific, but most launches have historically occurred at Poker Flat Research Range, Alaska or White Sands Missile Range, New Mexico
Launch Vehicles	Unspecified

Table 4—Launch Vehicles Considered in this Study

Vehicle Category	**Corresponding Vehicles Retained for Study**
Scientific Balloons	Super pressure and Ultra-long duration balloons
Sounding Rockets	Black Brant IX
Launch Vehicles	Analysis is not vehicle specific, however, the following vehicles were used as representatives to some degree in the analysis formulation • Mature: Atlas V, Delta IV, Falcon 9 • Emerging: SpaceX Starship

Table 5—General Assumptions Regarding Propellant Types

	Types of Propellants that May Be on Board	**Assumptions Made in this Study**
Scientific Balloon	None	None
Sounding Rocket	Solid propellants	Solid propellants
Launch Vehicle–Mature	Mono-propellants, bi-propellants (liquid), solid propellants	Mixed (see preceding discussion)
Launch Vehicle–Emerging	Mono-propellants, bi-propellants (liquid), solid propellants	Mixed (see preceding discussion)

The next stage of the analysis involves scenario characterization. For each launch context (i.e., each sequence), a series of events are considered to establish whether a payload damage event occurs, and if so where the payload lands, what hardware insults will control the amount of damage the payload experiences, and whether a release of radiological material occurs beyond the payload envelope. The next stage of the analysis involves exposure characterization. For each scenario characterization (i.e., each sequence), a series of events are considered to establish the conditions most heavily influencing a potential radiological exposure. Using the above approach, event sequences (with associated conditional probabilities) are developed to cover a wide range of potential scenarios. Each sequence leads to a distinct end-state, which is then analyzed using HotSpot (LLNL, 2010 and LLNL, 2020) to estimate the associated radiological exposures for that set of events. The result of this analysis, referred to as the scenario-based analysis, is a distinct HotSpot output that provides point estimates for each sequence. Combined with the foregoing probability estimates, the outcome is a broad set of sequence likelihoods and consequences covering a broad range of potential situations.

Regarding uncertainty in the consequence estimates, several key parameters in the HotSpot analysis are selected, and simple histograms are assigned to capture the uncertainty in these parameters. HotSpot is then run in a Monte Carlo sampling mode for the sequence with the highest probability-weighted consequence to arrive at an uncertainty distribution around the point estimate previously calculated. This uncertainty distribution is then used as a generic measure of uncertainty for that launch situation and is ascribed as the relative uncertainty distribution for all other sequence point estimates for that launch situation.

At this point, the study has defined a broad set of sequence likelihoods and consequences, with associated uncertainty distributions. Along with providing individual and aggregated simulation results, these can be used to develop complementary cumulative distribution functions (CCDFs), which provide a very useful representation of the risks associated with the situations considered. The approach summarized herein is described in far greater detail in Volume 2.

3.3. Step 2a—Variables used for scenario-based analysis

While many different boundary conditions are relevant, it was necessary to choose a subset of variables that are most relevant to the intended use of this study. The following variables were selected:

- accident phase and associated impact location in the case of an accident;
- the posited controlling hardware insult;
- the associated release fractions;
- the release height and associated release energy;
- the distance to the nearest receptor; and
- the duration the receptor would be exposed via groundshine (having also been exposed to the passing plume).

In each case, multiple (typically three) outcomes were considered (i.e., binning of a wider set of potential outcomes) and these outcomes were probabilistically-weighted, as discussed in the following sections.

3.4. Step 2b—Grouping of parameters and representative selection for scenario-based analysis

For accident phases, the authors defined a set of phases suitable for use across the three considered vehicle types considered, though some phases are not applicable to some vehicle types. The phases defined were:

- At Lift-Off (ALO)–*this is generally intended to include pre-launch activities after the radioactive material is onboard*

- Off-Pad (OP), but still over launch facility property or monitored waters
- Down-Range (DR), i.e., off launch facility property
- Fall from Sub-Orbital (SO)
- Reentry (RE)

Particularly in the case of large launch vehicles, it was necessary to map these phases to notional flight timeline, performance, and critical flight event characteristics in order to use a broad set of operating experience, given that differing launch vehicles can have very different flight characteristics. It was also necessary to make specific assumptions about the likelihood of launch vehicles flying over land during ascent, given the difference between coastal and non-coastal launch sites in this regard. Again, details are provided in Volume 2.

This study uses the assumption that a single hardware insult will be dominant for a given accident scenario, owing to the fact that the material in question generally does not have engineered safety features that would allow it to survive multiple/cumulative insults. Operating experience was used for each vehicle type to define which insult types (impact and rain-of-debris, over-pressure, aero-heating, and fire) are attributable to each accident phase. As previously mentioned, the scientific balloon and sounding rocket analysis uses operating experience specific to NASA's activities in these areas. For large launch vehicles, a combination of industry-wide operating experience and past studies was used.

Each combination of vehicle type, accident location, and controlling insult considers the range of potential radiological release fractions in terms of the overall and respirable fraction of radiological material released (i.e., the source term). Since this study does not use mechanistic modeling for this portion of the analysis, and since there is only partially relevant data to leverage, judgment is used in defining a central tendency, and a higher and lower estimate. In this manner, each combination of vehicle type, accident location, and controlling insult will have three potential source terms.

Next, release heights and release energies are specified for various situations. These situations include the case of a non-energetic or non-buoyant ground release, an energetic or buoyant ground release, and in-air releases. Here, a key modeling assumption inherent to the use of HotSpot comes in to play. While the underlying modeling assessed releases at various heights, implemented heights were capped at 900 m due to this modeling limitation. This limitation reflects HotSpot's fundamental reliance on Gaussian plume modeling within the atmospheric boundary layer (i.e., relatively close to the ground and below an elevation where additional meteorological phenomena are relevant). This relatively low cap on the possible release height has the effect of over-estimating doses because less atmospheric dispersion occurs prior to the material reaching ground level (and a receptor). Conversely, this same limitation may cause an under estimation of other figures of merit (like ground concentration above a specified level), though these are not considered further here. However, this is a secondary concern given the very small quantities of radioactive material in question in this study. Again, due to the large degree of uncertainty, high, central, and low estimates are used.

The final set of boundary conditions to describe involves the location of a receptor (i.e., the individual receiving a dose from the postulated radiological release) and the duration of time that receptor spends in the vicinity of the radiological contamination. Typical stand-off distances and operational considerations were used to determine the credibility of a receptor being within 10m, 100m, or 1,000m of the impact location of the released material. Similarly, typical operational considerations and incident response activities (if relevant) were used to determine the credibility of the receptor being exposed for at least 30 minutes, 4 hours, or 96 hours.

3.5. Step 2c—Developing correlations and probabilistic distributions for scenario-based analysis

For flight phases and impact locations, operating experience was used to define the probabilities of having a payload damage event. In the cases of scientific balloons and sounding rockets this operative experience review/usage was specific to NASA's activities in these areas. In the case of large launch vehicles, the review utilized the Seradata SpaceTrak launch and satellite database. A number of assumptions were made in this area and these are documented in detail in Volume 2. Note that the analysis performed here is not equivalent to the launch vehicle probability of failure used in some other applications and should not be used outside of the context described in Volume 2.

The resulting phase-specific likelihoods of a failure resulting in potential payload damage are provided in Table 6.

Table 6—Summary of Mission Phase Likelihoods of a Failure Resulting in the Payload Impacting Land
[These estimates are specific to the context of the present study.]

	Scientific Balloons	**Sounding Rockets**	**Mature LVs**	**Emerging LVs**
ALO	Addressed within "Off-pad"	< 1% (<1 in 100)	<1% (<1 in 100)	<1% (<1 in 100)
OP	<1% (<1 in 100)	7% (1 in 14)	<1% (<1 in 100)	<1% (<1 in 100)
DR	12% (1 in 8)	Not considered	1% (1 in 100)	13% (1 in 8)
SO	N/A	Addressed within "OP"	1% (1 in 100)	8% (1 in 12)
RE	N/A	N/A	<1% (<1 in 100)	<1% (<1 in 100)

For assigning conditional probabilities to the differing potential controlling insults during different phases of flight, this study uses a combination of operating experience, past studies (in the case of large launch vehicles), and engineering judgment. This assessment led to a relative probability of each relevant insult being the controlling insult for a specific phase/vehicle, such that all relevant insults are carried forward in the analysis. The outcome of this assessment is provided in Table 7.

Table 7—Summary of Controlling Insult Likelihoods

Accident Phase	Controlling Insult Designator (see key at bottom)	Scientific Balloon	Sounding Rocket	Launch Vehicles, Mature and Emerging
ALO	OPress	Incorporated in "OP"	0.33	0.33
	Fire		0.33	0.65
	IRoD		0.34	0.02
OP	OPress	N/A	0.20	0.01
	Fire	N/A	0.20	0.85
	IRoD	1	0.40	0.14
	I-Aero	N/A	0.20	N/A
DR	OPress	N/A	N/A	0.27
	Fire	N/A		0.18
	IRoD	1		0.54
	I-Aero	N/A		0.01
SO	OPress	N/A	N/A	0.17
	Fire			0.01
	IRoD			0.33
	I-Aero			0.49
RE	OPress	N/A	N/A	0.1
	IRoD			0.36
	I-Aero			0.54

[OPress = Over-pressure; IRoD = Impact and rain-of-debris; I-Aero = Insult from aero-heating]

For scientific balloons and sounding rockets, release fractions were developed using extrapolations of information presented in DOE-HDBK-3010-94 (DOE, 2013). For launch vehicles, information was used from the study of a Cm-244 source in the 2014 Nuclear Risk Assessment for Mars 2020 (Sandia, 2014). In all cases, the high degree of uncertainty in these estimates was acknowledged by specifying a high, central, and low release fraction set (overall and respirable). The values used are provided in Table 8, Table 9, and Table 10. Recall that these are values for material that is assumed to not have engineered safety features. It would be inappropriate to attribute these release fractions with situations where the material-at-risk has engineered safety features.

Table 8—Release Fraction Assumptions for Scientific Balloons

	Conditional probability	Total Release Fraction (RF)	Respirable Release Fraction (RRF)[1]
Lower Estimate	0.1	1E-3	1.6E-4
Intermediate Estimate	0.8	1E-2	1.6E-3
Upper Estimate	0.1	0.1	1.6E-2

[1] This refers to the fraction of respirable material released relative to the initial material-at-risk, rather than as a fraction of the overall release (the latter of which is the formulation input into HotSpot)

Table 9—Release Fraction Assumptions for Sounding Rockets

		Conditional Probability	**Total Release Fraction (RF)**	**Respirable Release Fraction (RRF)[1]**
OPress	Lower estimate	0.1	5E-3	1.5E-3
	Intermediate estimate	0.8	1E-2	1E-2
	Upper estimate	0.1	1	0.5
Fire	Lower estimate	0.1	5E-4	2.5E-4
	Intermediate estimate	0.8	1E-2	1E-2
	Upper estimate	0.1	1.0	0.5
IRoD	Lower estimate	0.1	1E-2	1.6E-3
	Intermediate estimate	0.8	0.1	1.6E-2
	Upper estimate	0.1	1.0	0.16
I-Aero	Lower estimate	0.1	1E-2	1E-2
	Intermediate estimate	0.8	1E-2	1E-2
	Upper estimate	0.1	1.0	0.5

[1] This refers to the fraction of respirable material released relative to the initial material-at-risk, rather than as a fraction of the overall release (the latter of which is the formulation input into HotSpot)

Table 10—Release Fraction Assumptions for Launch Vehicles

Accident Phase	**Controlling Insult**	**Conditional Probability**		**Total Release Fraction (RF)**	**Respirable Release Fraction (RRF)[1]**
ALO	OPress Fire I-RoD	Lower estimate	0.1	1.0	0.18
		Intermediate estimate	0.8	1.0	0.46
		Upper estimate	0.1	1.0	1.0
OP	OPress Fire IRoD	Lower estimate	0.1	1.0	0.18
		Intermediate estimate	0.8	1.0	0.46
		Upper estimate	0.1	1.0	1.0
DR	OPress Fire IRoD I-Aero	Lower estimate	0.1	1.0	0.18
		Intermediate estimate	0.8	1.0	0.46
		Upper estimate	0.1	1.0	1.0
SO[1]	OPress Fire IRoD I-Aero	Lower estimate	0.1	1.0	0.18
		Intermediate estimate	0.8	1.0	0.46
		Upper estimate	0.1	1.0	1.0
RE	OPress IRoD I-Aero	Lower estimate	0.1	1.0	0.18
		Intermediate estimate	0.8	1.0	0.46
		Upper estimate	0.1	1.0	1.0

[1] This refers to the fraction of respirable material released relative to the initial material-at-risk, rather than as a fraction of the overall release (the latter of which is the formulation input into HotSpot)

For specifying the height/elevation at which the release occurs (considering buoyancy effects when relevant), POLU analysis and other sources were used to make judgment-based assignments. These assignments are shown in Table 11. Again, a modeling limitation associated with HotSpot results in all initial release heights being capped at 900m, and this is expected to have the effect of over-estimating individual radiological exposures where relevant.

Table 11—Applied Release Height Summary

	Lower Value (10% Probability)[1]	**Central Tendency (80% Probability)[1]**	**Upper Value (10% Probability)[1]**
	Ground level release for accidents prior to 1st stage separation[2]		
Scientific Balloon	N/A	N/A	N/A
LV–Mature	70 m	350 m	900 m [Note 3]
LV–Emerging	150 m	750 m	900 m [Note 3]
Sounding Rocket	20 m	200 m	500 m [Note 3]
	Ground level release for accidents after 1st stage separation		
Scientific Balloon	N/A	N/A	N/A
LV–Mature	10 m	180 m	900 m [Note 3]
LV–Emerging	70 m	325 m	900 m [Note 3]
Sounding Rocket	5 m	50 m	280 m
	In-air accident		
Scientific Balloon	N/A	N/A	N/A
LV–Mature	200 m	500 m [Note 3]	900 m [Note 3]
LV–Emerging	200 m	500 m [Note 3]	900 m [Note 3]
Sounding Rocket	50 m	250 m [Note 3]	500 m [Note 3]

[1] Conditional probability provided in parenthesis

[2] Based on the postulated damage event characterization assumptions, ground level releases for accidents prior to 1st stage separation are applied to fire insults during the ALO, OP, and DR accident phases for launch vehicles and the ALO accident phase for sounding rockets.

[3] These values were specifically adjusted downward in light of the 900 meter maximum height limitation in HotSpot's general plume model.

For the distance to the nearest receptor and the length of time that receptor is assumed to be present, relative probabilities were assigned to each of the credible boundary conditions. These assignments were made based solely on judgement, as opposed to any operating experience data, and were informed by discussions with knowledgeable personnel. The resulting analytical assumptions are shown in Table 12 and Table 13. Note that while the baseline results for this study include assumptions regarding specific locations of receptors, the maximum dose computed by HotSpot at any location for each simulation was also tracked and retained. These results will be discussed later.

Table 12—Summary of Assigned Receptor Distance Likelihoods

	Phase	**10 m**	**100 m**	**1 km**
Scientific Balloon	**OP**	0.9	0.1	-
	DR	0.9	0.09	0.01
Sounding Rockets	**ALO**	0.1	0.89	0.01
	OP	0.5	0.4	0.1
Mature and Emerging LVs	**ALO**	-	0.01	0.99
	OP	-	0.01	0.99
	DR	0.33	0.33	0.33
	SO	0.01	0.1	0.89
	RE	0.01	0.1	0.89

Table 13—Summary of Assigned Receptor Duration Likelihoods

		For 10m distance			**For 100m distance**			**For 1km distance**		
		0.5 hrs	**4 hrs**	**96 hrs**	**0.5 hrs**	**4 hrs**	**96 hrs**	**0.5 hrs**	**4 hrs**	**96 hrs**
Scientific Balloon	**OP**	0.5	0.5	-	0.5	0.5	-	-	-	-
	DR	0.1	0.8	0.1	0.1	0.8	0.1	0.1	0.8	0.1
Sounding Rocket	**ALO**	0.5	0.5	-	0.5	0.5	-	0.5	0.49	0.01
	OP	0.5	0.49	0.01	0.5	0.49	0.01	0.5	0.4	0.1
Mature and Emergent Launch Vehicles	**ALO**	-	-	-	0.9	0.1	-	0.9	0.1	-
	OP	-	-	-	0.5	0.5	-	0.5	0.5	-
	DR	0.1	0.8	0.1	0.1	0.8	0.1	0.1	0.8	0.1
	SO	0.01	0.5	0.49	0.01	0.5	0.49	0.01	0.5	0.49
	RE	0.01	0.1	0.89	0.01	0.1	0.89	0.01	0.1	0.89

3.6. Step 2d—HotSpot analysis for scenario-based analysis

All of the foregoing boundary conditions are input into a spreadsheet that tracks the accident scenarios being studied. Those boundary conditions and a default HotSpot input template are then read by a Python script, and that Python script then generates the input files for all scenarios to be executed. The Python script then runs HotSpot repeatedly in batch mode to produce the resulting outputs. The HotSpot output files are then read by the Python script and entered back into Excel, where they are combined with the associated probability information to arrive at the set of doses and probabilities for all of the sequences of interest (54 for scientific balloons, 459 for sounding rockets, and 1,107 for large Launch Vehicles(LVs)).

3.7. Step 3a—Define parameters and groupings for scenario-independent analysis

With the scenario-dependent (i.e., scenario-based) analysis complete, the next step is to perform the scenario-independent (i.e., variability) analysis. This step is important because the scenario-dependent analysis only addresses some aspects of uncertainty, such as the uncertainty in the release fractions and release height. Variability in atmospheric transport and dispersion parameters is not part of the scenario-dependent analysis, and instead is addressed here.

All of the modeling assumptions within HotSpot were considered for potential treatment within the variability analysis. Ultimately, six parameters were selected for variation. These are:

- Atmospheric conditions (stability class and wind speed)–see Table 14
- Dry deposition–see Table 15
- Wet deposition (rain out)–see Table 16
- Terrain–see Table 17
- Resuspension–modeled to be on/off with 50/50 probability
- Sample time–varied by virtue of the fact that a default value of 10 minutes is used in general, but an adjusted time of 60 minutes is automatically adjusted by HotSpot when resuspension is active

Table 14—Atmospheric Conditions Considered

Bin	**Stability Class**	**Correlated Average Wind Speed**	**Assumed proportion**
Bin 1	F stability	1 m/s	0.25
Bin 2	D stability	4 m/s	0.5
Bin 3	B stability	10 m/s	0.25

Table 15—Respirable Source Term Deposition Velocities Considered

Bin	Deposition Velocity (cm/s)	Assumed proportion
Bin 1	0.10	0.25
Bin 2	0.30	0.25
Bin 3	0.50	0.25
Bin 4	1.00	0.25

Table 16—Rainout Coefficients Considered

Vehicle	Bin	Rain Rate (mm/hr	Rainout Coefficient (s^{-1})	Assumed proportion
Scientific Balloon	Bin 1	0	0	0.80
	Bin 2	0.5	0.0001	0.19
	Bin 3	20	0.0017	0.01
Sounding Rocket	Bin 1	0	0	0.80
	Bin 2	1	0.0002	0.19
	Bin 3	20	0.0017	0.01
Launch Vehicle	Bin 1	0	0	0.6
	Bin 2	0.5	0.0001	0.35
	Bin 3	20	0.0017	0.05

Table 17—Terrain Distributions Considered

Vehicle	Bin	Assumed proportion
Scientific Balloons and Sounding Rockets	Standard	0.9
	City	0.1
Launch Vehicles	Standard	0.99
	City	0.01

3.8. Step 3b—Perform scenario-independent analysis

The Python script described previously selects the scenario that resulted in the highest probability-weighted consequence, that is the product of dose and probability, as the base scenario for the variability analysis. Excel is used to do Monte Carlo sampling of the scenario-independent parameters discussed in the preceding section and these are combined (by the Python script) with the other fixed parameters specific to the selected scenario to generate 400 additional HotSpot model run inputs.

Once the variability analysis HotSpot input files are generated the Python script executes the 400 runs for the variability analysis (again, using HotSpot in batch mode).

3.9. Step 3c—Develop variability distributions based on scenario-independent analysis

The variability results are extracted from the HotSpot output files to a separate spreadsheet. Using the output spreadsheets from the scenario-based and variability analyses, the Python script applies the distribution of variability analysis to each of the scenario-based analysis results. This is equivalent to using the variability analysis results to generate a probability distribution function that specifies the spread in variability results about a point estimate, where the point estimate is the result of the scenario-dependent analysis. In other words, an assumption is made that the spread in the variability results for the chosen scenario is generally attributable to the other scenarios, on a relative basis.

3.10. Step 4—Integrate analyses

The results are compiled in a separate spreadsheet and are sorted in ascending order by dose and corresponding cumulative probability. For instance, the scientific balloon model includes 54 end-state results for the scenario-based analysis. Application of the distribution of the 400 results of the variability analysis to each scenario-based result produces a total of 21,600 results. To be clear, the variability analysis does not introduce new payload damage probability. The probability point estimate for each sequence-dependent analysis result is apportioned amongst the 400 variability simulations (in accordance with the associated probability density function) such that the cumulative payload damage probability in the integrated results is identical to the cumulative payload damage probability form the scenario-dependent results. Put differently, the variability analysis serves to provide richer information about the range of potential outcomes, but it does not inflate the overall probability of seeing a payload damage event.

3.11. Step 5—Present results graphically

Using the methodology presented in the preceding sections, a total of eight radioisotope and vehicle combinations, a.k.a., launch situations, were analyzed, as follows:

(i)	Scientific Balloon	0.054 mCi of Cm-244
(ii)	Scientific Balloon	54 mCi of Cd-109
(iii)	Sounding Rocket	0.054 mCi of Cm-244
(iv)	Sounding Rocket	1 Ci of H-3
(v)	Mature Launch Vehicle	0.027 mCi of Am-241
(vi)	Mature Launch Vehicle	1 Ci of Fe-55
(vii)	Emerging Launch Vehicle	54 mCi of Cd-109
(viii)	Emerging Launch Vehicle	1 Ci of H-3

In all cases, the quantity of the radioisotope is selected such that the resulting A2 mission multiple is 0.001. The results of these analyses were scrutinized and used to generate scatter plots and CCDFs. All results are provided in Volume 2. Here, a few results are provided to illustrate the general material. For instance, the scatter plot results for sounding rockets and mature launch vehicles are shown in Figure 2 and Figure 3. These plots illustrate general clustering of results, the presence of some results that tend to drive probability or consequences but not both, and the modest delineation between the two different isotopes with the same A2 mission multiple.

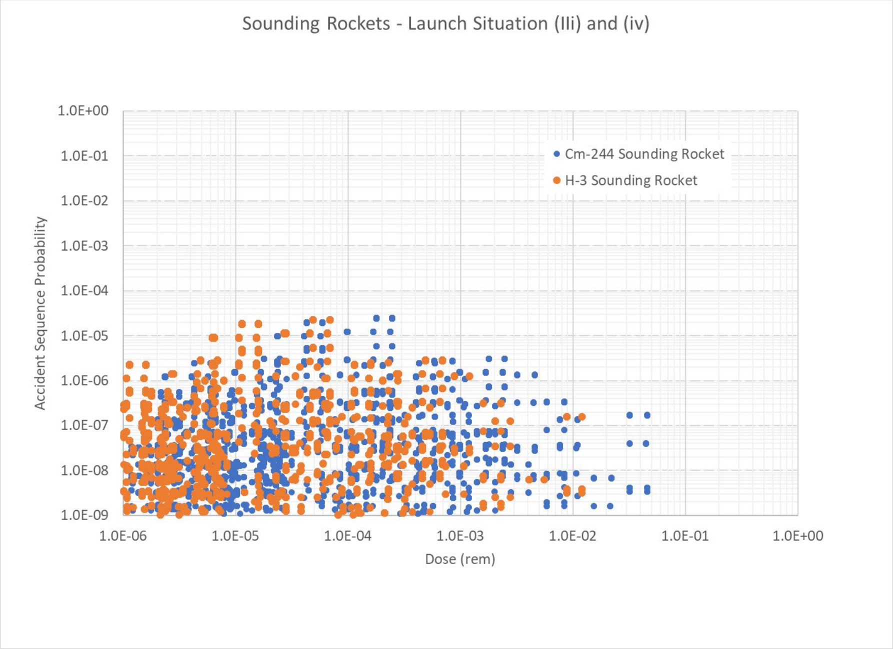

Figure 2—Probability vs. Consequence Results for Sounding Rocket Cases

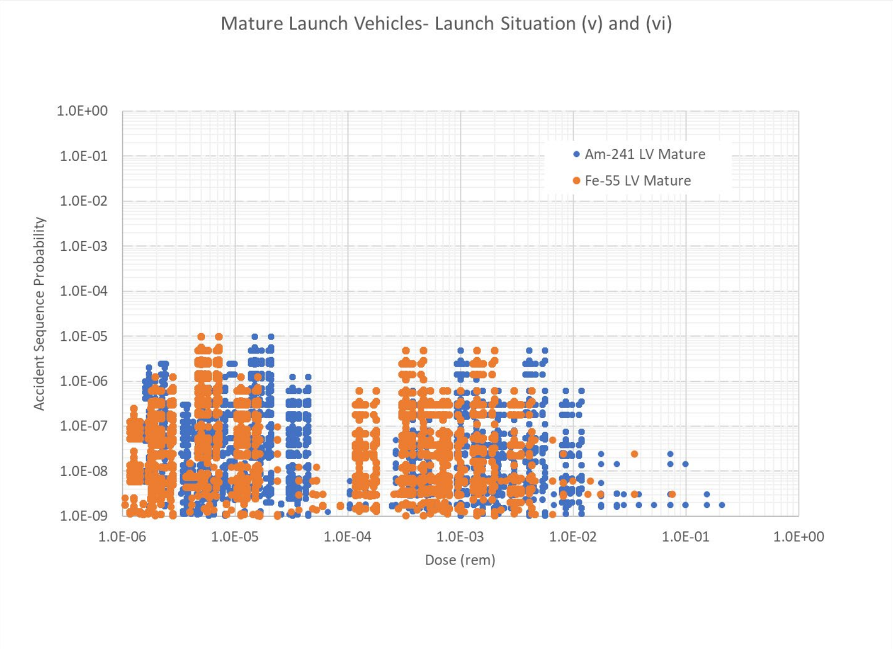

Figure 3—Probability vs. Consequence Results for Mature Launch Vehicle Cases

The combined results of scenario-based and variability analyses are presented as CCDFs. CCDFs combine the likelihood and consequence information, including modeled uncertainties, into a single representation of the risk. CCDFs can be “read” in two ways. The reader can pick a dose on the x-axis, read up to the curve, and then read across to the y-axis to obtain the probability of exceeding that dose. Alternatively, the reader can pick a probability on the y-axis, read across to the curve, and then read down to the x-axis to obtain the dose that would not be exceeded at that probability. The former case is illustrated in Figure 6.

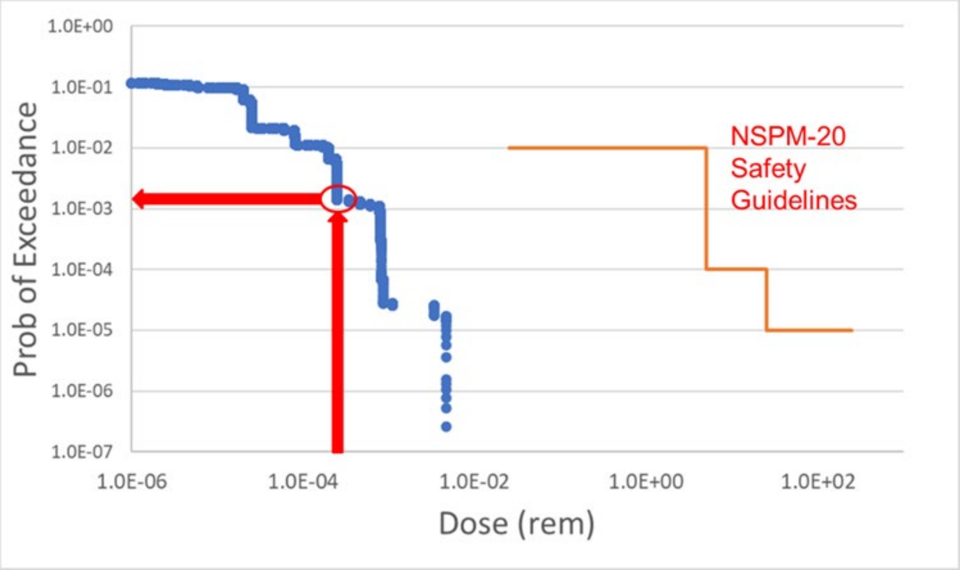

Figure 4—Example of How to Read a CCDF

Again, a subset of the results presented in Volume 2 are provided here, for brevity. These results are for launch scenarios (i), (iii), (v), and (vii), and are provided in Figure 5, Figure 6, Figure 7, and Figure 8. The CCDFs include a comparison to the Safety Guidelines described in NSPM-20, tiering triggers also found in NSPM-20, and other regulatory guidelines, including the Nuclear Regulatory Commission Regulatory Guide 4.20, "Constraint on releases of airborne radioactive materials to the environment for licensees other than power reactors" (100 mrem) and Environmental Radiation Protection Standards for Nuclear Power Operations as outlined in 40 CFR Part 190 (25 mrem). The former threshold (NSPM-20) is not directly applicable in the sense that NSPM-20 proposes these Safety Guidelines for use with space nuclear systems, though they are derived from terrestrial accident evaluation guidelines that are applied broadly for particular classes of terrestrial facilities. Here, they serve to provide a very useful barometer. The latter two regulatory thresholds are for normal, annual radiological releases. They are not directly relevant to the current situation and are only plotted to provide general context.

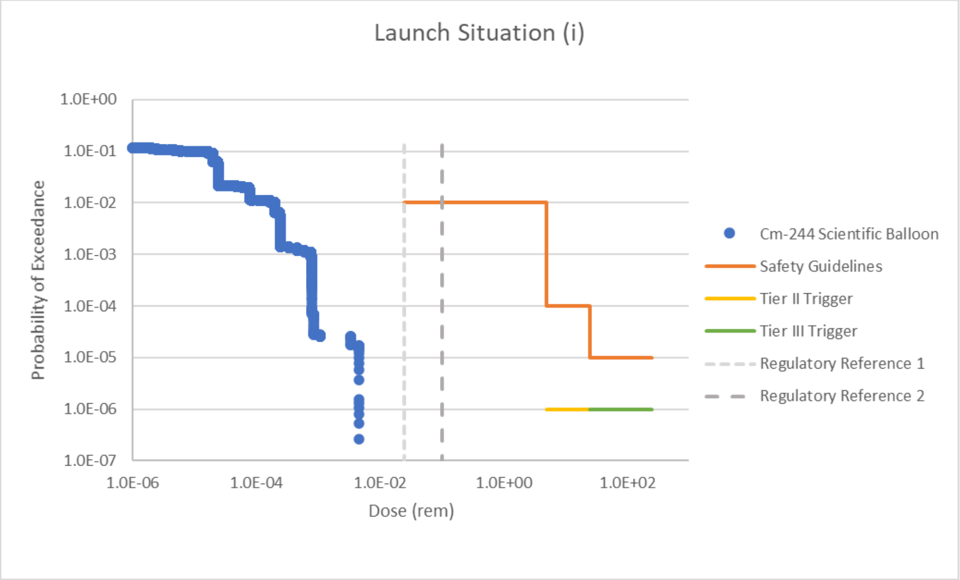

Figure 5—CCDF for a Scientific Balloon with 0.054 mCi of Cm-244

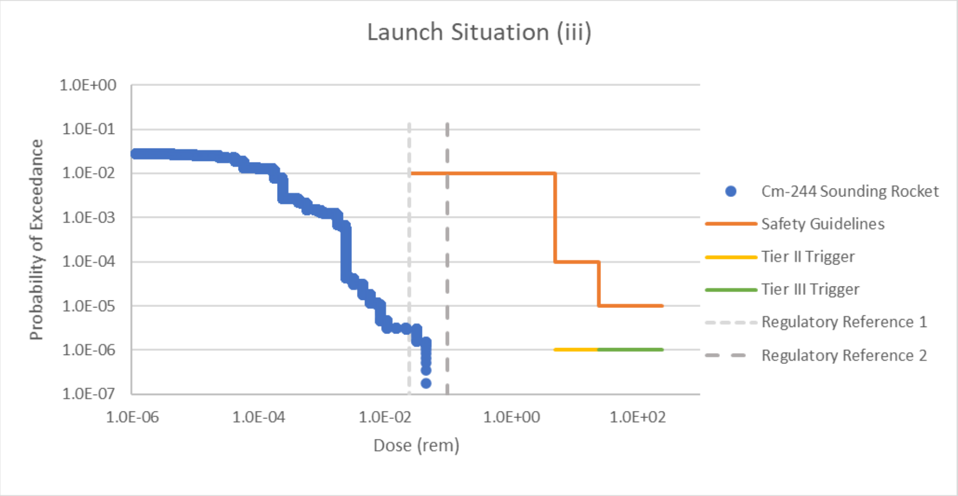

Figure 6—CCDF for a Sounding Rocket with 0.054 mCi of Cm-244

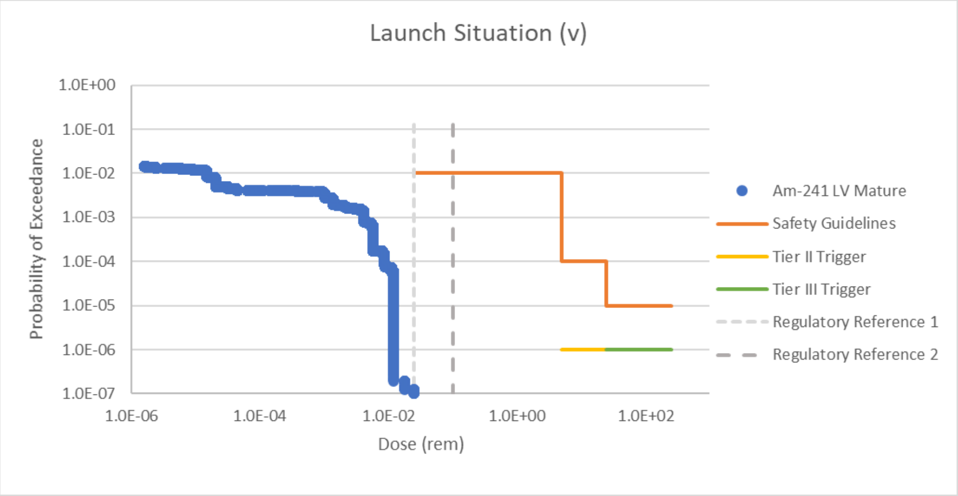

Figure 7—CCDF for a Mature Launch Vehicle with 0.027 mCi of Am-241

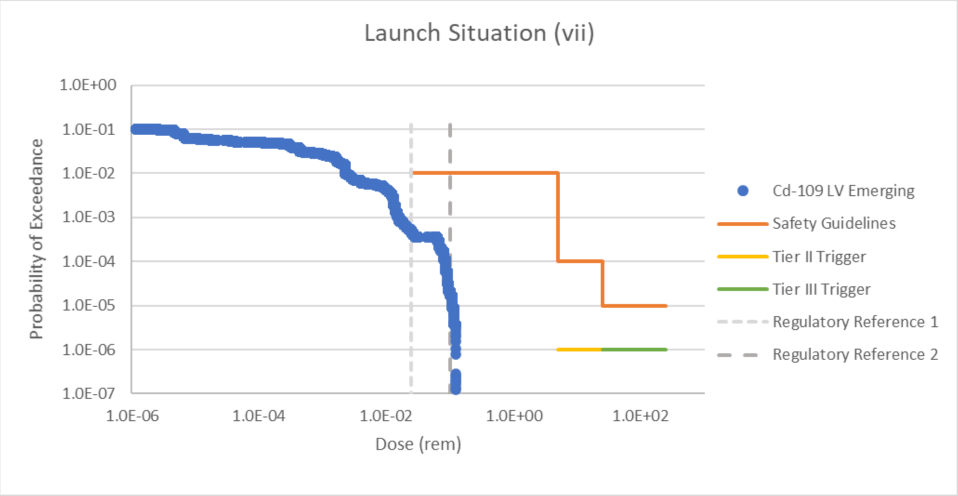

Figure 8—CCDF for an Emerging Launch Vehicle with 54 mCi of Cd-109

3.12. Step 6—Document key assumptions, analysis, and results

The following key assumptions are highlighted so that the audience has these in mind when reading this report or using the results of this study:

- Credit is not taken for eliminating LVs with poor past flight performance during the LV selection process; this makes that aspect of the analysis conservative if it were applied to missions with a risk classification associated with low risk tolerance (for reasons other than it carrying small quantities of radioactive material), or if the information were extrapolated to flights carrying larger quantities of radioactive material or space nuclear systems, where this aspect would be considered during LV selection.
- All flights involving radioactive material follow a recovery plan that includes a search for the payload, when applicable (i.e., there will be no case where personnel decide a priori to not attempt to recover a payload following normal or accident conditions).
- Adequate incidental shielding exists in normal flight configurations to preclude the possibility of a consequential dose for an uneventful flight (i.e., the same basic shielding that will protect personnel working around the vehicle during pre-launch will protect a bystander during a routine landing)[3].
- The treatment of plume rise (effective release height) is deliberately biased in a direction that should result in higher doses to a receptor in order to compensate for limitations in the analytical tools used. This refers both to how buoyancy results are implemented generally, as well as HotSpot's limitation of not allowing initial release heights of greater than 900 meters. Other measure of impacts, and particularly the amount of land that might require contamination assessment, may be under estimated using these assumptions.
- In the variability analysis performed using HotSpot, only those correlations intrinsically handled within HotSpot are reconciled; random sampling of input parameters does not address correlation between parameters, to the extent that it exists. The analysis also does not attempt to distinguish between aleatory and epistemic sources of uncertainty; these limitations do not inherently make the results more conservative or more non-conservative and may contribute to an under or over-representation in the spread of results.
- Consequence analysis assumes that there is a receptor downwind (i.e., that receptors are subject to the dose at the centerline of a plume), which is equivalent to assuming that the surrounding population is azimuthally symmetric; this assumption will produce more conservative results.

The baseline graphical results have already been presented in the preceding section.

A number of sensitivity analyses were also performed and are documented in Volume 2. These are briefly described here:

- Scientific balloon—probability of payload damage during a routine flight: An otherwise routine balloon flight could land on awkward terrain (given the lack of precise control during landing) that could cause payload damage due to tumbling. No quantitative basis existed for the likelihood of this occurring, and an assumed value was used in the baseline analysis. In this sensitivity study, that assumed value of 10% is adjusted to 1% and 25% for the sake of illustrating the

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[3] This is of most relevance to a scientific balloon flight, wherein it is more likely for a routine flight to land on private property, wherein a bystander might spend more time around the undamaged payload prior to its retrieval by flight personnel.

overall results' sensitivity to this assumption. These variations result in a probability for the down-range phase of 4% or 28%, relative to the baseline assumption of 13%. Both launch situations (i) and (ii) were included in this sensitivity study. All other input assumptions from the initial analyses were kept constant. As expected, the distribution of doses is the same in the initial analysis and the sensitivity study with a corresponding shift up or down in the probabilities caused by the adjusted probability assumptions. The impact is relatively small when compared to the margin to the NSPM-20 Safety Guidelines.

- Launch Vehicle—uncertainty in launch vehicle reliability: Empirical data was considered when developing the LV failure probabilities. Some subjectivity was inherent in the translation of the available information in to modeling assumptions. In this sensitivity study, the assumed probabilities for each impact location were adjusted by a factor of two. These adjustments resulted in total probabilities of an accident of 2.5% to 10% for mature LVs and 12% to 47% for emerging LVs. Launch situations (v) and (vii) were included in this sensitivity study. All other input assumptions from the initial analyses were kept constant. As expected, the distribution of dose results is the same in the initial analysis and the sensitivity study and the upward/downward shift in the CCDF is relative to the adjusted probability assumptions. The impacts are modest relative to the margin to the NSPM-20 Safety Guidelines
- Launch vehicle and sounding rocket—release height for the overpressure controlling insult for an ALO impact location: The over-pressure controlling insults are modeled as an in-air release. For consistency in the modeling approach, this assumption is applied for all over-pressure insults, regardless of accident phase. In this sensitivity study, the end states including an over-pressure insult for an ALO impact location were modelled as a ground level release, (i.e., a release height equal to zero). It is reasonable to assume that this initiating insult could happen at or very near the pad and not result in a buoyant release. Launch situations (iii) through (viii) were included in this sensitivity study. All other input assumptions from the initial analyses were kept constant, including the sampled parameters in the setup of the variability analysis. There was virtually no difference in the initial results and the results of the sensitivity study.
- Launch Vehicle and sounding rocket—release height probability: Release height assumptions were binned as low, central tendency, and upper values. Probabilities were subjectively assigned as 10%, 80%, and 10%, respectively. The authors acknowledge that consideration of elevated releases can significantly impact dose calculations. Due to HotSpot's treatment of release height, some adjustments were already made to the assumed values. Therefore, this sensitivity study evaluated adjustments to assumed probabilities. In this study, the upper and lower probability assumptions were adjusted by a factor of two, with the central tendency probability also adjusted accordingly. Launch situations (iii) and (v) were included in this sensitivity study. Because this was an additional evaluation of release height impacts, all other input assumptions from the preceding sensitivity study discussed above were used. There was virtually no difference in the preceding sensitivity results and the results of this sensitivity study.
- Dose conversion factors: Because Federal Guidance Report (FGR)-13 contains the most current methods and models for calculating risk coefficients, the baseline modelling of the launch situations in this study assumed FGR-13 Dose Conversion Factors (DCFs). However, as noted in FGR-13, consideration is also given to FGR-11. FGR-13 provides numerical factors for use in calculating radiation dose to individuals from low-level exposure to radionuclides. As stated in FGR-13, "Although many of the biokinetic and dosimetric models used here are updates of models used in FGR-11, the present report does not replace either that document or FGR-12 or affect their use for radiation protection purposes" (Eckerman et al, 1999). At the time of publication of FGR-13, the dose coefficients provided in FGR-11 and FGR-12 were used by Federal agencies for determining conformance with radiation protection standards (Eckerman et al, 1999). The risk coefficients in FGR-13 were "intended for use in assessing risks from radionuclide exposure, in a variety of applications ranging from analyses of specific sites to the

general analyses that support rule making. In this sensitivity study, all launch situations were modelled using FGR-11 DCFs. All other input assumptions from the initial analyses were kept constant. Generally, the modeled dose results using FGR-11 DCFs were slightly higher compared to the modeled results using FGR-13 DCFs. The exceptions were launch situations (iv), (vi), and (viii), where the modeled dose results using FGR-11 DCFs were lower than the modeled results using FGR-13 DCFs. The changes between the baseline and sensitivity were minimal to modest in terms of the margin to the NSPM-20 Safety Guidelines.

- HotSpot calculated maximum dose: The HotSpot calculated maximum dose values are tracked in the scenario-based and variability analyses. The results are not used in the baseline analysis because they include non-physical outputs (namely, doses associated with receptor locations where personnel and spectators are not permitted to be during launch and including instances where any such individual is far more likely to be harmed by blast, toxics inhalation, or falling debris). Nevertheless, consideration of these results is given in this sensitivity study since it is known that the baseline results will not always produce a limiting result given that receptors are only considered at discrete locations. In this sensitivity study, the initial results and HotSpot-calculated maximum dose results were compared for all launch situations. As expected, the HotSpot calculated maximum dose results were higher than the baseline results in most instances[4]. The HotSpot-calculated maximum dose sensitivity results do show a fairly large impact in some cases. However, they never exceed the NSPM-20 Safety Guidelines.
- HotSpot versions: The programming tool used here can be used with HotSpot versions 2.07.1 and 3.1.2. All of the HotSpot analysis discussed to this point was performed using version 3.1.2. The flexibility was written into the programming script with the goal of minimizing revisions with future updates to HotSpot. Based on discussions with the developers of the HotSpot code, there are no differences in the atmospheric dispersion modeling routines in these two versions. Only operational updates were made, along with other specific adjustments or corrections (e.g., a correction related to the treatment of dose conversion factors for tritium). In this sensitivity study, the results for all launch situations modelled using versions 2.07.01 and 3.1.2 were compared. The results using each HotSpot version were the same, except for launch situations (iv) and (viii), which specifically relate to DCFs applied in each version.

3.13. Step 7—Review analysis and results

Based on the totality of work documented herein, and in Volume 2, the following findings and conclusions were made.

Ground level releases are the most risk significant. While this finding is affected by modeling limitations inherent to this methodology, it does not appear to be overly sensitive to these limitations. This result is somewhat intuitive in the sense that, for small radioactive sources, the air concentration will become de minimus fairly quickly, and so a receptor would need to be relatively close to the release point to receive an appreciable dose.

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[4] There are specific instances where the HotSpot-calculated maximum dose results are lower than the baseline results. This relates to some nuanced aspects of how the variability analysis is performed (using the highest probability-weighted consequence sequence from the receptor-based results) and how it is applied. This ramification of the methodology is described in greater detail in Volume 2, and simply reflects the assumptions inherent in the methodology.

For all situations modeled (including the scenario-based analysis, the scenario-independent variability analyses, and the sensitivity analyses), the computed doses are:

- below the NSPM-20 Safety Guidelines in all cases;
- below 25 mrem in the large majority of cases;
- only larger than 25 mrem at exceedance probabilities below 1 in 100;
- only larger than 100 mrem at exceedance probabilities below 1 in 1,000;
- never above 300 mrem (which is the average natural background dose in the continental U.S.).

The foregoing analysis demonstrates that these findings are not sensitive to particular modeling inputs.

Notably, the spread in results is generally consistent across vehicle types. Put differently, given the range of results seen due to attributes like radionuclide, flight phases, insult types, weather conditions, etc., the different vehicles studied are not clearly distinct in terms of the level of radiological risk computed. The higher energetic hazards posed by sounding rockets relative to balloons, and by large LVs relative to sounding rockets, influence the likelihood of a receptor being proximate to a mishap location. In this sense, the flight analysis and hazard mitigation that occurs for non-radiological hazards (distance-focused overpressure, toxics, and debris) serves as an effective surrogate for managing the radiological hazard for the small sources studied here. This evidence supports the use of a single A2 mission multiple for the categorical relief threshold for all vehicle types.

Also on the topic of vehicle class, the results for emerging launch vehicles primarily differ from those of mature launch vehicles in terms of the probability. The addition of a higher propellant hazard did not affect the results, albeit that the modeling in this area was very simplified.

As an aside, mean results were tabulated for the eight baseline scenarios studied (two per vehicle type) for the variability analysis that was performed for the highest probability-weighted consequence and applied across all sequences for that particular scenario. In some ways, this is a measure of the central tendency of the sequence with the highest probability-weighted consequence and a barometer of the overall scale of these results. If the use of the A2 mission multiple were a perfect surrogate for spaceflight, noting that it wasn't developed with spaceflight in mind, then these central tendencies would be on-the-order of 5 mrem[5]. This is generally observed to be the case here. The mean values for the variability analysis of the highest probability-weighted consequence sequence for the 8 launch scenarios ranged from 0.4 mrem to 11.9 mrem. Thus, the results generally corroborate the relevance of using A2 as a surrogate for spaceflights involving these small quantity radioactive sources.

Finally, as an additional step, the authors worked with colleagues within the Department of the Air Force to receive feedback during the conduct of the study and to undertake a peer review of the study upon its completion. Two senior technical personnel from Sandia National Laboratories who have been involved in the safety reviews for past launches of space nuclear systems performed a peer review of Volume 2, and all comments were dispositioned prior to issuing the report. The authors are grateful to the Department of the Air Force and their contractors for playing this role.

3.14. Step 8—Plans for issuance and use

This step is addressed via the remaining sections in this report.

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[5] The reason for this is that the Q-system calculates the A2 value based on a 5-rem dose at an A2 multiple of 1 (equivalent to a 5 mrem dose at an A2 multiple of 0.001). Recall that the 8 baseline scenarios studied here used a quantity of the radioisotope corresponding to an A2 mission multiple of 0.001.

4. The Broader Context

4.1. What other factors impact the decision?

In the current set of NASA Nuclear Flight Safety requirements, many activities related to Nuclear Flight Safety are already non-applicable for quantities of radioactive material in the range of relevance for this categorical relief. For instance, for all missions involving an A2 mission multiple of less than one, the following situation already exists irrespective of this categorical relief:

- a nuclear safety analysis performed by the mission owner is not required;
- a nuclear safety review performed by either an interagency review group or the NASA Nuclear Flight Safety Officer is not required;
- a publicly available executive summary describing a completed nuclear safety review is not required;
- an Agency Views request of other Federal agencies is not required;
- radiological contingency planning is not required;
- NASA General Counsel consultation is not required;
- Nuclear Flight Safety activities to ensure insight after launch authorization are not required; and
- annual reporting to OSTP is not required.

In addition, all relevant Payload Safety and Range Safety requirements remain in effect (i.e., they are unaffected by this categorical relief).

In terms of NPR 8715.26, the only requirements that are being categorically waived are the submission of a launch or reentry request (supplanted by a notification of the same), the requirement of launch or reentry concurrence by the NASA Nuclear Flight Safety Officer, and the sharing of information with the NASA NEPA Manager.

While the explicit effect of relaxing the above requirements is minimal, there may be an implicit effect that is worth acknowledging, given that notification and monitoring within the categorical relief envelope would not receive the same degree of attention as meeting established requirements. Moving to a notification-only posture for launches or returns within the categorical relief envelope may have the effect of reducing:

- the reliability of recovering radioactive material after mishaps or accidents;
- the reliability of advising personnel and the public that radioactive material may be present in accident debris;
- the likelihood of having assets on hand during launch or return to identify source integrity following an accident, or to promptly take de-contamination measures;
- interagency coordination during routine launches or returns (e.g., communications with the FAA for FAA-licensed flights that contain NASA radioactive material in the payload);
- internal communications during routine launches or returns (e.g., a Center having sufficient advance notice that a source is returning from space so as to ensure proper licensing to receive that material at the Center);
- ensuring international coordination when sources are being launched from NASA facilities outside the US.

In this sense, the establishment of the categorical relief threshold is a tradeoff amongst many different considerations that tend to either pull in the direction of providing a more robust safety posture or pull in the direction of allocating more resources than a particular activities' level of risk warrants. In this sense, the categorical relief is a statement of risk posture, given that an adequate level of safety already exists.

4.2. How should the decision be made?

As stated in NASA/SP-2010-576, "Risk-informed decision making is distinguished from risk-based decision making in that risk-informed decision making (RIDM) is a fundamentally deliberative process that uses a diverse set of performance measures, along with other considerations, to inform decision making. The RIDM process acknowledges the role that human judgment plays in decisions, and that technical information cannot be the sole basis for decision making. This is not only because of inevitable gaps in the technical information, but also because decision making is an inherently subjective, values-based enterprise. In the face of complex decision making involving multiple competing objectives, the cumulative wisdom provided by experienced personnel is essential for integrating technical and nontechnical factors to produce sound decisions."

In this sense, the technical analysis described in Section 3 is informative but not sufficient. In this case, it is part of the deliberative process of assessing a wide range of potential accident conditions and consequences. Other factors are also important, and they are touched upon here:

- Meeting requirements: As discussed in Section 4.1, effectively only the requirement to obtain NASA Nuclear Flight Safety Officer concurrence is being categorically waved; all other Nuclear Flight Safety requirements levied on missions are already not applicable for radioactive material in the quantities in question, and Payload Safety and Range Flight Safety requirements are unaffected by the categorical relief.
- Safety margin: The analysis performed produced results that fall below safety guidelines, by a wide margin in almost all cases.
- Defense-in-depth: The low consequences tabulated are generally a function of vehicle reliability, some degree of protection offered by the source (though no specific engineered safety features have been credited), and the distance to receptors; removal of any one of these three factors would have only a modest effect on the results, as demonstrated through the sensitivity analyses described.
- Feedback: Notification is still required, and the NASA Nuclear Flight Safety Officer will maintain a list of all missions that have utilized the categorical relief envelop; the Nuclear Flight Safety Officer will carry out an annual review, notify Center Radiation Safety Officers (RSOs) and relevant mission owners if there are discrepancies in implementation and make adjustments to the categorical relief construct as appropriate.

In this vain, there is only a small degree of additional risk being introduced by the categorical relief concept, so long as the threshold is set at a sufficiently low level, and so long as routine monitoring (e.g., continued close interaction with Center RSOs) prevents important "escapes" from the process.

5. Outcome

5.1. New categorically exempt payloads

To balance the various tradeoffs between efficiency and risk, the categorical relief threshold of an A2 mission multiple of 0.001 is affirmed by this quantitative analysis and its associated risk-informed decision. The analysis performed here has demonstrated that such missions will compare favorably with relevant safety and risk criteria, even when generic assumptions are made, with some of these assumptions skewing results toward a conservatively biased direction where underlying information is insufficient to support a more realistic treatment. Treatment of uncertainty, including uncertainty propagation and sensitivity analysis, have demonstrated the robust nature of this finding. Peer review by external peers has further confirmed the analysis' validity. Finally, factors other than quantitative consequences and risk have been considered. Based on the totality of this information:

- Missions with an A2 mission multiple of 0.001 or less may utilize the categorical relief treatment.

As stated elsewhere, this threshold should not be construed to indicate that missions with A2 mission multiples greater than 0.001 pose undue risk. On the contrary, factoring in mission-specific information (e.g., vehicle reliability, radioactive source physical and chemical form, engineered safeguards, relevant receptor restrictions) may result in risk estimates that are lower than the ones tabulated herein.

For reference, during the period of 2012 to 2021, this categorical relief threshold would have been applicable to 21 of 25 NASA spaceflights involving radioactive material. As a result, selecting a more aggressive (higher) threshold would not have significantly affected the number of missions able to leverage the categorical relief concept.

5.2. Process for using this categorical exemption

Per NPR 8715.26, Section 4.4.2.4, "For missions involving radioactive material, but not including an SNS, the MDAA, in consultation with the cognizant Center Radiation Safety Officer(s), shall request concurrence from the NFSO or Chief, SMA (in accordance with Table 1), except where an Office of Safety and Mission Assurance (OSMA)-issued categorical relief memo is being applied (in which case only a notification is required)." The "Radioactive Materials On-Board Report" in NPR 8715.26 Appendix F remains a convenient means of providing the basic information relevant to establishing the categorical relief applicability, but the minimum required set of information is the mission name or designation and the total estimated activity at the time of spacecraft integration of each radioisotope to be flown.

To ensure good situational awareness of any changing circumstances, the Nuclear Flight Safety Officer will review all launches and reentries handled in accordance with this categorical relief on an annual basis, including verification that the A2 mission multiples were accurately calculated. This review will be documented in a note to file, and any discrepancies will be discussed directly with the relevant Mission Directorates and Center RSOs.

5.3. Use of this analysis for other Nuclear Flight Safety concurrences

The analysis described herein can provides useful information to nuclear safety reviews for larger radioactive source launches or returns, in several ways:

- it presents a general framework for estimating the range of individual exposure radiological consequences attributable to a launch or return activity;
- it provides various underlying information sources for constitutive elements of a radiological risk assessment; and
- it provides a Python, Excel, and HotSpot-based tool suitable for performing scoping assessments of individual exposure radiological risk, including the generation of CCDFs from embedded uncertainty analysis.

It is anticipated that this information and these capabilities will be used in the future, within this study's stated limitations, to assess other activities. That said, this study and the associated tool are generally not suitable for demonstrating safety and estimating risk for space nuclear systems (e.g., radioisotope power systems with engineered safety features) owing to stated limitations (e.g., the assumption that a single controlling insult will be responsible for a large majority of hardware damage and that cumulative damage effects need not be considered).

5.4. Key limitations of the overall effort

The following key limitations of this effort are provided to minimize inappropriate use of the approach and results described in this report:

- This work focuses on very small quantities of radioactive material integrated into spacecraft and associated with launch and return operations, in the context of Government-sponsored or Government-licensed activities, and as such:
    - robust Payload and Range Safety activities associated with addressing hazardous material more generally are presumed;
    - crew safety measures that would address any interactions between crew and the radioactive material during flight or during in-space operations are assumed;
    - separate activities related to non-radiological contingency planning and mishap investigation are assumed.
- This work makes a number of simplifying assumptions documented in this analysis (and compiled in a specific section on key assumptions in Volume 2) that should be reviewed prior to using the work outside of its direct applicability.
- This work has an implicit assumption that the general cadence of launches using radioactive material in the quantities of interest, as well as the features of the radioactive material, the vehicles, and the launch sites being used, will remain similar to the situation that existed over the past 25 years. Major changes in these factors may warrant re-visitation of the conclusions of this study, while moderate changes in the same would generally not affect the conclusions.

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