Risk Estimation Methodology for Launch Accidents

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Abstract: As compact and light weight power sources with reliable, long lives, Radioisotope Power Systems (RPSs) have made space missions to explore the solar system possible. Due to the hazardous material that can be released during a launch accident, the potential health risk of an accident must be quantified, so that appropriate launch approval decisions can be made. One part of the risk estimation involves modeling the response of the RPS to potential accident environments. Due to the complexity of modeling the full RPS response deterministically on dynamic variables, the evaluation is performed in a stochastic manner with a Monte Carlo simulation. The potential consequences can be determined by modeling the transport of the hazardous material in the environment and in human biological pathways. The consequence analysis results are summed and weighted by appropriate likelihood values to give a collection of probabilistic results for the estimation of the potential health risk. This information is used to guide RPS designs, spacecraft designs, mission architecture, or launch procedures to potentially reduce the risk, as well as to inform decision makers of the potential health risks resulting from the use of RPSs for space missions.

Keywords: Radioisotope Power Systems, launch safety, launch accident analysis, probabilistic risk assessment.

1. INTRODUCTION

For fifty years nuclear power sources have enabled exploration missions to deep space and locations where solar panels are impractical or inefficient [1]. The United States (U.S.) Department of Energy (DOE) provides space nuclear systems to the National Aeronautics and Space Administration (NASA) for use on civilian space missions with special requirements for spacecraft electrical power and thermal heating. These energy sources fall into two general classes, either Radioisotope Power Systems (RPSs) for electrical power or Radioisotope Heater Units (RHUs) for local component heating. RPSs are compact and light weight, have long lives, and are highly reliable. These qualities enable space missions with high power requirements. Figure 1 shows the General Purpose Heat Source (GPHS), which contains and protects the fuel pellet, and serves as the heat source in various RPS designs and the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) [2], which is the current-generation RPS.

Due to the radioactive nature of the RPS and RHU, use on a specific mission must be approved by the U.S. Executive Branch per Presidential Directive / National Security Council Memorandum 25 (PD/NSC-25). As part of the launch approval process, the DOE prepares a Safety Analysis Report (SAR) in order to quantify the potential health risks from a launch accident. Figure 2 shows the flow of information and calculations with the SAR code suite. The suite consists of several hundred thousand lines of code and scripts and has been developed under control of a detailed quality assurance program. The risk estimations compare the potential risks involved with the probability of occurrence. This SAR is provided to the Interagency Nuclear Safety Review Panel (INSRP), which performs an independent review and assessment of the potential risks posed by the mission. The INSRP in turn prepares a Safety Evaluation Report (SER) documenting the review. The results of the SAR and SER are submitted to the White House Office of Science and Technology Policy (OSTP) for

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approval to proceed with the mission. If the risk estimates are acceptable, OSTP recommends to the President that the mission be approved.

Figure 1: a) General Purpose Heat Source (GPHS), b) Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)

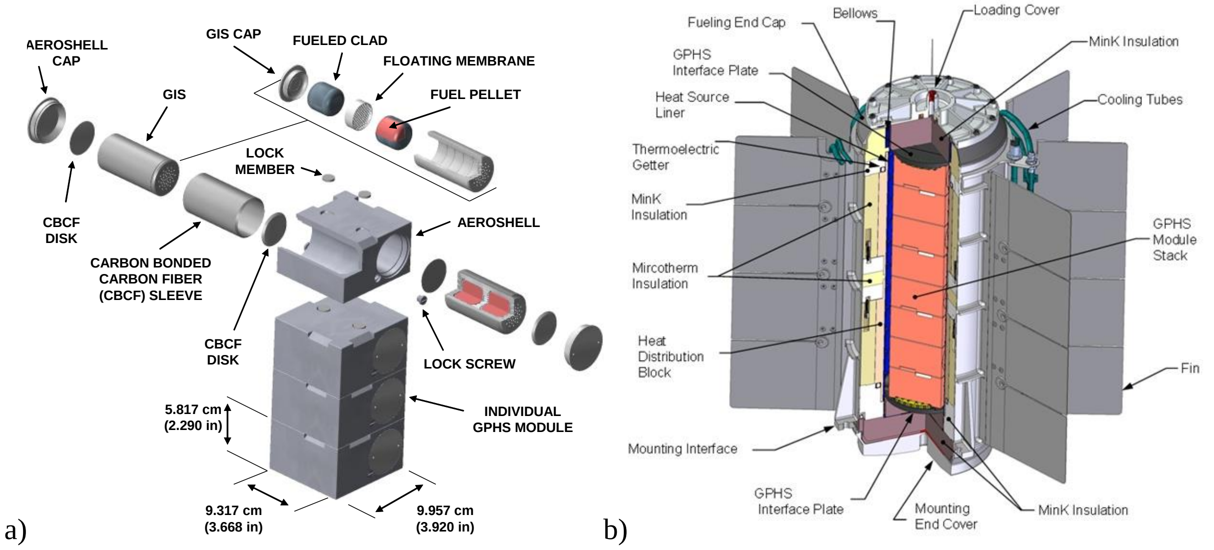
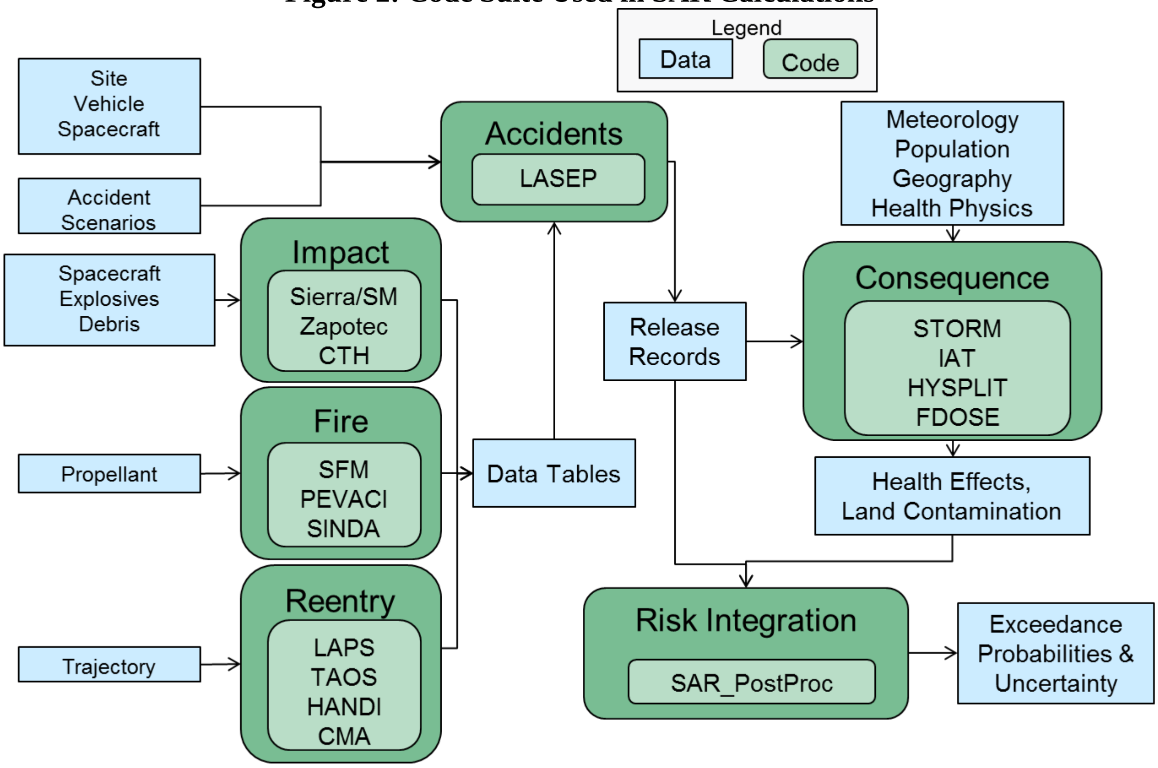


Figure 2: Code Suite Used in SAR Calculations



The safety analysis documented in the SAR includes an extensive series of analyses, primarily computer simulations of both a probabilistic and a deterministic nature. The analyses consider mechanistic and phenomenological models to simulate the progression of a launch accident, environments associated with such accidents, transport of radioactive material, and subsequent consequences to the public. Models are executed many times to accurately characterize the probabilistic nature of the event and in turn determine the potential risk. The methodology of this risk estimation is the focus of this paper. The risk estimation considers: 1) potential accidents associated with the launch, and their probabilities and accident environments; 2) the response of the radioisotope hardware to accident environments with respect to source terms (that portion of the release that becomes airborne) and their probabilities, and 3) the radiological consequences and mission risks associated with such releases.

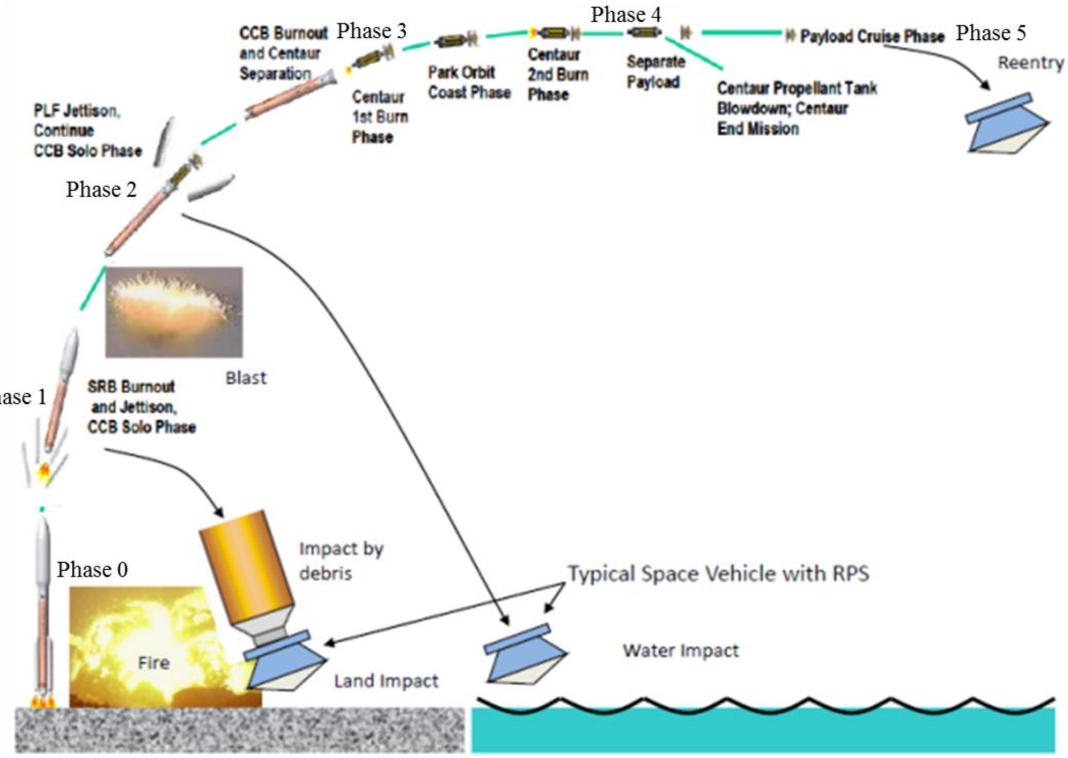
2. REPRESENTATIVE ACCIDENT SCENARIOS

For the purpose of the risk analysis, the mission is usually 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 RPS to just prior to start of the Stage 1 liquid rocket engines (LREs) at t_1.
- Phase 1: Early Launch, $t_1 \leq T < t_x$, from start of Stage 1 LRE(s), to just prior to t_x, where t_x is the time after which there would be no potential for debris or intact vehicle configurations resulting from an accident to impact land in the launch area, and water impact would occur.
- Phase 2: Late Launch, $t_x \leq T$, from t_x to when the launch vehicle reaches an altitude of nominally 30,480 m (100,000 ft), an altitude above which re-entry heating could occur.
- Phase 3: Suborbital Re-entry, from nominally 30,480 m (100,000 ft) altitude to the end of Stage 2 burn 1.
- Phase 4: Orbital Re-entry, from end of Stage 2 burn 1 to Stage 2 / spacecraft separation.
- Phase 5: Long-Term Re-entry, after spacecraft separation until no chance of Earth re-entry.

Figure 3 shows a typical mission profile for a solid rocket motor assisted launch, illustrating the various configurations that can occur. As seen in Figure 3, the RPS response is highly dependent on the time of an accident. The accident time will determine the possible impact surfaces and velocities, as well as the local environment, such as blast overpressure, fragment impacts and fire environments.

Figure 3: Typical Mission Profile of a Solid Rocket Motor Assisted Launch



The various potential accident environments are grouped into Representative Accident Scenarios (RASs) based on similarities to the environment and sequence of events experienced by the RPS. Similar RASs can be found within the different mission phases, but are kept separate as to not preclude the ability to determine the risk for each phase independently. Results for each RAS are calculated and combined together to determine the risk for each phase, as well as the overall mission risk, based on the relative probability of each RAS.

3. ACCIDENT ENVIRONMENT MODELING

The simulation of the RPS response to the accident environments is embodied in a computer code entitled Launch Accident Sequence Evaluation Program (LASEP) [3]. The location and state of the RPS is simulated from the initial insult, generally occurring at altitude, through Earth impact and any subsequent thermal environments associated with the accident. The outcome of the simulation involves determining whether a release of hazardous material occurs and, if so, the characteristics of the release, which include the release's quantity, location, and particle size distribution.

The calculated response of the RPS to accident environments is based on physical principles, prior safety testing of RPSs and their components, along with modeling of the response of the RPS and its components to accident environments using computer codes. This information allows estimates to be made of the probability of release of material and the amount of the release for the range of accident scenarios and environments that could potentially occur during the mission. The protection provided by the RPS components minimizes the potential for release in accident environments. Potential responses of the RPS and its components in accident environments are summarized generally as follows:

- <u>Explosion Overpressure and Fragments</u>: Liquid propellant explosions from launch vehicle destruct and resulting fragments are estimated to result in some RPS damage but no release.

- <u>Impact</u>: Fracturing of the RPS and its components under mechanical impact conditions provide energy absorbing protection to the radioactive material. Some impacts of an intact RPS or GPHS modules on steel or concrete near the launch pad could result in small releases, depending on the impact velocity. Ground impact of an intact space vehicle (SV) for an early launch accident is expected. The combined effect of the SV hitting the ground and the RPS subsequently being hit by the SV components above it occasionally results in a release, depending on the impact velocity and orientation. Larger debris impacting the RPS could result in higher releases for certain orientations.

- <u>Thermal</u>: Exposure of released material to a liquid propellant fireball environment would be of short duration (nominally 20 s or less). Very minor vaporization of the exposed particulates would occur depending on the timing of the ground impact release and the fireball development. For the launch vehicles which include solid rocket motors, exposure of released material to the higher-temperature, longer-burning, solid propellant could lead to more substantial vaporization of exposed material.

- <u>Re-entry</u>: Most of these impacts occur in water with no release. Land impact can result in releases that are similar in nature to those from impact near the launch pad, but without the presence of solid propellant fires. Re-entry will result in some heating and ablation of the surface of the GPHS modules, but no containment failure or release into the air. When these separated components impact land, there is a potential for release from the GPHS module during impact on rock. No release is expected from a water impact or soil/sand impact.

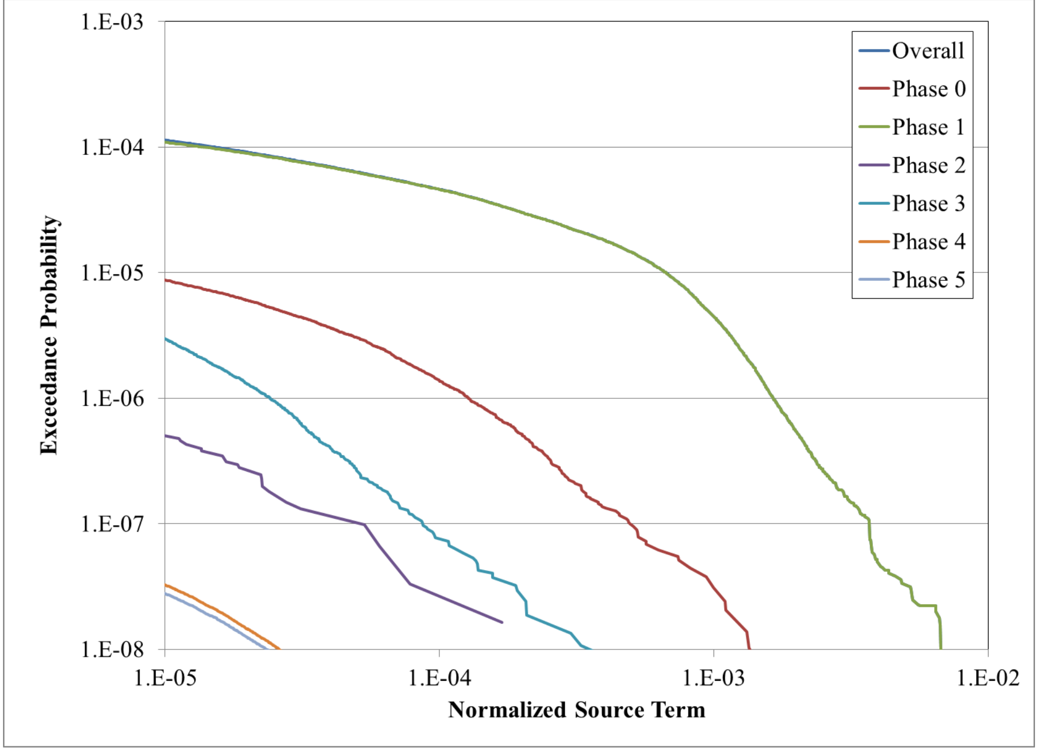
4. SOURCE TERMS

Due to the complexity of modeling the full RPS response deterministically on dynamic variables, the evaluation is performed in a stochastic manner with Monte Carlo simulations. The variability in the time, relative position/orientation and strength of the impact, explosion or fires, along with the variability in the response of the RPS, add to the complexity. The models are executed many times to accurately characterize each RAS. Each execution cycle, which simulates the occurrence of a single accident, is termed a trial. Within a RAS, results for each trial are independent because a new set of random numbers are generated for each trial. A large number of the simulations can result in no release.

By gathering statistics on the outcomes for all trials, the probability of release and the distribution of releases for each RAS, according to geographic location, altitude, particle size, and total quantity can be estimated. Each trial is assumed to be equally probable. Probability distributions for the releases are constructed for each RAS. Probability distributions can be presented in several different ways. Complementary cumulative distribution functions (CCDFs), which give the probability that any given level is exceeded, are used in this analysis.

The release CCDFs (referred to as source terms) for each RAS are assembled together into source terms for each phase of the mission and the overall mission. Figure 4 shows an example of typical source terms for each phase, as well as for the overall mission. The source terms in Figure 4 are normalized by the total inventory for convenience. As seen in Figure 4, for this mission and configuration, the source term for Phase 1, Early Launch, dominates the total mission and completey overlaps the curve for the overall mission. The other phases contribute much less to the overall mission, with Phases 4 and 5 contributing the least. Comparing the relative source terms for the various phases gives an indication of which phenomena need detailed modeling and validation. Comparing the source terms for the individual RASs within the foremost phase can illuminate which phenomena or sequence of events dominate the response. Examination of the RAS source term can help determine what aspects of the RPS, space vehicle or mission could be modified to reduce the mission risk.

Figure 4: Typical Normalized Source Term CCDFs for Each Phase and Overall Mission



5. TRANSPORT MODELING

The source terms calculated from the accident modeling are composed of a wide range of particle sizes. Large particles tend to deposit rapidly near the point of release and produce a high contamination gradient in ground surface concentrations, while scarcely contributing to material inhalation. In contrast, small particles remain airborne for a longer time and, due to diffusion effects, develop a small gradient in ground surface concentrations, while largely contributing to material inhalation in the surrounding areas.

The source term particles can be elevated by thermal buoyancy effects from liquid propellant fireballs or from solid propellant fires during launch accidents. Meteorological conditions vary in space and time, which governs the transport and diffusion of the released material. These conditions include wind velocity components, relative humidity, atmospheric turbulence and pressure. The local meteorology strongly affects both the potential rise of the particles from the fire environments and the transport of the particles to the surrounding areas. These conditions can vary greatly day to day or even within a few hours. The majority of the uncertainty in the transport modeling arises from the large variations in meteorological conditions.

The transport of the hazardous material is calculated for a collection of independent observations with a sampled value of three main input variables: release trial result, meteorological date, and time of day of the accident. Each combination is termed an observation. Exhaustively considering all possible combinations would be computationally prohibitive. A quasi-Monte Carlo method (a Halton sequence) is used to generate combinations of source term, weather day and launch time. This method facilitates construction of consequence CCDFs and estimation of uncertainty in the CCDFs, but the resolution of the low-probability, high-consequence tail of the CCDF is necessarily limited by the sample size and the computational expense of consequence calculations. To provide additional resolution in the tail of the CCDF within computational constraints, a form of importance sampling is used.

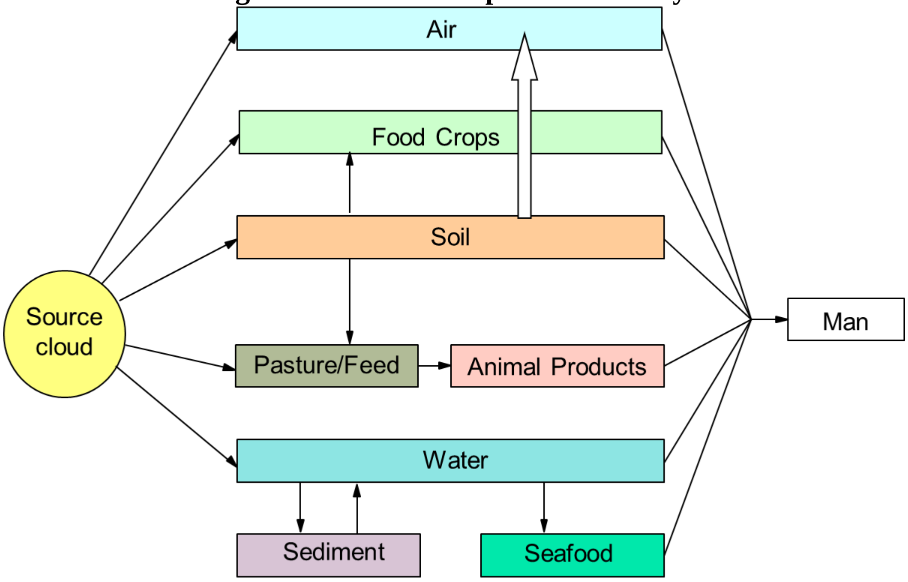
Conceptually, the importance sampling technique used involves partitioning the probability space being sampled into two disjoint sets, A and B, with B representing the low-probability, high-consequence events. The sets A and B are sampled separately, applying a higher sampling density to B, and consequences are calculated for each sample element. In importance sampling, the portion of a parameter's range that is associated with high consequences is preferentially sampled; results obtained with this sampling technique are then appropriately weighted when combining the results to obtain a CCDF. Analysis of results has shown a strong correlation between the amount released and the resulting consequences to the public. The importance sampling technique is applied to the source term trials that have larger amounts of material released. This reduces the total amount of computational time and resources needed in the transport calculations.

6. CONSEQUENCES

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

Multiple exposure pathways are considered in these types of analysis. Figure 5 illustrates the potential exposure pathways and their relationships. One pathway is direct inhalation of the released cloud, which could occur over a short duration (minutes to hours). The other exposure pathways result from deposition onto the ground and are calculated over a 50-yr exposure period. These pathways include groundshine, ingestion, and additional inhalation from resuspension. A 50-year committed dose period is assumed for the material that is inhaled or ingested.

Figure 5: Potential Exposure Pathways



The maximum individual dose is the mean (for historical meteorological conditions) maximum (for location) dose delivered to a single individual for a given accident, considering the probability distribution over all release conditions. Collective dose is the sum of the radiation dose received by all individuals exposed to radiation from a given release in units of "person-rem." Internal doses are determined using particle-size dependent dose conversion factors based on ICRP-66/67 [4] [5] and ICRP-60 [6].

The health effects represent incremental cancer fatalities over 50 years induced by releases, determined using a health effect estimator for the general population based on recommendations by the Interagency Steering Committee on Radiation Standards (ISCORS) [7]. 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 to zero, rather than assuming a threshold dose below which there would be no health effects. To estimate the total health effects within the population, the probability of incurring a health effect is estimated for each individual in the exposed population, given a release, and then the probabilities are summed over that population.

Potential environmental contamination criteria for assessing contaminated land areas are 1) areas exceeding specified screening activity concentration levels and 2) dose-rate related criteria considered by the U.S. Environmental Protection Agency (EPA), the Nuclear Regulatory Commission (NRC), and the DOE in evaluating the need for land clean up following radioactive contamination [8]. The resuspension contribution to dose assumes that no mitigation measures are taken. The potential for crop contamination is based on the Derived Intervention Limit (DIL), as defined by the Food and Drug Administration (FDA) [9]. The DIL is converted to a cropland deposition threshold by considering the annual average uptake factor of deposited radionuclides and annual crop yields (kilogram of edible food per square meter of land). The number of square kilometers of cropland that exceeds this value for each crop type is determined from atmospheric transport calculations, cropland location maps, and the average fraction of each crop type in the area.

Risk is defined as the expectation of health effects in a statistical sense (i.e., the product of total probability times the health effects resulting from a release, and then summed over all conditions leading to a release). The risk is determined for each mission phase and the overall mission. Since the health effects resulting from a release equals the sum of the probability of a health effect for each individual in the exposed population, risk can also be interpreted as the total probability of one health effect given the mission (for risk much less than one).

7. CONCLUSIONS

Due to the hazardous material that can be released during a launch accident, the potential health risk of an accident must be quantified, so that appropriate launch approval decisions can be made. The risk is calculated by modeling the response of the RPS to potential accident scenarios and the subsequent transport of the hazardous material in the environment and in human biological pathways. Due to the complexity of modeling, the evaluation is performed in a stochastic manner with a Monte Carlo simulation. The results are summed and weighted by appropriate likelihood values to give a collection of probabilistic results for the estimation of the potential health risk. This information is used to guide RPS designs, spacecraft designs, mission architecture, or launch procedures to potentially reduce the risk, as well as to inform decision makers of the potential health risks resulting from the use of RPSs for space missions.

Acknowledgements

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. This work is supported by the DOE Office of Space and Defense Power Systems. SAND2014-1670C.

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