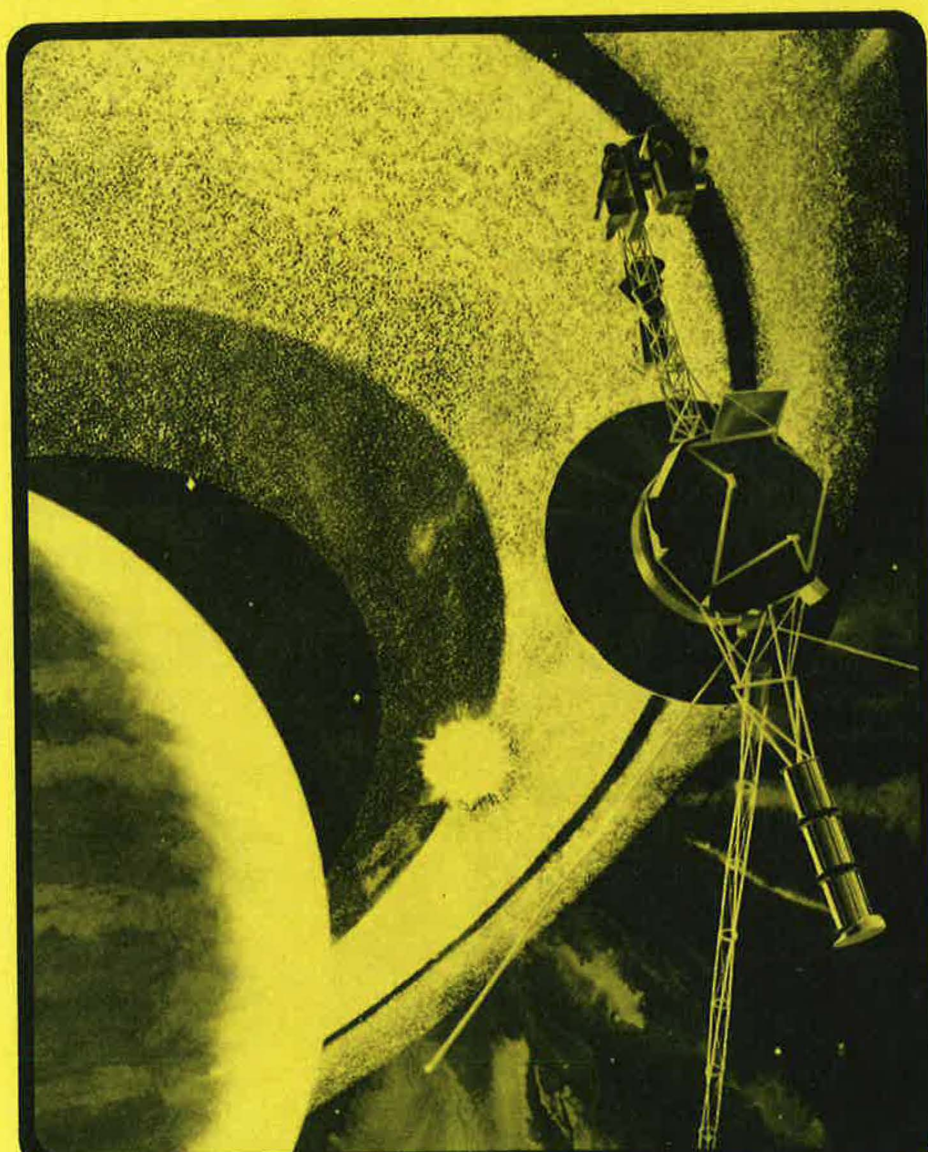
NUCLEAR SAFETY

VOL 22-4



TECHNICAL PROGRESS REVIEW

JUL • AUG 1981

General Safety Considerations

Edited by J. R. Buchanan

Overview of the U. S. Flight Safety Process for Space Nuclear Power

By Gary L. Bennett*

Abstract: *The two current types of nuclear power sources used in U. S. spacecraft are described along with the flight safety philosophies governing their use. In the case of radioisotope thermoelectric generators, the design philosophy consists of containment, immobilization, and recovery of the nuclear materials. For reactors, the emphasis is on maintaining a subcritical configuration in all credible accident environments. To document the safety activities, a safety analysis report is prepared for each mission. These reports, which are based on the probabilistic risk assessment methodology pioneered by the space nuclear safety community, are subjected to an interagency safety review before a recommendation is made to approve the launch of a nuclear-powered spacecraft.*

The recent spectacular flights by Jupiter and Saturn of the National Aeronautics and Space Administration (NASA) spacecraft *Voyager* and *Pioneer* have also marked additional milestones in the continuing successful and safe use of nuclear electric power in outer space. Since 1961, the United States has launched 22 NASA and military spacecraft having all or part of their power requirements supplied by nuclear power sources. Twenty-one of these spacecraft were powered by radioisotope thermoelectric generators (RTGs) and one by a nuclear reactor. Table 1 summarizes the space nuclear power sources launched by the United States to date. Electric-power output per individual nuclear power source has ranged from 2.7 W(e) for SNAP-3A to 500 W(e) for SNAP-10A. The history of these sources has shown that they can be safely and reliably built and launched to meet a variety of mission objectives.[1] Future missions committed to nuclear power include NASA's *Galileo* mission which will launch an orbiter and atmospheric probe to Jupiter and the International Solar Polar Mission (ISPM) which will obtain scientific data on the sun and solar wind from high heliographic latitudes.

As stated in a 1978 working paper[2] submitted by the United States to the United Nations Committee on the Peaceful Uses of Outer Space:

> Since its inception, the U. S. space nuclear power program has placed great emphasis on safety of people and protection of the environment. A continuing primary objective has been to avoid undue risks by designing systems to safely contain the nuclear fuel under normal and potential accident conditions.

*Gary L. Bennett is Chief of the Safety and Isotope Fuels Branch in the Department of Energy Space and Terrestrial Systems Division. He obtained the Ph.D. degree in physics from Washington State University in 1970. He has also worked on several nuclear reactor safety research programs at the Idaho National Engineering Laboratory and the Nuclear Regulatory Commission. He has worked on the nuclear rocket program at the National Aeronautics and Space Administration's Lewis Research Center and was the government flight safety manager for the nuclear power sources used on the USAF LES 8/9 communications satellites and the NASA *Voyager* spacecraft. In 1980 and 1981, he served as a member of the U. S. delegation to the United Nations Working Group on the Use of Nuclear Power Sources in Outer Space and has served as an adviser to the U. S. delegation to the Scientific and Technical Subcommittee of the United Nations Committee on the Peaceful Uses of Outer Space. He has written a number of papers on nuclear safety and the use of nuclear electric power in outer space, and one novel (*The Star Sailors*).

Table 1 Summary of Space Nuclear Power Sources Launched by the United States (1961–1980)

Power source*	Spacecraft	Mission type	Launch date	Status
SNAP-3A	Transit 4A	Navigational	June 29, 1961	Successfully achieved orbit
SNAP-3A	Transit 4B	Navigational	Nov. 15, 1961	Successfully achieved orbit
SNAP-9A	Transit-5BN-1	Navigational	Sept. 28, 1963	Successfully achieved orbit
SNAP-9A	Transit-5BN-2	Navigational	Dec. 5, 1963	Successfully achieved orbit
SNAP-9A	Transit-5BN-3	Navigational	Apr. 21, 1964	Mission aborted; burned up on reentry
SNAP-10A	Snapshot	Experimental	Apr. 3, 1965	Successfully achieved orbit
SNAP-19B2	Nimbus-B-1	Meteorological	May 18, 1968	Mission aborted; heat source retrieved
SNAP-19B3	Nimbus III	Meteorological	Apr. 14, 1969	Successfully achieved orbit
SNAP-27	Apollo 12	Lunar	Nov. 14, 1969	Successfully placed on lunar surface
SNAP-27	Apollo 13	Lunar	Apr. 11, 1970	Mission aborted on way to moon; heat source returned to South Pacific Ocean
SNAP-27	Apollo 14	Lunar	Jan. 31, 1971	Successfully placed on lunar surface
SNAP-27	Apollo 15	Lunar	July 26, 1971	Successfully placed on lunar surface
SNAP-19	Pioneer 10	Planetary	Mar. 2, 1972	Successfully operated to Jupiter and beyond
SNAP-27	Apollo 16	Lunar	Apr. 16, 1972	Successfully placed on lunar surface
Transit-RTG	"Transit" (TRIAD-01-1X)	Navigational	Sept. 2, 1972	Successfully achieved orbit
SNAP-27	Apollo 17	Lunar	Dec. 7, 1972	Successfully placed on lunar surface
SNAP-19	Pioneer 11	Planetary	Apr. 5, 1973	Successfully operated to Jupiter and Saturn and beyond
SNAP-19	Viking 1	Mars	Aug. 20, 1975	Successfully landed on Mars
SNAP-19	Viking 2	Mars	Sept. 9, 1975	Successfully landed on Mars
MHW	LES 8/9†	Communications	Mar. 14, 1976	Successfully achieved orbit
MHW	Voyager 2	Planetary	Aug. 20, 1977	Successfully operated to Jupiter and Saturn and beyond
MHW	Voyager 1	Planetary	Sept. 5, 1977	Successfully operated to Jupiter and Saturn and beyond

*SNAP-10A was powered by a nuclear reactor; the remainder were powered by radioisotope thermoelectric generators.

†LES = Lincoln experimental satellite.

This article presents a brief overview of the U. S. philosophy in regard to space nuclear safety and the current flight safety review process.

Since its inception the U. S. program for the safe use of nuclear power in outer space has involved hundreds of scientists and engineers in several governmental agencies and private organizations. Space does not permit the identification of individual contributors; however, the principal Department of Energy (DOE)-supported organizations that have participated in the flight safety program in the past or are currently participating are Los Alamos National Laboratory, Applied Physics Laboratory (Johns Hopkins University), NUS Corporation, Sandia National Laboratories, General Electric Company, Teledyne Energy Systems, and TRW, Inc.

RATIONALE FOR USING NUCLEAR ELECTRIC POWER IN SPACE VEHICLES

When the development risks and potential benefits can be meaningfully identified in advance, cost–benefit analyses are conducted before a major nuclear electric-power application in outer space is undertaken. These analyses include mission requirements; environmental, health, and safety requirements; and other specific requirements (such as reliability, longevity, and survivability) and consider nonnuclear as well as nuclear alternatives.[3] The benefits to be derived from the use of nuclear electric-power sources in space can be seen in the following conditions:[1]

1. *Lifetime:* Nuclear power is the principal alternative for spacecraft which must operate for a long period of time.

2. *Environment:* Nuclear power sources are less vulnerable to external radiation damage (e.g., in the Van Allen radiation belts) and to other potentially hostile environments [e.g., meteoroids, Martian dust storms, and extreme temperatures (such as experienced on the lunar and Martian surfaces)].

3. *Self-sufficiency:* Nuclear power sources enable the spacecraft to be more autonomous. In addition, RTGs can be operated on the launch pad for systems checkouts prior to launch or from the orbiting space shuttle.

4. *Operational reliability:* Nuclear power sources in spacecraft have exhibited extremely high reliability. They provide a compact source of electrical energy with a good power-to-mass ratio. The small exposed area of nuclear power sources can reduce the overall size of the spacecraft, simplify attitude control, and reduce structural interactions. A nuclear power source can also be used to supply heat directly to selected spacecraft components without introducing electromagnetic interference.

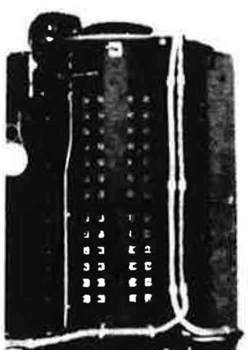
TYPES OF NUCLEAR POWER SOURCES USED IN SPACECRAFT

Two types of nuclear power sources have been used to generate electricity for spacecraft: RTGs and nuclear reactors. These two systems are discussed below.

Radioisotope Thermoelectric Generators

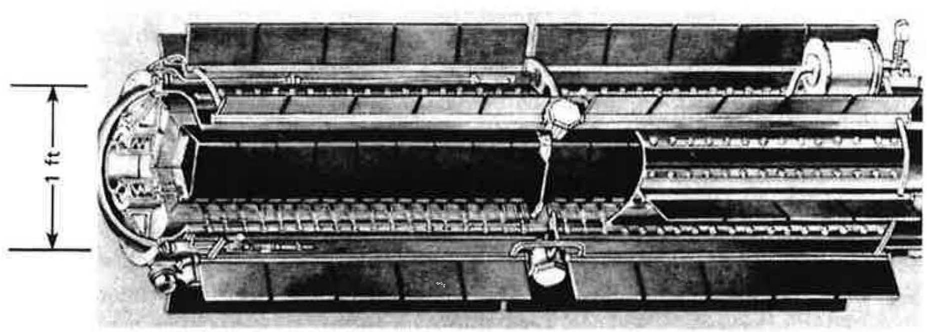
The RTG, which is the nuclear power source most often used in spacecraft by the United States, is a static device that directly converts the heat associated with the decay of a radioisotope to electricity by means of the Seebeck effect. Thus there are only two functional parts of an RTG: a thermoelectric converter and a heat source. For all U. S. space missions to date, the heat sources have been fueled with the radioisotope ^{238}Pu. This radioisotope has an appropriately long half-life (about 87.8 yr), which permits long operational lifetimes to be considered. 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. The principal safety objective associated with the use of ^{238}Pu is to keep it contained to prevent ingestion by humans and consequent exposure of the unprotected internal organs and bones to radiation.

Figure 1 shows the two most recent RTGs: the multihundred-watt (MHW) and general-purpose heat source (GPHS) RTGs. The MHW RTG provided the electric power for the NASA spacecraft *Voyager* (see Fig. 2). The GPHS RTGs are being designed and built to provide electric power for *Galileo* and the ISPM. Figure 3 is a cutaway drawing showing the key parts of the GPHS. As in the MHW heat source, the fuel ($^{238}PuO_2$) is contained in a modular form, with each module multiply encased to ensure its survival under a range of postulated accidents: graphitic outer coverings provide protection against the structural, thermal, and ablative environments of a potential reentry; additional graphitic components provide impact protection; and the iridium cladding provides postimpact containment.



MHW RTG

(a)



GPHS RTG

(b)

Fig. 1 Thermoelectric systems—nuclear power for space missions: (a) multihundred-watt radioisotope thermoelectric generator (MHW RTG); (b) general-purpose heat source radioisotope thermoelectric generator (GPHS RTG).

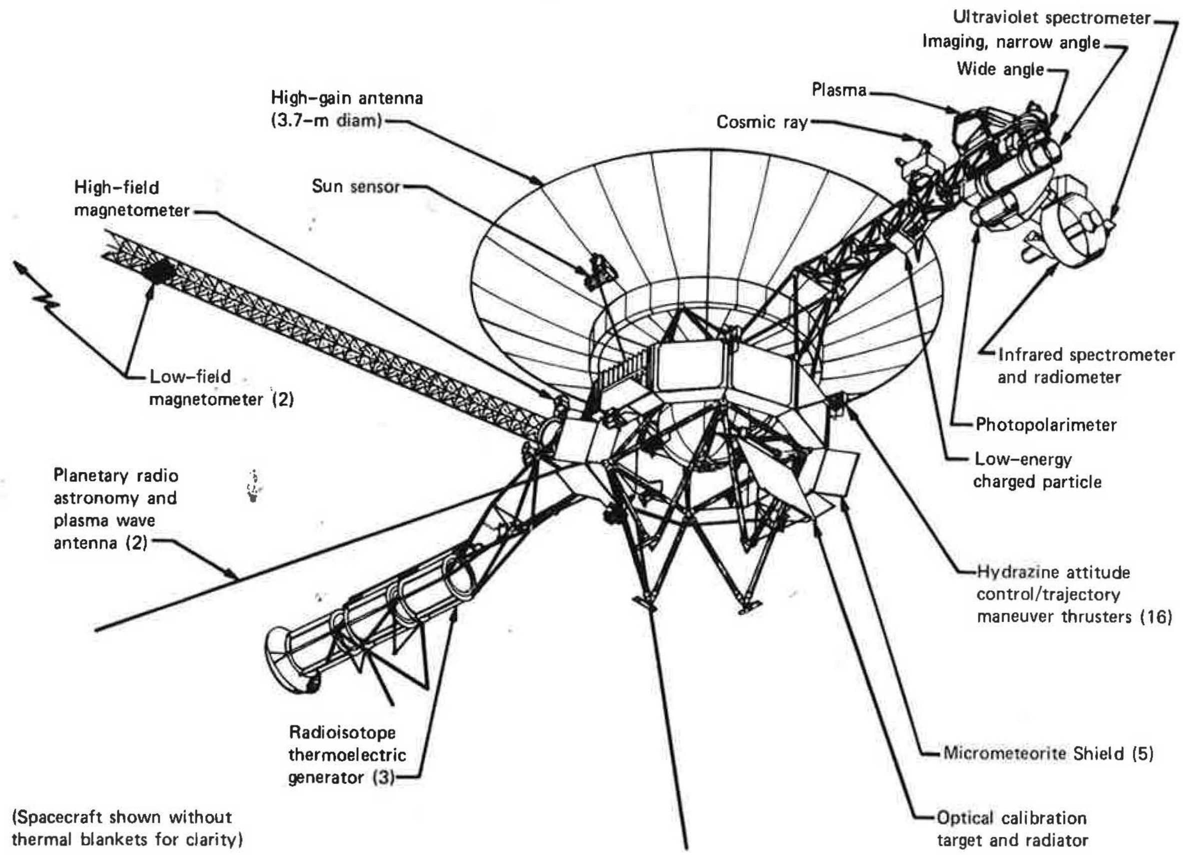


Fig. 2 *Voyager*—**mission module in cruise configuration.**

The major design requirements of the heat source are safety related; i.e., the design must provide for immobilization of the plutonium fuel to the maximum extent possible during all mission phases, including ground handling, transportation, launch, ascent, and orbit, considering such postulated accident environments as launch vehicle explosion or fire, reentry, impact, and postimpact situations.

Nuclear Reactors

Nuclear reactors can be (and have been) used on spacecraft to generate electricity. To date, the United States has launched only one nuclear reactor, the SNAP-10A.* However, the DOE is supporting a technology program to demonstrate that key components of an advanced reactor thermoelectric power system can be engineered to meet various performance objectives.[4]

Figure 4 shows the Space Power Advanced Reactor (SPAR) power plant. The uranium dioxide-fueled nuclear reactor is shown at the lower left of Fig. 4. The reactor core is contained within a cylindrical molybdenum can having a diameter of 29 cm and a height of 29 cm. Within this container are heat pipes which conduct heat to a ring of thermoelectric modules. A lithium hydride shadow shield is shown adjacent to the reactor. Beyond the thermoelectric modules is the heat-rejection radiator, which consists of panels of heat pipes that may be packaged in a number of different configurations. The SPAR is being designed to span a range of power levels from 10 to 100 kW(e).

For both types of nuclear power sources, it is also possible to use dynamic conversion systems (i.e., turbine/alternator) to increase the power output. The United States has studied these systems experimentally.

*The first nuclear power sources used in U. S. spacecraft were described by the general title SNAP, an acronym for "systems for nuclear auxiliary power." All odd-numbered SNAP sources use radioisotope fuel; even-numbered SNAP sources use nuclear fission reactors as a source of heat.

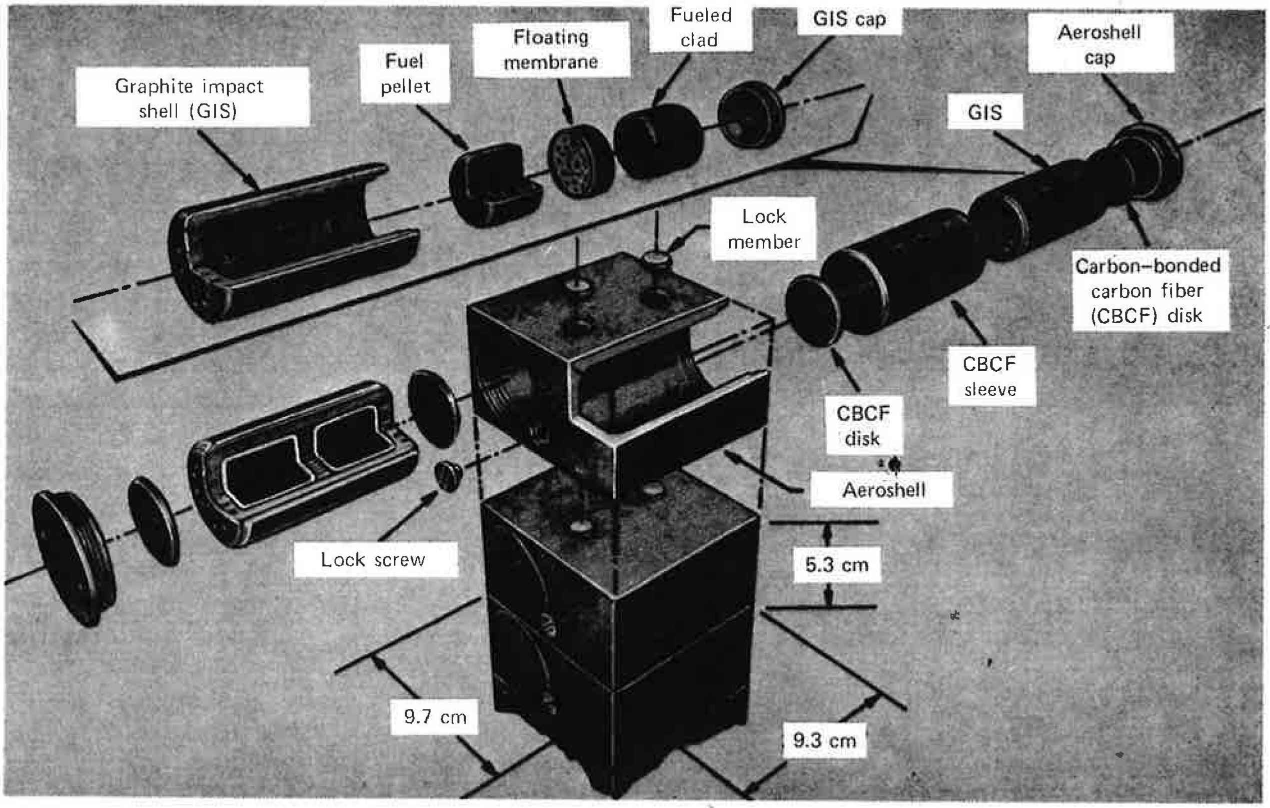


Fig. 3 General-purpose heat source modules showing the arrangement of the modules and the parts of each module. Eighteen modules are stacked inside a thermoelectric converter. Each module contains four 62.5-W(t) pellets of plutonium enclosed in protective layers of iridium and graphite.

DESIGN AND OPERATIONAL FLIGHT SAFETY PHILOSOPHY FOR NUCLEAR POWER SOURCES USED IN OUTER SPACE

For both types of nuclear power sources used in U. S. spacecraft, stringent design and operational flight safety measures are followed to protect the public and the environment under normal and postulated accident conditions. Hence the primary safety design objective is to minimize the potential interaction of the radioactive materials with Earth's population and environment so that exposure levels are within limits established by international standards. In the case of RTGs, this objective leads to a design philosophy of containment, immobilization, and recovery of the nuclear materials. Such a philosophy has been used by the United States in developing detailed design guidelines, and the United States has recommended this approach to the United Nations Working Group on the Use of Nuclear Power Sources in Outer Space.[5] (The Working Group, which was set up in 1978 as a result of the *Cosmos 954* accident, operates under the Scientific and Technical Subcommittee of the United Nations Committee on the Peaceful Uses of Outer Space.) As an example of the implementation of this philosophy, the fuel form for a radioisotope power supply would be selected to have minimal biological effects and its container would be environmentally qualified. In addition to the avoidance of accident consequences which include acute radiation exposure to individuals, the safety emphasis for reactors should generally be on maintaining a subcritical configuration in all credible accident environments so that no fission products are generated and released in the event of postulated core damage.[5]

The present operational philosophy, which has been adopted for orbital missions using either type of nuclear power source, requires the normal orbital lifetime to be long enough to allow for radioactive decay of the fuel or reactor fission products to a safe level (i.e., essentially background level) prior to a postulated reentry to Earth. This philosophy recog-

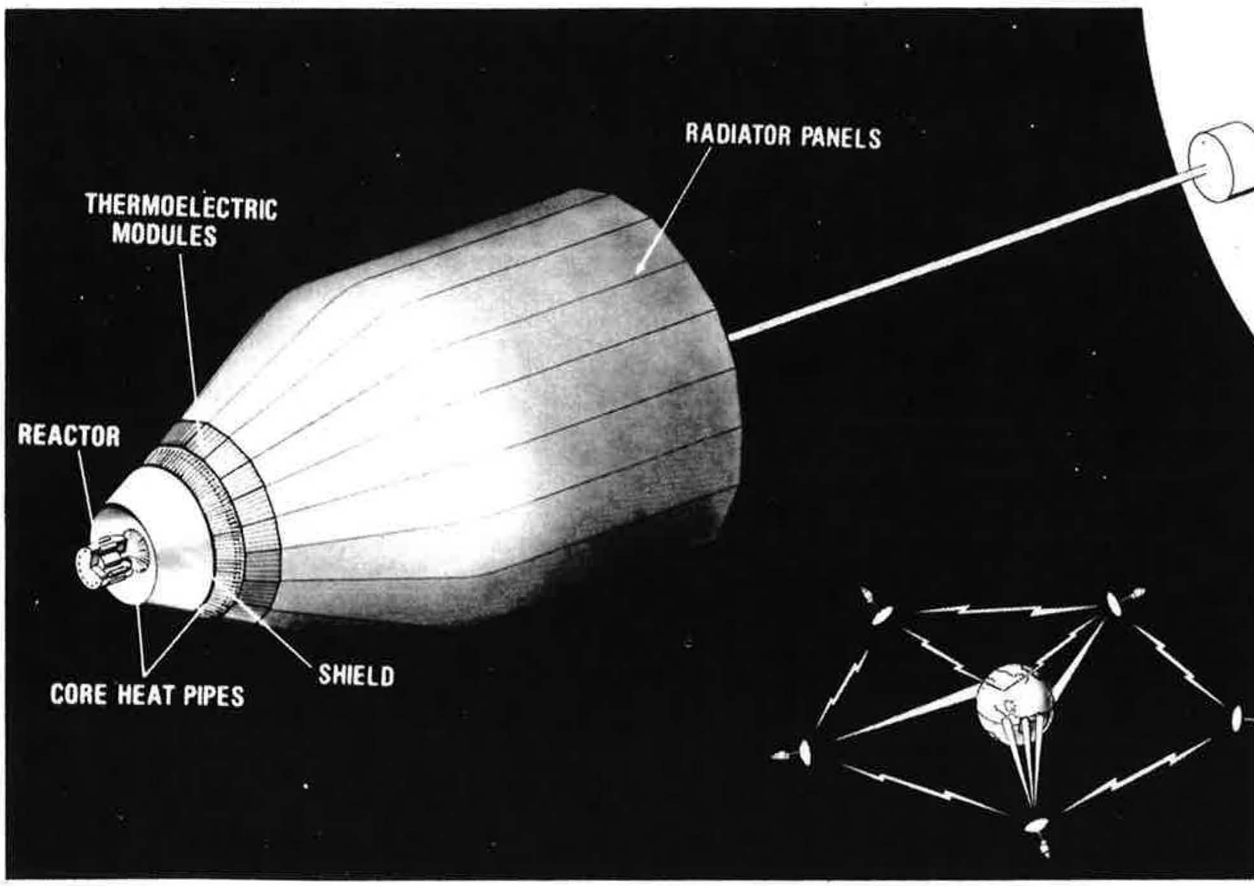


Fig. 4 Space Power Advanced Reactor (SPAR) power plant.

nizes, however, that planetary missions frequently must use low-altitude parking orbits from which to launch the spacecraft into deep space or high orbit trajectories.

In the only launch to date of a nuclear reactor by the United States (the SNAP-10A in 1965), the foregoing operational philosophy was implemented as follows: launch the appropriately shielded reactor in a subcritical mode, design it to prevent criticality at or after impact should the subcritical reactor reenter before startup, and delay startup until the spacecraft achieves an Earth orbit (or flight path) of sufficient duration to provide time for fission-product decay. The SNAP-10A was boosted to a 4000-yr orbit before startup of the reactor was initiated. The U. S. working paper[5] notes that "if reactors are intended for use in short-duration orbits, the safety assessment should include the duration of reactor operation [and] the duration of the orbit (both of which govern the available fission-product inventory) along with a probabilistic risk analysis of the type of reentry and ultimate disposal."

SPACE NUCLEAR SAFETY ANALYSIS*

Both types of nuclear power sources must, in all credible circumstances, be capable of controlling the radioactive materials so that, should the material ever reach Earth, the radiological risk would conform to recommended international limits.[5] Because even the most reliable systems pose a finite failure probability, the United States requires that the accident probability analyses as well as population dose and health effect analyses be completed prior to launch. These evaluations, which are independently reviewed by an Interagency Nuclear Safety Review Panel (INSRP), lead to a safety risk index which, when compared to mission benefits, provides a means for establishing flight approval criteria.

The U. S. space nuclear safety program pioneered the use of probabilistic risk analysis techniques to assess the safety of nuclear power sources. Risk

*This section follows Ref. 6 quite closely.

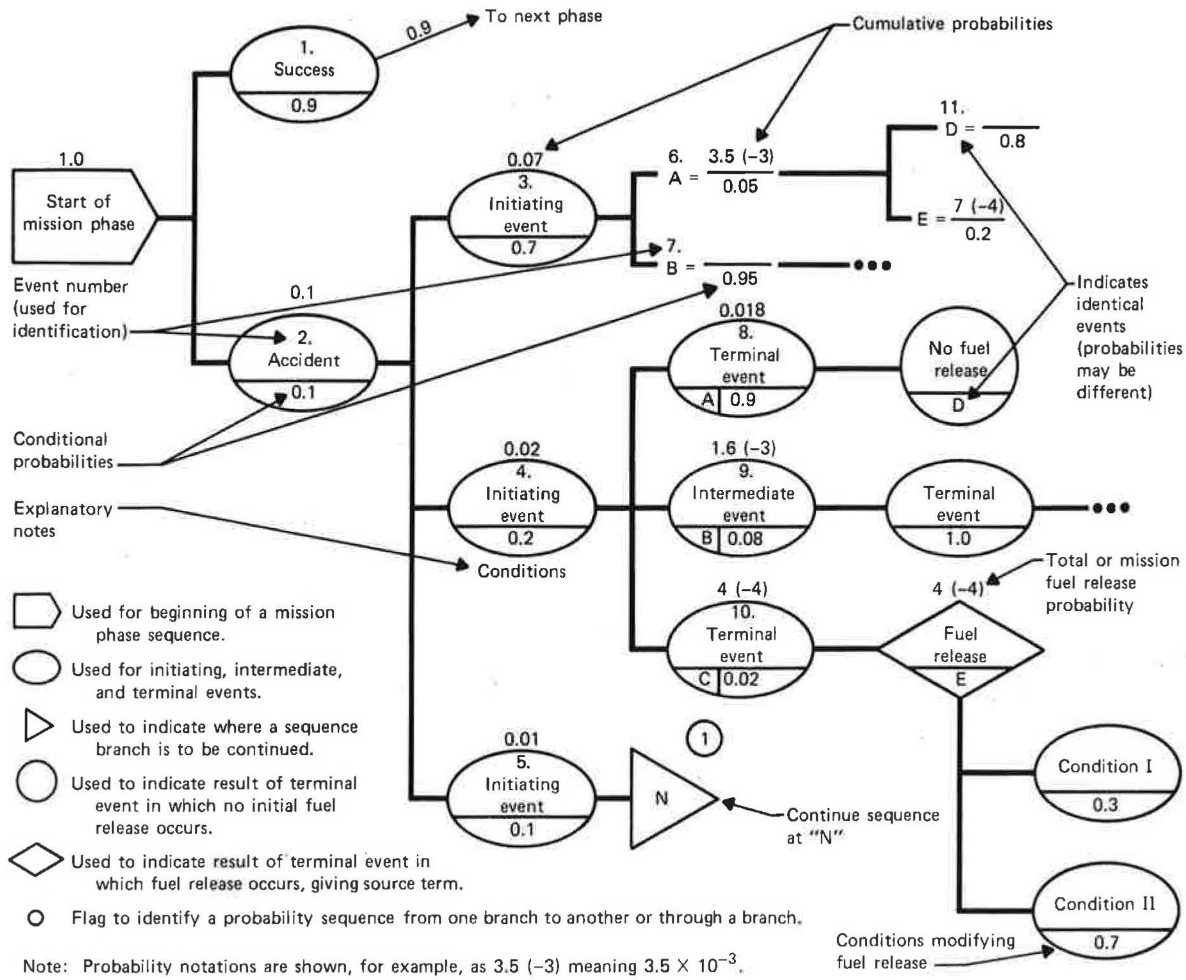


Fig. 5 Explanation of sequence tree construction and features.

analysis, as used in this context, refers to a quantitative assessment of the potential for human exposure to radiation* resulting from the use of a nuclear power source in a space application. The analysis consists of three basic steps: (1) determination of mission events having the potential for causing human exposure to radiation and their occurrence probabilities; (2) determination of the consequences of those events, in terms of the number of persons that could be exposed at various levels of exposure; and (3) evaluation of the nuclear system on the basis of the combination of steps 1 and 2 (Ref. 6). These three steps are discussed in more detail in the following sections.

*Exposure in this context refers to radiation exposure in excess of natural background radiation.

Events Having the Potential for Causing Human Exposure to Radiation

In general, each nuclear power source is analyzed with regard to its application to a particular mission. For a given mission the specific phases (e.g., prelaunch transportation and handling, launch, ascent, and final operation) must be defined so that normal procedures and mission events may be systematically analyzed to determine the results of an abnormal event.

The systematic analysis of each phase begins with an analysis of abort or failure modes with the objective of identifying potential single or multiple malfunctions that can potentially affect the nuclear power source during the complete mission. An explanation of the failure and abort sequence tree, which is a logic diagram used to develop the analysis, is shown in Fig. 5. In the case of the launch vehicle, the failure analysis includes the condition of the vehicle after failure and also the occurrence probability for that condition. For each of the vehicle conditions defined in the analysis, a sequence of adverse environments is defined, and this is followed by an evaluation of the response of the nuclear power source to each of the adverse environment sequences. If the analysis of an extreme environment shows that there is a potential for a fuel release, the occurrence probability can be determined from the interrelation of the failure analysis and sequence tree construction.

To evaluate the consequences of these events, the analyst must define the source terms. Within the context of space nuclear safety, a source term is the quantity of fuel which may be uncontrolled. In describing a source term, the analyst must consider its state (e.g., particle-size distribution, chemical form if changed from its original form, and degree of containment) and its location (e.g., at high altitude, on land, or in water; latitude and longitude; or random deposition during reentry from a specified orbit). Experiments conducted at the Los Alamos National Laboratory and Sandia National Laboratories define the response of nuclear power sources to postulated accident environments, including the condition of the fuel for source-term analyses.

When the first step of the risk analysis is completed, the analyst develops a series of specific nonnominal events that are postulated, with an associated probability of occurrence, to generate a known source term. The next step is to evaluate the consequences of the source terms.

Consequences of Events Having the Potential for Causing Human Exposure to Radiation

To determine the potential consequences of each of the source terms postulated in the first step of the risk analysis, the analyst estimates the environmental dispersion and the subsequent human uptake.

The *Overall Safety Manual*[6] contains technical models that may be used to analyze environmental dispersion and dose commitments. These models include meteorological, demographic, and Earth surface data. Combining the demographic data (telling how many people are located at what distance from a postulated release), the meteorological data (telling the dispersion characteristics and their frequencies of occurrence), and the dose models enables the analyst to approximate the number of persons that may receive a particular dose commitment as a result of a postulated release, including the probabilities associated with those potential exposures.

Nuclear System Evaluation

The third step in the risk analysis is to combine the results of the first two steps and assess the potential risks for the given mission.

The occurrence probability for each potential exposure event and the probable number of persons exposed at reference levels of dose commitment can be combined to generate the exposure expectation (and consequences or health effects) for each event of each mission phase. That is, the expected number of persons exposed at the reference dose levels, or greater, for each mission phase is given by

$$\langle N \rangle_{k,D_{\mathrm{ref}}} = \sum_i P_i \sum_j (p_{j/i}\, n_{j/i})_{D_{\mathrm{ref}}}$$

where $\langle N \rangle_{k,D_{\mathrm{ref}}}$ = expected number of persons exposed at a reference dose commitment level D_{ref} or greater for the kth mission phase

P_i = the probability of occurrence of the ith potential exposure event of mission phase k

$p_{j/i}$ = the frequency of occurrence of the jth set of environmental dispersion characteristics that may occur subsequent to the ith potential exposure event

$n_{j/i}$ = the number of persons exposed at the reference dose commitment level D_{ref} as a result of the jth set of environmental dispersion characteristics acting on the source term created by the ith potential exposure event

For each mission phase, $\langle N \rangle_{k,D_{\mathrm{ref}}}$ is determined for several values of D_{ref}, which may include organ doses from inhalation and ingestion and whole-body doses for external exposures. The overall mission risk may be determined from the probabilistically weighted consequences calculated for the mission.

SPACE NUCLEAR SAFETY REVIEW

Safety Analysis Reports

The United States requires that each space mission involving a nuclear power source be analyzed to assess the potential radiological risk of the mission to the world's population. These safety analyses begin at the initiation of the design concept and continue through the launch safety approval process. They are reported

Table 2 Contents of Safety Analysis Reports

Reference Design Document
Description of:
- —Mission and flight system summary
- —Nuclear power source (including type of fuel, design requirements, materials and their properties, radiation properties, power conversion subsystem, and ground support equipment)
- —Spacecraft (including location and attachment of the nuclear power source)
- —Mission profile
- —Launch vehicle (including flight safety and tracking)
- —Reference trajectory and flight characteristics (including launch conditions)
- —Launch site (including demographic, topographic, and meteorological characteristics)
- —Range and radiological safety

Accident Model Document
Description of:
- —Summary of mission and flight system
- —Accident and radiological models and data (including test data that support the analysis)
- —Vehicle and nuclear power source failure mode analysis (including prelaunch, launch, ascent, and space operation, with a description of the potential accident environment and flight contingency options)
- —Nuclear power source response-to-accident environments (including prelaunch, launch, ascent, reentry, breakup, impact, and postimpact—both land and water)
- —Mission failure evaluation (includes accident probabilities and quantity of radioactive material potentially released)

Nuclear Risk Analysis Document
A probabilistic description of the potential radiological risk to the world's population resulting from potential accidents which could involve the nuclear power source of a spacecraft

at a minimum of three major times during the development and fabrication of the nuclear power source.

The first of these reports, the Preliminary Safety Analysis Report (PSAR), is issued soon after a design concept is selected for a given mission. The PSAR includes a description of the nuclear power source and the mission as well as probabilistic radiological risk assessments as supported by the available conceptual design data base. The second report, the Updated Safety Analysis Report (USAR), is issued as soon as practical after the power system 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 third report, the Final Safety Analysis Report (FSAR), is normally issued about 1 yr 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 analysis tests.

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

In general, the safety analysis reports consider the following types of accident environments* (categorized by mission phase):

Prelaunch, Launch, and Ascent Phases:
- —Explosion overpressure.
- —Projectile impact.
- —Land or water impact.
- —Liquid propellant fire.
- —Solid propellant fire.
- —Sequential combination of the above.

Oribit and/or Flight Trajectory Phases:
- —Reentry.
- —Land or water impact.
- —Postimpact environment (land or water).

On-orbit contingency options (including retrieval) are considered as appropriate.

*Safety and safeguards in the fabrication, assembly, testing, handling, and transportation of the nuclear power source prior to the prelaunch phase are provided by normal DOE operational safety requirements and orders (e.g., surveys, reviews and approval of facilities, procedures, personnel, equipment, and emergency plans).

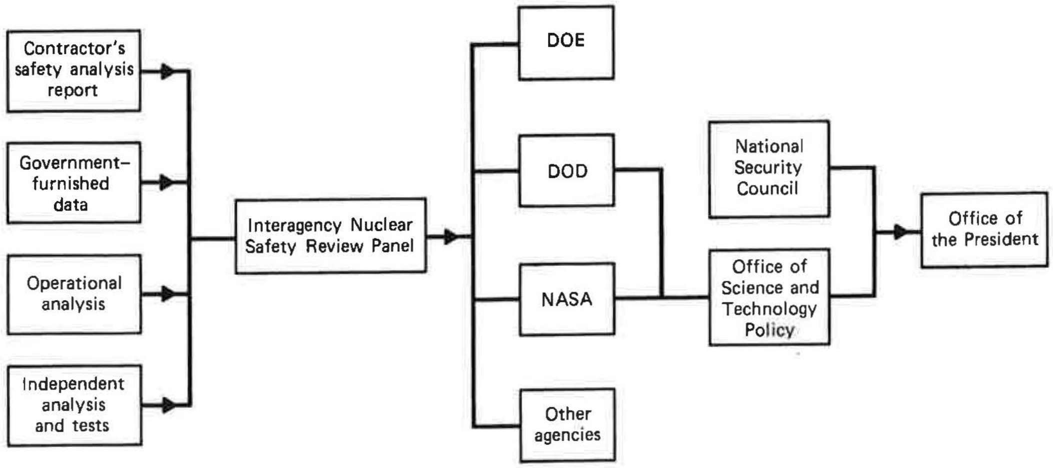


Fig. 6 Safety review and launch approval process.

Interagency Nuclear Safety Review Panel*

Every nuclear power source that is considered for use in a space application by the United States undergoes a safety review to establish that the risks associated with its use are commensurate with the benefits derived from its use. This review is undertaken and coordinated by an INSRP chaired by three coordinators appointed by the Secretary of the Department of Defense (DOD), the Administrator of NASA, and the Secretary of DOE. DOD and NASA personnel are involved because these two agencies have safety responsibilities and expertise both as launching organizations and as users of nuclear power sources for spacecraft. The DOE has responsibility for the safety of the nuclear power sources which it designs and produces for use in outer space. The Nuclear Regulatory Commission (NRC), the Environmental Protection Agency (EPA), and the National Oceanic and Atmospheric Administration (NOAA) also participate in these reviews. The INSRP was established in the mid-1960s to provide a review process for space launches involving nuclear material, and this approach has the following advantages:[7]

1. Expertise common to a specific participating agency can be made available to the other agencies, thereby eliminating possible duplication of effort.

2. At least one coordinator will not be involved in agency sponsorship of the mission nor will the representatives from EPA, NOAA, and NRC; therefore their participation will permit an objective approach and enhance the independence of the review.

3. It produces an environment conducive to the free and timely flow of information.

4. A unified nuclear risk assessment is provided for the mission approval process of the three agencies and higher approval authorities.

The safety review process begins with the submission of a Safety Analysis Report (SAR) by the nuclear power source developer. Approximately 100 scientists and engineers from a number of government agencies, laboratories, and universities assist in the review. These specialists evaluate the SAR and provide independent calculations and tests as required for INSRP considerations. The INSRP coordinators issue an independent nuclear risk assessment in the form of a Safety Evaluation Report (SER). This risk assessment considers the potential human exposures to radiation and the probabilities of exposure for all phases of the proposed mission. In addition to the calculated risks, the potential environmental impact of the mission or series of missions is assessed as an activity separate from the risk analysis.

Figure 6 depicts the generalized sequence of events in the flight safety review process. Recommendation for flight approval constitutes the affirmative judgment of the overall risk–benefit evaluation by DOE, DOD, NASA, and other agencies of the U. S. Government.

With respect to the international aspects of approval, it should be noted that in its 1981 report[8] the United Nations Working Group on the Use of Nuclear Power Sources in Outer Space (of which the United States is an active participant) stated that "the Working

*This section follows Ref. 7 quite closely.

Group reaffirmed its previous conclusion that nuclear power sources can be used safely in outer space, provided that all necessary safety requirements are met."

PROGRESS IN SYSTEM SAFETY*

Since its inception, the U. S. program for the utilization of nuclear power in outer space has placed great emphasis on the safety of the public and protection of the environment. A continuing primary objective of RTG safety has been to design nuclear power sources to safely contain or immobilize the nuclear fuel under all normal operating and potential accident conditions to avoid undue risks.

The earlier nuclear power sources through SNAP-9A were designed to contain the fuel if the mission were aborted on the launch pad or during early ascent but to permit complete burnup of the fuel in the stratosphere. Worldwide dispersion and dilution of the fine nuclear fuel particles would preclude local contamination. *Transit 5BN-3,* with a SNAP-9A power source, was launched on Apr. 21, 1964, but failed to achieve orbit and reentered the atmosphere over the ocean east of Africa. The RTG burned up on reentry, as it was designed to do. High-altitude atmospheric sampling data confirmed that the nuclear fuel did indeed burn up on reentry and that it was dispersed worldwide. The quantity of nuclear fuel particles that subsequently returned to Earth is insignificant compared to the existing ^{238}Pu settlement from earlier weapons tests.

All U. S. RTGs following SNAP-9A were designed to contain or immobilize the nuclear material through all credible accident conditions, including reentry and impact on Earth. In support of this requirement, rigorous quality assurance and ground testing activities are pursued for each mission assignment. These tests have included exposure of experimental hardware to such environments as aerodynamic heating, explosions, projectiles, impact, and propellant fires as well as land and water exposure. To verify the accomplishment of such safety-related efforts, a comprehensive interagency safety review, involving the best available expertise, is regularly conducted before soliciting launch approval for the mission (see preceding sections). Prior to launch, personnel from the cooperating agencies and their specialized contractor staffs who are experienced in the disciplines of operational safety and health physics assemble at the launch site to respond to any radiological emergency that might result from a potential malfunction.

In further support of these safety considerations, a worldwide high-altitude aircraft and balloon sampling program is maintained (1) to evaluate changing atmospheric conditions, (2) to take background measurements resulting from past weapons tests, and (3) to verify the dispersal of nuclear fuel particles which may have resulted from the aborting of a prior mission and subsequent burnup of the nuclear power source.

As noted earlier, to further enhance safety assurance, an operational philosophy has been adopted with respect to orbital missions: namely, that the final orbital lifetime must be long enough to allow for radioactive decay of the radioisotope fuel or reactor fission products to a reasonably safe level before the spacecraft reenters Earth's atmosphere. This philosophy recognizes that planetary missions frequently must use a low-altitude parking orbit from which to launch the spacecraft on deep space trajectories.

The significance and value of the safety assurance measures which had been adopted early in the program were substantiated in the following three events:

—SNAP-10A was successfully launched on *Snapshot* (a demonstration mission) on Apr. 3, 1965. The spacecraft was placed in a 4000-yr orbit, and the reactor was not started until this altitude was confirmed. The reactor operated for 43 days before experiencing a shutdown caused by a voltage regulator malfunction. At shutdown, the reactor contained a 2×10^5 Ci inventory. After 15 yr the inventory should decay to less than 100 Ci and after 100 yr to less than 0.1 Ci. At the estimated time of reentry, the radioactivity of the fission products will be insignificant.

—The NASA spacecraft *Nimbus-B1* was launched on May 18, 1968, but was aborted due to a guidance error. It was destroyed by the Range Safety Officer at an altitude of 30 km, and the radioisotope generators fell into the Santa Barbara Channel. Since these generators were designed for intact reentry and containment on impact, no nuclear fuel was released to the atmosphere or the ocean. The fuel capsules were recovered intact and were returned to fuel-processing facilities for recovery of the ^{238}Pu.

—The NASA spacecraft *Apollo-13* was damaged on the way to the moon after a successful launch on Apr. 11, 1970. The lunar module, with the fuel cask attached, reentered the atmosphere over the South Pacific. The effectiveness of the U. S. nuclear safety program was again demonstrated when the fuel cask landed in the ocean intact. It now rests in the

*This section follows Ref. 7 quite closely.

6-km-deep Tonga Trench. Postreentry surveys were made at all levels of the atmosphere downwind of the reentry area and confirmed that no nuclear fuel was released and that the nuclear fuel cask reentered intact as designed.

In summary, progress has been made in the U. S. space program to reduce the probability of release of radioactive fuel during normal operations and potential launch aborts. Because future spacecraft will require larger power sources with higher electric-power levels and larger fuel inventories, more stringent system safety requirements, increased hardware quality and reliability, and more sophisticated analytical and test methods to enhance the quality of risk assessments and source term evaluations are being developed and utilized.

CONCLUSIONS

The United States supports a rigorous space nuclear safety program which provides for the testing and analysis of nuclear power sources intended for use in outer space. Probabilistic risk analysis techniques are used to assess the safety of these nuclear power sources. A coordinated SER is used by decision makers in the launch approval process to evaluate the risks and benefits of a given nuclear-powered space mission.

REFERENCES

1. G. L. Bennett, J. J. Lombardo, and B. J. Rock, *Space Nuclear Electric Power Systems*, paper (AAS 80-220) presented at the 1980 Annual Meeting of the American Astronautical Society, Boston, Oct. 20–23, 1980 (to be published in Vol. 44 of *Advances in the Astronautical Sciences*). This paper lists a number of earlier documents on space nuclear power. Unfortunately, much of the seminal work has appeared only in internal memoranda and technical reports. A reasonably good overview of many of the actual and planned space nuclear electric-power sources may be obtained by reviewing the various annual proceedings of the Intersociety Energy Conversion Engineering conferences.
2. United States of America, *Uses of Radioactive (Nuclear) Materials by the United States of America for Space Power Generation*, working paper submitted by the U. S. to the United Nations Committee on the Peaceful Uses of Outer Space, U. N. Document A/AC.105/L.102, United Nations, New York, Mar. 15, 1978.
3. U. S. Department of Energy, *Fission Energy Program of the U. S. Department of Energy, FY 1981*, DOE Report DOE/NE-0006, NSIC, March 1980.
4. D. Buden, W. A. Ranken, and D. R. Koenig, *Space Nuclear Reactor Power Plants*, DOE Report LA-8223-MS, Los Alamos Scientific Laboratory, NTIS, January 1980.
5. United States of America, *Criteria for the Use of Nuclear Power Sources (NPS) in Outer Space*, working paper submitted by the U. S. to the United Nations Working Group on the Use of Nuclear Power Sources in Outer Space, U. N. Document A/AC.105/C.1/WG.V/L.8, United Nations, Jan. 23, 1980.
6. NUS Corporation, *Overall Safety Manual*, 4 vols., prepared for the U. S. Atomic Energy Commission, Space Nuclear Systems Division, 1974. (Currently being updated by NUS Corporation for the U. S. Department of Energy.)
7. United States of America, *Use of Nuclear Power Sources in Outer Space*, working paper submitted by the U. S. to the Scientific and Technical Subcommittee of the United Nations Committee on the Peaceful Uses of Outer Space, United Nations, New York, February 1979.
8. *Report of the Working Group on the Use of Nuclear Power Sources in Outer Space on the Work of Its Third Session*, Annex II of *Report of the Scientific and Technical Subcommittee on the Work of Its Eighteenth Session*, U. N. Document A/AC.105/287, Feb. 13, 1981.