Paper No. 900464
Preprint

SAFETY STATUS OF SPACE RADIOISOTOPE AND REACTOR POWER SOURCES

Gary L. Bennett

National Aeronautics and Space Administration
Propulsion, Power and Energy Division
Code RP
Washington, D. C. 20546

NASA

AIChE ANS SAE ACS AIAA ECS IEEE

25th Intersociety Energy Conversion Engineering Conference
"Twenty-Five Years of Progress and Future Prospects"

Bally's Hotel
Reno, Nevada
August 12–17, 1990

SAFETY STATUS OF SPACE RADIOISOTOPE AND REACTOR POWER SOURCES

Gary L. Bennett
National Aeronautics and Space Administration
Washington, D. C. 20546

ABSTRACT

The current overall safety criterion for both radioisotope and reactor power sources is containment or immobilization in the case of a reentry accident. In addition, reactors are to be designed to remain subcritical under conditions of land impact or water immersion. A very extensive safety test and analysis program was completed on the radioisotope thermoelectric generators (RTGs) in use on the *Galileo* spacecraft and planned for use on the *Ulysses* spacecraft. The results of this work show that the RTGs will pose little or no risk for any credible accident. The SP-100 space nuclear reactor program has begun addressing its safety criteria and the design is planned to be such as to ensure meeting the various safety criteria. Preliminary mission risk analyses on SP-100 show the expected value population dose from postulated accidents on the reference mission to be very small. The U. S. has an excellent record on space nuclear safety and the current nuclear power sources are the safest flown.

INTRODUCTION

Historically the United States has followed the practice of employing stringent design and operational flight safety measures to protect the public and the environment under normal and postulated accident conditions. The primary safety design objective is to minimize the potential interaction of the radioactive materials with Earth's population and environment. In the case of radioisotope thermoelectric generators (RTGs), this objective leads to a design philosophy of containment, immobilization, and recovery of the nuclear materials. For reactors, this objective leads to the requirement of not operating the reactor prior to achieving its planned operating orbit and ensuring a subcritical configuration under all credible accident environments so that no fission products are generated [1,2,3].

Each agency involved in the use of nuclear power sources (NPS) in space has its own regulations and, of course, there are overall Federal regulations regarding exposures to nuclear radiation. The U.S. practice is one of developing more detailed criteria, specifications and requirements in a top-down approach from these overall Federal regulations. Furthermore, the emphasis is on line management responsibility for safety with independent oversight at the various levels of line management. It cannot be emphasized enough that safety is the principal driver on the design of the nuclear heat source in NPS.

Finally, there is an overall flight safety review conducted by an independent Interagency Nuclear Safety Review Panel (INSRP) prior to the proposed launch of any NPS. The INSRP works under a presidential directive and agency guidelines to prepare a safety evaluation report (SER) that is submitted to the Office of the President as part of the launch approval request. The SER provides the necessary independent risk evaluation that will be used by decision-makers who must weigh the benefits of the mission against the potential risks [4].

The safety analysis and review process has a very practical aspect in that it provides information that can be used by contingency planners in responding to accidents that could occur. The U.S. has had three accidents involving NPS [2,3,4]:

- Failure of the Transit 5BN-3 navigational satellite with a SNAP-9A RTG to achieve orbit (21 April 1964). The SNAP-9A burned up and dispersed safely as designed
- Abort of the launch of the Nimbus-B1 meteorological satellite with two SNAP-19B RTGs (18 May 1968). The RTGs were recovered safely intact as designed.

- Damage of the Apollo 13 spacecraft after launch on 11 April 1970 leading to the intact reentry (as designed) of the SNAP-27 RTG fuel cask over the South Pacific on 17 April 1970.

A fourth incident affected the SNAP-10A reactor, which was successfully launched on 3 April 1965. Following approved guidelines the spacecraft was placed in a high-altitude orbit and the reactor was not started until this altitude was confirmed. The reactor operated for 43 days when a shutdown was safely effected following a malfunction of a voltage regulator on the spacecraft payload (not on the reactor) [5].

In each case cited, the NPS performed as they were designed to do and in no case did the NPS cause any spacecraft malfunctions. This successful performance testifies to the rigor of the U.S. flight safety process. Since 1961, the U.S. has successfully used 36 RTGs and one reactor as electrical power supplies in 21 space systems. (The interested reader is referred to Ref. 13 for an overview of the U.S. use of NPS.)

In providing a status report on RTG and space reactor safety the focus will be on the general-purpose heat source (GPHS) RTGs, which are in use on the *Galileo* spacecraft and planned for use on the *Ulysses* spacecraft, and the SP-100 space nuclear reactor because these are the current, ongoing programs.

GENERAL-PURPOSE HEAT SOURCE RADIOISOTOPE THERMOELECTRIC GENERATORS

The GPHS-RTG is a radioisotope-fueled, thermoelectric power source comprised of two major functional components: the thermoelectric converter and the radioisotope heat source. The GPHS-RTG is designed to provide a minimum of 285 We under initial space operational conditions for a thermal fuel loading of 4410 Wt. The GPHS-RTG system, shown in cutaway in Figure 1, has an overall radial envelope of 421.6 mm and axial envelope of 1140.5 mm with a mass of 55.90 kg [6].

The GPHS, shown in Figure 2, supplies the thermal power to the thermoelectric converter. The GPHS is comprised of rectangular parallelepiped modules, each having dimensions 93.17 mm by 97.18 mm by 53.08 mm, a mass of about 1.43 kg, and a thermal output of about 245 Wt. Each GPHS-RTG contains 18 independent GPHS modules stacked into a single column [7].

Safety considerations were key factors in the design of the GPHS. The modularity of the GPHS design reduces the potential source term from events such as projectile impacts. The smaller size of the modules in comparison to some of the earlier radioisotope heat sources means a reduced ballistic coefficient which in turn aids in reentry and impact performance. This compactness also facilitates testing of the GPHS. The plutonia fuel is high fired to in excess of 1700 K and so is expected to remain chemically stable if released into the environment. The post-impact containment shell (PICS) is made from an alloy of iridium which 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. Impact protection is provided by graphite impact shells machined from Fine-Weave Pierced Fabric (FWPF)™, a material originally developed by AVCO Corporation for reentry vehicle nose cones. A thermally insulating graphite sleeve made of Carbon-Bonded, Carbon Fiber (CBCF) fits between each graphite impact shell assembly and the aeroshell to control the temperature of the iridium during a postulated reentry/impact accident. The aeroshell, which is also made from FWPF™, is designed to protect the two graphite impact shell assemblies in each module from the severe aerothermodynamic environment that may be encountered during a postulated reentry [7].

The calculation of risk is done on the basis of the probability of occurrence of an event and the consequences of the event. The consequences are determined from the response of the NPS to the postulated accidents. In the case of the GPHS-RTG and its components the responses were determined by extensive testing and analyses. The tests accomplished to support the calculational models used in the accident analyses included [7,8,9]:

- Shock tube tests (12 total) up to 15.2 MPa static overpressure
- Bullet impact tests (8 total) up to 684 m/s impact speed
- Flyer plate tests (4 total) up to 1170 m/s
- Bare fueled clad impact tests (32 total) on steel, concrete and sand
- GPHS module impact tests (13 total) on concrete and steel
- Solid rocket booster (SRB) fragment

impact tests in a gas gun (5 total) and on a rocket sled (2 total)

- Fragment/fuselage tests (3 total) to determine the effect of fragment speed and rotation of a large fragment as it penetrates the Space Shuttle fuselage.
- Solid propellant fire test (temperatures above 2330 K)
- Drop tests and vertical wind tunnel tests for terminal velocity and subsonic motion
- Subsonic heating rate tests
- Static stability tests
- Subsonic aerodynamic measurements
- Low-speed wind tunnel tests
- High-speed aerodynamic tests
- Thermal stress tests
- Environmental transport/interaction tests

From the foregoing tests and the related analyses, the risk of flying the GPHS-RTGs has been shown to be vanishingly small [7,8,9]. The independent assessment provided by the INSRP SER concluded that "The risks to people from postulated accidents were either health-related (increased probability of cancer) or economic (loss of property or property value due to contamination). The cancer risk is from alpha-emitting Pu-238 incorporated into lung, bone, or liver. There are estimates in the scientific literature of risk to these organs from long-lived alpha particles of approximately the same energy which indicate that the organs have similar radiation sensitivities. As one method of placing the missions risks into perspective, it should be recalled that about 50-60 percent of the average annual background radiation doses in the United States are due to radon daughter product exposure. The remaining 40-50 percent are approximately evenly divided among internal radiation, cosmic radiation and terrestrial radiation. Typical annual individual doses are about 0.35 rem. Using a fatal cancer risk factor of 2E-4/rem, a lifetime risk of about 0.5 percent can be calculated to be attributed to background radiation. Thus, of the average person's fatal cancer risk of 20 percent, about 2.5 percent of this risk can be attributed to background radiation, half of which is due to alpha radiation.

"In the accident cases evaluated, the maximum individual fatal cancer risk increments have been calculated to be 9E-5 or less. Therefore, the Pu-238 dose resulting from accidental release would add no more than 0.009 percent risk to the nominal 20 percent risk of contracting a fatal cancer; i.e., raising the 20 percent to 20.009 percent" [10].

SP-100 SPACE REACTOR POWER SYSTEM

The SP-100 space reactor power system (SRPS) is a reactor-powered thermoelectric power source comprised of two major functional components: a compact, high-temperature (>1300 K), fast-spectrum reactor power assembly (RPA) to produce thermal power and a thermoelectric energy conversion assembly (ECA) to convert the thermal power to electrical power. Using thermoelectric conversion the SRPS produces 100 kWe but with the inclusion of dynamic conversion higher power levels (~1000 kWe) are possible. The SRPS is shown in Figure 3 along with a diagram of the RPA core. The overall length, including the extension boom that couples the RPA and ECA is about 23 m. The equivalent core diameter is 325 mm and the reactor vessel outer diameter is 357 mm. Including the radial reflectors takes the outer diameter to 551 mm. The mass depends on the mission and can be on the order of 4000 kg [11].

The RPA contains the 2.4-MWt liquid metal (lithium) reactor, a radiation shield to minimize the dose at the payload, 12 hinged beryllia (BeO) control drives, the auxiliary cooling loop (ACL) that is designed to remove heat in the event that the primary system loses its coolant, reactor instrumentation and controls (I&C) multiplexers, a structural interface ring for mating to the ECA, and a reentry heat shield to provide for intact reentry and effective burial of the reactor during a postulated reentry accident. (Effective burial is defined to mean that the fuel, the reactor vessel and its internal components are within the formed impact crater and are below normal grade level.) The reactor core contains 984 fuel pins containing uranium nitride (UN) pellets. The cladding for the fuel pins is PWC-11 which is separated from the UN pellets by a bonded rhenium liner. Seven boron carbide (B_4C) safety rods are inserted in the core during all prelaunch, launch and ascent operations to ensure subcriticality during postulated accidents. The safety rods are withdrawn after the operational orbit is achieved but they can be inserted again on demand or after completion of the mission [11].

As in the case of the RTGs, safety has been the principal driver on the design of the RPA.

Consistent with overall U.S. safety criteria, the reactor is designed to prevent inadvertent criticality during handling or in accident situations (such as postulated fires, core compaction, projectile impacts, overpressure, and immersion/flooding). Criticality is prevented by two separate features [12]:

- The RPA safety rods and reflector control elements are physically locked in their shutdown positions until final orbit acquisition. Two independent signals are required to release the rods and elements. Either the safety rods or the reflector elements can be used to shut down the reactor (at beginning of mission [BOM] opening any 7 of 12 reflectors or inserting any 1 of 7 safety rods will shut down the reactor).
- The RPA has a large shutdown reactivity margin which is aided by the neutron-absorbing rhenium liner.

Bumpers protect the reactor against impacts of micrometeoroid and orbital debris. Should a piece of debris manage to penetrate the bumpers and cause a loss of coolant the reactor will shut down safely and automatically and radiate the decay heat. Similarly, a loss of electrical power to the control system will cause the spring-actuated reflector elements and safety rods to move to their shutdown positions.

The keys to SP-100 safety may be summarized as:

- The reactor is launched "cold" (i.e., no radioactive fission products and nonoperating)
- The reactor is designed to prevent accidental startup during launch and ascent
- The reactor is started only after achieving the operating orbit
- The reactor is designed to remain in a safe condition even under accident situations
- The reactor is intended to remain in space after startup and it will be designed such that it can be transferred to a high permanent storage orbit at end of mission (EOM)
- Even though the reactor is designed for a high storage orbit, for additional margin, the reactor has been designed to survive postulated accidental reentries and impact

The following general kinds of safety tests are planned to address the various safety issues:

- Explosion tests (including flyer plates and shrapnel)
- Impact tests
- Additional critical tests to assess various water and soil immersion events
- Solid propellant fire tests
- Loss-of-coolant accident test with electrically heated full model
- Arc-heated wind tunnel tests for reentry simulations

In a recent presentation on the mission risk analysis (MRA) for the SP-100 reference mission it was concluded that the radiological risk from space nuclear power systems can be made very small. Specifically it was concluded that [12]:

- The expected value population dose calculated in the SP-100 MRA is .05 person-rem, which is very small compared to the 1.5 billion person-rem per year from natural radiation
- The probability of large individual doses is small. The calculated probability of an individual receiving more than 100 mrem is 1×10^{-12}

CONCLUSIONS

Safety is the driving force in the design of the nuclear heat sources in U. S. RTG and reactor programs. The key NPS safety design requirements and design features have been identified through years of analysis and testing. These safety design features have been incorporated into the NPS designs. In the case of the GPHS-RTG and the SP-100 SRPS the risks from postulated accidents are for all practical purposes essentially zero.

REFERENCES

[1] United States of America, "Criteria for the Use of Nuclear Power Sources (NPS) in Outer Space," working paper submitted by the United States 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, 23 January 1980.

[2] G. L. Bennett, "Overview of the U. S. Flight

Safety Process for Space Nuclear Power," Nuclear Safety, (22)4: 423-434, July-August 1981.
[3] G. L. Bennett, "Flight Safety Review Process for Space Nuclear Power Sources," paper number 879046, Proceedings of the 22nd Intersociety Energy Conversion Engineering Conference, 10-14 August 1987, Philadelphia, Pennsylvania.
[4] G. L. Bennett, "The Safety Review and Approval Process for Space Nuclear Power Sources," paper in preparation for Nuclear Safety.
[5] G. L. Bennett, "On the Application of Nuclear Fission to Space Power," in 50 Years with Nuclear Fission, American Nuclear Society, La Grange Park, Illinois (1989).
[6] G. L. Bennett, C. W. Whitmore, and W. R. Amos, "On the Development of the Power Sources for the Ulysses and Galileo Missions," Proceedings of the European Space Power Conference held in Madrid, Spain, 2-6 October 1989 (European Space Agency publication ESA SP-294, August 1989).
[7] G. L. Bennett, et al. "Development and Implementation of a Space Nuclear Safety Program," in Space Nuclear Power Systems 1987, Orbit Book Co., Malabar, Florida.
[8] G. L. Bennett, et al., "Update to the Safety Program for the General-Purpose Heat Source Radioisotope Thermoelectric Generator for the Galileo and Ulysses Missions," in Space Nuclear Power Systems 1988 (in press), Orbit Book Co., Malabar, Florida.
[9] General Electric Co. and NUS Corp., Final Safety Analysis Report for the Ulysses Mission, (6 documents numbered ULS-FSAR-001 to ULS-FSAR-006), General Electric Company, King-of-Prussia, Pennsylvania and NUS Corporation, Gaithersburg, Maryland (March 1990).
[10] R. C. Nelson, L. B. Gray, and D. A. Huff, "The Interagency Nuclear Safety Review Panel's Galileo Safety Evaluation Report," in Proceedings of the Seventh Symposium on Space Nuclear Power Systems, CONF-900109, held in Albuquerque, New Mexico, 7-10 January 1990.
[11] P. R. Pluta, M. A. Smith, and D. N. Matteo, "SP-100, A Flexible Technology for Space Power from 10s to 100s of KWe," paper number 899287 in Proceedings of the 24th Intersociety Energy Conversion Engineering Conference, held in Crystal City, Virginia, 6-11 August 1989.
[12] D. R. Damon, M. I. Temme, and N. W. Brown, "SP-100 Mission Risk Analysis," paper presented at the Seventh Symposium on Space Nuclear Power Systems, held in Albuquerque, New Mexico, 7-10 January 1990.
[13] G. L. Bennett, "Historical Overview of the US Use of Space Nuclear Power," paper number IAF-ICOSP89-9-1 in Space Power 8(3) 1989.

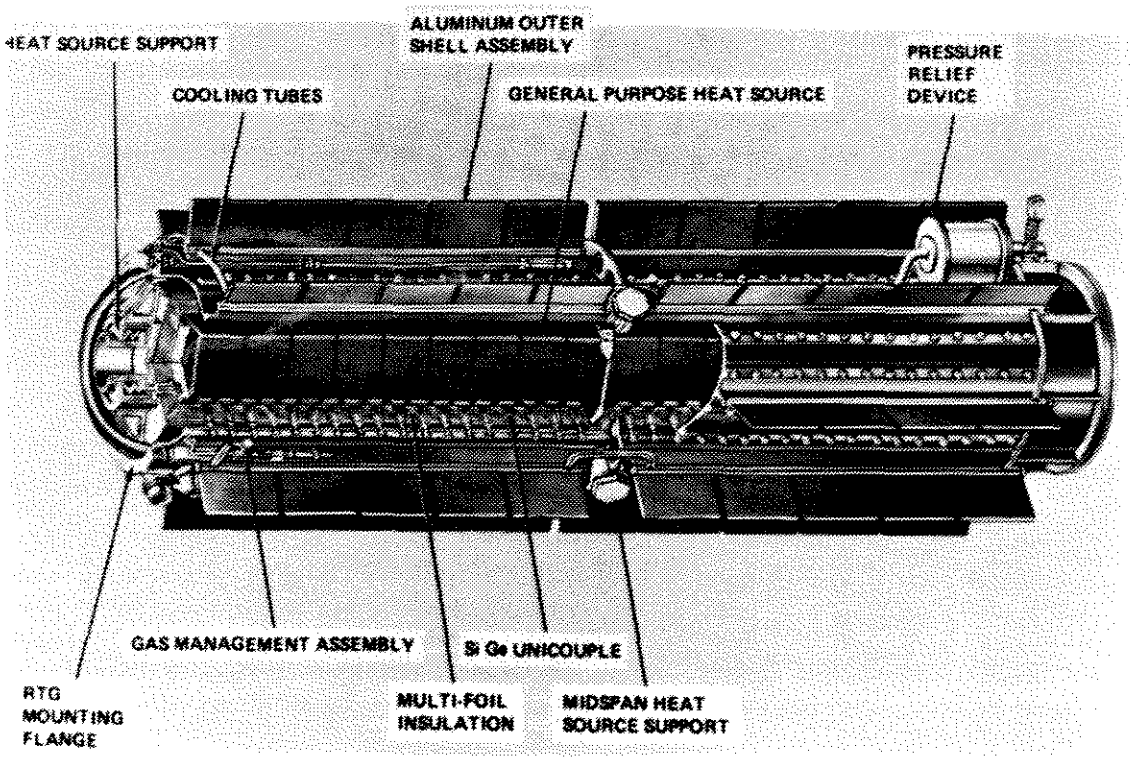

Figure 1: Cutaway of the General Purpose Heat Source Radioisotope Thermoelectric Generator

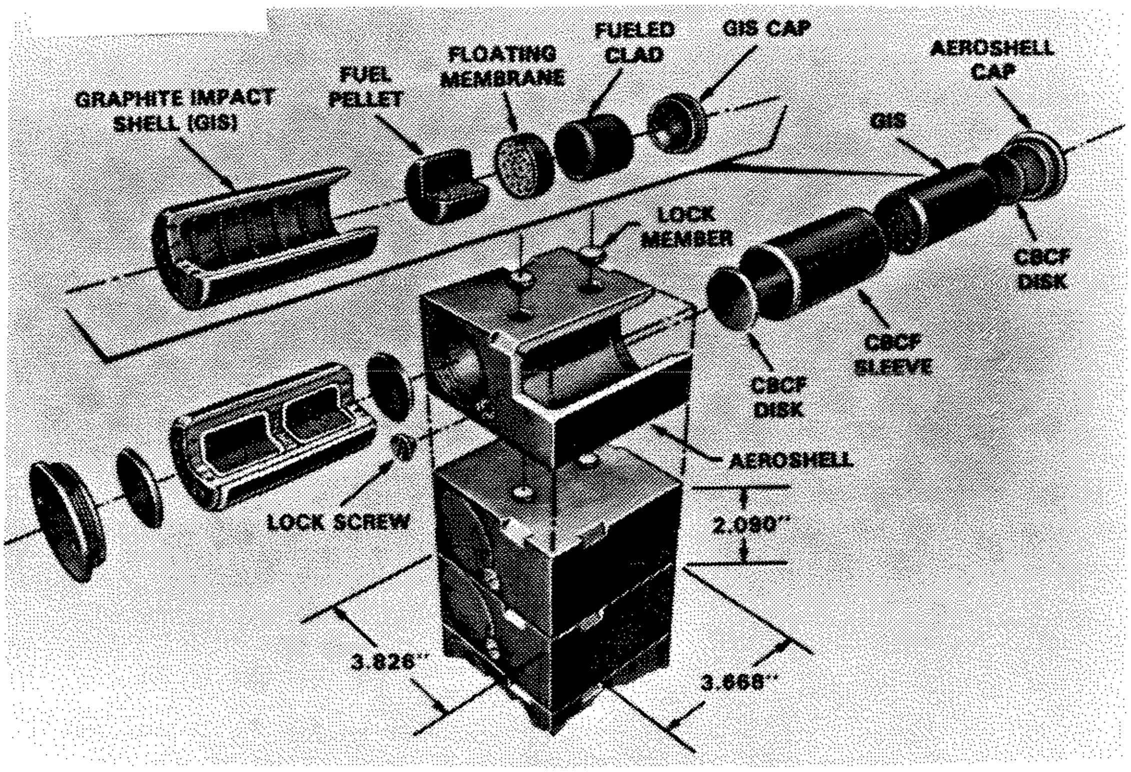

Figure 2: Cutaway of the General Purpose Heat Source RTG.
Note the Safety Features

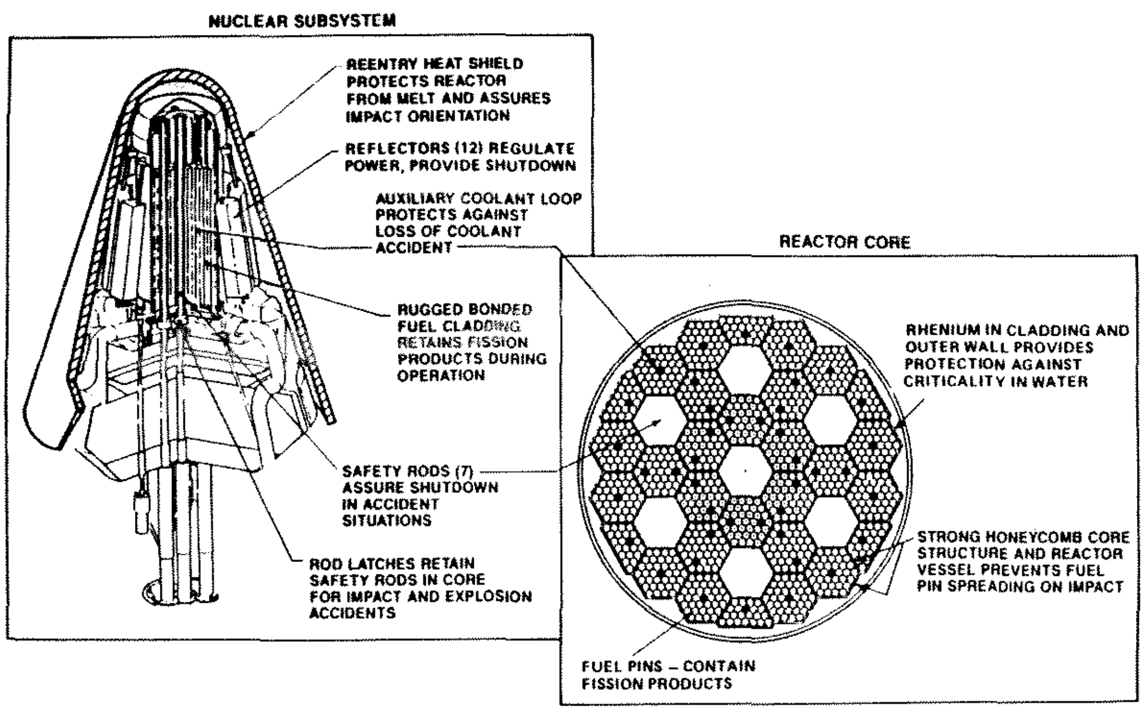

Figure 3: Cutaway of SP-100 Reactor Power Assembly Showing the Safety Features