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Radioisotope Power Systems Launch Safety Process

Daniel J. Clayton[a], Ronald J. Lipinski[a], and Ryan D. Bechtel[b]

[a]*Sandia National Laboratories: P.O. Box 5800, Albuquerque, NM, 87185, djclayt@sandia.gov*
[b]*Office of Space and Defense Power Systems, NE-75, U.S. Department of Energy, Germantown, MD 20874, Ryan.Bechtel@Nuclear.Energy.gov*

INTRODUCTION

Radioisotope power systems (RPSs) and radioisotope heater unites (RHUs) have played a crucial role in the exploration of the outer planets and deep space and are critical to the continuing expansion of our knowledge of the solar system in the twenty-first century. The alpha decay of plutonium-238 (Pu-238) fuel in the form of plutonium dioxide (PuO_2) provides the thermal and electrical power for these systems. The radioactive nature of the fuel requires that safety and environmental protection be an inherent part of the power system design, spacecraft design, and mission architecture. The U.S. Department of Energy (DOE) owns these power systems for US space missions and is responsible for performing safety and environmental impact analyses for the launch of such systems. This paper summarizes those activities.

NEPA AND LAUNCH APPROVAL PROCESSES

Due to the radioactive nature of the RPS and RHU, the safety of a mission that uses either component must be reviewed, as outlined in Figure 1. First, DOE prepares a Nuclear Risk Assessment (NRA) for the mission Environmental Impact Statement (EIS), as part of the National Environmental Policy Act (NEPA) process. This is an initial assessment of the potential risk of the proposed mission. After a detailed analysis of alternatives, NASA issues a record of decision in the Federal Register on whether or not to proceed with use of the RPS or RHU.

However, before the spacecraft can be launched, the mission must be approved by the White House per Presidential Directive / National Security Council Memorandum 25. As part of the launch approval process, DOE prepares a Safety Analysis Report (SAR). A separate mission specific Interagency Nuclear Safety Review Panel (INSRP) performs an independent review of the SAR and prepares a Safety Evaluation Report documenting the review. The INSRP is made up of representatives from DOE, NASA, DOD, EPA and other government agencies. The results of the DOE analysis and the INSRP review are submitted to the White House Office of Science and Technology Policy (OSTP) for approval to proceed with the mission. Overall, this process takes about 4-5 years.

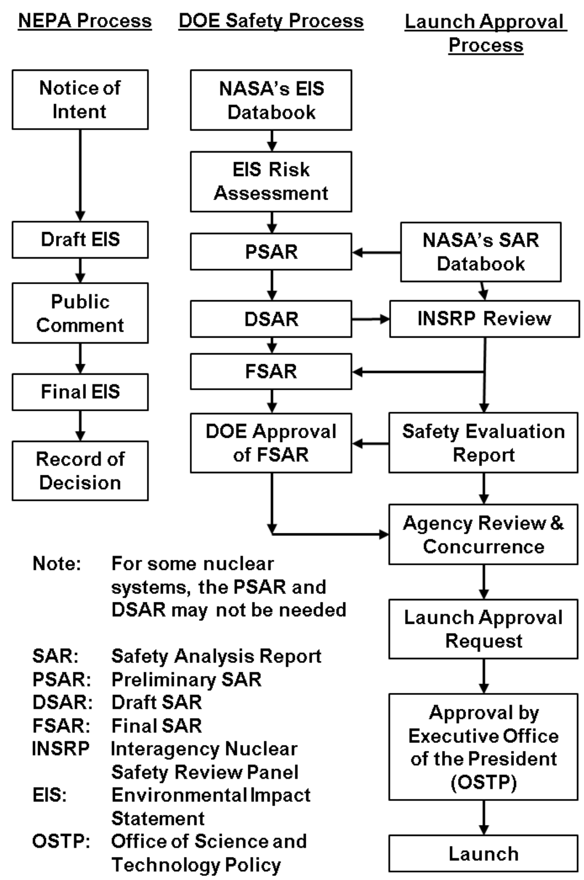

Fig. 1. NEPA and Launch Approval Processes.

LAUNCH SAFETY ANALYSIS MODELS

The safety analysis for both the NRA and the SAR is performed by Sandia National Laboratories (SNL) for the DOE/Office of Nuclear Energy. The goal of the safety and risk analysis is to make a quantitative estimate of risk for use by decision makers. The risk analysis also provides information to mission designers on areas where nuclear safety could be improved by making modifications to the launch vehicle, spacecraft or mission architecture. Such changes can be made early in the mission design to reduce the risk of the mission. The primary outputs of the risk analysis are:

- Probability of a release of plutonium dioxide fuel.
- Probability distribution of the potential amount of plutonium dioxide fuel released.
- Probability distribution of potential health effects produced (incremental latent cancer fatalities over 50 years).
- Probability distribution of potential land contamination above specified levels.
- Risk (mean number of health effects times the total probability of fuel release).

To obtain this information, numerous phenomena need to be modeled:

- Blast and impacts.
- Launch vehicle propellant fires.
- Spacecraft and RPS or RHU atmospheric re-entry from space.
- Accident sequence paths.
- Atmospheric transport and food pathways.
- Health effects.

The modeling of these phenomena is performed by an extensive launch safety code suite. Figure 2 shows the flow of information and calculation within the code suite. NASA provides a launch vehicle "Databook" that summarizes the launch vehicle characteristics, spacecraft configuration, accident environments (such as blast levels, fragment size distributions, velocities for solid rocket booster and hardware debris, and propellant fire temperatures), and probabilities of various categories of accident, including time dependence after liftoff.

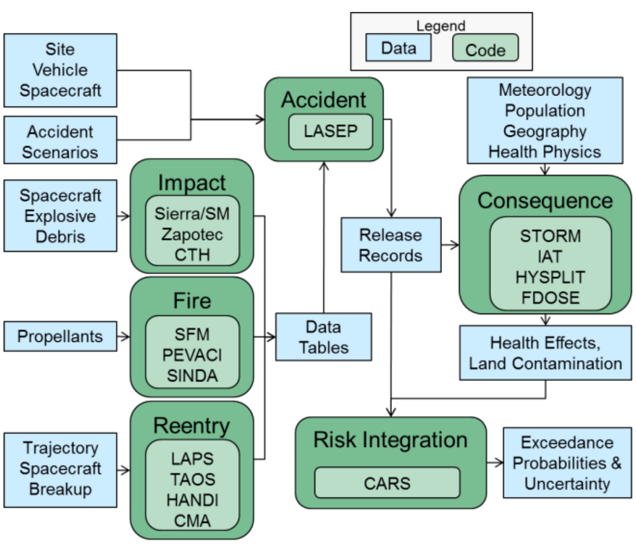

Fig. 2. Code Suite Used in SAR Calculations.

Detailed simulations are made of the primary phenomena in accident environments that can lead to fuel release. The results of these simulations are summarized in look-up tables. The Launch Accident Sequence Evaluation Program (LASEP) [1] uses the Databook information to simulate numerous random accident sequences and establish the environments that the RPS or RPS hardware will experience. LASEP draws upon the look-up tables provided by the impact, fire, and reentry codes to determine the amount released for each accident sequence. It then builds a probability distribution for the possible release amounts. Typically several million trials are run, each one different, in determining the probability distribution for possible release amounts and size distribution of nuclear fuel.

This distribution function for fuel release is then sampled and used as the source term for tens of thousands of consequence simulations in which the weather conditions and other atmospheric transport and health-effect parameters are randomly varied. Health effect models are used to convert exposures into estimated incremental latent cancer fatalities that might occur over the 50 years following the accident. This results in a probability distribution for possible consequences, including potential health effects and land contamination. The code suite consists of several hundred thousand lines of codes and scripts, and has been developed under control of a detailed quality assurance program.

Blast and impact modeling includes the following mechanical insults to the RPS and its components:

- Blast waves from the launch destruct and propellant explosions or deflagrations.
- Fragments and debris generated by blasts.
- Impact of the RPS onto the ground (or onto the components of the spacecraft as the spacecraft hits the ground).
- Partial breakup of the RPS and release of its components as insults occur.
- Impact of spacecraft debris or launch vehicle debris onto the RPS or its components.
- Impact of solid propellant fragments onto the RPS or its components.

Sandia's Sierra/SM solid mechanics code is used to simulate most of these events [2]. SIERRA/SM is a three-dimensional Lagrangian finite element (FE) code for analysis of solids and structures. It provides capabilities for explicit dynamic and implicit quasistatic and dynamic analyses. The code is under continuous development by SNL for the DOE. The code is specifically written for a parallel computing environment, which makes it suitable for the solution of very large problems. Figure 3 shows a cutaway of the MMRTG model with the mesh used. It also shows the start of a simulation of a 45^{o} impact onto steel at 100 m/s. This is considerably faster than the terminal velocity of about 60 m/s. Even with this extreme velocity, no fuel is released in the simulation, due to the numerous layers of containment and protection.

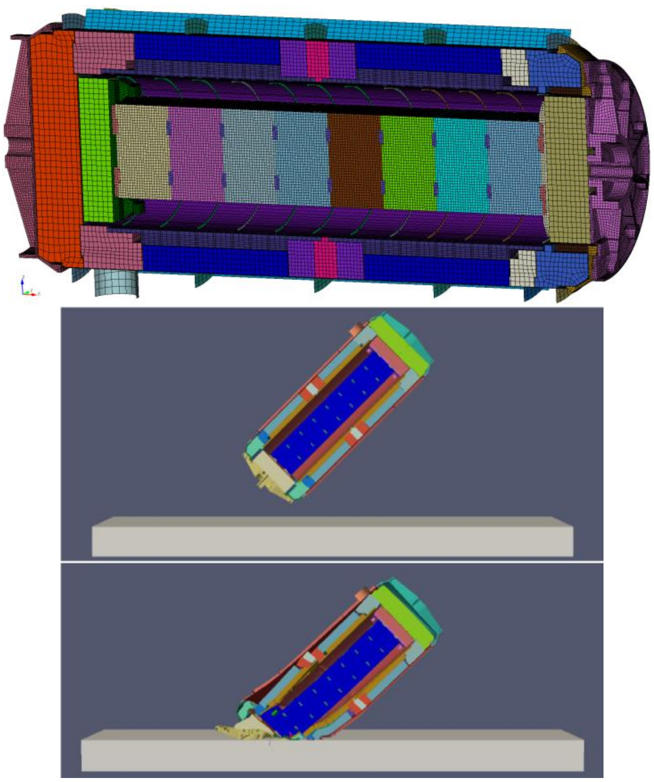

Fig. 3. MMRTG gridded model and start of 100 m/s impact simulation.

Propellant fire modeling includes the following effects:

- Liquid propellant vaporization of plutonium dioxide fuel that is enclosed in RPS hardware or exposed from previous insults.
- Solid propellant vaporization of plutonium dioxide fuel that is enclosed in RPS hardware or exposed from previous insults.
- Highly complex interactions beneath and surrounding burning solid propellant fragments, including burning the several chemical constituents, gaseous heat convection, thermal radiation, droplet impingement, slag buildup, and geometric feedback effects.

The Sandia Fire Model (SFM) code [3] is used to determine the effects of liquid propellant fireballs. Sandia's Plutonium Entrainment and Vaporization after a Coincident Impact (PEVACI) code is a Sandia-developed model that is used to determine fire response for released fuel or bare fuel clads to solid propellant fires.

Situations leading to reentry of the spacecraft into the Earth's atmosphere prior to insertion into the mission's interplanetary trajectory are grouped as follows:

- Suborbital: Reentry due to accidents that occur after achieving 100,000 ft altitude and prior to the attainment of the nominal Earth parking orbit.
- Circular Orbit Decay: Reentry from circular orbital decay. (All orbits eventually become circular in response to atmospheric drag.)
- Powered, Elliptic Delayed, and Elliptic Prompt Reentry: These are reentry modes associated with misdirection of thrust. Powered Reentry results when the misdirection forces the spacecraft into the atmosphere with the attached upper stage is still thrusting. Reentry at velocities higher than orbital reentry is possible, but very unlikely.

The Sandia-developed Loop Analysis Program Software (LAPS) code [4] is used to systematically assess the response of these various re-entry conditions. It drives four detailed phenomena codes. The Trajectory Analysis and Optimization Software (TAOS) code [5] determines the trajectory through space and the atmosphere. The Heating Analysis Done Interactively (HANDI) program determines the boundary layer heating of the re-entry object [6]. The Charring Materials Analysis (CMA) code [7] is used to determine the surface thermochemistry evaluation of the boundary layer at the wall to provide the connective juncture between the heating and thermal response codes. The net result of this analysis is a thermal and ablative history of the reentry object, a determination of whether it hits the ground intact or breaks up, and determination of the break-up altitude if it does break up.

As noted above, the simulation of the RPS response to the accident environments is done by LASEP. The RPS response is dependent on the time after liftoff and nature of the accident. These affect the possible impact surfaces and velocities, as well as the local environment, such as blast overpressure, fragment impacts, and fire environments. 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 quantity, location, and particle size distribution. As noted previously, LASEP draws upon the look-up tables provided by the impact, fire, and reentry codes to determine the amount released for each accident sequence. It then builds a probability distribution for the possible release amounts.

The source terms calculated from the accident modeling are composed of a wide range of particle sizes. Larger 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. Smaller particles remain airborne for a longer time and contribute mostly to health effects. 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.

The transport of the released particulate PuO2 fuel is determined by the Sandia-developed Transport Of Radioactive Materials (STORM) code. STORM calls the Initial Atmospheric Transport code to determine the initial rise of the fireball and particles, and then uses the National Oceanic and Atmospheric Administration's Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model [8] to determine the subsequent transport and deposition.

Following the transport of the released material, the radiological consequences 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. Multiple exposure pathways are considered in these types of analysis. The dominant risk pathway is direct inhalation of the released cloud, which could occur over a short duration (minutes to hours). Other exposure pathways result from deposition onto the ground. These pathways include groundshine, ingestion, and additional inhalation from resuspension.

STORM calls the Fortran DOSE (FDOSE) code to determine the health effects from the plume passage. COMIDA2 [9] is used to estimate the health effects from ingestion of food products. Both use biological effects models based on methods prescribed by the National Council on Radiation Protection and Measurements and the International Commission on Radiological Protection (ICRP) [10,11,12]. 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) [13].

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, and the DOE in evaluating the need for land clean up following radioactive contamination. The resuspension contribution to dose assumes that no mitigation measures are taken.

STORM randomly selects a source term from the LASEP runs and combines it with a randomly-selected meteorological date and time of day for the accident to produce one "observation" of transport and deposition. Numerous combinations are simulated to build up a probability distribution for the various consequence types and mean values. The risk (the product of total probability times the health effects resulting from a release, summed over all conditions leading to a release) is determined for each mission phase and the overall mission.

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