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A Nuclear Source Term Analysis for Spacecraft Power Systems

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Abstract

All US space missions involving on board nuclear material must be approved by the Office of the President. To be approved the mission and the hardware systems must undergo evaluations of the associated nuclear health and safety risk. One part of those evaluations is the characterization of the source terms, i.e., the estimate of the amount, physical form, and location of nuclear material, which might be released into the environment in the event of credible accidents. This paper presents a brief overview of the source term analysis by the Interagency Nuclear Safety Review Panel for the NASA Cassini Space Mission launched in October 1997. Included is a description of the Energy Interaction Model, an innovative approach to the analysis of potential releases from high velocity impacts resulting from launch aborts and reentries.

1 Introduction

All United States space missions involving launch vehicles carrying significant amounts of nuclear material are required by US law to obtain approval from the Office of the President [1]. Pursuant to that approval, the mission and the hardware systems must undergo evaluations of the associated nuclear health and safety risks. These evaluations are documented in a Safety Analysis Report, prepared by the organization proposing the mission, and a Safety Evaluation Report, prepared by an independent Interagency Nuclear Safety Review Panel (INSRP). The process by which INSRP evaluates the nuclear safety for the mission has been described in some detail in a number of papers [e.g., 2 and 3] and summarized in a previous paper [4]. Briefly, the process consists of

- Characterizing the physical description and probabilities of the launch abort and reentry environments that might result in the release of nuclear materials into the environment,

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- Assessing the responses of the nuclear material and its containment to the imposed environments, specifically determining the probability that the material might be released to the unrestricted environment, and, if so, the amount, form, and location of the projected releases or "source terms,"
- Determining how these source terms might be dispersed in the biosphere,
- Estimating any resultant health, safety, and environmental effects associated with the releases, and
- Reporting for the decision maker(s) the probabilities of release, the magnitudes of the potential consequences, and the related uncertainties.

The incorporation of quantitative risk assessment techniques enables explicit consideration of probabilities and uncertainties, allowing the analyst to communicate both quantitative results and a measure of his confidence in those results.

Several recent space missions have had their onboard electrical power provided by General Purpose Heat Sources (GPHSs) as the thermal energy source for the Radioisotopic Thermoelectric Generators (RTGs). In addition, missions have included Light Weight Radioisotopic Heater Units to maintain the temperatures of critical components at tolerable levels. In both these systems, the thermal energy is derived from the radioactive decay of plutonium. The nuclear material is encapsulated in containment systems designed to resist the rigors of the operational and accidental environments projected for the mission, including overpressures and shrapnel from propellant explosions, high velocity impacts on various surfaces, and thermal environments from reentry and propellant fires.

This paper deals primarily with the assessment of source terms for a recent mission—the Cassini Mission to explore Saturn and its moons.

2 Previous Approach for Estimating Source Terms

The source terms are characterized in engineering analyses based upon calculational models of the systems and processes representing the threats presented to the containment systems. For the missions using GPHS-RTGs, the components which might be exposed to the potentially damaging environments are fueled clads, modules (clads encased in protective graphite), or complete units. (These components are described in the INSRP Power Systems SubPanel Cassini Report [5].) In past evaluations by both project and review teams, the calculational models have utilized Monte Carlo analyses because much of the input information describing the threat scenarios and the systems responses has been subject to substantial uncertainty and variability. These analyses incorporate test data from several series of experiments designed to demonstrate the responses of the containment systems to the threatening environments.

The test data and the analysis models for impact events have presented damage to the nuclear material and containment in terms of a single parameter, distortion. Distortion is defined in terms of the two-dimensional ellipticity of the cladding encapsulating the radioisotopic fuel, i.e., the deformation of the cladding from its original circular cross-section. This representation of the damage mechanism introduces a number of uncertainties. First, while the fueled clad may be impacted from virtually any direction, the definition of distortion applies strictly only for impacts normal to the cylindrical axis. Second, the test data shows different failure potentials for cladding failure for equal distortions, and total distortion from sequential impacts does not indicate the same failure potential as similar distortions from a single impact. Also, distortion, as defined, is related to the difference between two similar measurements so that distortion is subject to substantial measurement error. These issues have been of concern in previous analyses and have contributed significantly to uncertainty in the results.

3 Energy Interaction Model

However, for the Cassini Mission, the Power Systems SubPanel, one of the analysis teams supporting the INSRP review, developed an innovative approach and methodology, referred to as the Energy Interaction Model. This model relates projections of failure of the containment systems, release amounts, and respirable fractions of the release to the existing database without requiring the use of Monte Carlo techniques. Further, the methodology is based on straightforward utilization of fundamental experimental variables such as impact energy and velocity. The Energy Interaction Model should be regarded still as a somewhat immature formulation, having been utilized in only one analysis, but it has been published recently [6] in an attempt to encourage its continued development and utilization in other situations.

Briefly, the Energy Interaction Model deals with a clad, module, or complete GPHS-RTG impacting on some surface or being impacted by debris in an explosion. The model is based on the concept that the clad failure probability is proportional to the fraction of the impact kinetic energy imparted to the nuclear component as deformation energy. Thus, the probability that radioactive material will be released and the amount and physical form of the released material are related to the velocity of the impact and the masses and stiffness of the impacting objects. To date the model has shown good agreement with experimental results from the GPHS Safety Test Program, and its use substantially facilitated the INSRP evaluation of the nuclear risk associated with the Cassini Mission. The use of the model proved particularly advantageous in supporting the uncertainty analysis, since the model requires substantially less computation than previous approaches. Further work is required, however, to develop and demonstrate the model as a reliable analysis tool for broader applications.

3 Results for Cassini

In their independent evaluation of potential source terms for the Cassini Mission, the PSSP identified several differences in the modeling phenomenology and in the utilization of the available test data which might influence the overall nuclear risk associated with the mission. These issues and their potential implications are described in detail in the PSSP Cassini Report [5]. In summary, the PSSP estimated releases from accidents during the launch phase to be somewhat smaller but somewhat more probable than projected in the Cassini Final Safety Analysis Report (FSAR) [7]. For post-reentry Earth impacts following out-of-orbit and inadvertent Earth gravity assist flyby reentries, the projected PSSP source terms were substantially smaller than those in the FSAR.

For the Cassini Mission, the PSSP recommended that four accident cases be considered as potential significant contributors to overall mission risk. This recommendation was based on initiating accident probabilities (determined by the INSRP Launch Abort SubPanel), conditional probabilities of release given the environments resulting from the accident scenarios, and the projected amounts of material released. The four cases are:

1. The Total Boost Vehicle Destruct,
2. The Nominal Orbital Reentry ,
3. The Intermediate/Steep Angle Earth Gravity Assist (EGA) Reentry, and
4. The Shallow Angle EGA Reentry.

On the basis of the analyses and evaluations documented the FSAR and the INSRP Safety Evaluation Report for Cassini [8], the Office of the President approved the mission and Cassini was launched in October 1997.

4 Conclusions

Evaluations of the nuclear safety associated with space missions involving nuclear material on board the launch are indispensable in the launch approval process. These analyses also provide valuable guidance during development phases of missions and equipment to improve the overall safety of the missions. Incorporating the concepts of quantitative risk assessment allows descriptions of both the projections of risk and the analysts' confidence in those projections. This enhances both the safety of the mission and the ability to communicate effectively the results of safety assessments to those charged with review and oversight responsibility.

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References

1. Presidential Directive/National Security Council Memorandum-25, "Scientific or Technological Experiments with Possible Large Scale Adverse Environmental Effects and Launch of Nuclear Systems into Space," The White House, December 14, 1977.

2. Sholtis, Joseph A., Jr., John P. Joyce, and Robert C. Nelson, "US Flight Safety Review/Approval Process for Nuclear-Powered Space Missions," Proceedings of the Seventh Symposium on Space Nuclear Power Systems, CONF-900109, pp. 569-571, Albuquerque, New Mexico, January 7-10, 1990.

3. Frank, Michael V., David Pyatt, and John W. Lyver, III, "An Overview of the Space Nuclear Risk Assessment and Review Process of the Interagency Nuclear Safety Review Panel," International Conference on Probabilistic Safety Assessment and Management, Crete, Greece, June 24-28, 1996.

4. McCulloch, W. H., "Nuclear Source Term Evaluation for Launch Accident Environments," International Conference on Probabilistic Safety Assessment and Management, Crete, Greece, June 24-28, 1996.

5. "Power Systems SubPanel (PSSP) Report to the Interagency Nuclear Safety Review Panel (INSRP) for the National Aeronautics and Space Administration Cassini Space Mission," August 1997.

6. Coleman, James R., Joseph A. Sholtis, Jr., and W. H. McCulloch, "The Energy Interaction Model: A Promising New Methodology for Projecting GPHS_RTG Cladding Failures, Release Amounts, & Respirable Release Fractions for Postulated Pre-Launch, Launch, and Post-Reentry Earth Impact Accidents," Space Technology and Applications International Forum, 15th Symposium on Space Nuclear Power and Propulsion, Albuquerque, New Mexico, January 25-29, 1998.

7. "GPHS-RTGs in Support of the Cassini Mission, Final Safety Analysis Report (FSAR)," Lockheed Martin Missiles & Space, Philadelphia, Pennsylvania, prepared for U.S. Department of Energy under Contract No. DE-AC03-91SF18852, November 1996.

8. Interagency Nuclear Safety Review Panel, Safety Evaluation Report for the National Aeronautics and Space Administration Cassini Mission, July 1997.