SAN096-0983C

CONF-960647--9

Nuclear Source Term Evaluation for Launch Accident Environments

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1 Introduction

When United States space missions involve launching vehicles carrying significant quantities of nuclear material, US law requires that prior to launch the mission be approved by the Office of the President. This approval is to be based on an evaluation of the nuclear safety risks associated with the mission and the projected benefits [1]. To assist in the technical evaluation of risks for each mission, an Interagency Nuclear Safety Review Panel (INSRP) is instituted to provide an independent assessment of the mission risks. INSRP's assessment begins with a review of the safety analysis for the mission completed by the organization proposing the mission and documented in a Safety Analysis Report (SAR). In addition, INSRP may execute other analyses it deems necessary. Results are documented and passed to the decision maker in a Safety Evaluation Report (SER). The INSRP review and evaluation process has been described in some detail in a number of papers [e.g., 2 and 3].

INSRP is assisted in its evaluation by a team of technical experts organized in five subpanels.

> The Launch Abort SubPanel (LASP) considers the potential launch scenarios which might result in the nuclear material's being released into the biosphere. This consideration includes the characterization of the hazardous environments to which the nuclear material might be submitted.

> The Reentry SubPanel (RESP) considers the potential reentry scenarios which might result in the nuclear material's being released into the biosphere. This consideration includes the characterization of the hazardous environments to which the nuclear material might be submitted.

* This work was performed at Sandia National Laboratories and supported by the U.S. Air Force under Sandia Proposal No. 65930218.

The Power Systems SubPanel (PSSP) determines, with a degree of rigor deemed appropriate, the response of the nuclear material to those environments characterized by LASP and RESP. Specifically, PSSP defines the nuclear source term, i.e., the amount of nuclear material which might be released as a result of exposure to the hazardous environments and the physical description of those releases (the particle size distribution and the location).

The Meteorology Subpanel (MET) determines how the source term characterized by PSSP might be dispersed in the biosphere.

The Biomedical and Environmental Effects Subpanel (BEES) determines what health, safety, and environmental effects might be caused by the dispersed nuclear material.

In recent years, INSRP analyses have begun to incorporate the techniques of quantitative risk assessment to address the safety issues associated with launches involving nuclear material. This enables the explicit consideration of uncertainties and probabilities in the analyses. In addition, this provides an effective means by which the analyst can communicate to the decision maker both the results of his analyses and an evaluation of his confidence in those results.

This paper deals primarily with the Power Systems SubPanel's assessment--describing the approach for characterizing source terms that might result from the hazardous environments which might be encountered in space missions.

2 Source Term Evaluation

The hazardous environments to which the nuclear material and its containment might be submitted are determined by LASP and RESP and can be conveniently grouped into four categories, thermal (burning solid or liquid propellants and reentry heating), fragment (flying debris generated in energetic, i.e., explosive, events), blast (excessive pressures and shocks associated with energetic events), and ground impact. The safety analyses documented for the mission in the SAR and subsequently evaluated and complemented by PSSP determine the response of the nuclear material to the environments. These analyses utilize data generated in tests in which test articles, simulating various expected physical configurations for the nuclear material, are submitted to representative environments. Generally, the analyses take the form of computer representations of the nuclear material and its containment as it responds to the imposed environments. Most often the analysis demonstrates that the release of nuclear material is not expected. (Otherwise the mission would be neither proposed nor approved.) If, however, the result suggests that some nuclear material might be released to the biosphere, the analysis produces estimates of the amount released, its particle size distribution, and its location. This determination typically includes the impact of immediate post-release environments such as vaporization and coagulation of the released material in propellant fires. The final result is a collection characterized source terms that might be available for distribution in the biosphere as results of the hazardous environments imposed on the nuclear material. In addition, the analyses provide estimates of the probabilities for each of the releases.

These characterized source terms, then, are used in subsequent analyses to estimate their dispersion and potential biomedical and environmental impacts.

3 Recent Results

3.1 Mission Description

Most recently this process has been applied to the Ulysses space mission. The mission objective is the investigation of the properties of the sun (corona, solar wind, heliospheric magnetic field, cosmic rays solar radio bursts and plasma waves, and interplanetary neutral gas and dust) as a function of solar latitude. The spacecraft was launched into earth orbit on board the Space Shuttle from the Kennedy Space Center in October 1990. From earth orbit, it was propelled toward Jupiter by two upper stage boosters. A gravity assist maneuver around Jupiter then deflected the Ulysses spacecraft out of the ecliptic plane into a polar orbit about the sun, allowing the first solar observations from outside the plane of the solar system. More extensive descriptions of the Ulysses Mission are available in the Final Safety Analysis Report (FSAR) [4] and the SER [5].

3.2 System Description

The onboard electrical power for the spacecraft has been provided by a General Purpose Heat Source (GPHS) as the thermal energy source for the Radioisotopic Thermoelectric Generator (RTG). The GPHS-RTG is a nuclear power system containing approximately eleven kilograms of plutonia fuel formed into seventy-two ceramic pellets, each encased in an iridium clad. The clads are contained within graphite impact shells, which, in turn, are contained in GPHS modules, also graphite, providing addition protection. Thus, several containment barriers must be compromised to permit any release of the radioactive material to the biosphere. The GPHS-RTG is shown in Figure 1 of Reference 3 and complete descriptions are given in the FSAR and SER cited above.

3.3 Analysis Description

For the Ulysses Mission, a systems analysis code has been developed by General Electric (now Lockheed Martin) AstroSpace Division. The code, referred to as Launch Accident Scenario Evaluation Program Version 3 (LASEP3), was derived from previous versions used for the Galileo Mission. A detailed description of

LASEP3 and its use in estimating the nuclear risks associated with the Ulysses Mission is provided in the Ulysses Final Safety Analysis Report [4]. The code models the sequences of events to which the nuclear system might be subjected. In general, for accidents during launch and ascent phases, the system could first be threatened by explosive environments, including both blast effects and impacts from debris fragments. If this initial threat occurs significantly above the ground, a secondary threat would occur when the nuclear system (possibly damaged by the first threat) impacts the ground, either in water or on surfaces of varying hardness. Also, at various times during the accidents, the system could be exposed to thermal environments due to the burning of propellants. Tests have indicated that these thermal environments are insufficient by themselves to cause any release. However, should they occur after the mechanical threats have produced releases, the physical characteristics of the released material could be modified. Reentry events, occurring later in the mission, could submit the nuclear system to reentry heating and ground impacts.

A fundamental aspect of LASEP3 is the utilization of empirical data to characterize the environments and systems responses. During the development of the GPHS and its utilization on previous missions, a number of tests have been completed to characterize the system's response to postulated accident environments. These tests are reviewed in some detail in the PSSP Report for Ulysses [6]. The use of the data from these tests in the evaluation of nuclear risks for the Ulysses Mission is complicated by at least two factors: First, the numbers of tests have been limited so that the data base is quite limited, and, second, many of the tests were specific to launch configurations and orientations different from Ulysses. Analytical evaluations of the data were undertaken to ensure conservative results from using the data in the Ulysses analyses.

Because of variabilities in the underlying test data and other uncertainties in the characterization of the imposed accident environments and the system response, LASEP3 incorporates Monte Carlo techniques in the response calculations. This requires the accident response calculations to be repeated many times with the various model parameters selected at random from a range of possible alternatives to produce a range of possible outcomes for each accident sequence. The results are best presented statistically, i.e., in terms of frequencies of occurrence, probabilities, averages, expected values, etc. The results of the analyses for the mission safety assessment are documented in detail in the Ulysses FSAR [4].

In their independent evaluation of risk for the Ulysses Mission, the PSSP also used LASEP3, incorporating modifications to reflect some differences in phenomenology and input data thought to be potentially significant by the PSSP. Also, some sensitivity analyses were done to evaluate the effects of varying some of the uncertain analysis parameters. The changes to the code, the reasons for the changes, and the implications of the results are presented in the PSSP Report for Ulysses [6]. In comparison to the FSAR analysis, the INSRP results indicated somewhat increased probabilities for release and somewhat larger releases.

For Ulysses, evaluations by LASP and RESP determined that sixteen accident scenarios, fifteen launch accidents and inadvertent reentry, should be considered as potential means by which nuclear material might be released. Based on considerations of the probabilities of release, the sizes of the projected releases, and the possibility that post-release modification might increase the health impacts of the release, four scenarios were determined in the PSSP analysis to be the most probable primary contributors to overall mission risk:

a. Solid Rocket Booster (SRB) random failure for Mission Elapsed Time (MET) = 1-10 sec

b. SRB random failure for MET = 11-20 sec

c. SRB random failure for MET = 105-120 sec

d. Inadvertent reentry

Five other scenarios were identified as probably less important but needing to be carried through the evaluation of their health effects to ascertain their contribution to overall risk:

e. On-pad external tank explosion before ignition

f. Vehicle tipover and tower impact for MET = 0-2 sec

g. Near-pad external tank explosion with pad and trench explosion for MET = 0-10 sec

h. SRB random failure for MET = 21-57 sec

i. SRB random failure for MET = 58-104 sec.

The safety analysis, completed by the Ulysses Project team and documented in the FSAR[4], and the safety evaluation, completed by INSRP and documented in the SER[5], were provided to the Office of the President. These documents present independent, quantified estimates of the nuclear risk for the mission and describe the uncertainties associated with the use and interpretation of available test information and the assumptions made in the analyses. These assessments, along with descriptions of the potential benefits of the mission, provided the basis for the launch approval decision. After due consideration, the mission was approved, and the Ulysses spacecraft was launched in October 1990.

4 Conclusions

Safety analyses, incorporating the techniques and concepts of quantitative risk assessment, are being used to evaluate the health, safety, and environmental risks associated with space missions involving nuclear material. During design of the missions and the hardware systems, these analyses identify the dominant contributors to risk so that safety can be designed in rather than imposed on the design. Further, by including explicit consideration of uncertainties and probabilities, the results of the analyses may be presented in terms which describe not only the results but also the analysts' confidence in the results. This approach enhances both the safety of the mission and the ability to demonstrate that safety to those with review and oversight responsibility.

References

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