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Use of nuclear power sources in outer space

Workshop on the Use of Nuclear Power Sources in Outer Space: the United States approach to risk assessment and its role in implementing an effective safety programme for nuclear power source applications in outer space

Paper submitted by the United States of America**

Summary

The United States of America subjects its planned nuclear power source applications in outer space to a safety analysis and risk assessment process consistent with the relevant guidance recommended in the Safety Framework for Nuclear Power Source Applications in Outer Space, jointly published by the Scientific and Technical Subcommittee and the International Atomic Energy Agency in 2009. The United States safety analysis for nuclear power sources begins with an understanding of the launch vehicle, spacecraft, mission design and launch rules. These inputs are used to characterize a range of postulated accident scenarios to create a launch accident environment and the probabilities of such an accident occurring. Safety testing of nuclear power source components and continuum mechanics modelling are used to understand how the nuclear power source and nuclear fuel will respond in a variety of accident scenarios. The accident environments, accident probabilities, safety testing results and computer simulations are combined in a safety analysis to characterize the risk of the mission. The safety analysis is then reviewed by a group of national experts who are independent of the mission. The comments and results of

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[*] A/AC.105/C.1/L.306.

[**] The present document is based on conference room paper A/AC.105/C.1/2011/CRP.5.

the review are integrated into a second iteration of the safety analysis, which is again subject to independent review. This nuclear safety analysis and review process encourages constant improvement in the mission's risk assessment and facilitates the identification of potential safety enhancements in the mission's design and future NPS designs.

I. Introduction

1. The United States Department of Energy provides space nuclear power 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 lightweight, have long lives, and are highly reliable. They are enabling for space missions where the use of solar energy is impractical. At the time of this writing, the United States space programme has two types of RPSs: the radioisotope thermoelectric generator (RTG) and the advanced stirling radioisotope generator (ASRG). All previous United States RPS missions have used RTGs. The ASRG is still under development.

2. The planets and moons and their surfaces are often distant and shadowed from the Sun or have harsh environments. Use of RPSs is currently the only means available to carry out these explorations. Radioisotopes, however, represent a hazard. From the earliest days when a SNAP-3 was displayed on President Eisenhower's desk in January 1959, safety has been and continues to be a central consideration of the United States space nuclear power programme.[1] In carrying out those explorations over the past 50 years, the United States has harnessed that power, evaluated the potential hazards, controlled the risks and successfully and safely extended its knowledge of the solar system, consistent with the Safety Framework for Nuclear Power Source Applications in Outer Space (A/AC.105/934). This paper will discuss how the Department of Energy performs a nuclear launch safety analysis.

II. Nuclear safety aspects

3. The RPSs and RHUs use plutonium dioxide PuO_2 fuel, in which heat is produced primarily by the alpha decay of plutonium-238 (Pu-238). The radioactive nature of PuO_2 poses potential hazards during the launch and operation of spacecraft using such systems in case of a mission accident. For this reason, the Department of Energy and NASA treat safety as an inherent feature of design, manufacturing and application of nuclear power systems in outer space, consistent with section 5.2 of the Safety Framework. Design features reflect safety-related considerations, including a radioisotope (Pu-238) that is easily shielded; a radioisotope fuel form (an oxide that is rugged, chemically stable, insoluble and has a high melting temperature); and chemically stable barriers (ductile iridium cladding and temperature-resistant carbon-carbon composites) to minimize the potential for risks to the public. Figure 1[2] shows the many layers of protection surrounding the fuel. In United States RPSs, a PuO_2 fuel pellet encapsulated in iridium is called a fuelled clad (FC). Two FCs are placed in a row inside a graphite impact shell made of carbon-carbon composite called fine weave pierced fabric (FWPF). The graphite

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[1] United States of America, Department of Energy, *Atomic Power in Space: A History* (Washington, D.C., 1987), p. 17.

[2] See figure 1 in A/AC.105/C.1/2011/CRP.5, available from www.unoosa.org/oosa/COPUOS/stsc/wgnps/index.html.

impact shell protects the FCs during impacts. The graphite impact shell is wrapped in a thermally resistant carbon material to protect the fuel from the heat of re-entry and other thermal insults. Two thermally insulated graphite impact shells are placed inside a general-purpose heat source (GPHS) module made of FWPF. The GPHS module is an aeroshell that prevents a release of fuel during re-entry and also protects the fuel in impact scenarios. Several GPHS modules may be stacked together within an RPS. All of these inherent safety features are complemented with safety testing to evaluate the response of the systems to potential accident scenarios.

4. The safety of nuclear power systems in outer space cannot be separated from the integrated safety features of the launch vehicle, upper stage, spacecraft, flight termination system and mission profile. NASA has an extensive programme to ensure the reliability of the launch vehicles and spacecraft. Additional important elements of this integrated approach to safety are supporting range safety organization and related contingency planning activities prior to and during launch.

5. The Department of Energy conducts probabilistic risk assessments to determine the potential responses of that hardware in the event of accidents and characterize any potential fuel releases from the RPS. Atmospheric transport and dispersion modelling of postulated fuel releases is used to estimate the potential for human exposure to the fuel and subsequent consequences and risks for a full range of accident scenarios.

III. Nuclear systems safety testing

6. Consistent with section 5.2 (c) of the Safety Framework, the United States nuclear launch risk assessment is supported by over 30 years of safety tests, ranging from component-level testing to full-scale converter sections. The safety testing has focused on the response of an FC to various insults. Typically, the FC response is reported in terms of clad gross distortion, crack dimensions (if any) and PuO_2 particle size distribution. The safety tests include the following:

(a) *Explosive overpressure tests*. Early testing featured shock tube tests, also referred to as explosive overpressure tests. This test series evaluated the effects of a shock wave hitting either a GPHS module or RTG as the result of an explosion. The test module was oriented with one of the side surfaces normal to the direction of shock-wave propagation. Simulant graphite blocks were placed on either side of it to simulate a stack of three modules. The FCs in the test module were filled with a uranium dioxide (UO_2) fuelsimulant;

(b) *Fragment projectile tests*. Fragment tests were conducted to determine the effects of small fragments and projectiles impinging on the GPHS as a result of a launch vehicle explosion. Tests were initially conducted with FWPF plates to determine the velocity attenuation afforded by the GPHS module alone. These were followed by tests of half-module targets using aluminium bullets. In addition, this test series examined the impact of titanium bullets against bare clads;

(c) *Drop tests*. Drop tests from a helicopter were conducted during the development of the GPHS module to determine the terminal velocity of the GPHS module and examine how it would tumble to the ground;

(d) *Solid propellant fire tests*. Two GPHS module components were exposed to an extended duration fire from a large cube of solid propellant. These components, a bare FC and an impact assembly composed of a graphite impact shell with two FCs, were placed on each side of the propellant block and directly exposed to the fire. A UO_2 fuel simulant was used in both components;

(e) *Bare clad impact tests*. Bare clad impact tests were conducted to determine the FC and fuel response to impacts against different media. The test conditions were designed to reflect those that could result from an accident on-pad or during early ascent. Bare clad impact tests were conducted with FCs containing either UO_2 or PuO_2;

(f) *General-purpose heat source impact tests*. The GPHS module impact testing was designed to simulate the atmospheric re-entry and subsequent Earth impact experienced by a GPHS module in the aftermath of an orbital abort. The GPHS modules used in these tests were machined to remove a small layer of graphite from all exterior surfaces. The amount removed was based on twice the expected thickness of material ablated during an accidental re-entry. All FCs within the GPHS modules were filled with PuO_2 fuel. The modules were subject to a heat profile expected during re-entry prior to being impacted at predicted re-entry velocities. The impact angle was varied in these tests. The modules were impacted against steel;

(g) *Large fragment tests*. Large fragment tests involve the impact of a large fragment from a launch vehicle casing against a simulated section of an RTG. A series of rocket sled tests were conducted to simulate a large fragment impact. A simulated heat source was located inside the simulated RTG and heated to pre-launch temperatures at time of impact. The simulated RTG consisted of a stack of eight GPHS modules, with two modules containing UO_2 simulant FCs and six modules made from bulk graphite, which contained solid molybdenum slugs representing FCs;

(h) *Flyer plate tests*. The flyer plate tests involved the flat-on impact of a thin plate-like fragment against an FC filled with UO_2 fuel simulant. The plate was composed of spacecraft-grade aluminium. The FCs used in the first three tests were remnants from one of the shock tube tests. The FCs were heated prior to testing, with the goal that they be at their pre-launch temperature;

(i) *Edge on flyer plate tests*. The edge on flyer plate tests simulated the impact of large plate-like fragments against fully loaded GPHS modules as well as bare FCs. All clads contained a UO_2 fuel simulant. The plates were accelerated to their target in an edge-on impact configuration using a sled track;

(j) *RTG end-on impact tests*. The purpose of the RTG impact tests was to produce test data on FC distortion versus GPHS module stack position in the RTG and the variability in distortion at each position. A secondary objective was to obtain data on fractional fuel-simulant release in the event of a breach in the FC. A simulated RTG with a stack of nine simulated GPHS modules loaded with UO_2 FCs was heated to pre-launch temperatures. For this test a rocket sled propelled the simulated RTG into a concrete target;

(k) *Iridium ductility testing*. The fuel clads used to encapsulate the PuO_2 fuel are made of iridium. To better understand the properties of the cladding material, tensile tests were performed at a variety of temperatures to characterize the response of iridium as a function temperature and strain rate;

(l) *Solid propellant fire characterization tests*. A series of tests were conducted to investigate and characterize the environments underneath and near various types of solid propellants when burning in atmospheric conditions and to measure the response of various isotopic materials or surrogates to those environments.

IV. Nuclear safety analyses

7. In the United States, space nuclear power systems are subject to several types of safety and environmental reviews during their development and application, such as those described in section 5.3 of the Safety Framework. The focus of the reviews is on the Safety Analysis Report and related documents prepared as part of the launch approval processes. Elements of these documents important in review processes include:

(a) *Launch Vehicle Databook*. NASA prepares a Launch Vehicle Databook specific to the mission for use in the Department of Energy's development of analyses and safety analysis reports for the launch approval process. The Databook presents detailed reference design information regarding the mission, launch vehicle, spacecraft, launch complex, mission timeline and trajectory. In addition, the Databook identifies the range of potential accidents and related accident environments (explosion overpressure, fireball, fragment, impact and re-entry) and probabilities;

(b) *Safety Analysis Report*. Each mission involving use of a nuclear power system in outer space is formally analysed by the Department of Energy to assess the nuclear safety and potential mission risks. The safety analyses are documented in safety analysis reports at three iterative levels as part of the launch approval process. The reports include a Preliminary Safety Analysis Report, a Draft Safety Analysis Report and a Final Safety Analysis Report;

(c) *Safety Evaluation Report*. As part of the launch approval process, an external group called the Interagency Nuclear Safety Review Panel reviews the NASA Databook and the Department of Energy’s Safety Analysis Report and performs an independent safety assessment of the mission. The Review Panel documents the review and independent assessment in the Safety Evaluation Report. During this process, NASA and the Department of Energy provide additional information that might be requested by the Review Panel in resolving potential technical issues. Early drafts of the Safety Evaluation Report and comments by the Review Panel may be integrated into later versions of the Safety Analysis Report to strengthen the safety analysis.

V. Safety analysis computational overview

8. The launch safety analysis is performed using a suite of computer codes to model various stages and phenomena of the accident sequence, radioisotope release

("source term"), radioisotope transport and consequences.[3] NASA develops the Databook for the launch vehicle and accident probabilities and environments. This serves as input to the calculations. Phenomenological codes determine the response of the RPS hardware to blast, impact, fires and re-entry. The codes produce a set of look-up tables, which are used as input to determine the source term for a given accident scenario. Typically the safety features of the RPS prevent a release of material. Should a release occur, the source term is transferred to a consequence suite of codes to determine how far any released material might be transported and what health effects or environmental effects might result. The final product of the risk assessment is a distribution of probability of accident, probability of release, possible consequences, mean values and an estimate of the risk.

A. Blast and impact

9. The potential accident scenarios that can arise are more extensive than can be tested. Therefore, the safety analysis relies on numerical modelling to augment the existing safety test database. The potentially damaging environments that must be modelled are the blast from the launch destruct event, the impact of the RPS hardware on the ground and the impact of debris and solid propellant fragments onto the RPS hardware. Continuum mechanics codes are used to explicitly model the accident environments defined within the Databook. The programmes include non-linear constitutive models and accurately analyse large deformations that may lead to geometric non-linearities. These numerical simulations of mechanical damage due to blast and impact conditions provide an estimate of the damage to the power source (and its components), particularly the damage to the FCs within the power source. Estimates of the FC exposure, breach and deformation are determined from the numerical simulations. The assessment is performed on a clad-by-clad basis for each accident case, with the results being provided to a release model embedded in the source term analysis code. The release model determines the quantity and particle size distribution of the PuO_2 of any released material based on the clad damage information provided from the numerical simulations.

10. These numerical simulations examine mechanical loading conditions such as blast, ground impacts, impacts from spacecraft fragments and, for some missions, debris from an intact spacecraft. The mechanical damage in most cases is due to a complex chain of events. The numerical simulations decouple the complex chain of events and feed the source term analysis code information about individual events that can then be used to account for the progressive chain of events. The source term analysis code provides details on FC exposure, deformation and breach within matrices of ground impact events, fragment impacts, spacecraft debris impact and blast. These individual results can then be combined for an estimate of the resulting release due to mechanical loading.

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[3] For the computation flow for the launch approval safety analysis, see figure 2 in A/AC.105/C.1/2011/CRP.5, available from www.unoosa.org/oosa/COPUOS/stsc/wgnps/index.html.

B. Fire and thermal analysis

11. The launch accident environment can have liquid propellant fires and solid propellant fires. The United States has built several layers of protection into its hardware to help prevent a release of RPS fuel in the event of a launch area accident. For instance, liquid propellant fires are not expected to burn hot enough to melt the iridium clad containing the RPS fuel. Several codes are used to model the liquid propellant fires, solid propellant fires, thermal-mechanical impacts and vaporization environments effects on the RPS hardware and fuel.

12. Inputs to the code characterize the solid propellant ground fire, the buoyant cloud and the distribution of any released PuO_2 mass into bins of various particle sizes from a coincident or near-coincident impact. From this starting point, the code suite predicts the composition and particle-size distribution of aerosols containing PuO_2 in the buoyant cloud. In effect, the code transforms the source term (mass by size bin) of PuO_2 particles released by mechanical insult into one that includes the effects of vaporization, condensation and particle agglomeration.

C. Re-entry analysis

13. RPS-enabled spacecraft may be subject to inadvertent re-entry scenarios. The GPHS module is designed to survive re-entry conditions, and a suite of codes are used to evaluate and confirm the design of the module. Several codes are used together to provide an integrated solution to the sequential physics problems of motion, heating, thermal response, chemistry and inviscid flowfields that may be encountered during re-entry. Evaluation of the parametric re-entry space requires performing thousands of solutions for the re-entry flight dynamics, aerodynamic surface heating, and the ablation and thermal response of the GPHS module. This analysis is performed for each individual mission since each mission has unique orbital characteristics. The thermal, physical and velocity results of this analysis are passed onto the source term analysis.

D. Source term analysis

14. The source term is the amount and form of the RPS fuel, if any, which may be released. Since the hardware is designed to contain the fuel, the source term may have a null value. The source term for the launch safety analysis is generated using a Monte Carlo code that generates millions of potential outcomes for a single mission analysis. It attempts to characterize all threatening elements of the launch accident environment.

15. Each simulation starts with a determination of where the accident occurs by randomly sampling a probability distribution function from the launch vehicle. The source term code then steps through all the insults that would occur in that accident: including the initial blast, in-air fragment impacts, ground impact of the RPS, impact of solid propellant or other large fragments on the RPS, rain of debris, and liquid and solid propellant fires. Various distributions are sampled throughout the simulation, resulting in millions of unique solutions.

16. The final result from source term analysis is a distribution of potential PuO_2 fuel releases for the consequence analysis to sample. Details on the final releases include mass released, particle-size distribution, release location and fire environment parameters. The results also define the probability of a release given an accident, which, combined with the accident probability, yields the total probability for the scenario.

E. Consequence analysis

17. The consequence suite is a set of codes that calculates the atmospheric transport of released RPS fuel and the subsequent consequences in terms of health effects, doses and land contamination. Health effects are characterized as the number of latent cancer fatalities over the subsequent 50 years. The linear no-threshold dose model is used along with an option for a *de minimis* (threshold) value. The code suite is run stochastically for numerous scenarios, called “observations”. The specific source term, weather conditions and time of launch are randomly selected for each observation. Importance sampling is used to ensure that combinations of variables that result in low-probability, high-consequence events are considered in the analysis.

18. Atmospheric transport is accomplished using a Lagrangian-trajectory, Gaussian puff model with a capability to handle multiple particle-size source terms. The transport and diffusion of material in a cloud puff are governed by meteorological conditions that can vary in space and time. These conditions include wind components at grid points, stability class, height of mixing layer and roughness of the surface below. Each source cloud, defined with characteristics such as particle size, initial cloud dimensions and initial coordinates, is tracked in time steps through a four-dimensional wind field (three spatial dimensions plus time).

19. When puff interaction with the ground occurs, the calculation of air and ground concentrations at defined grid points is initiated. Following the transport and concentration calculation, the potential doses and health effects to exposed population are evaluated. A separate module computes potential doses based on dose conversion factors for the different dose pathways. Since the source terms may involve various particle sizes and the resolution may change from one application to another, this built-in module does not restrict the dose conversion factor values to a fixed list of particle sizes. The dose and health effect calculations also encompass other data related to potentially contaminated areas, such as population density, land usage, food production and food consumption.

20. The results of the consequence suite are combined into tables of mean consequences, various percentile consequences and risk (mean consequence times release probability). Complementary cumulative distribution function graphs are also created. These graphs show the probability that a particular level of consequence or greater might occur. These results provide the technical basis for the decision maker to assess the risk introduced conducting an RPS application in outer space.

VI. Conclusion

21. RPSs have made it possible to explore the depths of the solar system from the Sun to Pluto, to orbit the outer planets and observe their moons, each stranger than the next, and to travel to the outer reaches of the solar system and beyond. While RPS applications often involve significant amounts of radioisotope materials, the United States has established an extensive safety programme supported by a rigorous risk assessment process to assess potential mission risks and ensure that the missions are conducted safely. Consistent with the Safety Framework, the United States application of risk assessment: serves an essential function in the design and development process for RPSs and all development phases of RPS applications; supports the justification process for RPS applications; and provides the technical foundation for the launch nuclear safety authorization process.