43

Safety Aspects of Thermoelectrics in Space

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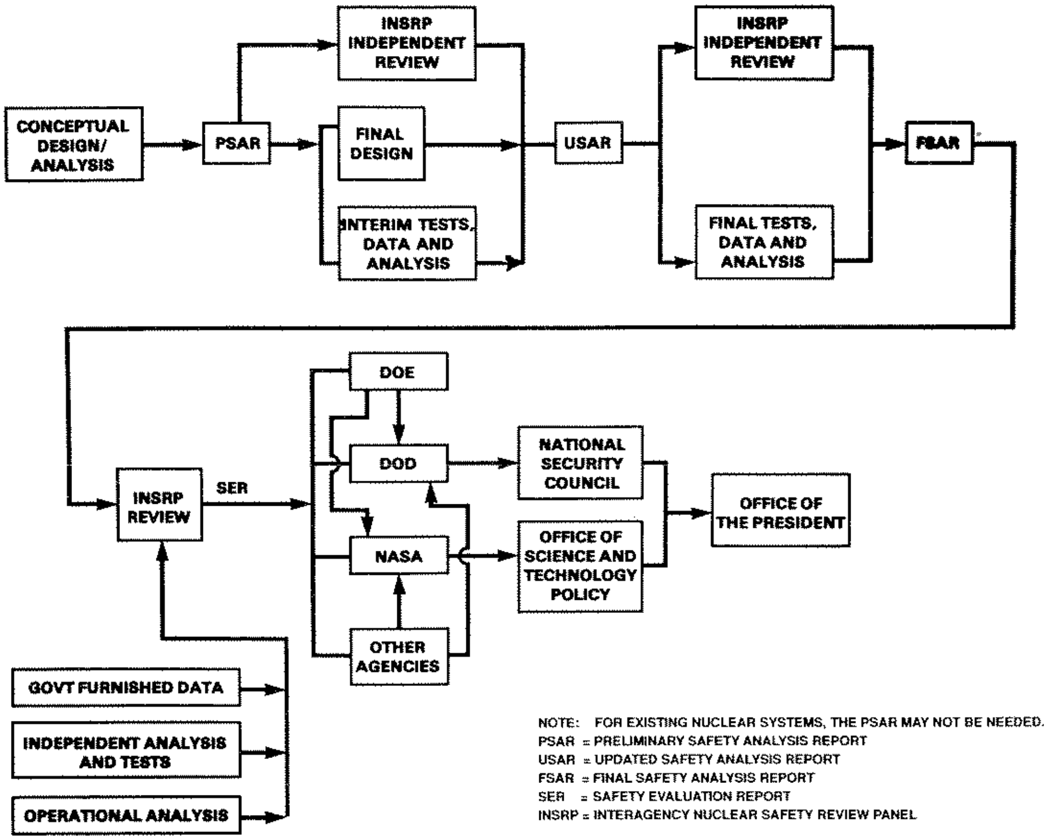
43.1 Introduction

The purpose of this chapter is to describe the safety review and approval process used in the U.S. for the launch of any nuclear-powered spacecraft. This process can be traced back to 1961 with the first launch of a nuclear power source (NPS) by the U.S. From the beginning there has been an emphasis on the safe use of NPS, including a requirement to obtain launch approval from the Office of the President because of the international policy implications of such launches.[1–5] The latest codification of the launch approval process is Presidential Directive NSC/25, dated December 14, 1977, which covers any federal undertaking (non-nuclear as well as nuclear) that may have "major and protracted effects on the physical or biological environment". With regard to space nuclear systems, the Presidential Directive states:[6]

> A separate procedure will be followed for launching space nuclear systems. An environmental impact statement or a nuclear safety evaluation report, as appropriate, will be prepared. In addition, the President's approval is required for launches of spacecraft utilizing radioactive sources containing more than 20 curies of material in Radiotoxicity Groups I and II and for more than 200 curies of material in Radiotoxicity Groups III and IV (as given in Table I of the NASC report of June 16, 1970 on "Nuclear Safety Review and Approval Procedures"). An ad hoc Interagency Nuclear Safety Review Panel consisting of members from the Department of Defense, Department of Energy, and National Aeronautics and Space Administration will evaluate the risks associated with the mission and prepare a Nuclear Safety Evaluation Report. The Nuclear Regulatory Commission should be requested to participate as an observer when appropriate. The head of the sponsoring agency will request the President's approval for the flight through the Office of Science and Technology Policy. The Director is authorized to render approval for such launchings, unless he considers it advisable to forward the matter to the President for decision.



NOTE: FOR EXISTING NUCLEAR SYSTEMS, THE PSAR MAY NOT BE NEEDED.
PSAR = PRELIMINARY SAFETY ANALYSIS REPORT
USAR = UPDATED SAFETY ANALYSIS REPORT
FSAR = FINAL SAFETY ANALYSIS REPORT
SER = SAFETY EVALUATION REPORT
INSRP = INTERAGENCY NUCLEAR SAFETY REVIEW PANEL

FIGURE 1 Review process for the safety of space nuclear power systems.

Figure 1 illustrates the review process for the safety of space nuclear systems.

43.2 Safety Review Process

As shown in Figure 2 for the general-purpose heat source radioisotope thermoelectric generator (GPHS-RTG), safety is one of the two principal design requirements on an NPS (the other being performance). The primary safety objective is to minimize the potential interaction of the radioactive materials with earth's population and environment.[1] A formal review process has been established for the assessment of the safety of an NPS, as shown diagrammatically in Figure 1.

The safety review process consists of three sequential and required documents:

1. An Environmental Impact Statement (EIS) prepared very early in the project at the time of the initial decision to undertake the mission. Figure 3 illustrates the U.S. federal EIS process.
2. A Safety Analysis Report (SAR) prepared during the development of the NPS program.
3. A Safety Evaluation Report (SER) prepared by an independent interagency panel known as the Interagency Nuclear Safety Review Panel (INSRP) during the late stages of the program as independent input into the governmental decisions to launch the NPS.

Figure 4 shows the overall NPS program logic, illustrating how the safety, design, fabrication, and testing processes are interrelated. Table 1 lists the generic types of safety-related documents required for launch and space use of an NPS. The SAR, which is the major compilation of safety information and analyses by the U.S. Department of Energy (DOE) program office, and the SER, which provides an independent review of the SAR and is considered in the launch approval process, are the primary focus of this chapter. Although the focus is on the flight-related SARs and SER,

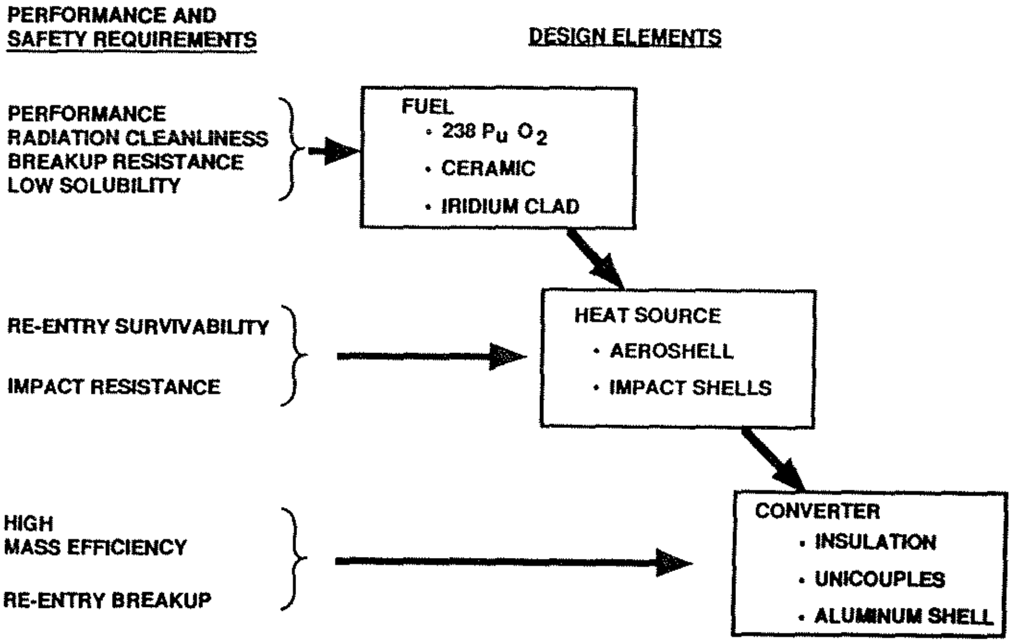


FIGURE 2 Diagram relating the performance and safety requirements to the design elements.

it is important to note that there are DOE (and other agency) orders governing safety, security, and safeguards in the fabrication, assembly, testing, handling, and transportation of NPS prior to launch. Another requirement is set forth in the Federal Radiological Emergency Response Plan and further codified in the various agency orders and plans for contingency planning in preparation for the launch of an NPS.[7]

43.3 Interagency Nuclear Safety Review Panel

As discussed in Section 43.1 the Interagency Nuclear Safety Review Panel (INSRP) is chartered to conduct an independent safety review (including technical risk assessment) of each proposed U.S. nuclear-powered space mission prior to launch. INSRP does not make a recommendation of launch approval or disapproval; rather, it provides the necessary independent risk evaluation that will be used in risk management by decision makers who must weigh the benefits of the mission against the potential risks.

The general process of forming an INSRP begins with a request to DOE and either NASA or the Department of Defense (DoD) from a user agency (NASA or DoD) when the user agency has an approved mission. An INSRP is chaired by three coordinators appointed by the Secretary of Defense, the Administrator of NASA, and the Secretary of Energy. DOE is involved because it provides the NPS and has statutory responsibility for the nuclear safety of its NPS. DoD and NASA are involved because of their launch vehicle safety expertise. The coordinators come from independent safety offices within the three agencies. The general INSRP operating plans, including organizational structure (subpanels) and support requirements, are established by the three coordinators. Under the Presidential Directive, the U.S. Nuclear Regulatory Commission (NRC) is invited to send representatives to INSRP meetings, although NRC is not part of the official review and approval process.[1-5] Historically, the U.S. Environmental Protection Agency (EPA) and the U.S. National Oceanic and Atmospheric Administration (NOAA) have participated as observers in these reviews. (EPA has a key role in emergency planning and NOAA has provided valuable input to meterological analyses.) At the time of Publication the Office of Science and Technology Policy has made NRC and EPA full-fledged members of INSRP for the planned Cassini mission to Saturn. Figure 5 shows the structure of INSRP as it was established for the Galileo mission and

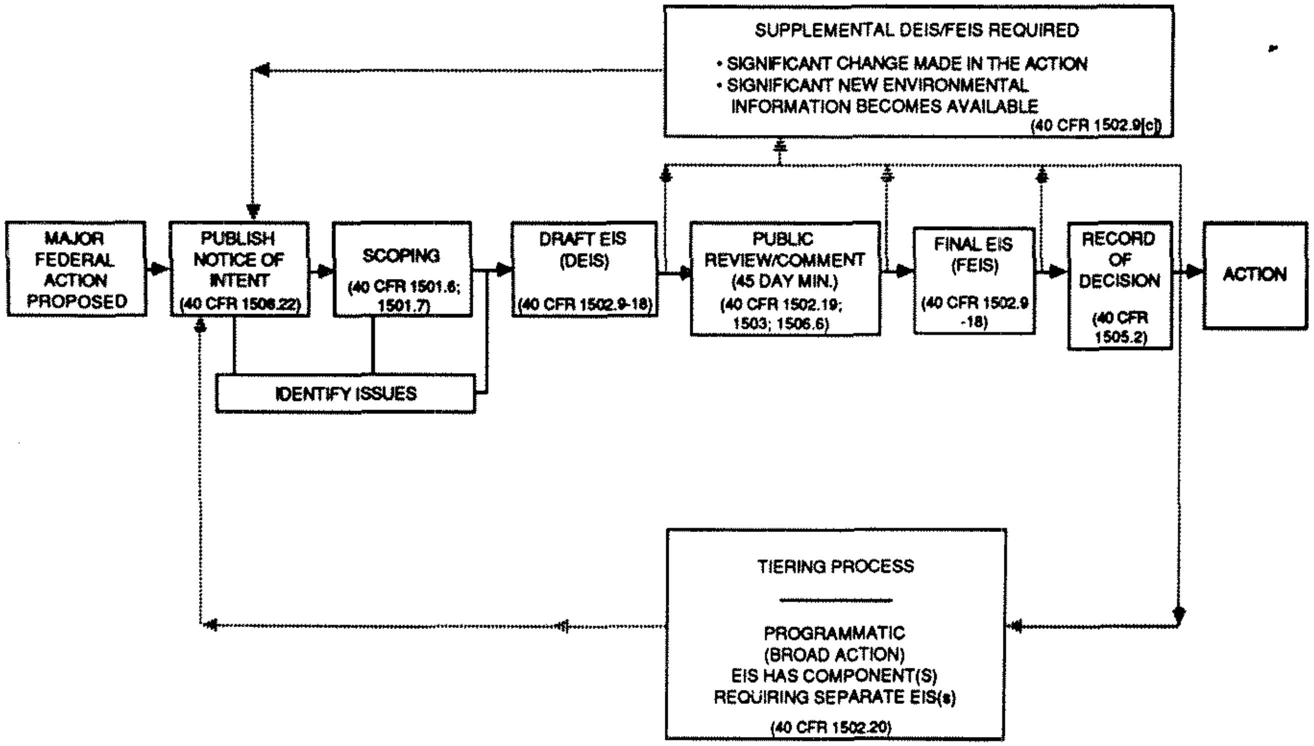


FIGURE 3 Federal EIS process.

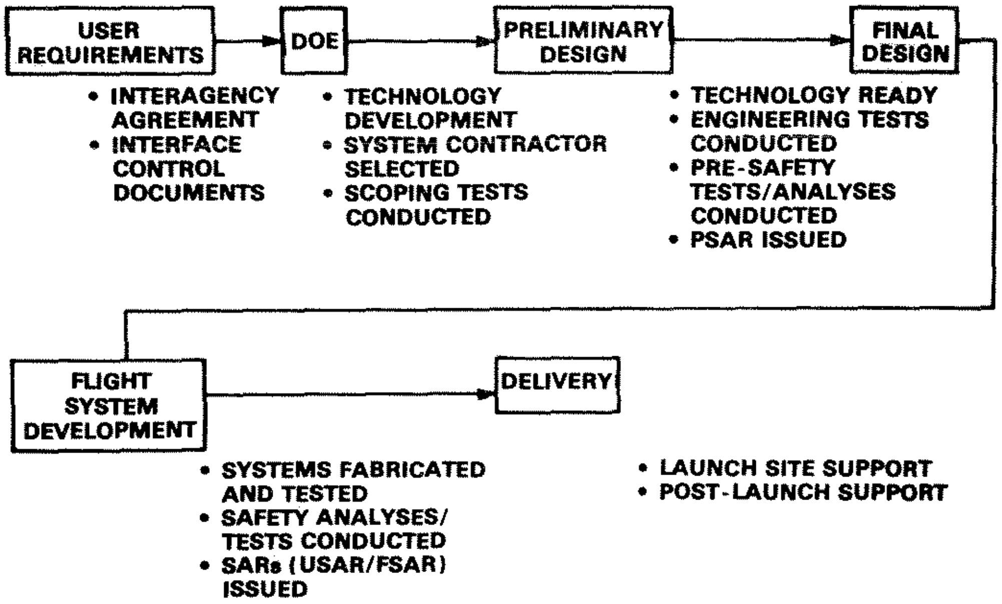


FIGURE 4 Overall program logic.

Table 1 Minimum Safety Documentation Requirements

Safety Assessment Report—Defines safety aspects of design and mission
Safety Program Plan—Outlines total safety program to achieve safety objectives
Radiological Protection Plan—Presents radiological protection and health physics program to protect people
Ground Safety Analysis Report (GSAR)—Assesses safety of site-specific operations, facilities, personnel, training, and equipment
Criticality Assessment Report—Assesses critically aspects of reactor or RTG/heat source, multiple storage/ transportation configurations
Safety Analysis Reports (Flight)—Provides overall nuclear risk analysis of the mission
Safety Analysis Report for Packaging (SARP)—Qualifies the shipping container for issuance of "certificate of compliance" for transportation
Emergency Preparedness and Responses Plan—Provides interagency plan to protect people and the environment in accident situations
Safety Evaluation Report (Flight)—Provides independent nuclear risk analysis of the mission

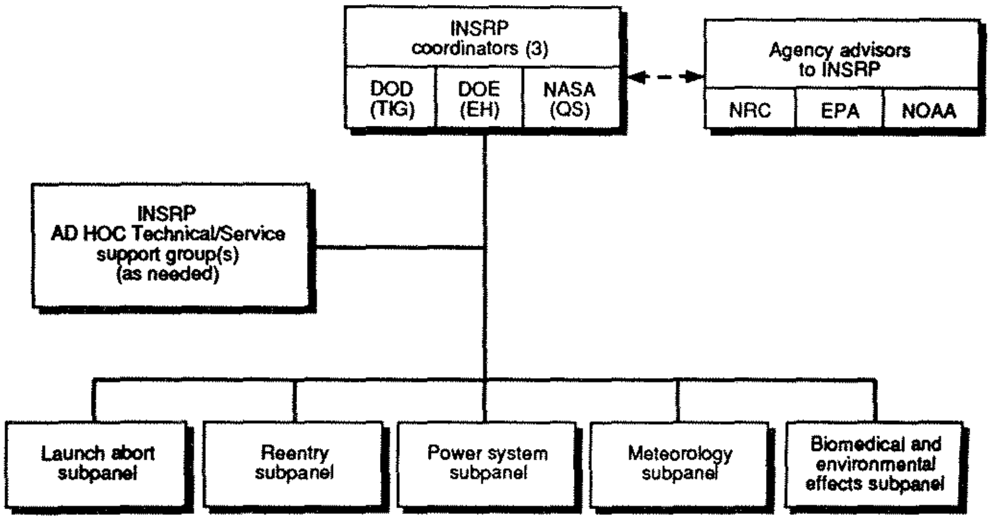


FIGURE 5 Organization of the Interagency Nuclear Safety Review Panel (INSRP).

the Ulysses mission, the two most recent U.S. space nuclear-powered missions. For the Galileo and Ulysses missions, the five subpanels were composed of approximately 50 scientists and engineers from a number of government agencies, national laboratories, industry, and universities, covering such specialties as missile flight analysis, chemical engineering, nuclear engineering and safety, thermal protection, and inhalation toxicology. The subpanels for Galileo and Ulysses were as follows:[4]

- *Launch Abort Subpanel:* Identifies and characterizes prelaunch, launch, and ascent accidents and their probabilities.
- *Reentry Subpanel:* Identifies and characterizes reentry accidents, their probabilities, and their effects on the nuclear system.
- *Power System Subpanel:* Characterizes the nuclear system response to prelaunch, launch, ascent, and post-re-entry Earth impact accidents, including any fuel releases postulated.
- *Meteorology Subpanel:* Characterizes the transport of postulated fuel releases within the atmosphere.
- *Biomedical and Environmental Effects Subpanel:* Characterizes the environmental and health effects of postulated fuel releases, including overall risks.

The INSRP approach has the following advantages:

1. A unified nuclear risk assessment is prepared and provided for the launch approval process of the three agencies and higher approval authorities. In the early missions, it was possible for each agency to conduct its own review, with the potential for three uncoordinated SERs. INSRP provides a mechanism to coordinate the independent reviews that the agencies are required to undertake.
2. Expertise common to a specific participating agency can be made available to the other agencies, which will eliminate possible duplication of effort.
3. At least one coordinator will not be involved in agency sponsorship of the mission nor will the representatives from NRC, EPA, and NOAA; therefore, their participation ensures an objective view and enhances the independence of the review.
4. The INSRP approach produces an environment conducive to free, open, and timely flow of information.

43.4 Safety Analysis Reports

The safety analysis report (SAR), which is generally prepared for the DOE program office, is the first step in the safety review process. As noted Figure 1, the INSRP review is a three-stage process with, in most instances, at least three formal INSRP reviews: one for the Preliminary Safety Analysis Report (PSAR), one for the Updated Safety Analysis Report (USAR), and one for the Final Safety Analysis Report (FSAR). Having three separate and sequential SARs allows INSRP to become familiar with the NPS and its proposed use and to provide input on the kinds of information they would like to see in the next SAR.

The PSAR is issued soon after a design concept is selected for a given mission. The PSAR includes a description of the NPS and the mission, as well as probabilistic radiological risk assessments as supported by the available conceptual design data base. The USAR is issued as soon as practical after the NPS design freeze. The USAR includes updated information on the mission, the failure modes analysis, and the radiological risk assessment, plus any safety tests and data required. The FSAR is normally issued about 1 year before the scheduled launch. The FSAR provides a description of the final design of the system, the mission, and radiological safety assessment data, including the results of the safety tests.[1-5]

The PSAR usually consists of two volumes: a Reference Design Document (RDD) and an Accident Model Document (AMD). The USAR (if sufficient information is available) and the FSAR include these two plus a third volume called the Nuclear Risk Analysis Document (NRAD). Table 2 shows an outline of the contents of the three volumes of the Ulysses FSAR.[8]

Table 2 Outline of the Ulysses Final Safety Analysis Report

- **Executive Summary**
- **Volume I—Reference Design Document**
  - Nuclear power system
  - Spacecraft description
  - Launch vehicle
  - Inertial upper stage description
  - Trajectory and flight characteristics
  - Flight contingency modes
  - Launch site
  - References
  - Appendix A—Plutonium fuel properties/characteristics
  - Appendix B—Properties of heat source and converter materials
- **Volume II (Book 1)—Accident Model Document**
  - Introduction
  - Summary of accident evaluation
  - Accident evaluation and failure mode analysis
- **Volume II (Book 2)—Accident Model Document—Appendices**
  - A—Accident definition and probabilities
  - B—Accident environments
  - C—Hydrocode analysis of RTG response to accident environments
  - D—Launch accident scenario evaluation program (LASEP)
  - E—JPL re-entry breakup analysis
  - F—Deleted (not applicable to Ulysses—for Galileo this was the appendix on the GPHS re-entry response for Venus-Earth-Earth-Gravity Assist (VEEGA) conditions)
  - G—Safety test program summary and results
  - H—Vaporization of PuO_2 in a space shuttle fireball
  - I—RTG/GPHS re-entry response
- **Volume III (Book 1)—Nuclear Risk Analysis Document**
  - Introduction
  - Methodology
  - Major accident scenarios and consequences
  - Integrated mission risk analysis
  - References
- **Volume III (Book 2)—Nuclear Risk Analysis Document—Appendices**
  - A—Risk assessment methodology
  - B—Biomedical aspects of plutonium-238 dioxide
  - C—Kennedy Space Center (KSC) meteorology
  - D—Particle size considerations
  - E—KSC vicinity demography and land use
  - F—KSC vicinity oceanographic, ground, and surface water studies
  - G—Worldwide demographic, land use, and oceanographic data

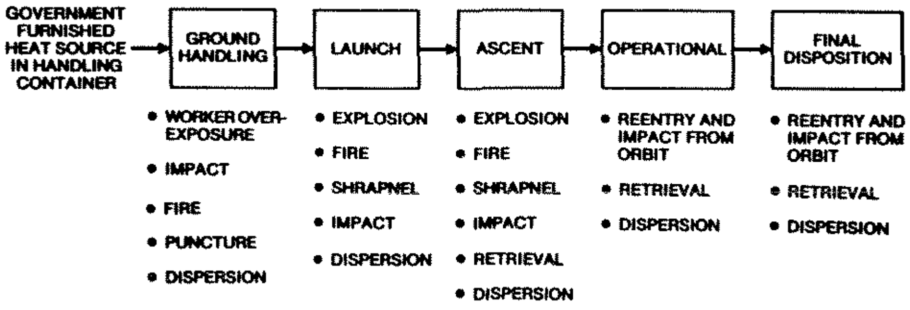


FIGURE 6 Safety encompasses evaluation of all mission phases.

In general, the SARs consider the following types of accident environments (categorized by mission phase; see also Figure 6):

1. Prelaunch, launch, and ascent phases:
    - Explosion overpressure
    - Projectile impact
    - Land or water impact
    - Liquid propellant fire
    - Solid propellant fire
    - Sequential combinations of the above
2. Orbit and/or flight trajectory phases:
    - Re-entry (which could follow an upper-stage explosion)
    - Land or water impact
    - Post-impact environment (land or water)

On-orbit contingency options (including using the spacecraft's propulsion system to boost a stranded spacecraft into a longer-lived orbit or retrieval) are considered as appropriate. Figure 7 shows the kinds of accidents considered for the Galileo mission.[9–11]

The safety analysis is conducted by evaluating each phase of the mission separately, as shown in Figure 8 for the Galileo mission. Each phase represents a change in configuration, location, and activity that can potentially affect the NPS in the event of a postulated accident. Since the mid-1960s, the U.S. has performed its safety analyses using probabilistic risk analysis (PRA) techniques. For Galileo and Ulysses the risk analysis begins with the construction of failure/abort sequence trees (FASTs) of the sort shown diagrammatically in Figure 9. Risk analysis, as used in this context, refers to a quantitative assessment of the potential for human exposure to radiation resulting from the use of an NPS in a space application. The concept of risk is more quantitatively defined in Figures 10 and 11.

The conduct of a risk analysis for a space mission using nuclear power requires (see Figure 12):[12]

- Definition of potential mission accidents and probabilities
- Determination of the types and severity of the resulting accident environments or stresses on the nuclear system
- Testing and/or analyzing the nuclear system to determine responses to the various accident environments
- Organization of the information on accidents, probabilities, and system responses into event trees (e.g., FASTs) for each mission phase (phases oriented to the potential for human risk)
- Analysis of radiological risk using radionuclide environmental pathway and dose models and worldwide data bases
- Appropriate contingency planning, launch safety preparations, and real-time accident analysis and recovery capability

References 9 to 11 describe in more detail the development and implementation of a space nuclear safety program that follows this logic. Figure 13 summarizes this process for the Galileo mission.

43.5 Safety Evaluation Report

The SER is prepared by INSRP to document its independent risk assessment. Table 3 is an outline of the SER prepared for the Ulysses mission. For the Ulysses mission the INSRP concluded that "Compared with the nominal 20-percent lifetime cancer fatality risk that everyone faces, the highest calculated added individual risk associated with the Ulysses mission increased lifetime cancer risk to no more than 20.00015 percent. If one considers that the likelihood of an accidental release that results in fatal cancer was less than 1 in 100,000, the actual added risk of fatal cancer associated with the Ulysses mission was much smaller than 0.00015%.

"Thus, the INSRP analysis suggested that the radiological risks associated with the Ulysses mission were relatively small".[13]

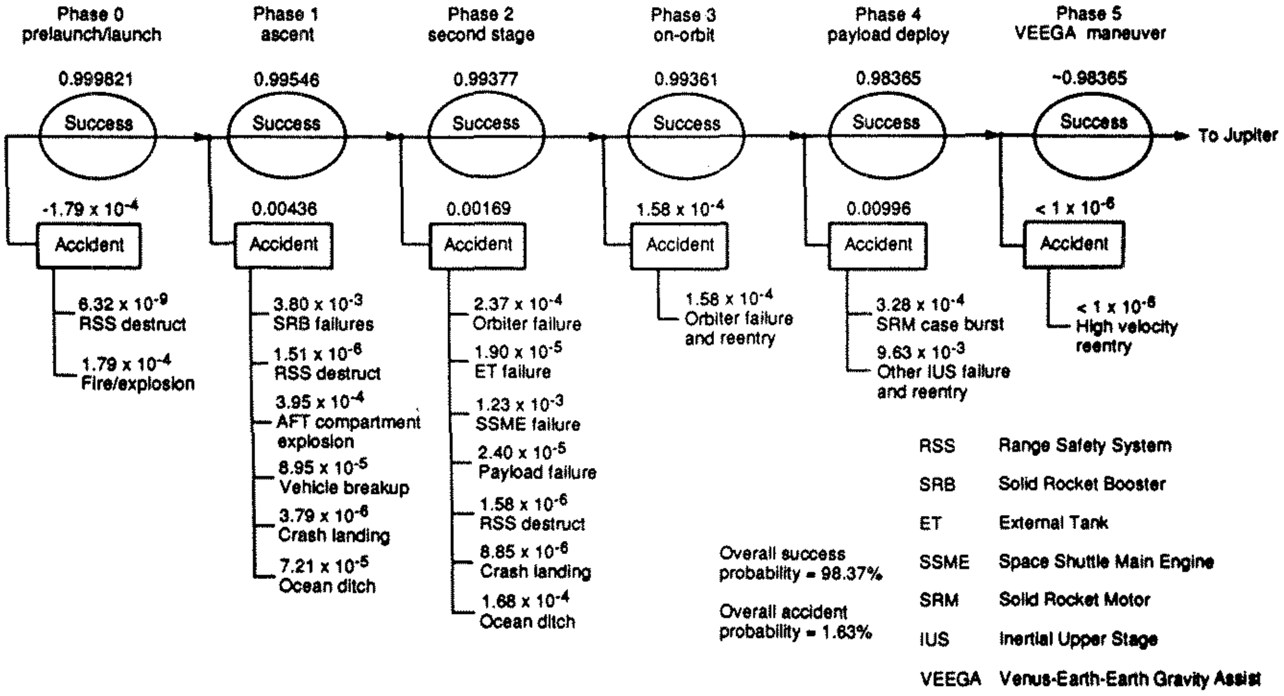


FIGURE 7 Mission success and accident probabilities for the Galileo mission.

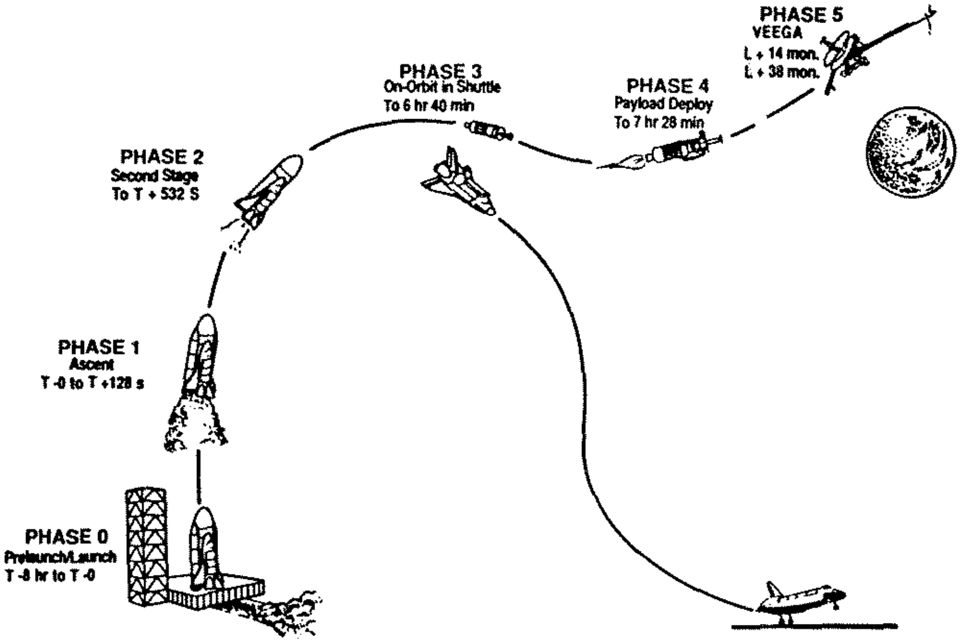


FIGURE 8 Mission phases for the Galileo mission.

43.6 Launch Approval

The completed SER is provided to DOE, NASA, and DoD for their review and concurrence. Upon receipt of letters of concurrence from the other two coordinating agencies on the INSRP signifying that their needs have been met, the launching agency submits a request for launch approval, along with the SER and other documentation if needed, to the Office of the President. Under Presidential Directive NSC/25, the Director of the Office of Science and Technology Policy (OSTP) is empowered to approve the launch. Military missions are also reviewed by the National Security Council (NSC). Consultation with and deferral to the President for launch approval may take place as circumstances warrant.

Flight approval constitutes an affirmative judgment by the U.S. Government, based on an overall risk-benefit evaluation, that the risks associated with the use of an NPS are warranted by the benefits to be derived from its use.

43.7 Historical Experience

The safety analysis and review process have a very practical aspect in that they provide information that can be used by contingency planners in responding to accidents that could occur. The U.S. has had three accidents involving NPS:[1,3,5]

- Failure of the Transit 5BN-3 navigational satellite with a SNAP-9A RTG to achieve orbit (April 21, 1964). The SNAP-9A burned up and dispersed as designed. (SNAP is an acronym for Systems for Nuclear Auxiliary Power.)
- Abort of the launch of the Nimbus-B 1 meteorological satellite with two SNAP-19B RTGs (May 18, 1968). The RTG heat sources were recovered intact, as designed.
- Damage to the Apollo 13 spacecraft after a successful launch on April 11, 1970, which led to the intact re-entry (as designed) of the SNAP-27 RTG fuel cask over the South Pacific Ocean on April 17, 1970.

A fourth incident affected the SNAP-10A reactor, which was successfully launched on April 3, 1965. Following approved guidelines, the spacecraft was placed in a high-altitude orbit, and the

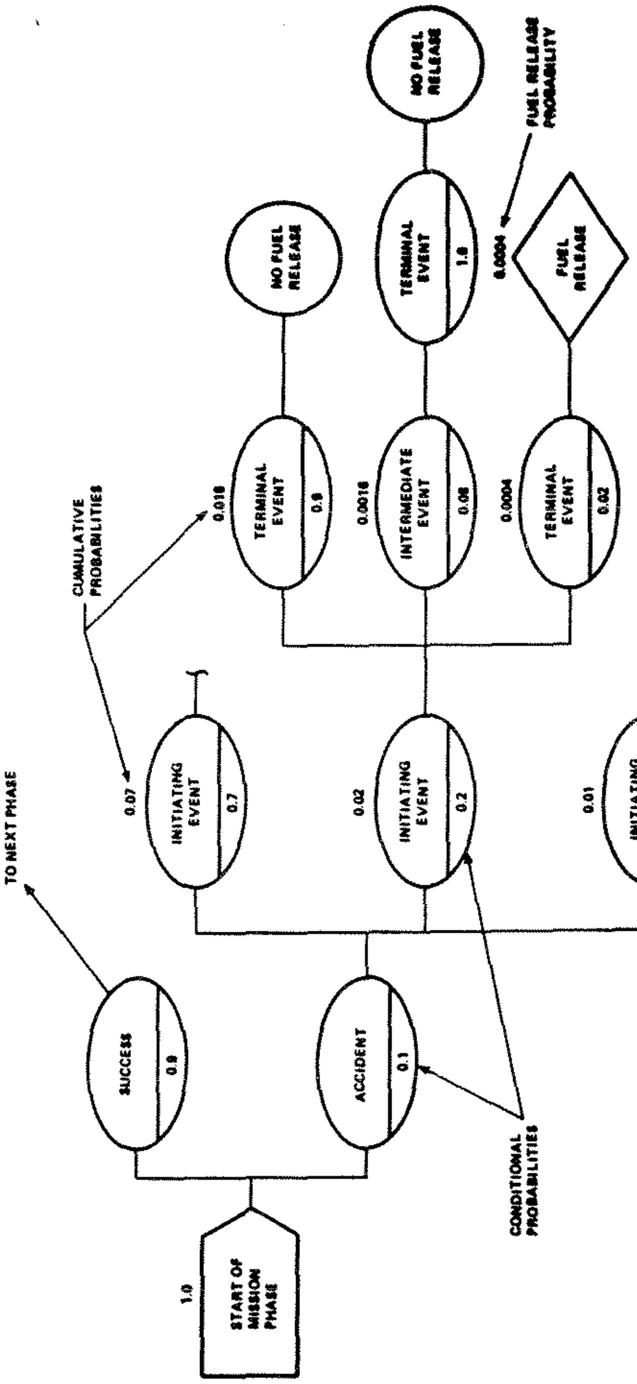
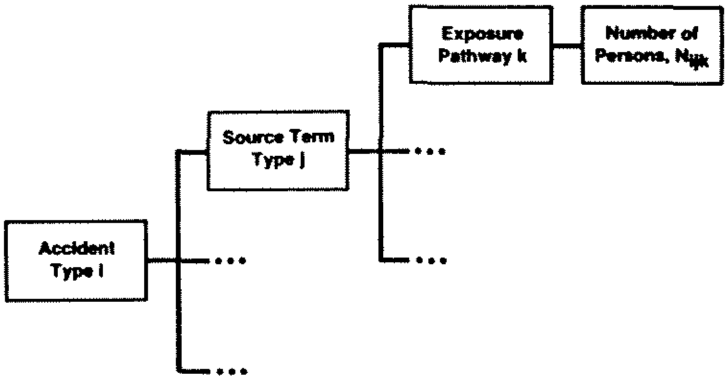


FIGURE 9 Simplified failure/abort sequence tree (FAST) displaying one of its sub-branches.



$$R = \sum_{ijk} P_i P_j P_k N_{ijk}$$

where

R = Overall Mission Risk Index in Terms of an Expectation of the Number of Persons Receiving a Dose Greater than a Given Dose Level D
P_i = Probability of Accident Type i
P_j = Conditional Probability of Release Type j Given Accident i
P_k = Conditional Probability of Exposure Pathway k Given Accident Type i and Release Type j
N_{ijk} = Number of Persons Receiving a Dose Greater than Dose Level D Given Accident i, Release Type j, and Exposure Pathway k

FIGURE 10 Process for evaluating overall mission risk.

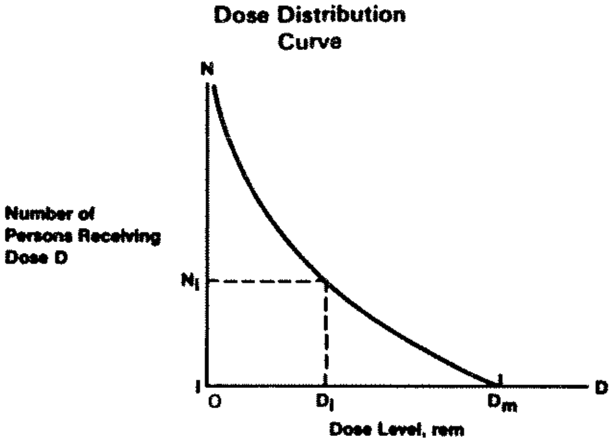
reactor was not started until this altitude was confirmed. The reactor operated for 43 d when a shutdown was safely and automatically effected following a malfunction of a voltage regulator on the spacecraft payload (not on the reactor).[14]

In each case cited, the NPS performed as they were designed to do and there were no measurable health effects. The existence of SARs coupled with teams of safety experts has provided decision makers with the necessary information to select the appropriate responses. The SARs also served to guide designers in improving the safety margins of succeeding NPS.

The former Soviet Union has had at least six re-entries of NPS as listed in Table 4.[15] In addition there was a close call with the reactor-powered Cosmos 1900 in 1988. All of the Soviet reactor incidents involved thermoelectric reactors (although the reactors apparently had nothing to do with the causes of the incidents).

43.8 Safety Criteria

This section discusses the general safety criteria applied to U.S. NPS, specifically, the GPHS-RTG, now in use on Galileo and Ulysses, and the SP-100 space nuclear reactor power system. Safety criteria have also been the subject of discussions in several organs of the United Nations following the re-entry of the reactor-powered satellite Cosmos 954 over Canada in 1978.[16] U.S. safety criteria are consistent with the original 1981 criteria developed by a U.N. working group.[16,17] More recent recommendatory but legally nonbinding criteria are being modified to improve their ". . . technical credibility and consistency with proven U.S. methods".[18]



- Maximum Individual Dose, D_m
- Number of Persons, N_i, Receiving Dose $\geq D_i$
- Total Population Dose in Person-rem

$$PD = \int_0^{D_m} N\, dD$$

- Potential Health Effects

$$H = k \times PD$$

FIGURE 11 Measures of radiological consequences.

Radioisotope Thermoelectric Generators

All of the RTGs flown by the U.S. have used ^{238}Pu as the radioisotope to provide the thermal power in the heat source. Plutonium-238 has been chosen to fuel the heat sources because this radioisotope satisfies the various safety and operational criteria. Plutonium-238 decays primarily by emitting alpha particles, which are completely absorbed in the heat source to produce the heat; hence, no special radiation shielding for these alpha particles is required. This radioisotope has an appropriately long half-life (about 87.8 years) and a power density that reduces the number of curies per gram while still permitting reasonable sizes for the heat source and long operational lifetimes. The principal safety objective associated with the use of ^{238}Pu is to keep it contained or immobilized to prevent inhalation or ingestion by humans and consequent exposure of the internal organs and bones to radiation.[1,3,5] How this is accomplished with the GPHS-RTGs in use on Galileo and Ulysses can be seen by referring first to Figure 14, which shows diagrammatically the layout of a GPHS-RTG. The basic components of the GPHS-RTG are the converter and the heat source. The RTG external envelope is based on a cylindrical geometry with an overall diameter of 0.42 m across the fins and a length of 1.14 m. The average mass of a flight RTG is about 56 kg.

The GPHS, shown in Figure 15, supplies the thermal energy to the thermoelectric converter. The GPHS is comprised of rectangular parallelepiped modules, each having dimensions of 93 × 97 × 53 mm, a mass of about 1.43 kg, and a thermal output of at least 245 W (t). Each GPHS-RTG contains 18 independent GPHS modules stacked into a single column. The GPHS was designed and tested for improved safety and power performance, and it represents a major step forward in RTG technology.[9,10]

Each GPHS module contains four plutonia fuel pellets of nominal thermal inventory of 62.5 W (t) (equivalent to about 1875 Ci of ^{238}Pu). The plutonium is enriched to about

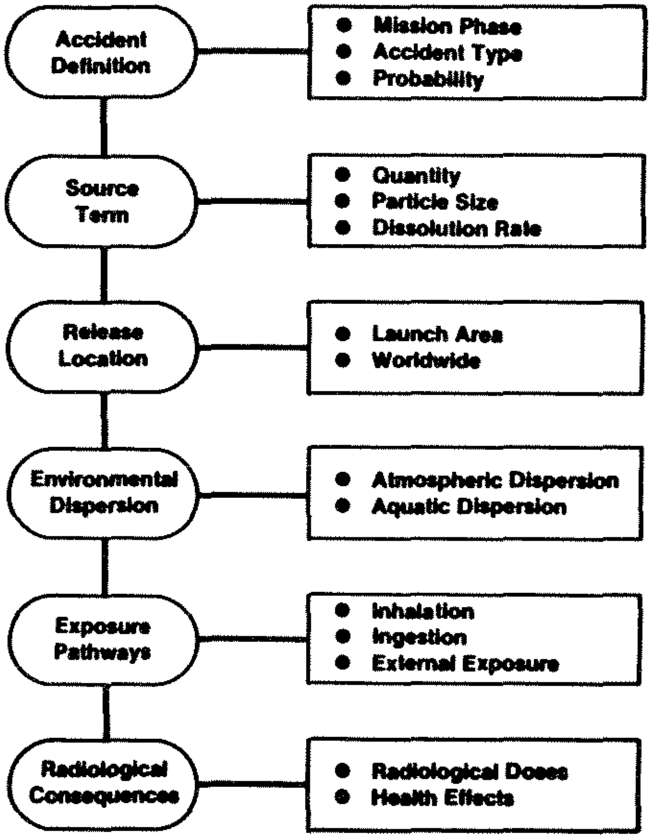


FIGURE 12 Logic diagram for analyzing radiological consequences.

83.5% ^{238}Pu. The GPHS thermal power requirement of 4.4 kW (t) translates into about 8.1 kg of ^{238}Pu per generator. Safety considerations were key factors in the design of the GPHS. The physical form of the fuel is a cylindrically shaped, ceramic pellet having an average diameter of 27.5 mm and an average length of 27.6 mm. The fuel is high fired to more than 1700 K and so is expected to remain chemically stable if released into the environment. Each pellet is individually contained in a post-impact containment shell or cladding made from an alloy of iridium. This alloy is capable of resisting oxidation in the post-impact environment while providing chemical and metallurgical compatibility with the fuel and graphitic components during high-temperature operation and postulated accidents. The iridium cladding has a frit vent that allows release of the helium produced by the alpha decay of the ^{238}Pu without releasing plutonium particles. The combination of fuel pellet and cladding is referred to as a fueled clad.[9,10]

Two of these fueled clads are encased in a graphic impact shell (GIS) machined from Fine Weave Pierced Fabric (FWPF)™, a three-dimensional carbon-carbon composite material produced by AVCO Corporation. Two of these graphite impact shell assemblies are inserted into an aeroshell, also machined from FWPF. A thermally insulating graphite sleeve made of carbon-bonded carbon fiber (CBCF) fits between each GIS assembly and the aeroshell and serves to control the temperature of the iridium during a postulated re-entry accident.[9,10]

The aeroshell, which is also made from FWPF, a material originally developed for re-entry vehicle nose cones, is designed to protect the two GIS assemblies from the severe aerothermodynamic

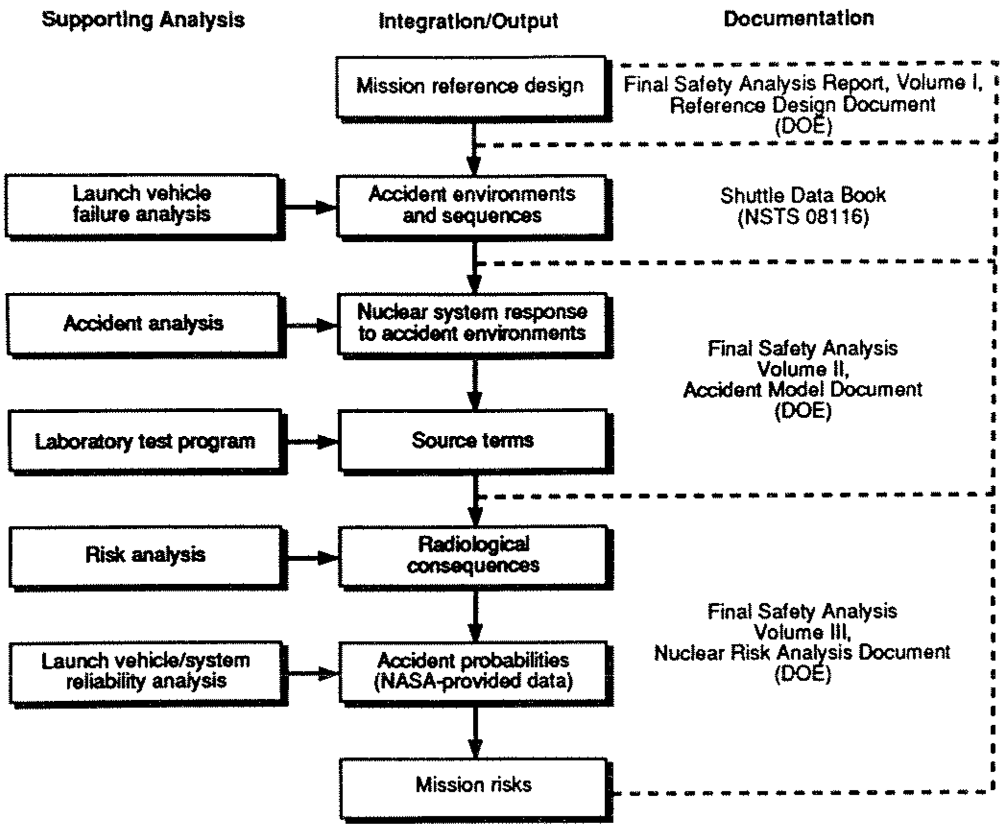


FIGURE 13 The safety analysis report process.

environment that may be encountered during a postulated re-entry. The GIS is designed to provide impact protection for the fueled clads under impact conditions associated with GPHS module terminal velocity. The cladding is intended to provide post-impact containment of the fuel.[9,10] Figure 16 shows the actual GPHS hardware. Figures 17 to 19 illustrate various tests that have been performed on GPHS hardware.

Reactors

As noted earlier, the U.S. has launched only one reactor, SNAP-10A, which coincidentally used thermoelectric conversion. Until 1993, the principal ongoing U.S. thermoelectric reactor technology program was the SP-100, which was jointly supported by NASA and DOE. The safety philosophy governing the SNAP-10A program and the SP-100 program is to keep the reactor subcritical in accident situations. In the case of SNAP-10A, the 44-kW (t) reactor was not operated at power before launch or until the final orbit was achieved. The final orbit (1288 × 1307 km) was chosen to be one with an orbital lifetime of more than 3000 years, well beyond the time (about 300 years) required for the decay of the majority of the fission products. At the time of the SNAP-10A launch, the U.S. safety philosophy on accidental re-entries was to disperse the reactor into small, nonrespirable-sized particles so that no significant doses occurred and no recriticality or safeguards issues would occur. Because of uncertainties over the ability to actually achieve such dispersion, the SP-100 reactor re-entry philosophy was to design for intact re-entry and burial.[19–21]

Table 3 Outline of the Ulysses Safety Evaluation Report

- **INSRP 90–01: Volume I—Executive Summary**
  - Introduction
  - Mission and system description
  - Launch site and environs
  - Safety procedures and equipment
  - Accidents considered and their probabilities
  - Analysis and conclusions
  - Appendix A—References
  - Appendix B—Ulysses INSRP participants
  - Appendix C—Acronyms and abbreviations
- **INSRP 90–01: Volume II—Overview of INSRP SER for Ulysses**
  - Purpose
  - SER methodology and approach
  - Reference documents
  - Appendix A—Tables used to determine source terms
  - Appendix B—Analysis of uncertainties inherent in the INSRP assessment of Ulysses mission risks
  - Appendix C—Acronyms and abbreviations
- **INSRP 90–01:Volume III—Compendium of Biographical Sketches of the INSRP Members**
- **INSRP 90–02—Launch Abort Subpanel Report**
  - Introduction
  - Approach
  - Activity summary
  - Launch abort subpanel conclusions
  - Appendix 1—Selected detail scenarios
  - Appendix 2—Supporting analysis summary for analytical studies and reviews
  - Appendix 3—Technical comments on the FSAR
  - Appendix 4—Resumes
- **INSRP 90–03—Re-Entry Subpanel Report**
  - Subpanel responsibility and membership
  - Background
  - Failure modes
  - Re-entry scenarios
  - Ulysses spacecraft breakup during re-entry
  - Re-entry modeling and experimental verification
  - Response to re-entry environments
  - Velocity at impact
  - Attitude at impact
  - Re-entry footprint
  - Surface at impact
  - Summary and conclusions
  - Recommendations
  - List of references
- **INSRP 90–04—Power System Subpanel Report**
  - Executive summary
  - Introduction
  - Mission and system description
  - Launch site and environs
  - Range safety procedures and equipment
  - Accidents considered and their probabilities
  - Power system subpanel review and evaluation
  - Results and conclusions
  - Appendix A—References
  - Appendix B—ORIGEN code calculations for Ulysses

Table 3 Outline of the Ulysses Safety Evaluation Report *Continued*

INSRP 90–05—Meteorology Subpanel Report
    Executive summary
    Summary of recommendations of the meteorology subpanel
    Introduction and background
    Exceptions taken with the dispersion and deposition FSAR procedures
    KSC climatology
    Dispersion methodology of the FSAR
    Deposition methodology of the FSAR
    Other key (and potentially problematic) assumptions
    Tests with a different dispersion methodology
    Estimates of uncertainties
    Conclusions
    References
    Appendix 1—The use of atmospheric transport and dispersion models in risk assessment
    Appendix 2—Deposition to the surface
    Appendix 3—Recommendations
    Appendix 4—Hourly wind roses for the period of the Ulysses launch: Kennedy Space Center and Orlando
INSRP 90–06—Biomedical and Environmental Effects Subpanel Report
    Executive summary
    Preface
    Introduction
    Radiological source terms
    Environmental transport and fate
    Land contamination and mitigation
    Radiation dose assessment
    Radiological consequences
    Summary
    References
    Biographies of the biomedical and environmental effects subpanel
INSRP 90–07—Uncertainty Analysis Report (Volume I)
    Introduction and summary
    Review of FSAR risk analysis methodology
INSRP 90–07—Uncertainty Analysis Report (Volume II)
    Introduction
    Objectives of the Ulysses risk analysis
    Technical approach
    Assessment of the significant factors
    Presentation of results
    Appendix A—Procedure of the Ulysses risk analysis

4 Re-Entries of Soviet Space Nuclear Power Sources

	Launch Date	Re-Entry Date	Type of Power Source	Comments
—	Jan 25, 1969	Jan 25, 1969	Reactor	Possible launch failure of a RORSAT (Radar Ocean Reconnaissance Satellite)
os 300	Sept 23, 1969	Sept 27, 1969	Radioisotope	One or both of these payloads may have been a Lunokhod and carrying a ^{210}Po heat source.
os 305	Oct 22, 1969	Oct 24, 1969	Radioisotope	Upper stage malfunction prevented payloads from leaving Earth orbit.
—	Apr 25, 1973	Apr 25, 1973	Reactor	Probable launch failure of RORSAT
os 954	Sept 18, 1977	Jan 24, 1978	Reactor	Payload malfunction caused re-entry near Great Slave Lake in Canada.
os 1402	Aug 30, 1982	Jan 23, 1983 (spacecraft) Feb 7, 1983 (reactor core)	Reactor	Payload failed to boost to storage orbit on Dec 28, 1982. Spacecraft structure re-entered at 25°S, 84°E. Fuel core re-entered at 19°S, 22°W.

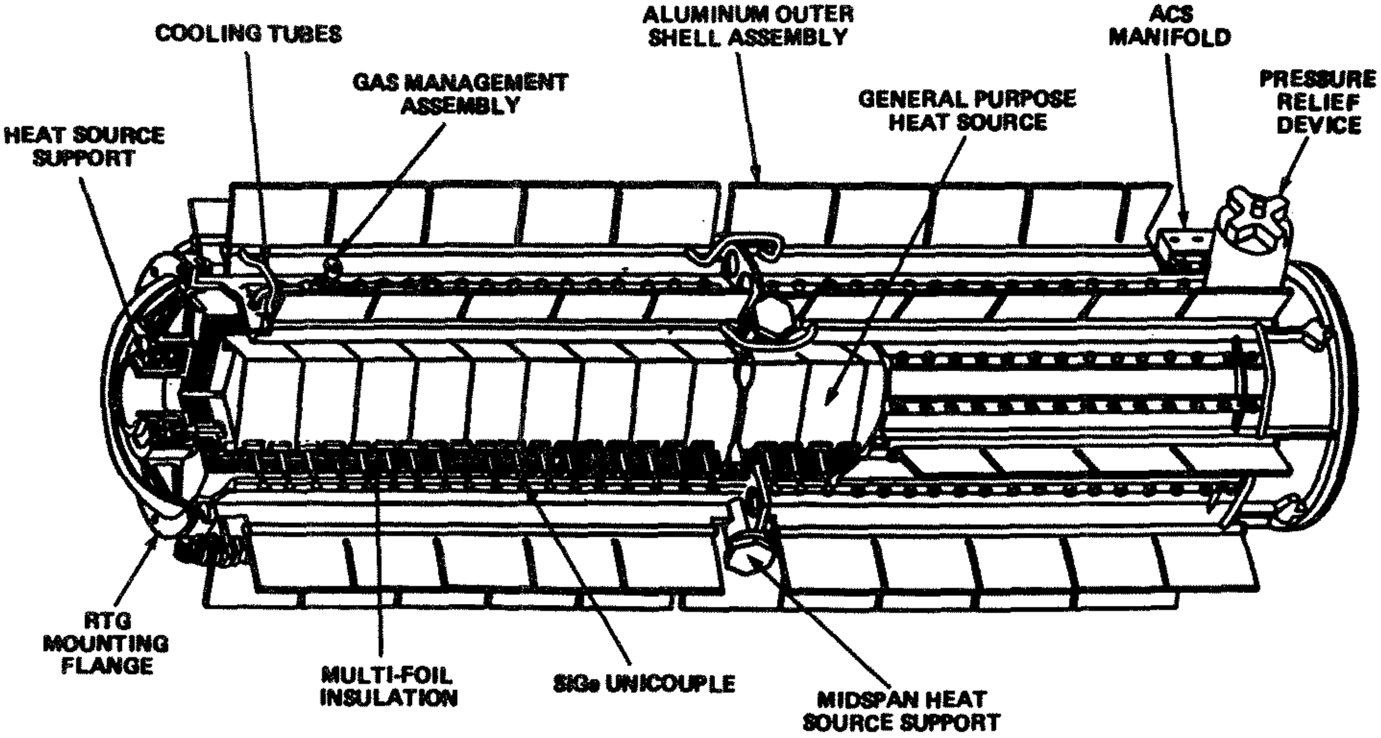


FIGURE 14 The general-purpose heat source radioisotope thermoelectric generator (GPHS-RTG).

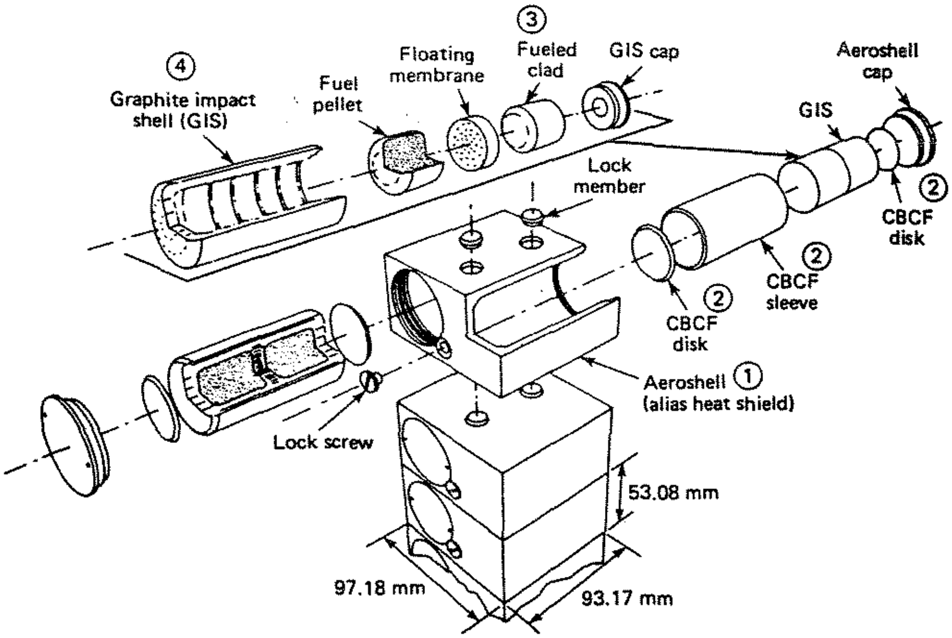


FIGURE 15 General-purpose heat source (GPHS) module component and assemblies.

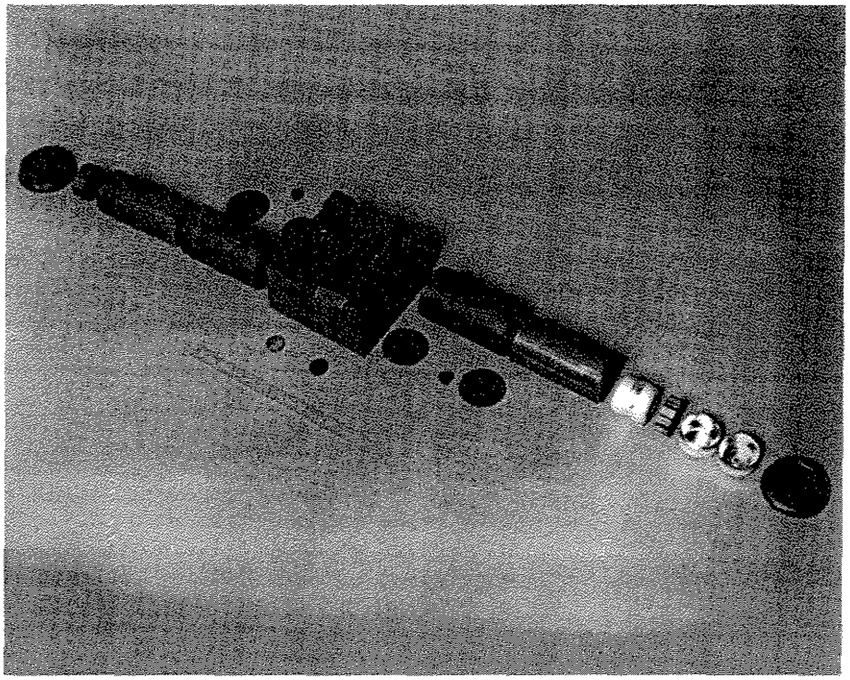


FIGURE 16 Picture of GPHS hardware.

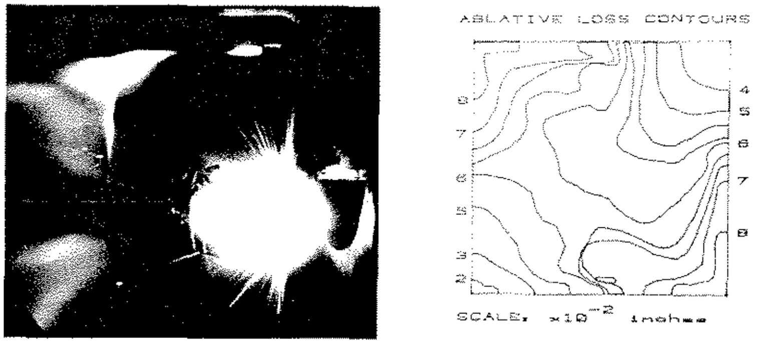


FIGURE 17 Picture of re-entry test of GPHS materials.

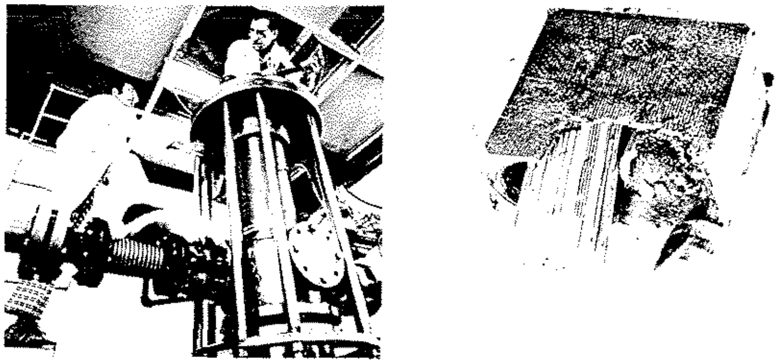
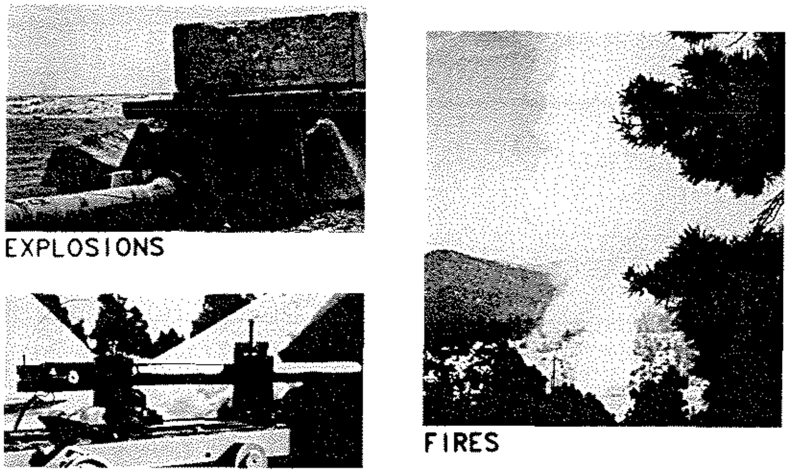


FIGURE 18 Picture of impact test of GPHS module.



EXPLOSIONS

FRAGMENTS

FIRES

FIGURE 19 Picture of launch accident tests of GPHS hardware.

43.9 Conclusions

Overall, the flight safety review and approval process as developed and implemented in the U.S. has been successful and accepted at the various involved levels of government. These procedures have led to a rigorous space nuclear safety program that provides for the testing and analysis of

NPS intended for use in outer space prior to their actual use. The safety of the NPS space missions is assessed by using PRA techniques. The SARs provide a project assessment of the risks, whereas the SER provides an independent assessment of the risks by the INSRP. A coordinated SER is used by the decision makers in the launch approval process to evaluate the risks and benefits of a given nuclear-powered space mission.

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